Confronting Higgs sectors with experimental data from LEP, Tevatron and LHC with HiggsBounds and HiggsSignals

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http://higgsbounds.hepforge.org/

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Part I:

HiggsBounds

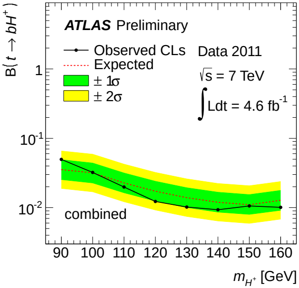
HiggsBounds - a program's portrait

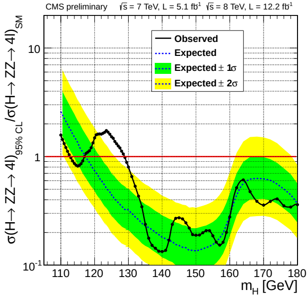
HiggsBounds

- *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*)
  $\rightarrow$ *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 to HiggsBounds

- Even after the discovery, exclusion limits 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).





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.

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

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

- Narrow width approximation must be applicable.

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

Some features of HiggsBounds

- If a Higgs search is carried out under certain assumptions (*e.g.* the SM, where production and/or decay modes are combined), HiggsBounds applies these limits *only* if the investigated model approximately *fulfills* these assumptions ("*SM-likeness test*").
- The signal rates of Higgs bosons with similar masses can be combined (relevant *e.g.* for $H/A \to \tau\tau$ in real MSSM with large $\tan\beta$).
- Many interfaces to spectrum calculators exist or included as examples (*e.g.* FeynHiggs, SPheno/SARAH, 2HDMC, CPsuperH...).

What will be new in HiggsBounds-4.0.0?

- framework for 8 TeV LHC data (extended input, new SM cross section functions),
- all relevant LHC exclusion limits with 8 TeV data (including HCP2012),
- *a few more features. . .*

Treatment of theoretical mass uncertainties

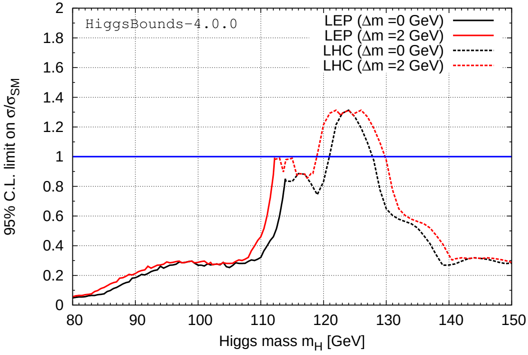
- If the Higgs mass m_i is a model prediction (e.g. in SUSY) we have to take into account its theoretical uncertainty Δm_i.
- HiggsBounds-4 is run for the three mass values m_i, $m_i \pm \Delta m_i$. The *most conservative result* is taken as the final result.

Toy example:

SM Higgs boson with a theoretical mass uncertainty:

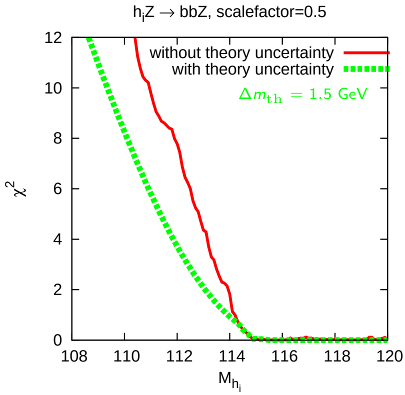
$\Delta m = 0$ GeV and $\Delta m = 2$ GeV.

$\Rightarrow$ unexcluded region broadens to $m_H \approx (119 - 130)$ GeV.



χ^2 information from LEP searches

HiggsBounds-4.0.0 can output a χ^2 value for the LEP Higgs searches, *with* or *without* a gaussian theoretical mass uncertainty.



- very useful for global BSM fits.
- *private version* already used in latest Fittino study, [arXiv:1204.4199]

What will be new in HiggsBounds-4.0.0?

- framework for 8 TeV LHC data
  (extended input, new SM cross section functions),
- all relevant LHC exclusion limits with 8 TeV data (including HCP2012),
- treatment of theoretical mass uncertainties (by variation),
- χ^2 information from the LEP Higgs searches.

Furthermore, we aim to publish a new documentation for `HiggsBounds-4.0.0`.

The new `HiggsBounds`-4.0.0 package will be released (hopefully) *before* Christmas! *Stay tuned*.

Part II:

HiggsSignals

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

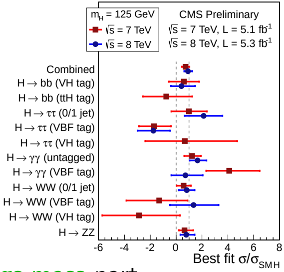
- evaluates the total χ^2 for both the signal strengths and/or the mass measurements, featuring two distinct χ^2 methods (peak- and mass-centered χ^2 methods),
- includes correlations among the major systematic uncertainties (*cross sections, branching ratios, luminosity, theory mass uncertainty*),
- 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.

Peak-centered χ^2 method

Tests agreement (model $\leftrightarrow$ data) at the *observed* mass.

- Define observables by the best-fit $\hat{\mu}$ at a *suspected/measured* Higgs mass $\hat{m}$.



- The total χ^2 consists of a signal strength and a Higgs mass part,

$$\chi^2_{\text{total}} = \chi^2_\mu + \sum_{\text{assigned Higgses } i} \chi^2_{m_i},$$

where only analyses with a *decent mass measurement* enter $\chi^2_{m_i}$.

$\Rightarrow$ Good method to get a global picture on Higgs coupling properties.

$\rightarrow$ used in on-going `Fittino` study (see Björn Sarrazin's talk).

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).

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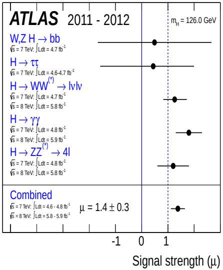
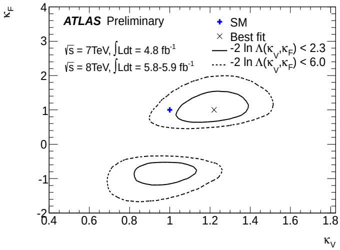
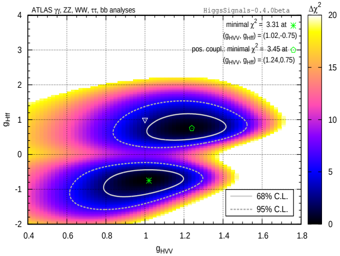




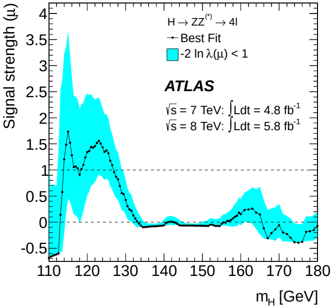


$\Rightarrow$ Pretty good agreement!

(Predicted) mass centered χ^2 method

Tests agreement (model $\leftrightarrow$ data) at the *model-predicted* Higgs mass.

- Define observables by best-fit $\hat{\mu}$ at the *model-predicted* Higgs mass m.
  - Need full $\hat{\mu}$-plots from experiment! $\rightarrow$
- Take into account theoretical mass uncertainty by variation of m.
- Combine signal rates of Higgs bosons (i, j) if $|m_i - m_j| \leq$ mass resolution.



$\Rightarrow$ Every neutral Higgs boson in the model can be tested

(if its mass is in the relevant mass range).

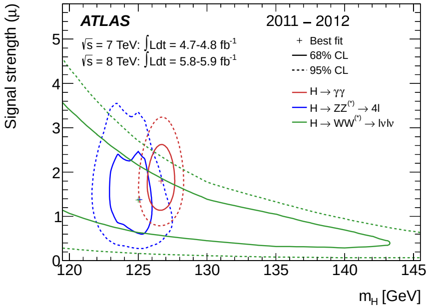
Fit in the $(m_H,\ \mu)$ plane of ATLAS results

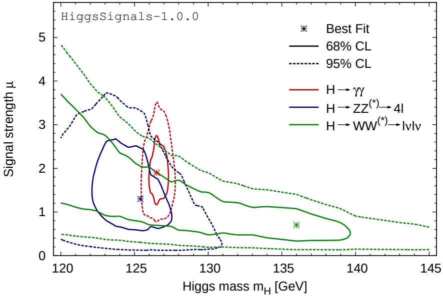
- For every point $(m_H,\ \mu)$, scan the mass range (m'_H) and test the hypothesis $(m'_H,\ \mu')$, where

$$\mu' = \begin{cases} \mu & \text{if} \quad m'_H = m_H \\ 0 & \text{if} \quad m'_H \neq m_H \end{cases},$$

  with the mass-centered χ^2 method. Sum the resulting χ^2 values.
- Find minimal χ^2 value in $(m_H,\ \mu)$ plane. Construct C.L. intervals from $\Delta\chi^2 = 2.3\ (1\sigma)$ and $5.99\ (2\sigma)$.

arXiv:1207.7214





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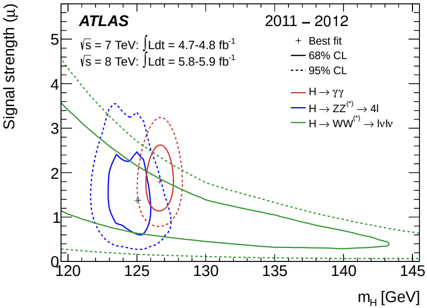
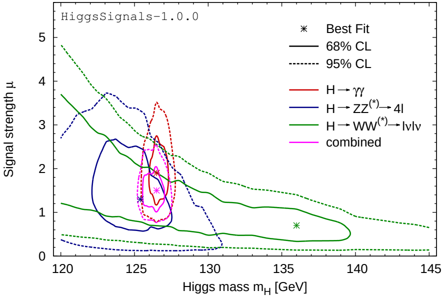
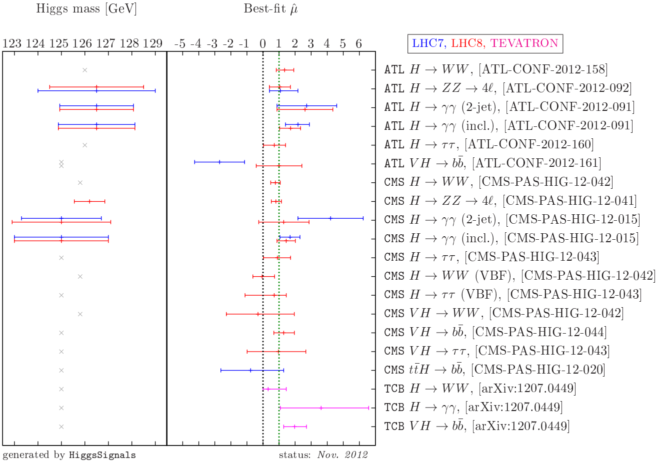




Full set of available experimental data

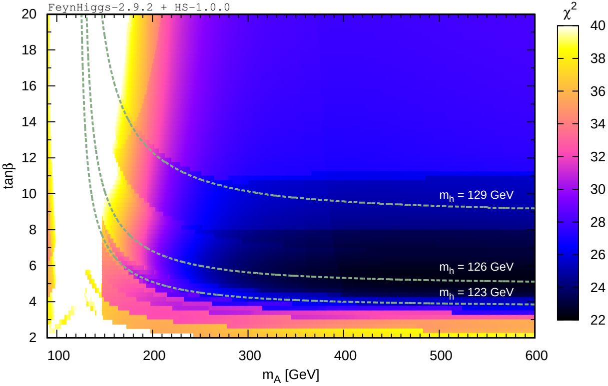


- Use mass measurements from ATLAS and CMS $H \to \gamma\gamma, ZZ$ searches *only*.

The $m_h^{\max}$ scenario

($M_{\mathrm{SUSY}} = 1$ TeV, $|X_t| = 2$ TeV, $\mu = 200$ GeV, $M_1 = 100$ GeV, $M_2 = 200$ GeV, $M_3 = 1200$ GeV)

1. Run HiggsSignals with peak-centered χ^2 method, $\Delta m_h^{\mathrm{th}} = \Delta m_H^{\mathrm{th}} = 2$ GeV.

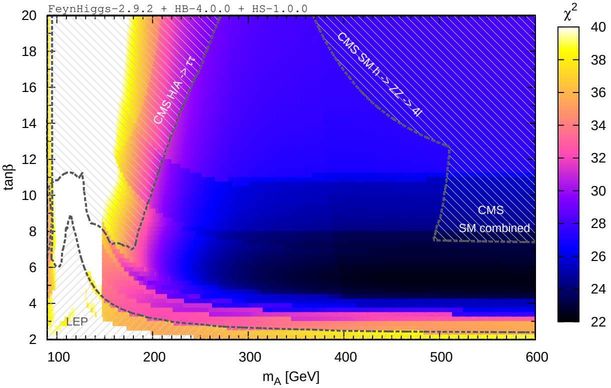


- Large m_A and $\tan\beta \gtrsim 4$ favored (decoupling limit).

The $m_h^{\max}$ scenario

($M_{\rm SUSY} = 1$ TeV, $|X_t| = 2$ TeV, $\mu = 200$ GeV, $M_1 = 100$ GeV, $M_2 = 200$ GeV, $M_3 = 1200$ GeV)

2. Run HiggsBounds to obtain 95% C.L. exclusion limits from LEP and LHC (*no* theory mass uncertainty yet).

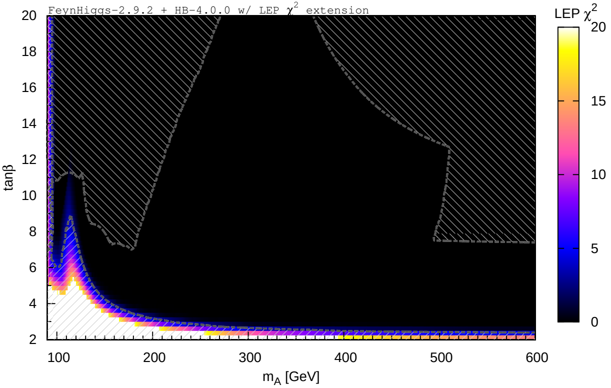


- CMS limits: $H/A \to \tau\tau$ (pre-ICHEP2012), SM $H \to ZZ^{(*)} \to 4\ell$ and SM combined (HCP2012).

The $m_h^{\rm max}$ scenario

($M_{\rm SUSY}$ = 1 TeV, $|X_t|$ = 2 TeV, μ = 200 GeV, M_1 = 100 GeV, M_2 = 200 GeV, M_3 = 1200 GeV)

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

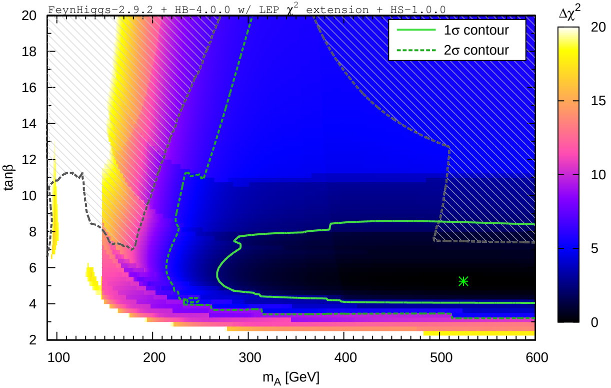


- Now we can add the χ^2 values of HiggsSignals and HiggsBounds (LEP).

The $m_h^{\max}$ scenario

($M_{\text{SUSY}} = 1$ TeV, $|X_t| = 2$ TeV, $\mu = 200$ GeV, $M_1 = 100$ GeV, $M_2 = 200$ GeV, $M_3 = 1200$ GeV)

4. Find best-fit point and CL contour regions.

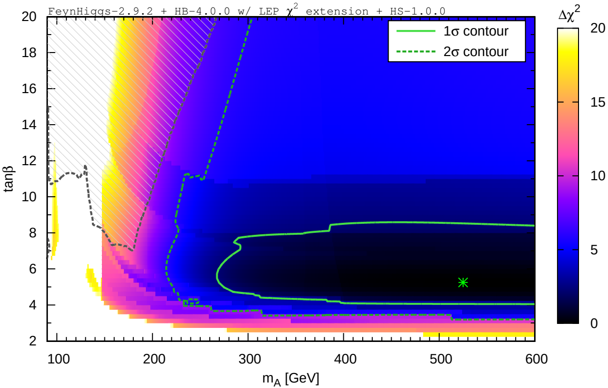


- minimal $\chi^2/\text{ndf} = 22.4/35$ at $(m_A, \tan\beta) = (525.0 \text{ GeV}, 5.3)$.
- HiggsBounds excludes part of the 68% C.L. region with $m_h \gtrsim 128$ GeV!?

The $m_h^{\max}$ scenario

($M_{\rm SUSY} = 1$ TeV, $|X_t| = 2$ TeV, $\mu = 200$ GeV, $M_1 = 100$ GeV, $M_2 = 200$ GeV, $M_3 = 1200$ GeV)

5. Take into account $\Delta m_h^{\rm th} = \Delta m_H^{\rm th} = 2$ GeV in HiggsBounds.



- Exclusion in large m_A region vanishes (now, $m_h \lesssim 130$ GeV is allowed).

Summary and Outlook

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

- HiggsBounds-4 will be *released very soon* and includes the newest 8 TeV LHC data, a treatment of the theoretical mass uncertainties, LEP χ^2 information...

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 on *coupling strength determination* and combined *mass-signal strength fit* 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.

Summary and Outlook

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Thank you for your attention!

Backup slides

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):

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

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

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

The SM likeness test succeeds, if

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

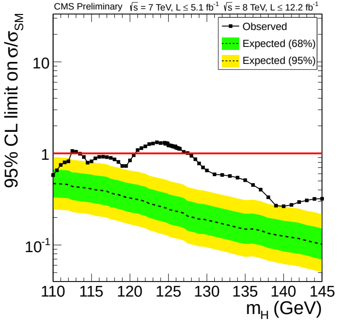
Performance tests with and without using SM weights $\to$ *backup slides*.

Modification of the statistical combination

Problem: For a model with a SM-like Higgs boson at $m \approx 125$ GeV, HiggsBounds typically selects the SM combination at 125 GeV as the most sensitive analysis.

- *Expected* exclusion (based on "background-only") is not valid here!

$\Rightarrow$ Model *not* excluded and constraints from remaining Higgs bosons are *not* applied!



Solution: Test *each* Higgs boson against its most-sensitive analysis and combine their results:

$$\text{model excluded} = (h_1 \text{ excluded}) \ \textbf{OR} \ (h_2 \text{ excluded}) \ \textbf{OR} \ldots$$

In most cases, the dilution of the 95% C.L. interpretation is *negligible*.

(Dilution appears only if two (or more) Higgs bosons are close to their exclusion limit).

peak-centered χ^2 method: *Higgs-to-peaks assignment*

Consider the possibility that the observed peak is a superposition of signal rates of several Higgs bosons.

- Evaluate the χ^2 contribution of every possible combination of Higgs bosons assigned to a peak observable,
- choose the combination with lowest χ^2 contribution, which in addition fulfills the following conditions:
  - Higgs bosons whose mass m matches the observed mass $\hat{m}$ within the mass uncertainty,

    $$|m - \hat{m}| \leq \sqrt{(\Delta m)^2_{\mathrm{exp.}} + (\Delta m)^2_{\mathrm{theo.}}}, \qquad (1)$$

    must be included in the combination.
  - if there is no χ^2 contribution from the Higgs mass for this peak observable, Higgs bosons not fulfilling Eq. (1) must not be included in the combination.

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.

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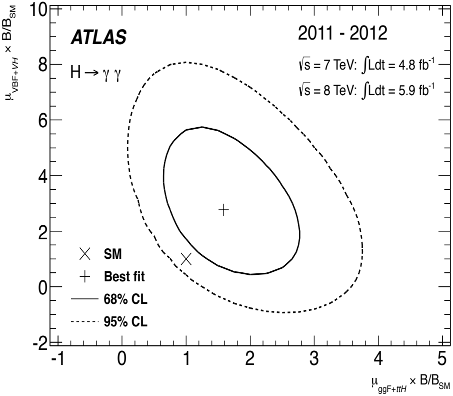

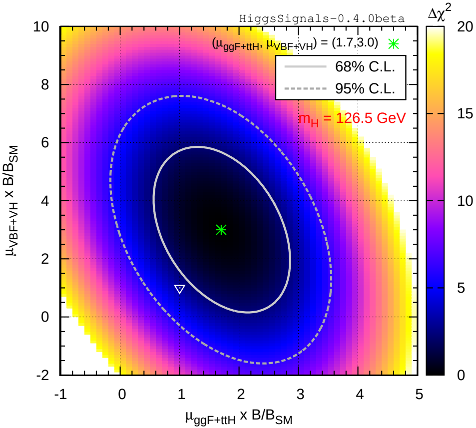

Combination of 7 and 8 TeV ATLAS $H \to \gamma\gamma$ results

- Take $\hat{\mu}$-plots from ATLAS SM $H \to \gamma\gamma$ search for 7 TeV and 8 TeV as observables.
- Scan over (m_H, μ) and for each (fixed) m_H, find minimal χ^2 and confidence regions $\Delta\chi^2 = 1$ (1σ) and 4 (2σ).

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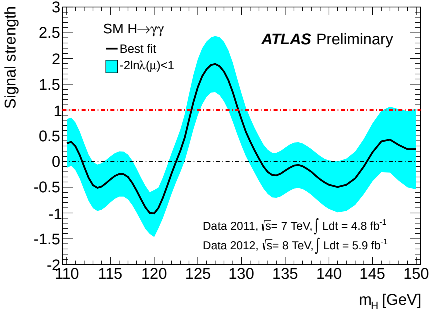

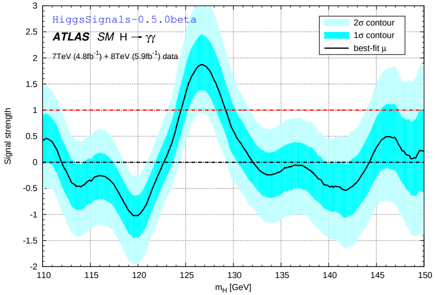

⇒ Very good agreement!