HiggsBounds and HiggsSignals
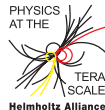## — current status and prospects —

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G. Weiglein   K. E. Williams

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http://higgsbounds.hepforge.org/

Charged Higgs 2012, Uppsala (Sweden), Oct. 10

HiggsBounds - a program's portrait

- *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*)
  → *you may subscribe to the mailing list to stay tuned!*
- *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;
  Comput. Phys. Commun. **182** (2011) 2605.

Introduction

- Exclusions (*i.e.* upper limits on the Higgs signal rate μ) are *still very important* to constrain models with extended Higgs sectors.
- HiggsBounds contains *most recent exclusion limits* from neutral and charged Higgs searches at the LEP, Tevatron and the LHC.
- It tests the model predictions against the 95% C.L. limits in a statistically well-defined way (*i.e.* using the *expected most sensitive analysis* only).
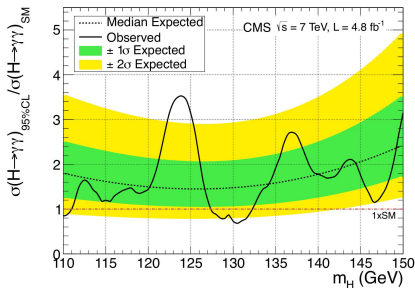
Higgs searches at colliders

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 (w/o efficiencies), need a *model-likeness test*.

Less model-dependent results

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

- *E.g.* the LEP search $e^+e^- \rightarrow (h_i)Z \rightarrow (b\bar{b})Z$ or searches for $H^{\pm}$ from t decay.
- Limits on the signal rate or branching ratios, *e.g.* $\mathcal{B}(t \rightarrow H^{\pm}b) \times \mathcal{B}(H^{\pm} \rightarrow \tau\nu)$.
- Easily applicable to lots of models.

HiggsBounds

- To determine the model predictions the user has to provide HiggsBounds with sufficient input:
  - ▸ Higgs masses and decay 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

- HiggsBounds contains fitted functions for SM Higgs production cross sections, branching ratios, etc. to normalize predictions correctly.

- Supported input format: datafiles, SLHA[1] or via subroutines.

- HiggsBounds can be applied to Higgs sectors with up to 9 neutral and/or charged Higgs bosons.

- Narrow width approximation must be applicable.

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[1]MSSM and NMSSM supported, need two extra blocks for effective Higgs couplings.

The Standard 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.

(We still assume that the signal efficiencies of the model are $\approx$ as in SM.)

The SM likeness test (since `HiggsBounds 3.8.0`)

Every considered signal topology ($\equiv$ production mode $\times$ decay mode) has an individual signal strength modifier c_i and SM weight ω_i ($\equiv$ relative contribution of the signal topology in the Standard Model):

$$c_i = \frac{[\sigma_{\mathrm{model}}(P(h))\mathcal{B}_{\mathrm{model}}(h \to F)]_i}{[\sigma_{\mathrm{SM}}(P(H))\mathcal{B}_{\mathrm{SM}}(H \to F)]_i}, \qquad \omega_i = \frac{[\sigma_{\mathrm{SM}}(P(H))\mathcal{B}_{\mathrm{SM}}(H \to F)]_i}{\sum_j [\sigma_{\mathrm{SM}}(P(H))\mathcal{B}_{\mathrm{SM}}(H \to F)]_j}.$$

Then, the overall signal strength modifier μ is approximated by (*neglecting efficiency effects*)

$$\mu = \sum_{i=1}^{N_c} \omega_i c_i \qquad \left(= \frac{\sum_i [\sigma_{\mathrm{model}}(P(h))\mathcal{B}_{\mathrm{model}}(h \to F)]_i}{\sum_j [\sigma_{\mathrm{SM}}(P(H))\mathcal{B}_{\mathrm{SM}}(H \to F)]_j} \right)$$

The SM likeness test succeeds, if

$$\boxed{\Delta \equiv \max_i \; \omega_i \left| \frac{\delta c_i}{\mu} \right| < \epsilon}\qquad \text{, with} \qquad \delta c_i = c_i - \mu \qquad \text{and} \qquad \epsilon = 2\%.$$

Performance tests with and without using SM weights $\to$ *backup slides*.

Where do we stand with `HiggsBounds`?

The *latest version* (`HiggsBounds-3.8.0`, released in May 2012) contains

- a significantly improved SM likeness test, where we introduced a *weighting procedure* of the signal topology rates.
  ⇒ wider applicability of SM Higgs searches to non-SM Higgs sectors.

- contains most recent results from 7 TeV LHC Higgs searches before *ICHEP2012*.

Currently, we are *preparing for the release* of `HiggsBounds-4.x.x`. It will contain

- framework for 8 TeV LHC data (extended input, new SM cross section functions)

- all relevant LHC exclusion limits from the 8 TeV data.

- χ^2 information from the LEP Higgs searches.

Furthermore, we aim to publish a new documentation for `HiggsBounds-4.x.x`.

HiggsSignals

Since July 4th, 2012 we have a discovery in the neutral Higgs searches!

$\Rightarrow$ Need to confront arbitrary Higgs sector predictions with the observations / discoveries in Higgs searches.

The currently developed program `HiggsSignals`

- evaluates the total χ^2 for both the signal strengths and the mass measurements,
- includes correlations among the major systematic uncertainties (*cross sections, branching ratios, luminosity, theory mass uncertainty*),
- includes many other features. . . (*e.g. automatic combination of nearly mass degenerate Higgs bosons, framework to include signal efficiencies, toy observables, etc.*).

`HiggsSignals` is a stand-alone program using the `HiggsBounds` libraries. Coding language is `Fortran90/2003`. Planned release: *before* Christmas 2012.

Cross section scaling for `ATLAS` $H \to \gamma\gamma$ search

- scale cross sections by factors $\mu_{ggF+ttH}$ and μ_{VBF+VH}.
- `ATLAS`: Combination of all 10 categories of $H \to \gamma\gamma$ search.
- `HiggsSignals`: Combination of *untagged* and *VBF-tagged* categories.
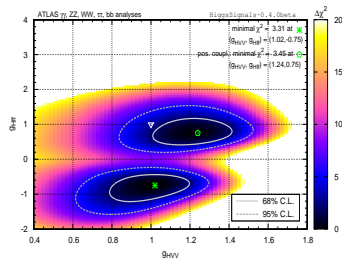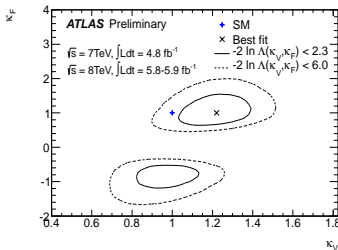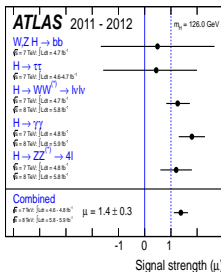

Phys. Lett. B 716 (2012) 1-29
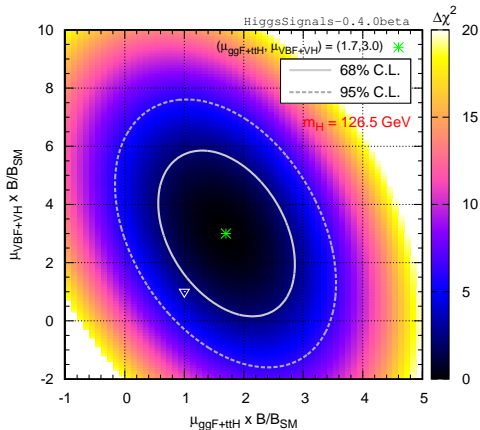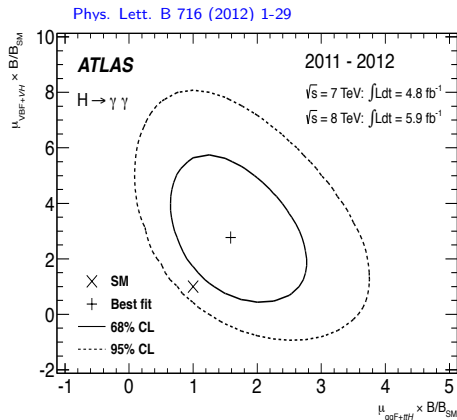
# Scaling of vector boson and fermion couplings

- scale fermion couplings with $\kappa_F \equiv g_{Hff}$ and vector boson couplings by $\kappa_V \equiv g_{HVV}$.
- $\rightarrow$ non-trivial scaling of loop-induced $H\gamma\gamma$ coupling.
- $\rightarrow$ loop-induced Hgg coupling scales with κ_F (effectively a fermion loop).

ATL-CONF-2012-127

$\Rightarrow$ Pretty good agreement with the ATLAS studies!

Full set of available experimental data

generated by HiggsSignals   status: Oct. 2012
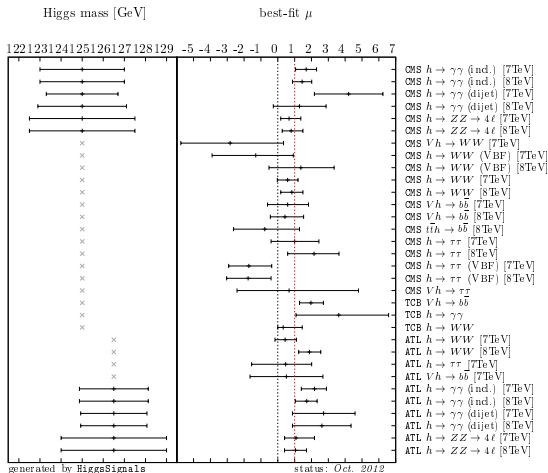
- Use mass measurements from ATLAS and CMS $H \rightarrow \gamma\gamma, ZZ$ searches *only*.
- *In the following example* we parametrize the Higgs mass uncertainty by a theory-box + exp.-gaussian pdf with $\Delta m_H^{\text{theory}} = 3$ GeV.

Did we observe the heavier CP-even Higgs of the MSSM?

$M_{\mathrm{SUSY}} = 1$ TeV, $|X_t| = 2.4$ TeV, $\mu = 1$ TeV, $M_1 = 100$ GeV, $M_2 = 200$ GeV, $M_3 = 800$ GeV
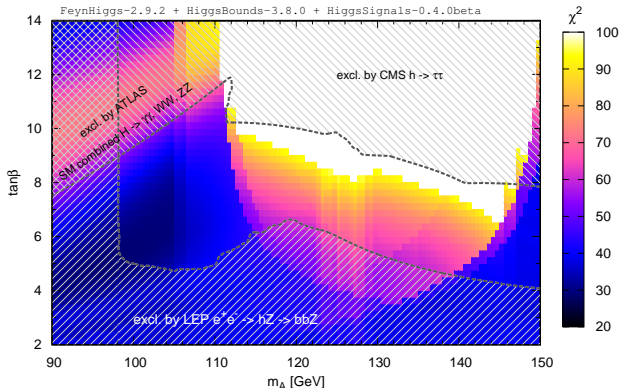
(suggested by S. Heinemeier, O. Stål, G. Weiglein '11 → Oscar Stål's talk)
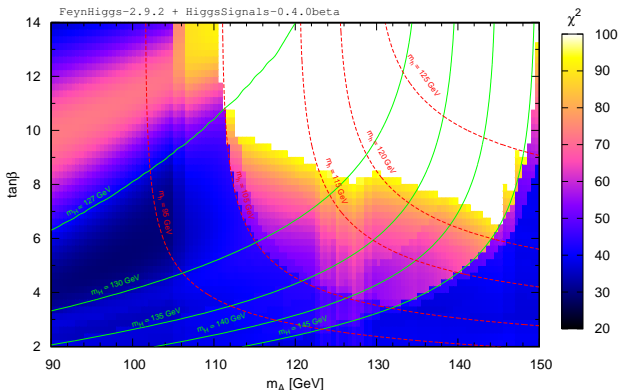
- low χ^2 region around $(m_A, \tan\beta) \approx (100, 6)$.
- high χ^2 region where signal rates of h and H are combined
  (i.e. for WW, $b\bar{b}$ and $\tau\tau$ analyses if $m_h, m_H \in (125 \pm 20$ GeV$)$).
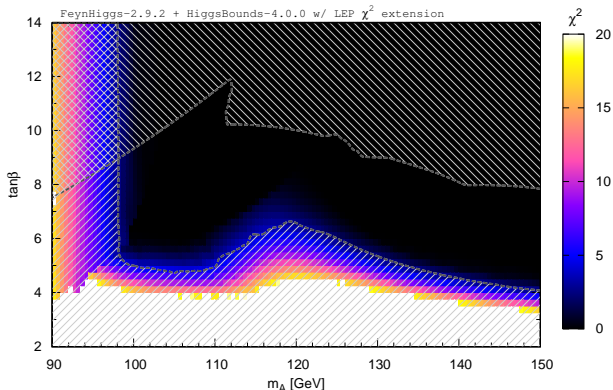
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- Run `HiggsBounds` to obtain 95% C.L. exclusion limits from LEP and LHC.
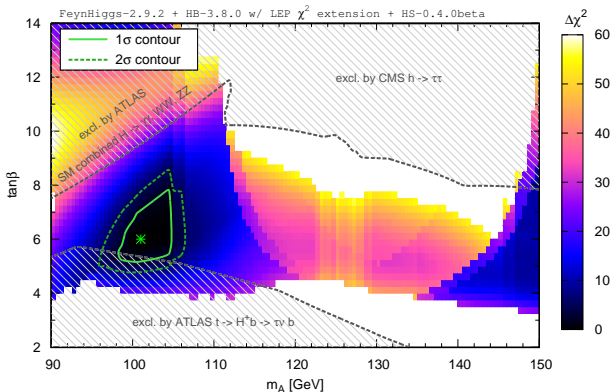
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FeynHiggs-2.9.2 + HiggsBounds-4.0.0 w/ LEP χ^2 extension

- Replace 95% *C.L.* LEP exclusion by the χ^2 information included in HiggsBounds.

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$M_{\mathrm{SUSY}} = 1$ TeV, $|X_t| = 2.4$ TeV, $\mu = 1$ TeV, $M_1 = 100$ GeV, $M_2 = 200$ GeV, $M_3 = 800$ GeV

- minimal $\chi^2/\mathrm{ndf} = 29.3/32$ at $(m_A, \tan\beta) = (101.0\,\mathrm{GeV}, 6.0)$:
  - SM-like heavy Higgs H with $m_H = 127.8$ GeV.
  - lightest Higgs h with $m_h = 92.3$ GeV and reduced hZZ coupling.
  - predicts $t \xrightarrow{1\%} H^+ b \xrightarrow{98\%} \tau^+ \nu_\tau b$ with $m_{H^+} = 126$ GeV
    (very close to current ATLAS 95% C.L. exclusion limit → Patrick Czodrowski's talk).

Summary and Outlook

HiggsBounds is a convenient tool to confront extended Higgs sectors with collider 95% C.L. exclusion limits from Higgs searches.

- The SM likeness test was significantly improved in HB-3.8.0 (*we strongly recommend to use this version!*).
- HiggsBounds-4 will be released in the near future (including 8 TeV LHC data).

The currently developed program HiggsSignals performs a χ^2 test of (extended) Higgs sector predictions to the observed signal(s) in the Higgs searches.

- Preliminary results of coupling strength determination agree fairly well with official results (as long as gaussian limit is applicable).

Simultaneous use of HiggsBounds and HiggsSignals gives interesting insights on the validity of the (extended) Higgs sector of new physics models.

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Thank you for your attention!

Backup slides

Performance of the SM likeness test (I)

- Look at ATLAS $H \to \gamma\gamma$ search, $(\text{singleH, vbf, } HZ, HW, t\bar{t}H)_{SM} \times (H \to \gamma\gamma)$, 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_{Hgg}^2 (other effective couplings $\equiv 1$).
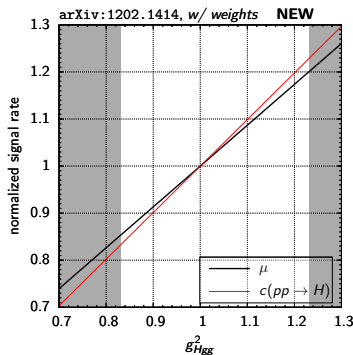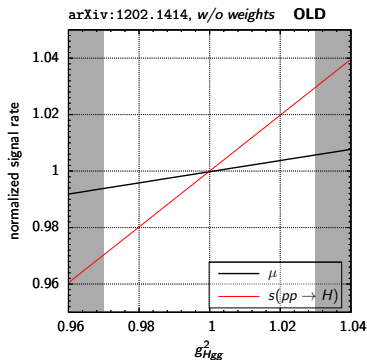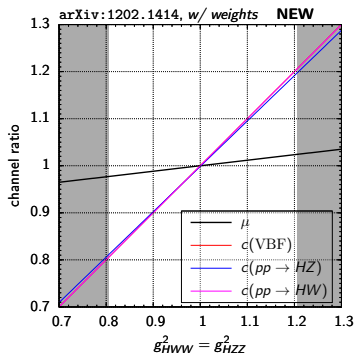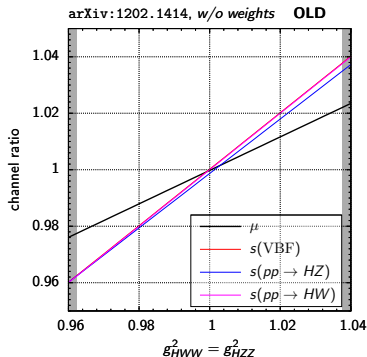

gray region: SM likeness test fails.

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

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

Performance of the SM likeness test (II)

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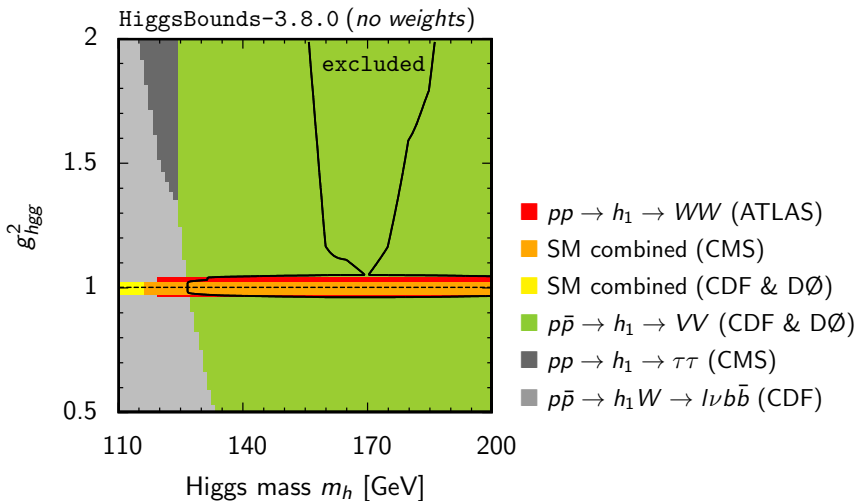

gray region: SM likeness test fails.

$\Rightarrow$ *w/ weights:* larger deviation allowed for VBF, *HZ*, *HW* because of low weights.
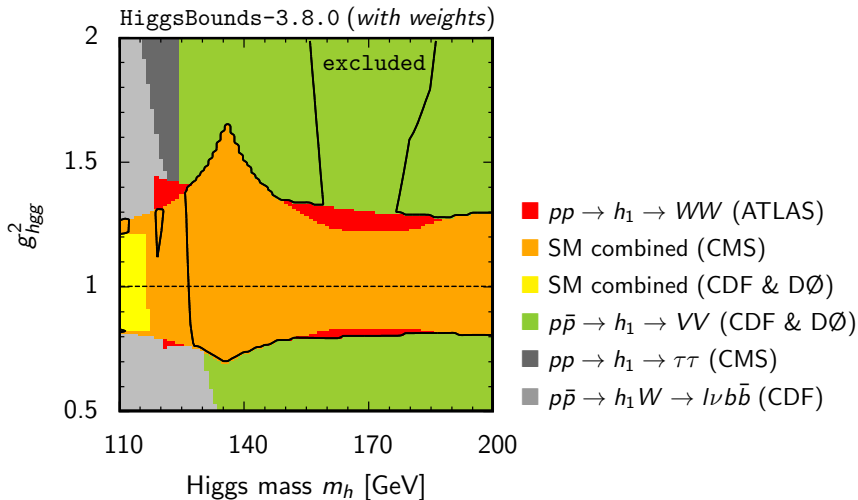
$\Rightarrow$ Analysis applies also to wider range in g_{HWW}^2, g_{HZZ}^2.

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

- Considered only exclusion limits from hadron colliders.

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

HiggsBounds-3.8.0 (*with weights*)

excluded

- 🟥 $pp \to h_1 \to WW$ (ATLAS)
- 🟧 SM combined (CMS)
- 🟨 SM combined (CDF & DØ)
- 🟩 $p\bar{p} \to h_1 \to VV$ (CDF & DØ)
- ⬛ $pp \to h_1 \to \tau\tau$ (CMS)
- ⬜ $p\bar{p} \to h_1 W \to l\nu b\bar{b}$ (CDF)

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