HiggsBounds 3.x.x and the HiggsSignals extension: status and prospects

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http://higgsbounds.hepforge.org/

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HiggsBounds - a program's portrait

HIGGSBOUNDS

- *Current version*: `HiggsBounds 3.8.0` (released 15th May)
- *Code language*: `Fortran90/2003` and `Fortran77` (*until* `HB 3.7.0`)
- *First release*: Feb. 2009
- *Authors*: P. Bechtle, O. Brein ('09-'12), S. Heinemeyer, O. Stål ('12-now), T. Stefaniak ('11-now), G. Weiglein, K. E. Williams ('09-'11)
- *Website*: http://higgsbounds.hepforge.org/ (with *online version*)
- *Short description*: `HiggsBounds` confronts arbitrary Higgs sectors with exclusion limits from direct Higgs searches at LEP, Tevatron and LHC.
- *References:*
  Comput. Phys. Commun. **181** (2010) 138, [arXiv:0811.4169 [hep-ph]];
  Comput. Phys. Commun. **182** (2011) 2605, [arXiv:1102.1898 [hep-ph]].

Outline

1. HiggsBounds
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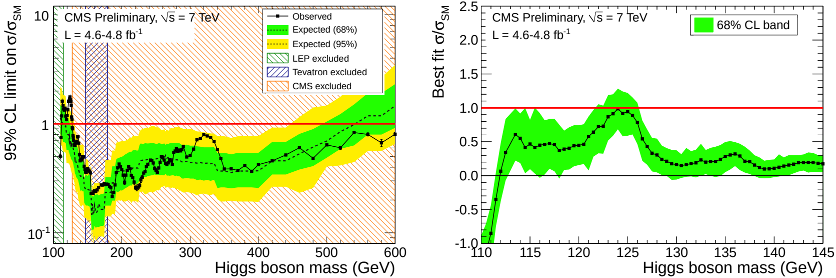
   - The HiggsBounds program
   - An improved model likeness test
   - Example applications
   - Summary
2. HiggsSignals extension
   - Motivation and basic idea
   - Planned features
   - Summary

Part I:

HiggsBounds

Introduction

- Past and present collider searches have not yet discovered a Higgs boson. (however, there are hints at the LHC → *second part of the talk*)



- Negative search results lead to exclusions (*i.e.* upper limits on the signal rate) ⇒ restricts the parameter space of Higgs models.
- *even after a discovery:* exclusion limits are still important to constrain other possible Higgs bosons.

Higgs searches

Results from Higgs searches are presented in two types:

Model-dependent results

The analysis has been carried out in the context of a particular model (*e.g.* the Standard Model (SM)).

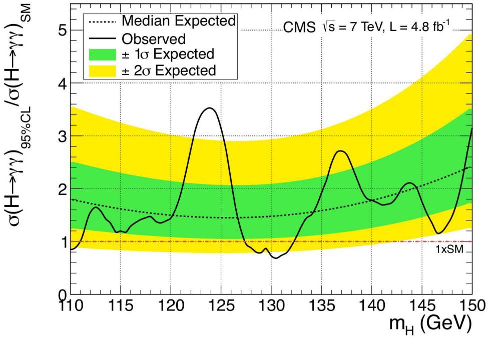
- Typically uses lots of search topologies, assuming their signal rates (*i.e.* cross section $\sigma \times$ branching ratio $\mathcal{B}$) to be *model-like* (*i.e.* scaled by universal factor).
- Upper limit on the universal scale factor, the signal strength modifier μ.
- not easily applicable to other models, need a *model-likeness test*.

Model-independent results

The analysis has been carried out for one particular signal topology.

- *E.g.* the LEP search $e^+e^- \to (h_i)Z \to (b\bar{b})Z$
- Limits on the signal rate.
- Applies to lots of models.

Example of model-dependent limits: Standard Model

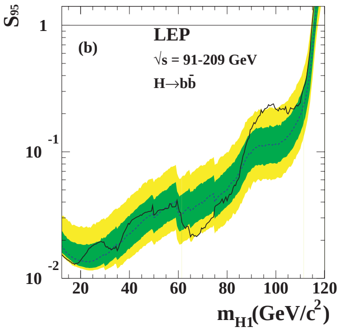


- CMS search for $(\mathrm{singleH},\ \mathrm{vbf},\ HZ,\ HW,\ t\bar{t}H)_{SM} \times (H \to \gamma\gamma)$ [arXiv:1202.1487]
- the signal strength modifier is given by

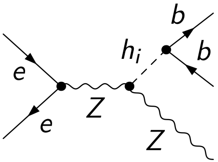
$$\mu = \frac{\sigma(\mathrm{singleH}) \times \mathcal{B}(H \to \gamma\gamma)}{\sigma(\mathrm{singleH})_{SM} \times \mathcal{B}(H \to \gamma\gamma)_{SM}} = \frac{\sigma(\mathrm{vbf}) \times \mathcal{B}(H \to \gamma\gamma)}{\sigma(\mathrm{vbf})_{SM} \times \mathcal{B}(H \to \gamma\gamma)_{SM}} = \ldots$$

- If the limit on μ is less than 1, the SM Higgs is excluded.

Example of a model-independent signal rate limit



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

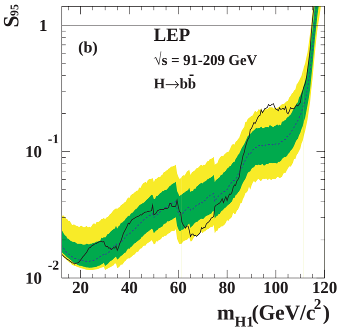


S_{95} is the maximum signal rate compatible with the data at 95% CL, normalized to the LEP SM signal rate.

Solid line: observed limit

Dashed line: expected for background

Example of a model-independent signal rate limit



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

How to use these limits:

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

$$\mu = \frac{\sigma(e^- e^+ \to h_i Z) \times \mathcal{B}(h_i \to b\bar{b})}{\sigma(e^- e^+ \to h_i Z)_{SM} \times \mathcal{B}(h_i \to b\bar{b})_{SM}}$$

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

2. If $\mu > S_{95}^{\mathrm{obs}}$, then this parameter point is excluded at 95% C.L..

Using more than one exclusion limit

When using more than one exclusion limit, care needs to be taken to ensure that the exclusion is still at 95% C.L..

1. Calculate μ^{pred} for each search channel.
2. Determine which search channel has the highest statistical sensitivity, *i.e.* which search channel has the largest $\mu^{\mathrm{pred}}/S_{95}^{\mathrm{exp}}$, using the expected limits based on simulations with no signal (*dashed line*).
3. Compare μ^{pred} and S_{95}^{obs} for this channel only. If $\mu^{\mathrm{pred}}/S_{95}^{\mathrm{obs}} > 1$, then parameter point is excluded at 95% C.L..

The HiggsBounds program

- HiggsBounds contains the *most recent exclusion limits* from neutral Higgs and charged Higgs searches at the LEP, Tevatron and LHC.
- It can be applied to arbitrary Higgs models with up to 9 neutral and/or charged Higgs bosons.
- There are different possibilities to use HiggsBounds:
  - the online-version on http://higgsbounds.hepforge.org/,
  - the command line version,
  - the library of subroutines.
- User has to provide as input:
  - Higgs masses and widths,
  - normalized Higgs production cross sections,
  - Higgs branching ratios, t-quark branching ratios

  This can be done at hadronic level, parton level, via effective couplings or via SLHA (*needs two extra blocks for effective couplings*).
- Narrow width approximation must be applicable.

Interfaces to HiggsBounds

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

- **FeynHiggs*** [T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein, K. E. Williams] for the MSSM

  → see Thomas' talk.

- **CPsuperH*** [(J. S. Lee, A. Pilaftsis, M. Carena, S. Y. Choi, M. Drees, J. Ellis, C. Wagner)] for the complex MSSM
- **2HDMC†** [D. Eriksson, J, Rathsman, O. Stål] for Two-Higgs-Doublet-Models
- **DarkSUSY†** [P. Gondolo, J. Edsjö, P. Ullio, L. Bergström, M. Schelke, E.A. Baltz, T. Bringmann, G. Duda]

  → see Joakim's talk.

- **NMSSMTools** [D. Das, U. Ellwanger, J. F. Gunion, C. Hugonie, C. C. Jean-Louis, A. Teixeira] for the NMSSM, interface written by C. Wymant: http://www.ippp.dur.ac.uk/∼SUSY/
- **SuperIso†** [F. Mahmoudi] for 2HDM's, MSSM and NMSSM. → see Nazila's talk.
- **Spheno†** [W. Porod, F. Staub] for MSSM. → see Florian's talk.
- **SARAH+Spheno†** [F. Staub] for any model implemented with SARAH. → see Florian's talk.

† includes interface to HiggsBounds

∗ interface to this program is included in HiggsBoundspackage

Some HiggsBounds features

- Internally, HiggsBounds takes care of the following complications:
  - The limit tables come with a variety of normalizations. HiggsBounds contains fitted functions for SM Higgs production cross sections, branching ratios, etc. to normalize them correctly.
  - HiggsBounds checks whether certain assumptions of a Higgs search are fulfilled (model-likeness, particular CP).
  - The signal rates of Higgs bosons with similar masses can be combined (relevant *e.g.* in high $\tan\beta$ region in the real MSSM).
- HiggsBounds contains χ^2 information for the LEP searches (*not yet official, but already used in* Fittino [arXiv:1204.4199] → see Xavier's talk.).

HiggsBounds output

SLHA output block (appended to SLHA input file):

```
Block HiggsBoundsResults      # results from HiggsBounds http://projects.hepforge.org/higgsbounds
# HBresult   : scenario allowed flag (1: allowed, 0: excluded, -1: unphysical)
# chan id number: most sensitive channel (see below). chan=0 if no channel applies
# obsratio   : ratio [sig x BR]_model/[sig x BR]_limit (<1: allowed, >1: excluded)
# ncomb      : number of Higgs bosons combined in most sensitive channel
# Note that the HB channel id number varies depending on the HB version and setting "whichanalyses"
#
    0    3.7.0     ||LandH||            # version of HB used to produce these results,the HB setting "whichanalyses"
#
#CHANNELTYPE 1: channel with the highest statistical sensitivity
    1          1           1                 # channel id number
    1          2           0                 # HBresult
    1          3   3.7765434478424251        # obsratio
    1          4           1                 # ncombined
    1          5 ||(e e)->(h1)Z->(b b-bar)Z   (hep-ex/0602042, table 14b (LEP))|| # text description of channel
#
```

webversion output:

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

parameter point is EXCLUDED at 95 per cent C.L.
using the process with highest statistical sensitivity:
 (p p)->h1+... where h1 is SM-like ([hep-ex] arxiv:1202.1488 (CMS))
which has a theoretical rate vs. limit of
  1.2946629463807193

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

The model-likeness test

and its recent improvement

The model likeness test

Many analyses are performed under the assumption that the tested model is similar to the Standard Model.

- The analysis has a different efficiency for each signal topology considered.
- For the exclusion limit, the efficiencies were unfolded under the assumption that the signal rate consists of the signal topologies in equal proportions as in the Standard Model.
- Efficiencies for all signal topologies considered by the analysis are rarely quoted.
- If the proportions among the signal topology rates differ significantly from those in the SM, a comparison of the predicted signal rate with the limit is *not* valid.

$\Rightarrow$ we apply these analyses only to parameter points passing a SM likeness test.

(*However, we assume that differences in the distribution shapes can be neglected!*)

The old SM likeness test (until HiggsBounds 3.7.0)

We check that none of the normalized production cross sections s_i (of process P_i) or normalized branching ratios b_i considered by the analysis,

$$s_i = \frac{\sigma_{\mathrm{model}}(P_i(h))}{\sigma_{\mathrm{SM}}(P_i(H))}, \qquad b_i = \frac{\mathcal{B}_{\mathrm{model}}(h \to F_k)}{\mathcal{B}_{\mathrm{SM}}(H \to F_k)}$$

differs much from the average normalized production cross section $\bar{s}$ or normalized branching ratio $\bar{b}$, ($N_s,\ N_b$ are number of production and decay modes)

$$\bar{s} = \frac{1}{N_s}\sum_{i=1}^{N_s} s_i, \qquad \bar{b} = \frac{1}{N_b}\sum_{k=1}^{N_b} b_k.$$

Quantitatively, we require

$$\boxed{\Delta = \max_{i,k}\left|\frac{\delta s_i}{\bar{s}} + \frac{\delta b_k}{\bar{b}} + \frac{\delta s_i \delta b_k}{\bar{s}\bar{b}}\right| < \epsilon,}$$

with $\epsilon = 2\%$ and

$$\delta s_i = s_i - \bar{s}, \qquad \delta b_k = b_k - \bar{b}.$$

The signal strength modifier is then given by $\mu = \bar{s}\bar{b}$.

Shortcomings of the old SM likeness test

1. **testing more channels than needed:** We specify production and decay modes separately. Thus, the model likeness test considers every possible combination of production and decay modes as signal topology. In fact, only certain combinations of production and decay modes are needed.

   For example:
   A combined search of $(p\bar{p}) \to HZ \to (b\bar{b})Z$ and $(p\bar{p}) \to h_i \to \tau^+\tau^-$ would be tested for all combinations,

   $$\begin{aligned} HZ \times (H \to b\bar{b}), &\qquad \mathrm{singleH} \times (H \to b\bar{b}), \\ HZ \times (H \to \tau^+\tau^-), &\qquad \mathrm{singleH} \times (\tau^+\tau^-), \end{aligned}$$

   although only two of them are relevant.

2. **no weighting:** The criteria does not take into account the relative contribution of a signal topology to the total signal rate. Thus, even for signal topologies with tiny contribution to the signal rate, the parameter point may fail if its contribution deviates by more than ϵ.

The new SM likeness test (since HiggsBounds 3.8.0)

We now specify every considered signal topology as production mode $\times$ decay mode and introduce a weighting of the signal topologies, (N_c is number of signal topologies)

$$c_i = \frac{[\sigma_{\rm model}(P(h))\mathcal{B}_{\rm model}(h \to F)]_i}{[\sigma_{\rm SM}(P(H))\mathcal{B}_{\rm SM}(H \to F)]_i}, \qquad \bar{c} = \sum_{i=1}^{N_c} \omega_i c_i, \qquad \delta c_i = c_i - \bar{c},$$

where the weight ω_i is given by the relative contribution of the signal topology in the Standard Model,

$$\omega_i = \frac{[\sigma_{\rm SM}(P(H))\mathcal{B}_{\rm SM}(H \to F)]_i}{\sum_j [\sigma_{\rm SM}(P(H))\mathcal{B}_{\rm SM}(H \to F)]_j}.$$

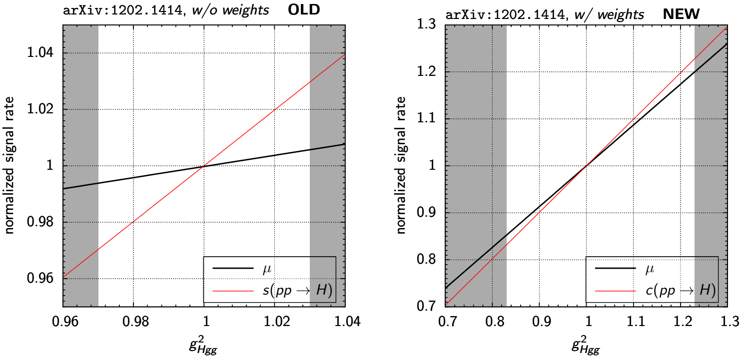
The SM likeness criteria now reads

$$\boxed{\Delta_j = \max_j \ \omega_j \left| \frac{\delta c_j}{\bar{c}} \right| < \epsilon},$$

and the signal strength modifier is simply given by $\mu = \bar{c}$.

Performance of the SM likeness test (I)

- Look at ATLAS $H \to \gamma\gamma$ search, $(\text{singleH}, \text{vbf}, HZ, HW, t\bar{t}H)_{SM} \times (H \to \gamma\gamma)$, at $m_H = 125$ GeV. Weights: $\omega = (87.7\%, 6.8\%, 1.8\%, 3.2\%, 0.5\%)$.
- We vary the dominant production mode (singleH) via normalized effective coupling squared g^2_{Hgg} (other effective couplings $\equiv 1$).



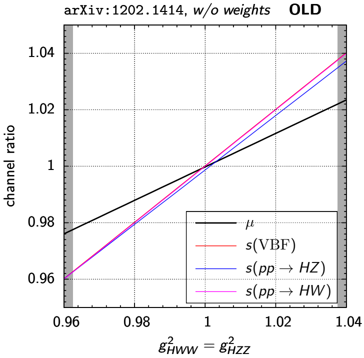
gray region: SM likeness test fails.

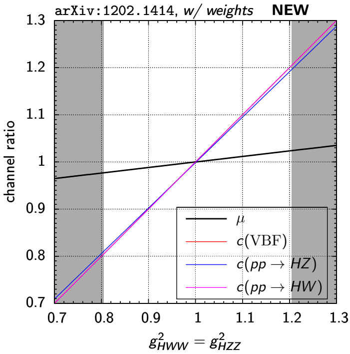
$\Rightarrow$ *w/ weights:* μ follows signal rate of dominant channel.

$\Rightarrow$ Analysis applies to wider range in g^2_{Hgg}.

Performance of the SM likeness test (II)

- Now, vary the subdominant production modes (VBF, HZ, HW) via normalized effective couplings squared $g^2_{HWW} = g^2_{HZZ}$ (other effective couplings $\equiv 1$).



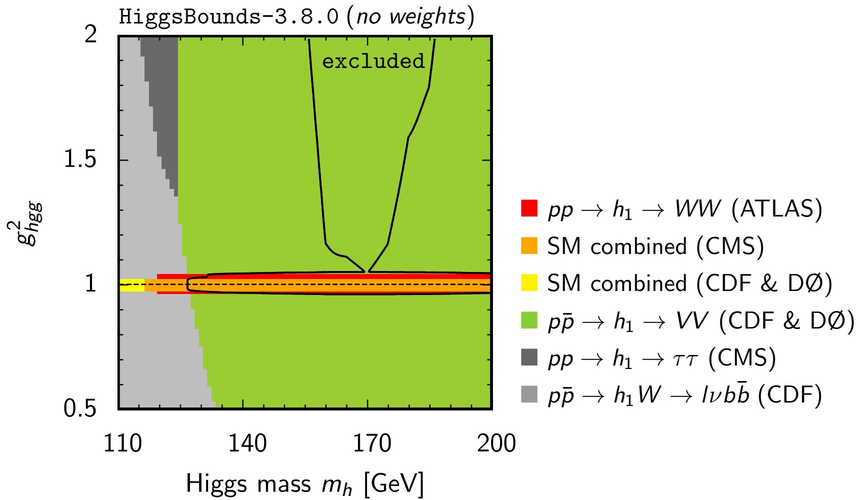


gray region: SM likeness test fails.

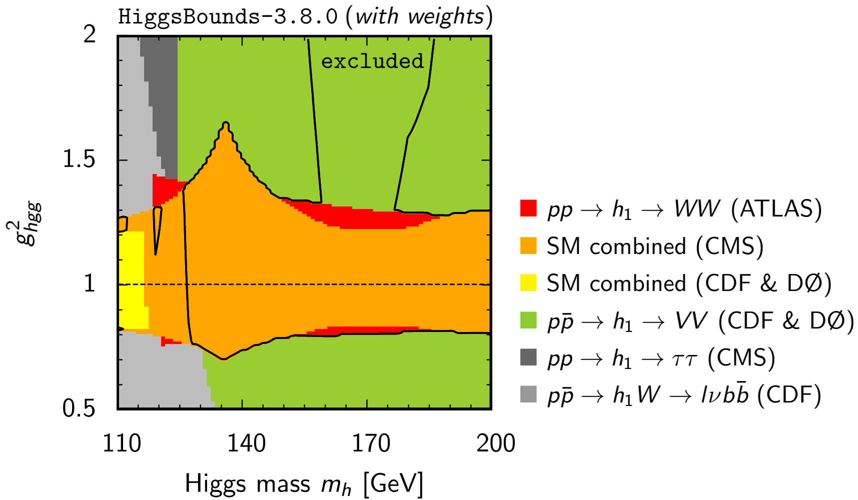
$\Rightarrow$ *w/ weights:* larger deviation allowed for VBF, HZ, HW because of low weights.

$\Rightarrow$ Analysis applies also to wider range in g^2_{HWW}, g^2_{HZZ}.

Example applications: (I) SM with modified effective coupling g^2_{Hgg}



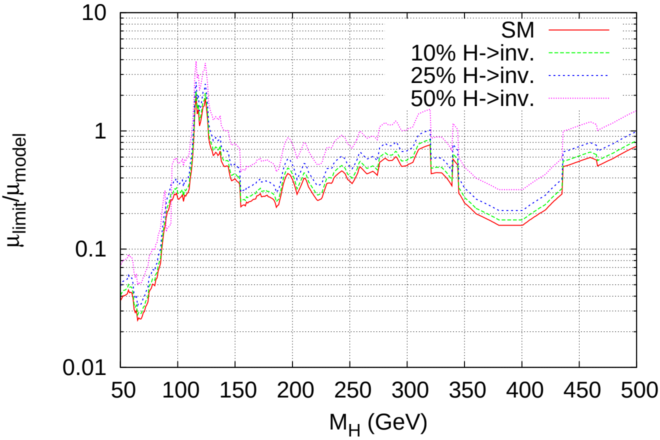
- Considered only exclusion limits from hadron colliders.



- Considered only exclusion limits from hadron colliders.

Example applications: (II) SM with invisible Higgs decay

Toy example: Standard Model Higgs + Higgs decay mode $H \to \text{invisible}$.

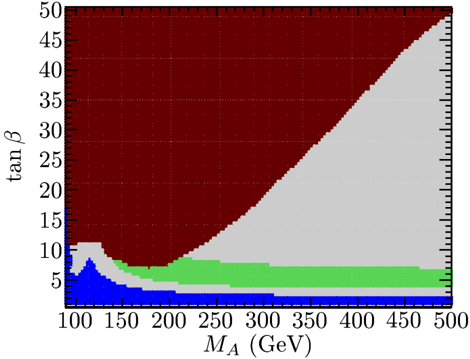


For $\mathcal{B}(H \to \text{inv.}) \leq 25\%$, the excluded mass region does not change much w.r.t SM.

Example applications: (III) MSSM: $m_h^{\max}$ scenario

[S. Heinemeier, O. Stål, G. Weiglein: arXiv:1112.3026]

new plot with `HiggsBounds` 3.8.0 *w/o weights*



$m_h^{\max}$ benchmark scenario:

$M_1 = 100$ GeV, $M_2 = 200$ GeV,
$M_{\rm SUSY} = 1$ TeV, $X_t = 2M_{\rm SUSY}$,
$m_{\tilde{g}} = 0.8 M_{\rm SUSY}$, $\mu = 200$ GeV,
$A_b = A_t$.

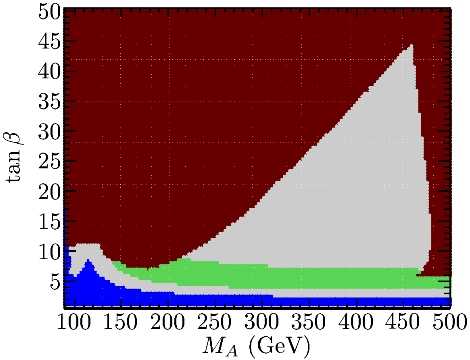
LEP excluded
LHC excluded
$m_h = 125 \pm 3$ GeV

- Exclusions from $pp \to h/H/A \to \tau^+\tau^-$ (CMS) and $e^+e^- \to hZ \to (b\bar{b})Z$ (LEP).
- For $pp \to H/A \to \tau^+\tau^-$ (CMS), signal rates of H and A have been combined if $|m_H - m_A| \leq 10$ GeV.

Example applications: (III) MSSM: $m_h^{\max}$ scenario

[S. Heinemeier, O. Stål, G. Weiglein: arXiv:1112.3026]

new plot with HiggsBounds 3.8.0 *w/ weights*



$m_h^{\max}$ benchmark scenario:

$M_1 = 100$ GeV, $M_2 = 200$ GeV, $M_{\rm SUSY} = 1$ TeV, $X_t = 2M_{\rm SUSY}$, $m_{\tilde{g}} = 0.8M_{\rm SUSY}$, $\mu = 200$ GeV, $A_b = A_t$.

LEP excluded
LHC excluded
$m_h = 125 \pm 3$ GeV

- Exclusions from $pp \to h/H/A \to \tau^+\tau^-$ (CMS) and $e^+e^- \to hZ \to (b\bar{b})Z$ (LEP).
- For $pp \to H/A \to \tau^+\tau^-$ (CMS), signal rates of H and A have been combined if $|m_H - m_A| \leq 10$ GeV.
- at high M_A: exclusion from SM Higgs search combination (CMS).

Summary of Part I: HiggsBounds

HiggsBounds is a convenient tool for particle theorists to test their favorite Higgs models against exclusion limits from LEP, Tevatron and the LHC.

With the latest version HB 3.8.0 we introduced a new SM likeness test which resolves the two major shortcomings of the old method. This leads to a wider applicability of SM Higgs analyses, which combine several signal topologies.

Even after a Higgs discovery, exclusion limits (and therewith HiggsBounds) are still important to test extended Higgs sectors.

Part II:

The HiggsSignals extension

The HiggsSignals extension

- Tentalizing hints for a "SM-like" Higgs boson at $m_h \approx 125$ GeV.
- How SM-like is it?

  $\Rightarrow$ need to investigate (all) search channels separately!

The HiggsSignals extension: basic idea

- Confront arbitrary Higgs sector prediction with hints for Higgs boson(s).
- Consider search channels separately and combine them.
- Return a total χ^2 probability for a given signal hypothesis:

  (i) How well does my model descibe a (local) excess in the data?
  (ii) How well does my model agree with the data observed?

$\Rightarrow$ Can be used in global (SUSY / BSM) fits.

- HiggsSignals is planned to be a stand-alone program using the HiggsBounds libraries.

peak-centered χ^2 method:

How well does my model describe a (local) excess in the data?

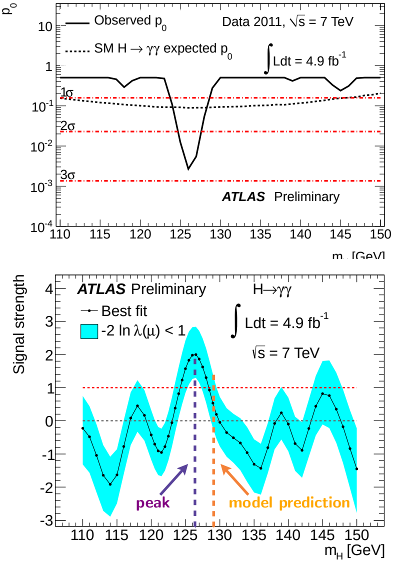
For each implemented analysis,

1. Find the excess in the data:
   - User specifies minimal significance $S_{\min}$ as peak definition.
   - Use p_0 plot to find peak via significance cut, *e.g.* $S \geq S_{\min} = 2\sigma$

$\Rightarrow$ *e.g.* $m^{\text{peak}} = 126$ GeV, $\mu^{\text{peak}} = 2$

2. Evaluate model prediction:
   - apply model likeness test

$\Rightarrow$ *e.g.* $m^{\text{pred}} = 129$ GeV, $\mu^{\text{pred}} = 1.4$



peak-centered χ^2 method:

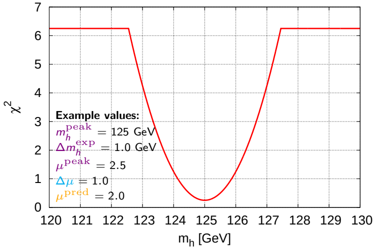
How well does my model describe a (local) excess in the data?

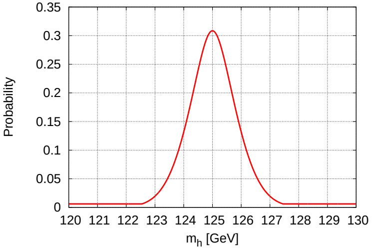
3. Calculate χ^2:

$$\chi^2 = \frac{\left(\mu^{\rm peak} - \mu^{\rm pred}\right)^2}{(\Delta\mu)^2} + \frac{(m_h^{\rm peak} - m_h^{\rm pred})^2}{(\Delta m_h^{\rm exp})^2 + (\Delta m_h^{\rm th})^2}$$

with cutoff at $\chi^2_{\rm max} = (\mu^{\rm peak})^2/(\Delta\mu)^2$.

- Assumes μ and m_h are gaussian distributed.
- *optional:* box-shaped probability density function (pdf) for m_h





peak-centered χ^2 method:

How well does my model describe a (local) excess in the data?

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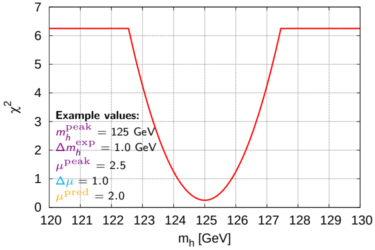
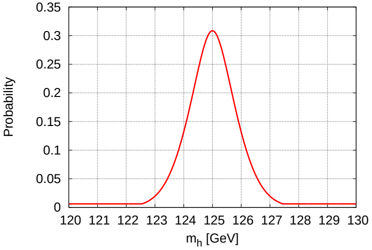
$$\chi^2 = \frac{\left(\mu^{\rm peak} - \mu^{\rm pred}\right)^2}{(\Delta\mu)^2} + \frac{(m_h^{\rm peak} - m_h^{\rm pred})^2}{(\Delta m_h^{\rm exp})^2 + (\Delta m_h^{\rm th})^2}$$

with cutoff at $\chi^2_{\rm max} = (\mu^{\rm peak})^2/(\Delta\mu)^2$.

- Assumes μ and m_h are gaussian distributed.
- *optional:* box-shaped probability density function (pdf) for m_h





Loop over all implemented analyses and calculate $\chi^2_{\rm tot} = \sum \chi^2$.

peak-centered χ^2 method: Complications

1. *assigning Higgs bosons to peaks:*
   - may have more than one peak in the μ-plot.
   - may have more than one Higgs boson in the model.
   - the peak(s) may be superposition(s) of Higgs bosons (overlapping within mass uncertainty).

$\Rightarrow$ try all possible combinations (including Higgs boson superpositions) and take the best one (*i.e.* w/ minimal χ^2).

2. *What to do if the Higgs boson fails the model-likeness test?*
   - *The signal strength modifier cannot be reliably calculated.*
   - Set $\mu^{\mathrm{pred}} \equiv 0$ for this Higgs if it is assigned to a peak ($\Delta\chi^2 = \chi^2_{\mathrm{max}}$).

   $\Rightarrow$ will prefer other Higgses passing the test to be assigned to peaks.

m^{pred}-centered χ^2 method:

How well does my model prediction agree with the data observed?

Evaluate the agreement between model prediction and observation at the predicted Higgs mass.

1. assume a probability density function (pdf) for predicted signal strength modifier:

$$g(m_h) = (\delta\text{-function, box, gaussian, th. box + exp. gaussian})$$

   (*normalized; depends on* m^{pred} *and* Δm)

2. Convolve $\mu(m_h)$ ($\equiv$ the observed μ-plot) with $g(m_h)$:

$$\mu^{\text{smeared}} = \int dm_h \, \mu(m_h) \, g(m_h)$$

3. Do the same with the 1σ error bands $\Rightarrow$ $\Delta\mu^{\text{smeared}}$.
4. Evaluate χ^2 probability (at the predicted Higgs mass):

$$\chi^2 = \frac{\left(\mu^{\text{smeared}} - \mu^{\text{pred}}\right)^2}{(\Delta\mu^{\text{smeared}})^2}$$

Possible way to run `HiggsSignals`: *Example*

- 1 analysis with 1 peak identified (by significance criterium).
- Model with 3 neutral Higgs bosons h_i $(i = 1, 2, 3)$, masses m_i in range of μ-plot.

1. Run *model likeness test* for all Higgs bosons and evaluate μ_i^{pred}.
   - h_1 and h_3 pass, h_2 fails the *model likeness test*.
   - calculate signal strength modifiers μ_1^{pred}, μ_3^{pred} and set $\mu_2^{\mathrm{pred}} \equiv 0$.
2. Check whether m_1 and m_3 overlap within mass uncertainty.
   - They don't overlap. (Otherwise consider also superposition $\mu_{13} = \mu_1 + \mu_3$, $m_{13} = (\mu_1 m_1 + \mu_3 m_3)/(\mu_1 + \mu_3)$ in the following step (3).)
3. Assign Higgs bosons to peak (find best combination).
   - h_1 is associated to peak. Evaluate χ_1^2 with *peak-centered* χ^2 *method*.
4. Check agreement between data and prediction for the other Higgs bosons:
   - Run m^{pred}*-centered* χ^2 *method* for h_2 and h_3 $\Rightarrow$ χ_2^2, χ_3^2.
5. Evaluate $\chi_{\mathrm{tot}}^2 = \sum_{i=1}^3 \chi^2$.

$\Rightarrow$ `HiggsSignals` output: χ_{tot}^2, ndf $(= 3)$, Probability $(\chi_{\mathrm{tot}}^2$, ndf), additional info.

HiggsSignals: input, user settings and output

Input for HiggsSignals

- same input required as for HiggsBounds.
- same input formats possible as in HiggsBounds, *i.e.* (*SLHA*, *effC*, *part*, *hadr*).
- additional input: theory uncertainties for the Higgs mass(es).

User settings

- which method: (*peak-centered* χ^2 *only*, m^{pred}*-centered* χ^2 *only*, *both*)
- pdf for predicted μ (for each method): (*box*, *gaussian*, *etc.*)
- peak definition: minimal significance S_{min}
- whether a superposition of Higgs bosons is allowed.

HiggsSignals output

- χ^2_{tot}, ndf, Probability (χ^2_{tot}, ndf)
- List of found peaks (with properties) and analyses considered.
- Information about the Higgs-to-peaks assignment for each analysis.

Summary of Part II: HiggsSignals extension

The future program HiggsSignals confronts arbitrary Higgs sector predictions with hints / signals seen in Higgs boson collider searches.

It evaluates the χ^2 probability for the two questions:

(i) How well does my model descibe a (local) excess in the data?

(ii) How well does my model agree with the data observed?

Internally, HiggsSignals takes care of

- possible combinations of assigning Higgs boson(s) to data excess(es).
- possible superpositions of the signal rates of Higgs bosons which are close in mass.
- whether an analysis can be reliably applied to a Higgs boson prediction.

HiggsSignals will (hopefully) become a useful tool for global SM and BSM fits and for other phenomenological studies!

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Thanks for your attention!

Backup Slides

m^{pred}-centered χ^2 method compared to CL_s method

- The probability obtained from $\chi = (\mu - \mu^{\mathrm{pred}})/(\Delta\mu)$ is

$$P(\mu,\ \mu^{\mathrm{pred}},\ \Delta\mu) = \frac{1}{2}\left(1 + \mathrm{erf}\left(\frac{\chi}{\sqrt{2}}\right)\right) \quad \approx CL_{sb}$$

- Evaluating $P(\mu,\ \mu^{\mathrm{pred}},\ \Delta\mu)$ with $\mu^{\mathrm{pred}} = 0$ gives *almost* CL_b, however, the uncertainty $\Delta\mu$ contains BG and signal uncertainties, not only BG uncertainty. Furthermore, CL_b is based on *one-sided* gaussian uncertainties, whereas the $\Delta\mu$ is a *two-sided* gaussian uncertainty.

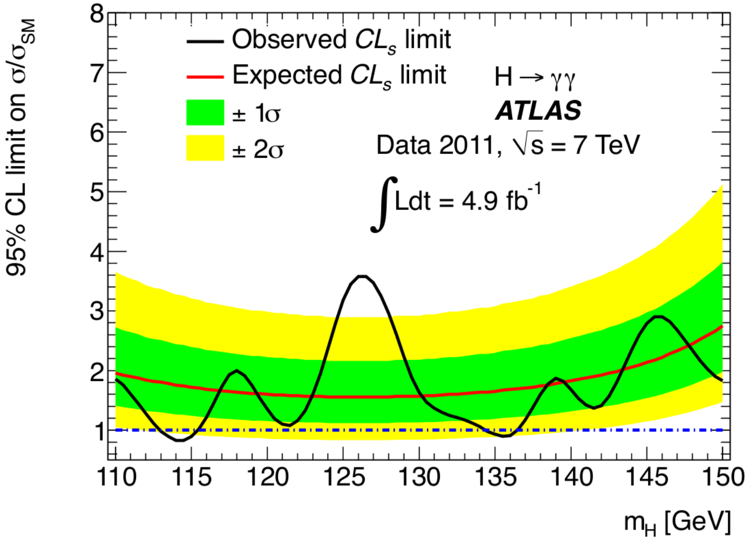
$$\Rightarrow P(\mu,\ 0,\ \Delta\mu) \begin{array}{ll} < CL_b, & \text{if} \quad \hat{\mu} > 0 \\ > CL_b, & \text{if} \quad \hat{\mu} < 0 \end{array}$$

- As a *cross-check*, the exclusion plot can be reconstructed by finding the μ^{pred} for which

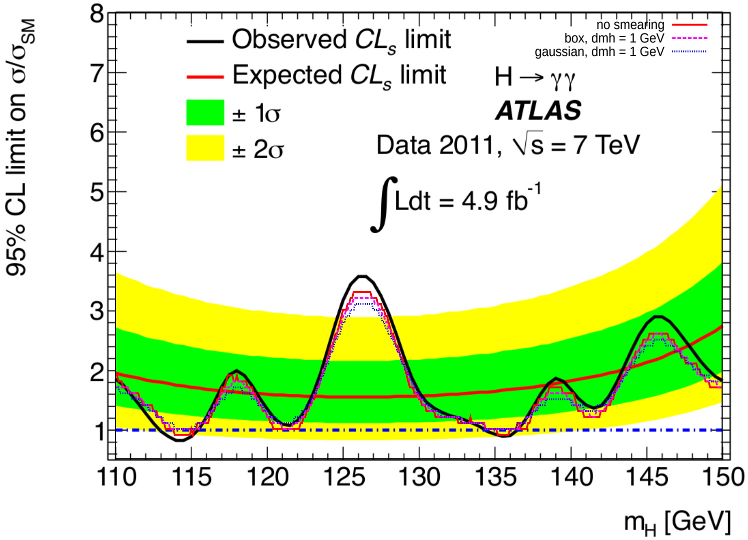
$$CL_s = \frac{CL_{sb}}{CL_b} \approx \frac{P(\mu,\ \mu^{\mathrm{pred}},\ \Delta\mu)}{P(\mu,\ 0,\ \Delta\mu)} \leq 0.05$$

- The discovery plot (local p_0) is given by $p_0 = 1 - CL_b \approx 1 - P(\hat{\mu},\ 0,\ \Delta\hat{\mu})$

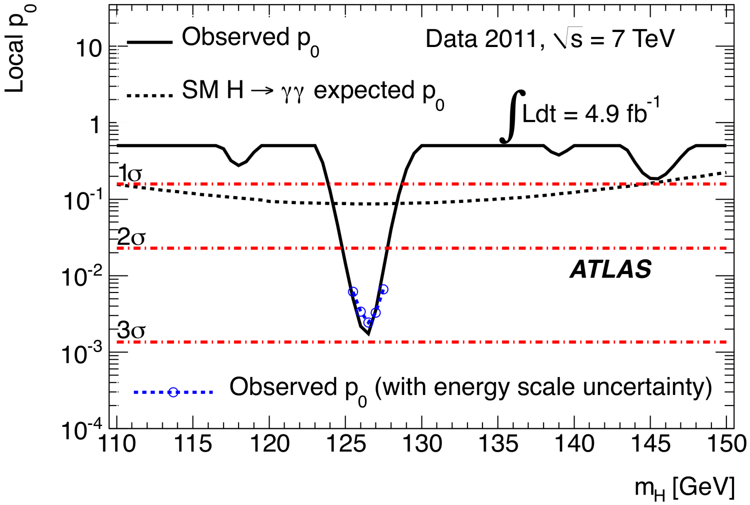
Cross check: Reconstruction of the exclusion plot



Cross check: Reconstruction of the exclusion plot



Reconstruction of the discovery plot



Reconstruction of the discovery plot