

# HiggsBounds and HiggsSignals

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*SLAC/Stanford LHC/ATLAS Physics Jamboree*

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# Constraining new physics with Higgs results

## ● Exclusion limits

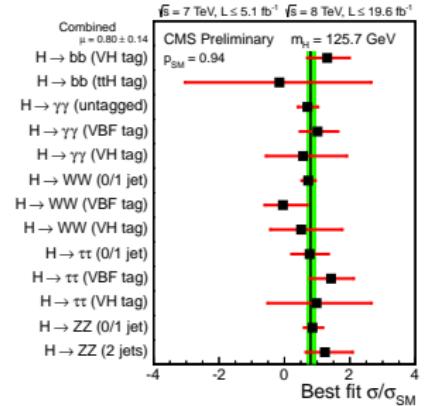
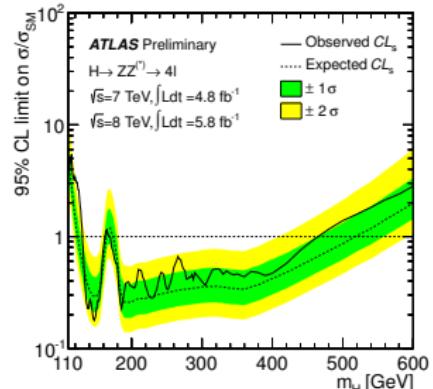
Still important ingredient to constrain extended Higgs sectors.

⇒ HiggsBounds

## ● Mass and rate measurements

Realistic new physics models must be compatible with mass and signal rate measurements of discovered Higgs state.

⇒ HiggsSignals



Testing theories against *exclusion limits* from Higgs searches:

# HiggsBounds-4

in collaboration with

P. Bechtle, (O. Brein), S. Heinemeyer, O. Stål, G. Weiglein, (K. Williams)

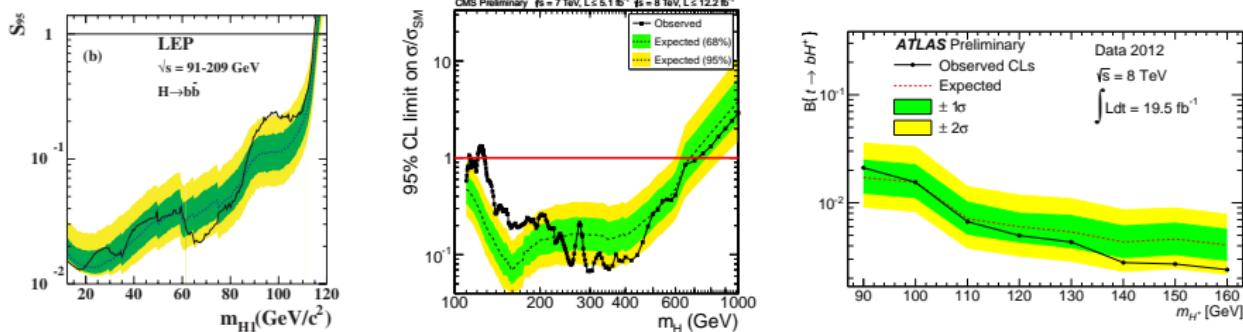


Eur.Phys.J. C74 (2014) 2693 [arXiv:1311.0055]

<http://higgsbounds.hepforge.org>

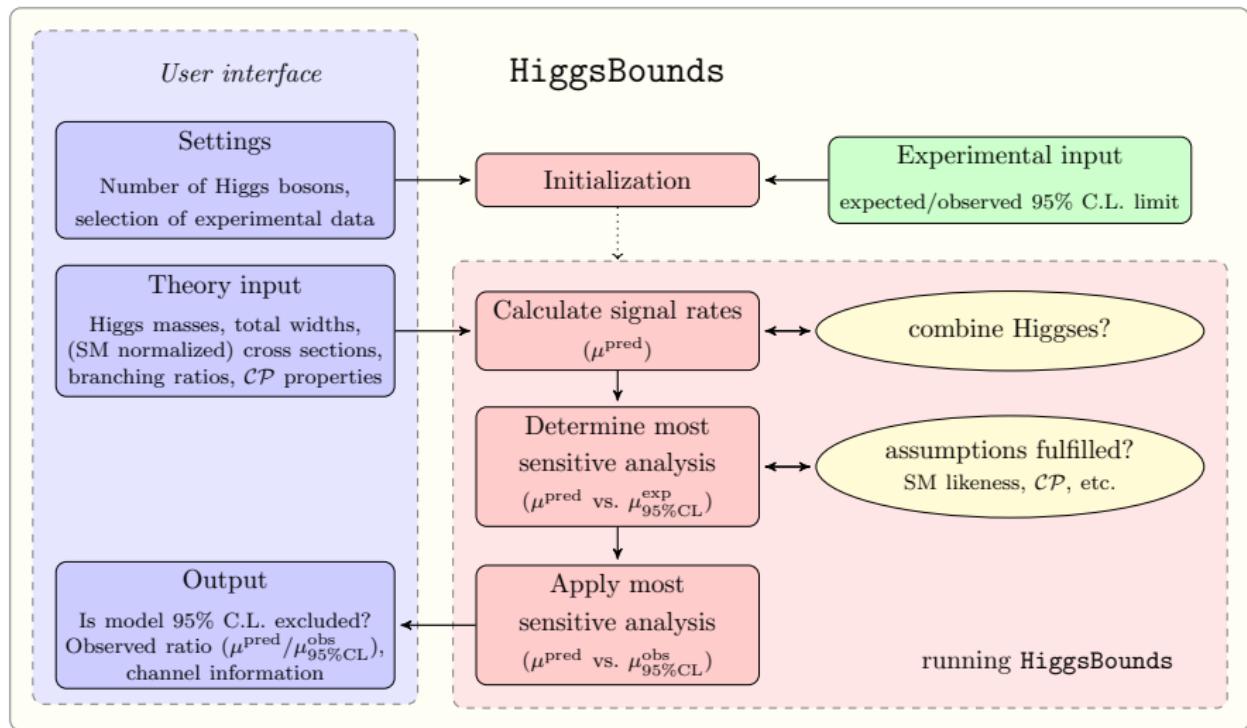
# Why HiggsBounds?

- $\gtrsim \mathcal{O}(100)$  limits from LEP, Tevatron and LHC experiments available for various channels / signal topologies.
- Different levels of applicability: from (almost) *model-independent* (e.g. at LEP) to *model-dependent* (SM Higgs searches at LHC) limits



- **HiggsBounds**: Fast, convenient, and statistically well-defined tool for theorists for testing their models against these limits.

# HiggsBounds in a nutshell



# Statistical procedure

- **HiggsBounds** first determines the most sensitive analysis for the model, and then applies only this exclusion limit.  
⇒ 95% C.L. is formally preserved.
- This **procedure may fail** if *expected exclusion* is based on “**wrong**” hypothesis (i.e. BG-only in the presence of an (established) signal)

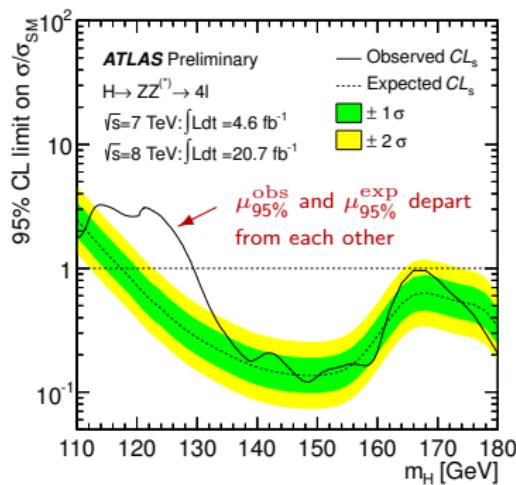
- **Workaround in HiggsBounds-4:**

Test every Higgs boson against its own most sensitive analysis.

(not strictly 95% C.L. exclusion anymore, but in most cases dilution of C.L. negligible.)

- For experiments:

⇒ Change hypothesis of expectation



# Applying SM Higgs searches to BSM physics

Given a SM Higgs analysis combining  $N$  search channels  
(i.e. production process  $\times$  decay process).

The total model-predicted signal rate (normalized to the SM) is then:

$$\mu^{\text{pred}} = \frac{\sum_{i=1}^N \epsilon_i [\sigma \times \text{BR}]_i}{\sum_{i=1}^N \epsilon_i [\sigma_{\text{SM}} \times \text{BR}_{\text{SM}}]_i}, \quad \epsilon_i : \text{efficiency of channel } i$$

**Problem:** Experiments often do *not* publish channel efficiencies  $\epsilon_i$ !

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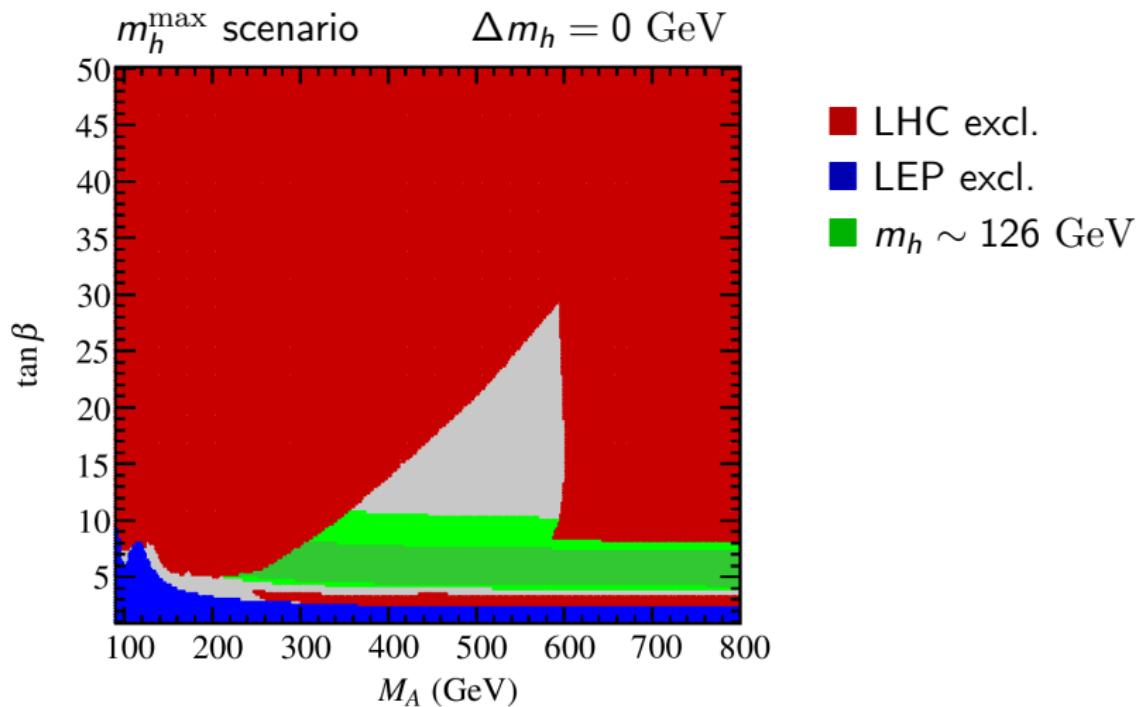
**Problem:** Experiments often do *not* publish channel efficiencies  $\epsilon_i$ !  
⇒ Have to *neglect* channel efficiencies!

**Way out:** Require that **the model** is **sufficiently SM-like** in the relevant channels,  
i.e. their relative proportions are similar as in the SM.

If not ⇒ Do not apply this analysis (conservative approach).

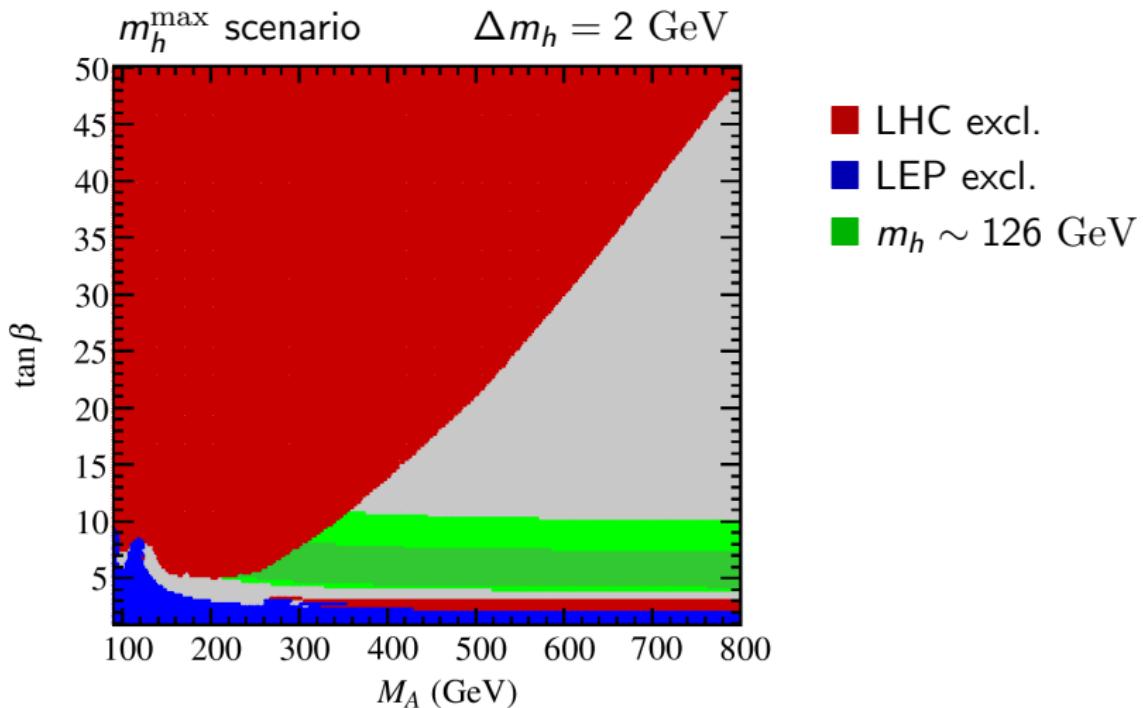
→ more information on *SM-likeness test* in backup-slides!

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



- SM Higgs combined analysis applies to  $h$  in region  $\approx$  decoupling limit.

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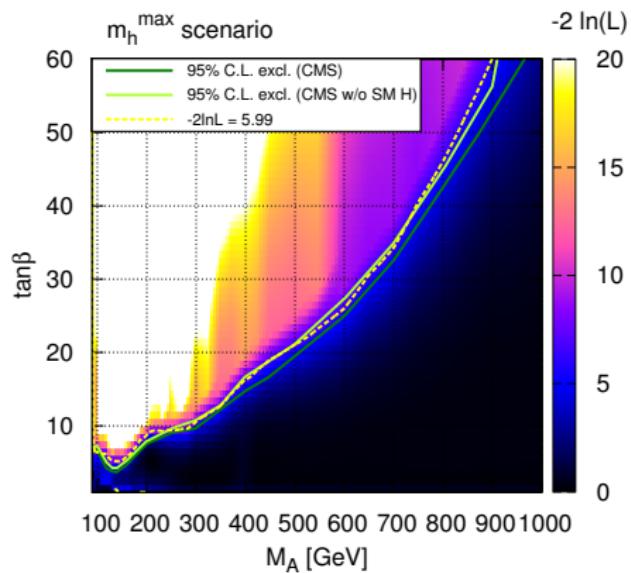
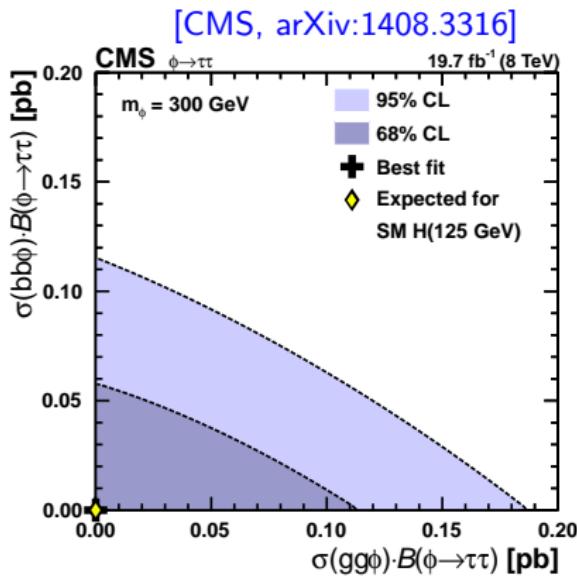


- SM Higgs combined analysis applies to  $h$  in region  $\approx$  decoupling limit.
- Exclusion vanishes if theoretical mass uncertainty taken into account.

# Current developments

Preparation of new [HiggsBounds-4.2.0 release](#), including

- new Summer 2014 results from ATLAS and CMS,
- a  $\chi^2$  extension for the [CMS MSSM  \$h/H/A \rightarrow \tau\tau\$  search](#):



2D likelihoods for fixed resonance masses

validation with MSSM benchmarks

Testing theories against *observations* in Higgs searches:

# HiggsSignals

in collaboration with

P. Bechtle, S. Heinemeyer, O. Stål and G. Weiglein

Eur.Phys.J. C74 (2014) 2711 [arXiv:1305.1933]

<http://higgsbounds.hepforge.org>

## HiggsSignals: The basic idea

- ① Take model-predictions of a given (arbitrary) Higgs sector for

$$m_k, \quad \Gamma_k^{\text{tot}}, \quad \sigma_i(pp \rightarrow H_k), \quad \text{BR}(H_k \rightarrow XX),$$

with  $k = 1, \dots, N$ ,  $i \in \{\text{ggH}, \text{VBF}, \text{WH}, \text{ZH}, t\bar{t}H\}$

for  $N$  neutral Higgs bosons as the program's user input.

*Optional input:* Theo. uncertainties for mass, cross sections and BR's.

- ② Calculate the predicted signal strength  $\mu$  for every observable,

$$\mu_{H \rightarrow XX} = \frac{\sum_i \epsilon_{\text{model}}^i [\sigma_i(pp \rightarrow H) \times \text{BR}(H \rightarrow XX)]_{\text{model}}}{\sum_i \epsilon_{\text{SM}}^i [\sigma_i(pp \rightarrow H) \times \text{BR}(H \rightarrow XX)]_{\text{SM}}}.$$

- ③ Perform a  $\chi^2$  test of model predictions against all available data from Tevatron and LHC, using signal rate and mass measurements.

Try to be as model-independent and precise as possible.

## HiggsSignals: The $\chi^2$ evaluation

In the  $\chi^2$  evaluation, we try to take into account the correlations of the major systematic uncertainties, that are publicly known. These are

- fully correlated luminosity uncertainty:  $\Delta\mathcal{L}$ ,
- fully correlated theoretical rate uncertainties:  $\Delta\sigma_i$ ,  $\Delta\text{BR}_i$ .

Other correlations of systematics can be incorporated if publicly known.

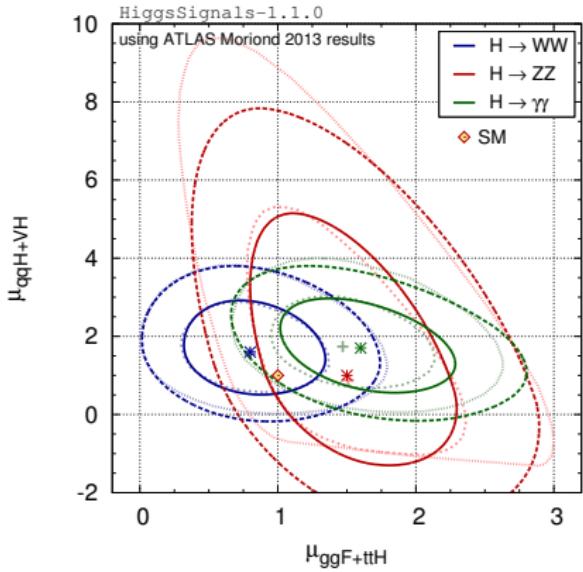
The global  $\chi^2$  for the signal strength measurements is then given by

$$\chi_{\mu}^2 = (\hat{\mu} - \mu)^T \mathbf{C}_{\mu}^{-1} (\hat{\mu} - \mu).$$

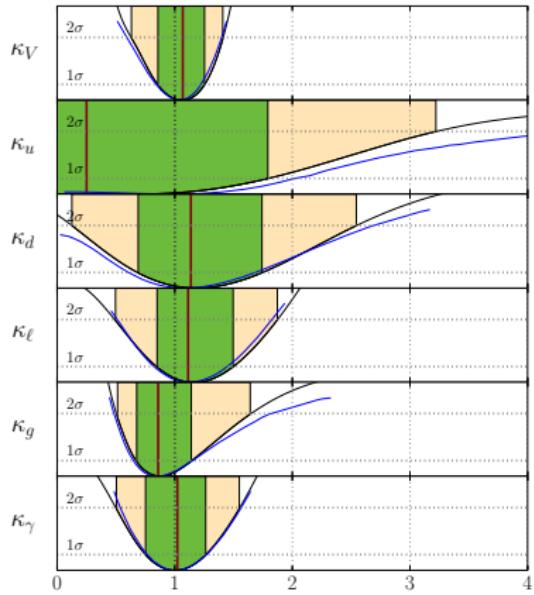
A similar calculation is done for the mass observables  $\Rightarrow \chi_m^2$ .

# Validation with ATLAS and CMS results

ATL-CONF-2013-034



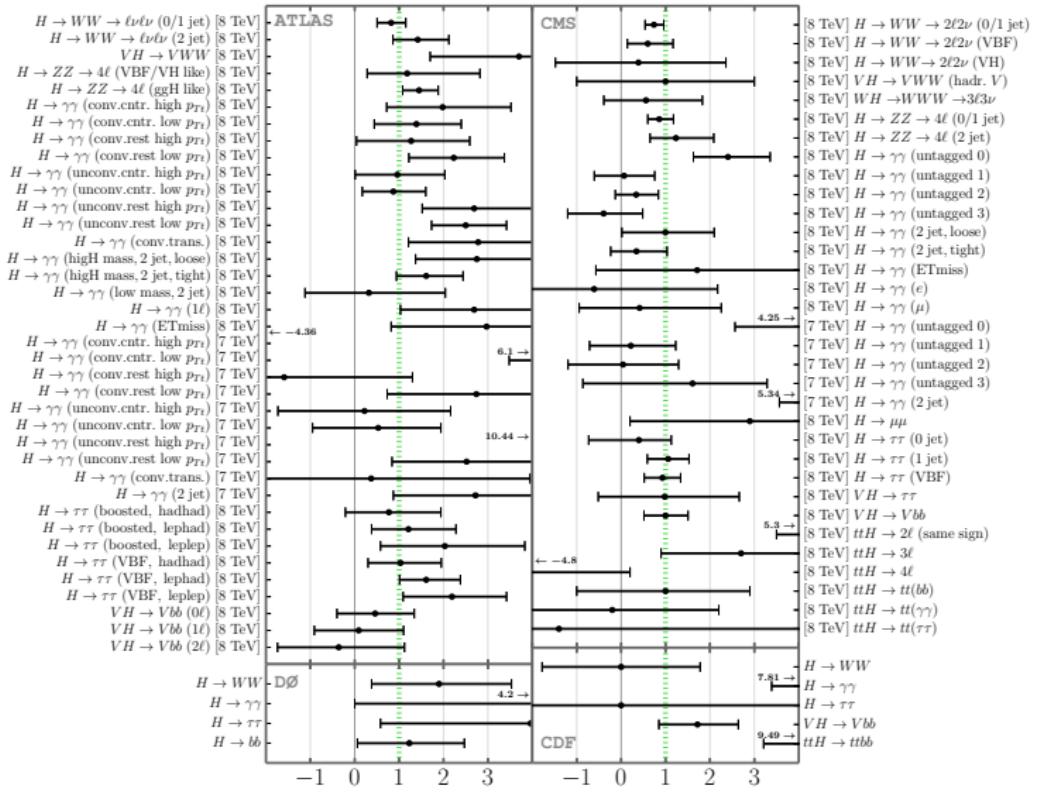
CMS-PAS-13-005



⇒ Generally good agreement! Main limiting factors / challenges:  
Missing public information on signal efficiencies, correlated systematics, . . .

# Observables included in HiggsSignals-1.2.0

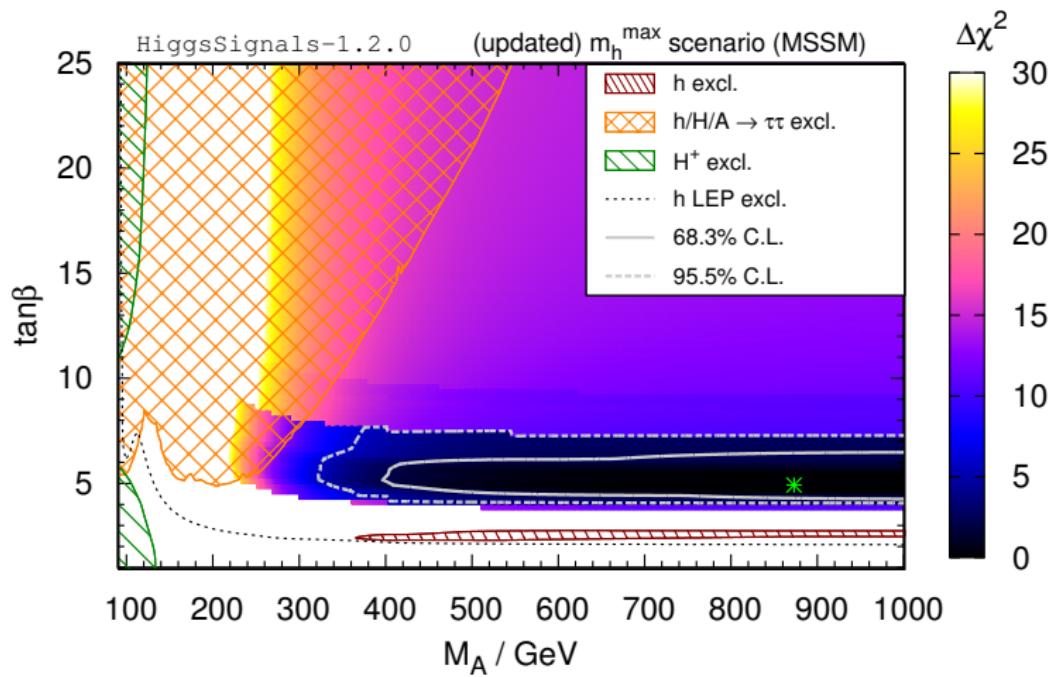
*in total:* 80 signal rate + 4 mass measurements



# Example applications

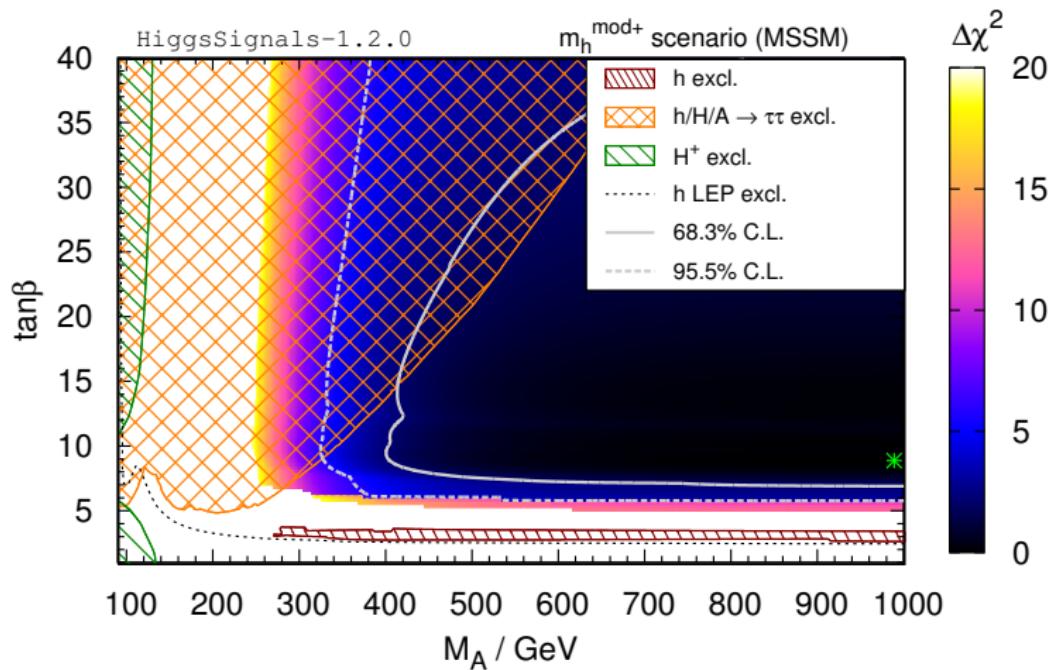
# Example: MSSM benchmark $m_h^{\max}$ scenario

Carena, Heinemeyer, Stål, Wagner, Weiglein '13, [arXiv:1302.7033]



# Example: MSSM benchmark $m_h^{\text{mod}+}$ scenario

Carena, Heinemeyer, Stål, Wagner, Weiglein '13, [arXiv:1302.7033]

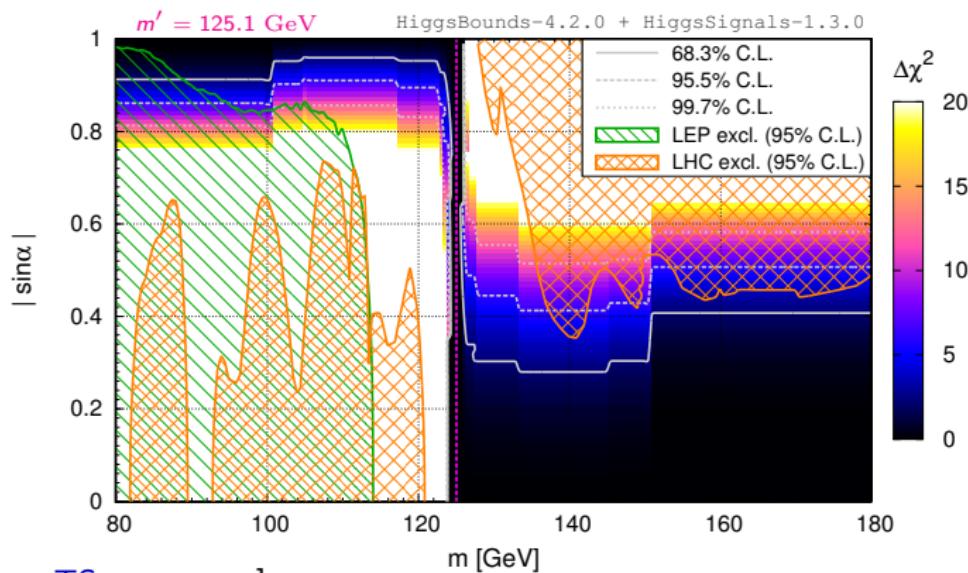


$$\chi^2/\text{ndf} = 85.2/83$$

# Real Higgs singlet extension of the SM

- consider SM extended by a real Higgs singlet with vev  $\neq 0$ .  
⇒ doublet-singlet mixing to physical states ( $h, H$ )

$$g_{hXX} = \cos \theta g_{HXX}^{\text{SM}}, \quad g_{HXX} = \sin \theta g_{HXX}^{\text{SM}}$$

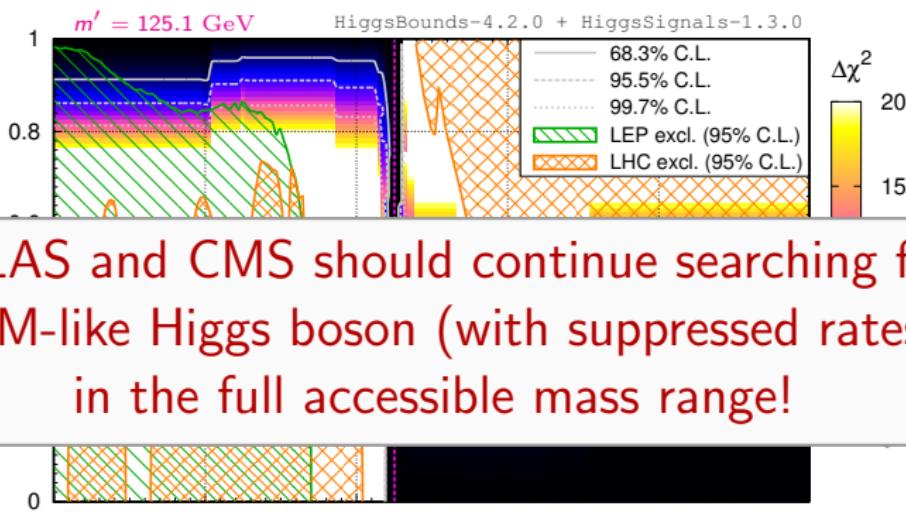


[T. Robens, TS, to appear]

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# Summary

[HiggsBounds](#) and [HiggsSignals](#) provide an interface between experiment and theory. They test the compatibility of BSM theories with latest Higgs data.

- Improvements in the implementation could be made if **signal efficiencies** are given in a more complete way (both for limits and measurements),
- transparent information about **correlations of systematic uncertainties** and their impact on the signal rate measurements is valuable.

New releases of [HiggsBounds](#) and [HiggsSignals](#) will appear soon, including

- latest results from the Summer 2014 conferences,
- CMS MSSM  $h/H/A \rightarrow \tau\tau$  likelihood information.

Feel free to sign up to the [mailing list](#) and stay tuned!

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Thanks for your attention!

# Backup Slides

# The SM likeness test

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

$$c_i = \frac{[\sigma_{\text{model}} \times \mathcal{B}_{\text{model}}]_i}{[\sigma_{\text{SM}} \times \mathcal{B}_{\text{SM}}]_i}, \quad \omega_i = \frac{[\sigma_{\text{SM}} \times \mathcal{B}_{\text{SM}}]_i}{\sum_j [\sigma_{\text{SM}} \times \mathcal{B}_{\text{SM}}]_j}.$$

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

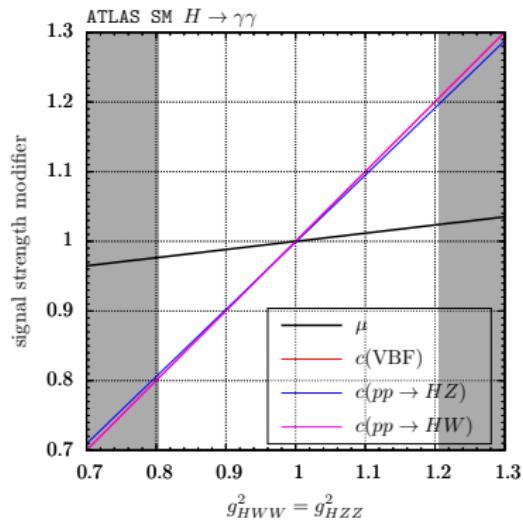
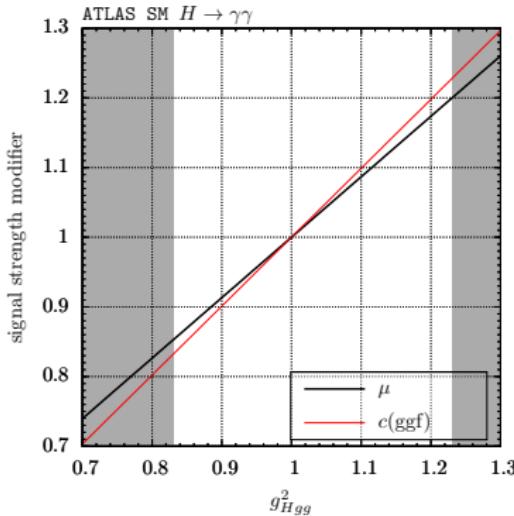
$$\mu \approx \sum_{i=1}^{N_c} \omega_i c_i \quad \left( = \frac{\sum_i [\sigma_{\text{model}} \times \mathcal{B}_{\text{model}}]_i}{\sum_j [\sigma_{\text{SM}} \times \mathcal{B}_{\text{SM}}]_j} \right)$$

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 of the SM likeness test

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



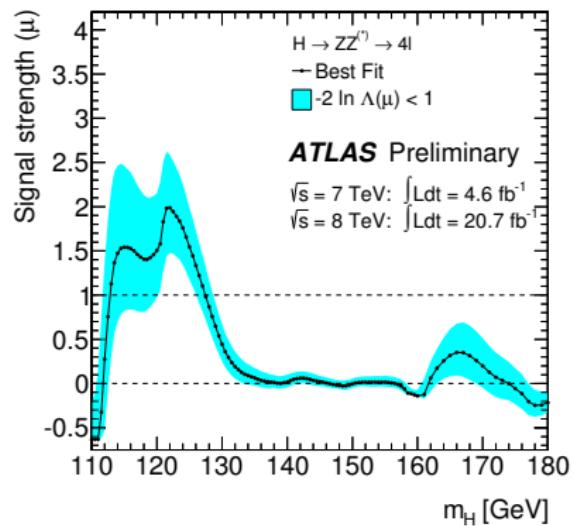
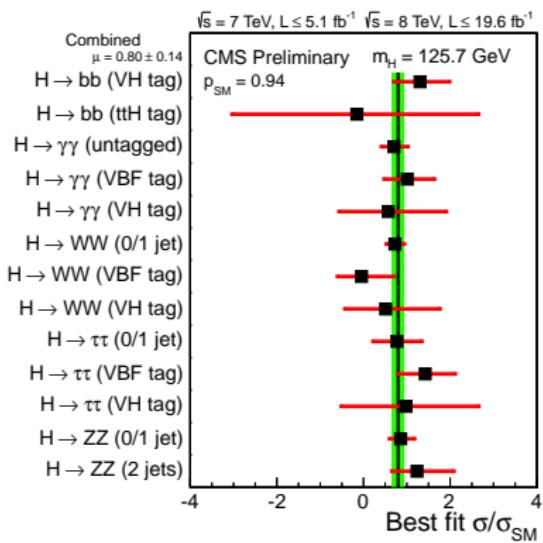
gray region: SM likeness test fails.

# Experimental input for HiggsSignals

- Signal strength measurements:

$$\mu_{H \rightarrow XX} = \frac{\sum_i \epsilon_{\text{model}}^i [\sigma_i(pp \rightarrow H) \times \text{BR}(H \rightarrow XX)]_{\text{model}}}{\sum_i \epsilon_{\text{SM}}^i [\sigma_i(pp \rightarrow H) \times \text{BR}(H \rightarrow XX)]_{\text{SM}}},$$

with  $i \in \{\text{ggH, VBF, } WH, ZH, t\bar{t}H\}$  and efficiencies  $\epsilon_i$ .



# Experimental input in HiggsSignals

The user can directly add/remove/edit observables via text files:

```
# Published at Moriond 2013.  
# Data read in from Fig. 25a.  
# No efficiencies are given (for this inclusive result)  
# Mass uncertainty contains 0.6 GeV (stat) and 0.5 GeV (syst) error.  
#(Gauss: 0.8, linear: 1.1)  
2013013101 201301301 1  
ATL-CONF-2013-013  
LHC, ATL, ATL  
(pp)->h->ZZ->4l  
8 25.3 0.036  
1 1  
1.1  
124.3 124.3 0.1  
4 -1  
13 23 33 43
```

124.3

1.293

1.697

2.194

# Efficiencies

Valuable information! Is included in **HiggsSignals** if available.

Expected signal and estimated background									
Event classes		SM Higgs boson expected signal ( $m_H=125\text{ GeV}$ )					Background		
		Total	ggH	VBF	VH	tH	$\sigma_{\text{eff}}$ (GeV)	FWHM/2.35 (GeV)	$m_{\gamma\gamma} = 125\text{ GeV}$ (ev./GeV)
7 TeV $5.1\text{ fb}^{-1}$	Untagged 0	3.2	61.4%	16.8%	18.7%	3.1%	1.21	1.14	$3.3 \pm 0.4$
	Untagged 1	16.3	87.6%	6.2%	5.6%	0.5%	1.26	1.08	$37.5 \pm 1.3$
	Untagged 2	21.5	91.3%	4.4%	3.9%	0.3%	1.59	1.32	$74.8 \pm 1.9$
	Untagged 3	32.8	91.3%	4.4%	4.1%	0.2%	2.47	2.07	$193.6 \pm 3.0$
	Dijet tag	2.9	26.8%	72.5%	0.6%	—	1.73	1.37	$1.7 \pm 0.2$
8 TeV $19.6\text{ fb}^{-1}$	Untagged 0	17.0	72.9%	11.6%	12.9%	2.6%	1.36	1.27	$22.1 \pm 0.5$
	Untagged 1	37.8	83.5%	8.4%	7.1%	1.0%	1.50	1.39	$94.3 \pm 1.0$
	Untagged 2	150.2	91.6%	4.5%	3.6%	0.4%	1.77	1.54	$570.5 \pm 2.6$
	Untagged 3	159.9	92.5%	3.9%	3.3%	0.3%	2.61	2.14	$1060.9 \pm 3.5$
	Dijet tight	9.2	20.7%	78.9%	0.3%	0.1%	1.79	1.50	$3.4 \pm 0.2$
	Dijet loose	11.5	47.0%	50.9%	1.7%	0.5%	1.87	1.60	$12.4 \pm 0.4$
	Muon tag	1.4	0.0%	0.2%	79.0%	20.8%	1.85	1.52	$0.7 \pm 0.1$
	Electron tag	0.9	1.1%	0.4%	78.7%	19.8%	1.88	1.54	$0.7 \pm 0.1$
	$E_T^{\text{miss}}$ tag	1.7	22.0%	2.6%	63.7%	11.7%	1.79	1.64	$1.8 \pm 0.1$

An interface to insert *relative efficiency scale factors*  $\zeta^i \equiv \epsilon_{\text{model}}^i / \epsilon_{\text{SM}}^i$  per tested parameter point and analysis is provided since **HiggsSignals-1.1**.

# Complications with multiple neutral Higgs bosons

Any neutral Higgs boson could be responsible for the observed signal.

- Higgs boson  $i$  is *assigned* to the observable  $\alpha$ , if its mass is close enough to observed signal position:

$$|m_i - \hat{m}_\alpha| \leq \Lambda \sqrt{(\Delta m_i)^2 + (\Delta \hat{m}_\alpha)^2} \quad \Rightarrow \quad \text{Higgs } i \text{ assigned}$$

with tuning parameter  $\Lambda \simeq 1$  (assignment range).

- If multiple Higgs bosons are assigned, their signal strengths are added incoherently:  $\mu_\alpha = \sum_i \mu_{\alpha,i}$
- If **no** Higgs boson is assigned to an observable  $\alpha$ , its  $\chi^2$  contribution is evaluated for **zero predicted signal strength**,  $\mu_\alpha = 0$ .

# Total $\chi^2$ vs. mass distribution of a SM-like Higgs boson

HiggsSignals provides three different probability distribution functions (pdfs) for the Higgs mass: **box-shaped**, **Gaussian**, **box-theo.+Gaussian-exp.**

Example: SM-like Higgs boson with  $\Delta m = 2 \text{ GeV}$  (and  $\Lambda = 1$ )

