

Higgs Coupling Scale Factor Fits with HiggsSignals

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We found something spectacular . . .

And would be even more spectacular if it was part of something else!

- HiggsSignals and HiggsBounds are tools to test arbitrary Higgs sectors against the measurements from LEP, the Tevatron and the LHC
- They use model independent input
- And they can test for any number of neutral or charged Higgs bosons

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- And they can test for any number of neutral or charged Higgs bosons
- OK, so what's a "Higgs boson" "model independently"?
- Basically everything which either
 - fully behaves like the SM Higgs boson in terms of selection efficiencies of individual channels (**no** agreement necessary in terms of masses or any couplings)
Use HiggsSignals and HiggsBounds out of the box
 - or something which kinematicall does not behave like a SM Higgs, but where you know how to modify the acceptances and or efficiencies for each affected channel
Use HiggsSignals and HiggsBounds and enter your own scale factors for the affected efficiencies

Constraining new physics with Higgs results

Exclusion limits

Still important ingredient to constrain extended Higgs sectors.

⇒ HiggsBounds

<http://higgsbounds.hepforge.org>

[PB, Brein, Heinemeyer, Stål, Stefaniak, Weiglein, Williams,

'08, '11, '13]

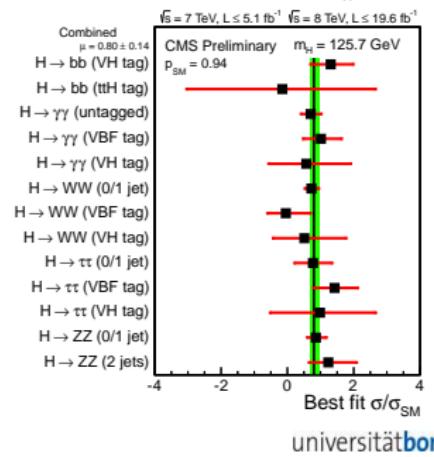
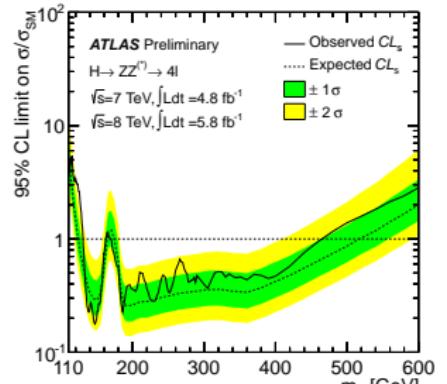


HIGGSBOUNDS

Mass and rate measurements

Realistic new physics models must be compatible with mass and signal rate measurements of discovered Higgs state.
And in the future also with its kinematics.

⇒ HiggsSignals



HiggsSignals

The program HiggsSignals

(PB, S. Heinemeyer, O. Stal, T. Stefaniak, G. Weiglein,
arXiv:1305.1933, arxiv:1403:1582)

- 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),
- includes correlations among the major systematic uncertainties (cross sections, branching ratios, luminosity, theory mass uncertainty),
- includes many more features:
 - It finds best assignment of Higgs bosons to the signal and automatically combines signal rates of Higgses overlapping within mass resolution,
 - Framework to include signal efficiencies,
 - New (even hypothetical) signals can be implemented by the user,
 - Toy measurements can be given to existing observables for statistical studies,
 - Signal rate uncertainties can be scaled for future projections,
 - ...

HiggsSignals is a stand-alone program using the HiggsBounds libraries. Coding language is Fortran90/2003.

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 μ for every observable.
- ③ Perform a χ^2 test of model predictions against all available data from Tevatron and LHC, using signal rate and mass measurements.

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The aim is to be as

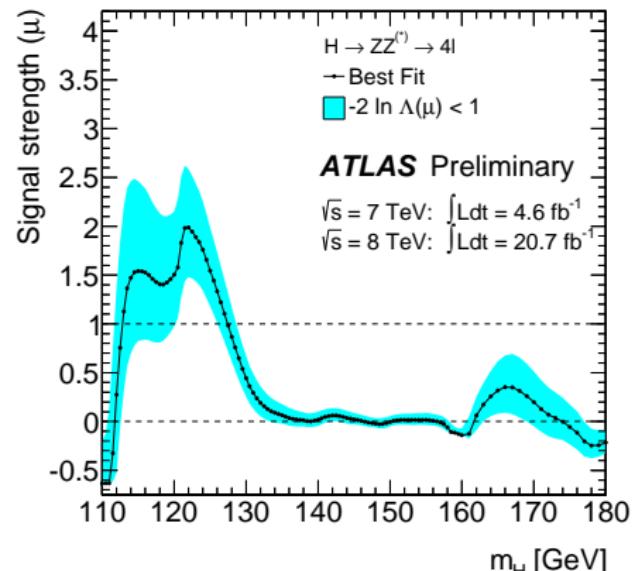
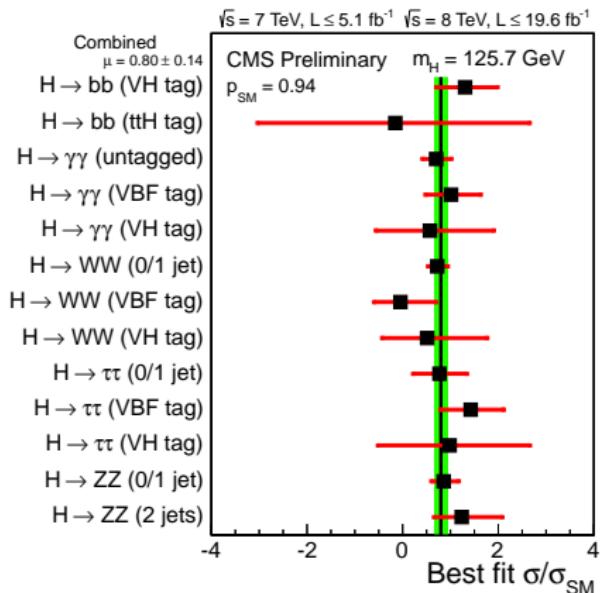
- model-independent as possible,
- precise as possible (given the limited public information available)

Experimental input

- 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 ϵ_i .



Experimental input

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
```

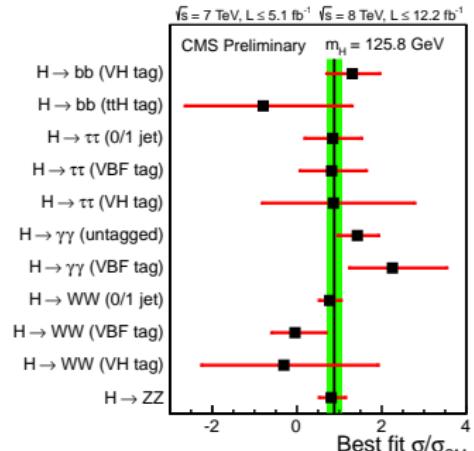
Peak-centered χ^2 method

- Tests agreement between model and data at the observed mass.
- Define observables by the best-fit signal strength, $\hat{\mu}_i$, at a hypothetical Higgs mass \hat{m}_i .
- The total χ^2 consists of a signal strength and a Higgs mass part,

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

- Only analyses with a good mass measurement enter $\chi_{m_i}^2$ ($H \rightarrow \gamma\gamma, ZZ$)
- Can be evaluated at different \hat{m}_i for each measurement
- Assign carefully chosen penalties if predicted Higgs m_i is too far off from \hat{m}_i

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



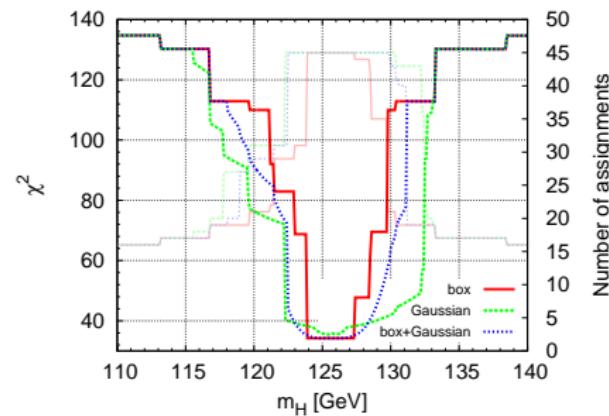
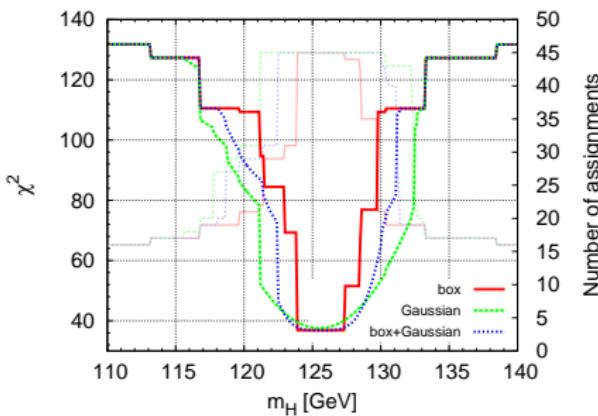
Efficiencies

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	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)
$7\text{ TeV } 5.1\text{ fb}^{-1}$	Untagged 0	3.2	61.4%	16.8%	18.7%	3.1%	1.21	1.14
	Untagged 1	16.3	87.6%	6.2%	5.6%	0.5%	1.26	1.08
	Untagged 2	21.5	91.3%	4.4%	3.9%	0.3%	1.59	1.32
	Untagged 3	32.8	91.3%	4.4%	4.1%	0.2%	2.47	2.07
	Dijet tag	2.9	26.8%	72.5%	0.6%	–	1.73	1.37
$8\text{ TeV } 19.6\text{ fb}^{-1}$	Untagged 0	17.0	72.9%	11.6%	12.9%	2.6%	1.36	1.27
	Untagged 1	37.8	83.5%	8.4%	7.1%	1.0%	1.50	1.39
	Untagged 2	150.2	91.6%	4.5%	3.6%	0.4%	1.77	1.54
	Untagged 3	159.9	92.5%	3.9%	3.3%	0.3%	2.61	2.14
	Dijet tight	9.2	20.7%	78.9%	0.3%	0.1%	1.79	1.50
	Dijet loose	11.5	47.0%	50.9%	1.7%	0.5%	1.87	1.60
	Muon tag	1.4	0.0%	0.2%	79.0%	20.8%	1.85	1.52
	Electron tag	0.9	1.1%	0.4%	78.7%	19.8%	1.88	1.54
	E_T^{miss} tag	1.7	22.0%	2.6%	63.7%	11.7%	1.79	1.64

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**.

Example: Simple SM scan in m_h



- Penalties cause flat lines for bad mass fit
- Assignment width can be chosen by the user dependent on model requirements

The χ^2 evaluation

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

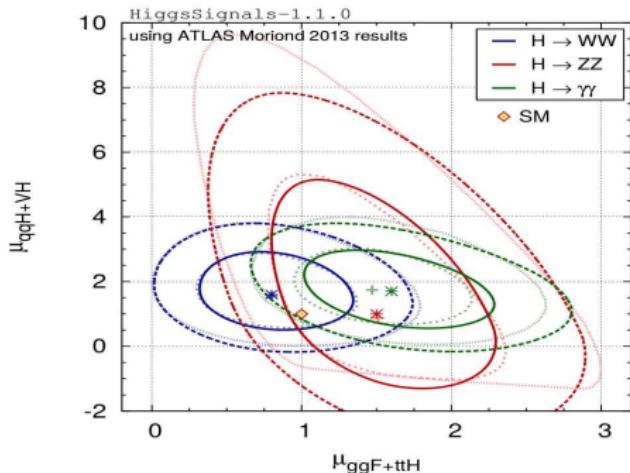
- fully correlated **luminosity uncertainty**: $\Delta\mathcal{L}$,
- fully correlated **theoretical rate uncertainties**: $\Delta\sigma_i$, ΔBR_i .

Other correlations of systematics could be incorporated if they were public. The global χ^2 for the signal strength measurements is then given by

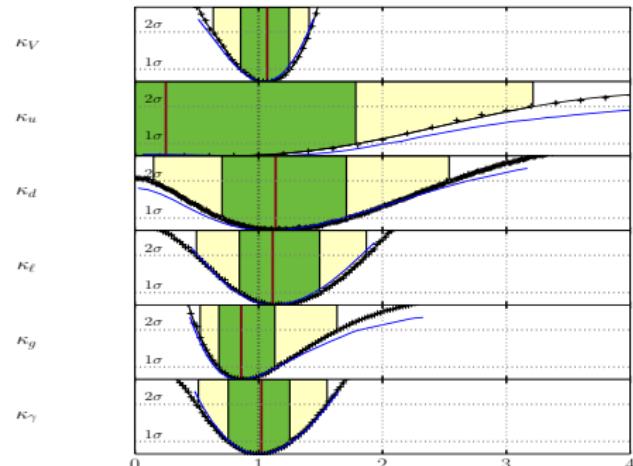
$$\chi_{\mu}^2 = (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})^T \mathbf{C}_{\mu}^{-1} (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu}).$$

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

Validation against ATLAS and CMS (Moriond 2013)



ATL-CONF-2013-034



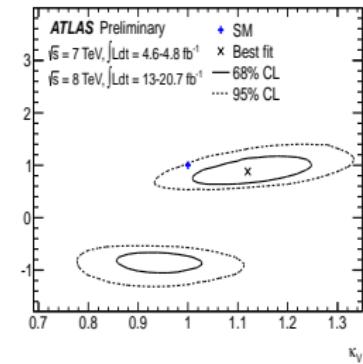
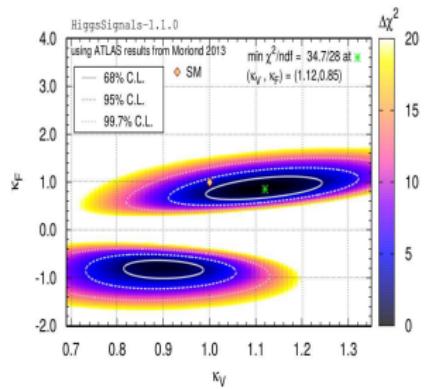
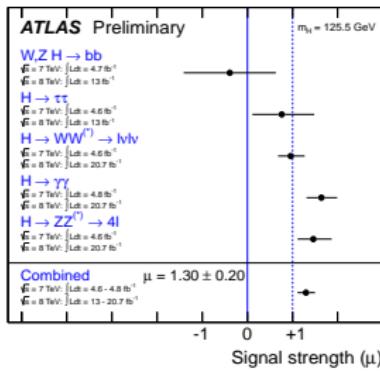
CMS-PAS-13-005

Generally good agreement Main limiting factors / challenges:

- Missing public information on signal efficiencies,
- Missing public information on correlations of exp. systematics,
- some measurements are performed at different m_H values than validation.

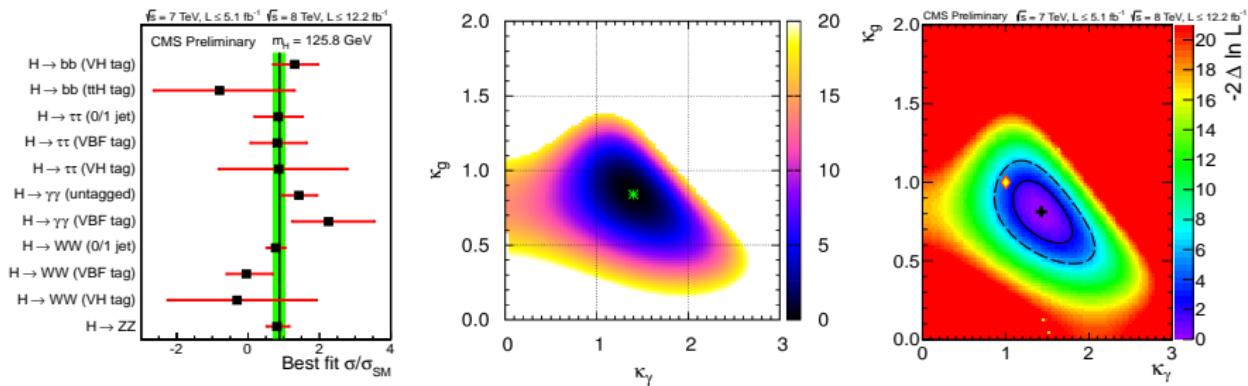
Test using ATLAS and κ_F, κ_V

- Test simple 2D effective coupling benchmark models, proposed in LHC Higgs Cross Section Working Group, Sep.12, [1209.0040]
- Scale fermion couplings by κ_F and vector boson couplings by κ_V
- non-trivial scaling of loop-induced $H\gamma\gamma$ coupling.
- loop-induced Hgg coupling scales with κ_F (effectively a fermion loop).
- No special treatment of negative μ ;

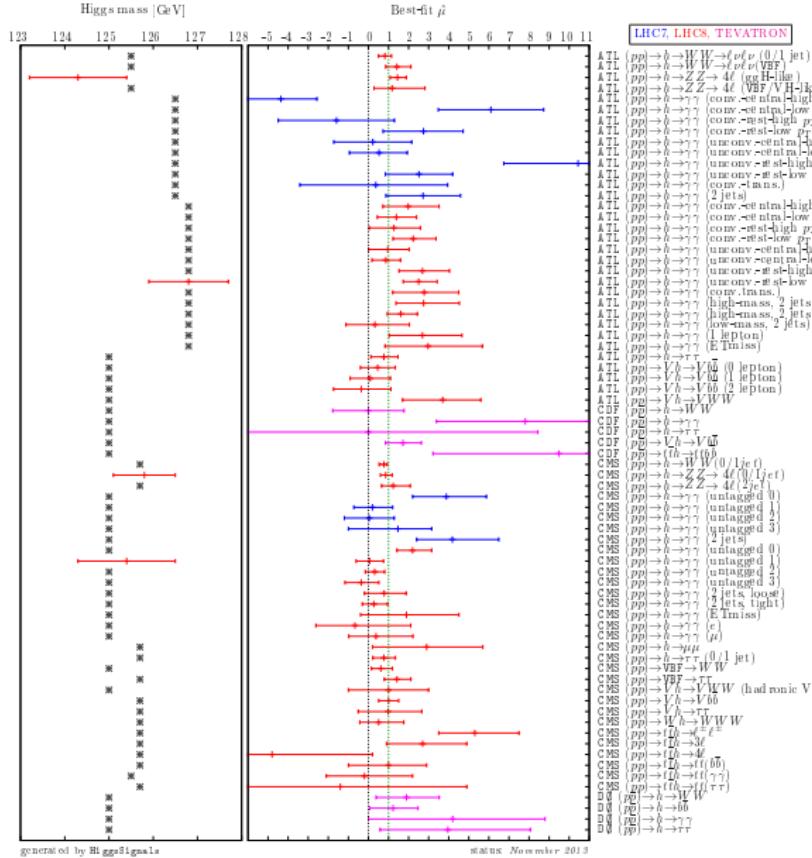


Test using CMS and κ_g, κ_γ

- Test simple 2D effective coupling benchmark models, proposed in LHC Higgs Cross Section Working Group, Sep.12, [1209.0040]
- scale loop-induced gluon couplings by κ_g and photon couplings by κ_γ . (keep tree-level couplings at their SM value)
- probing new physics contributions to loop-induced couplings.
- No special treatment of negative μ ;



Default set of observables (in HiggsSignals-1.1.0)



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 α , if its mass is close enough to observed signal position:

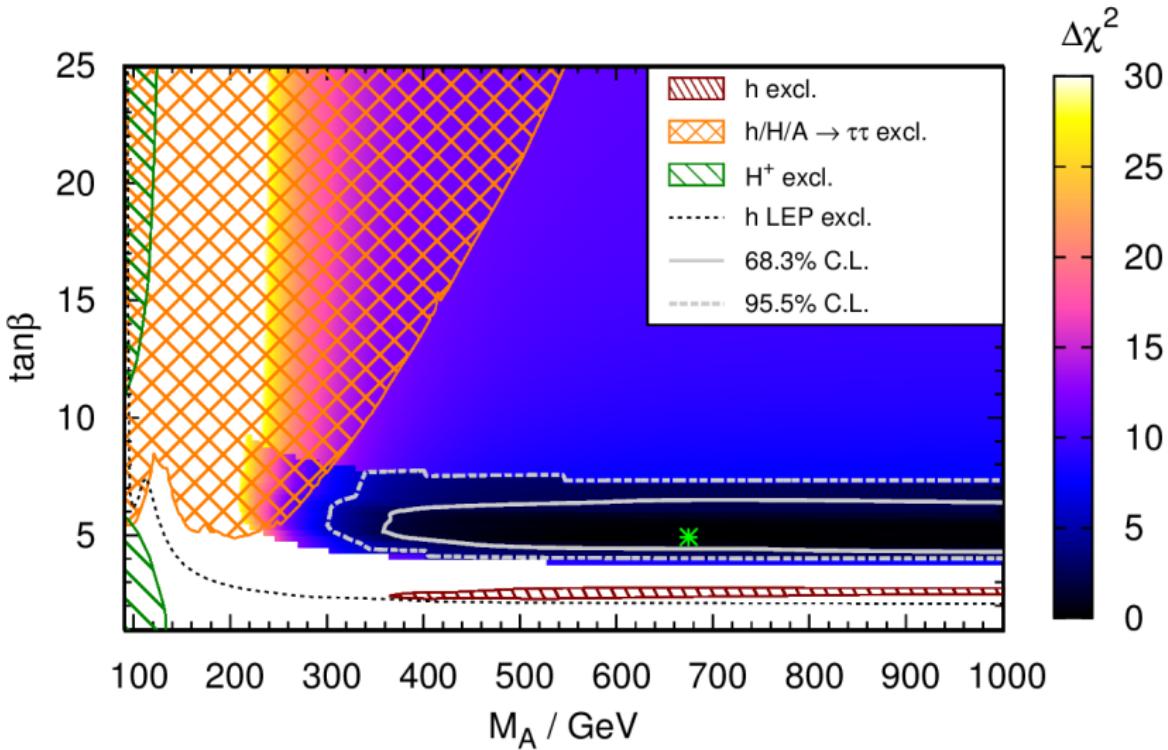
$$|m_i - \hat{m}_\alpha| \leq \Lambda \sqrt{(\Delta m_i)^2 + (\Delta \hat{m}_\alpha)^2} \quad \Rightarrow \quad \text{Higgs } i \text{ assigned}$$

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 α , its χ^2 contribution is evaluated for **zero predicted signal strength**, $\mu_\alpha = 0$.

Example: MSSM benchmark m_h^{\max} scenario

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

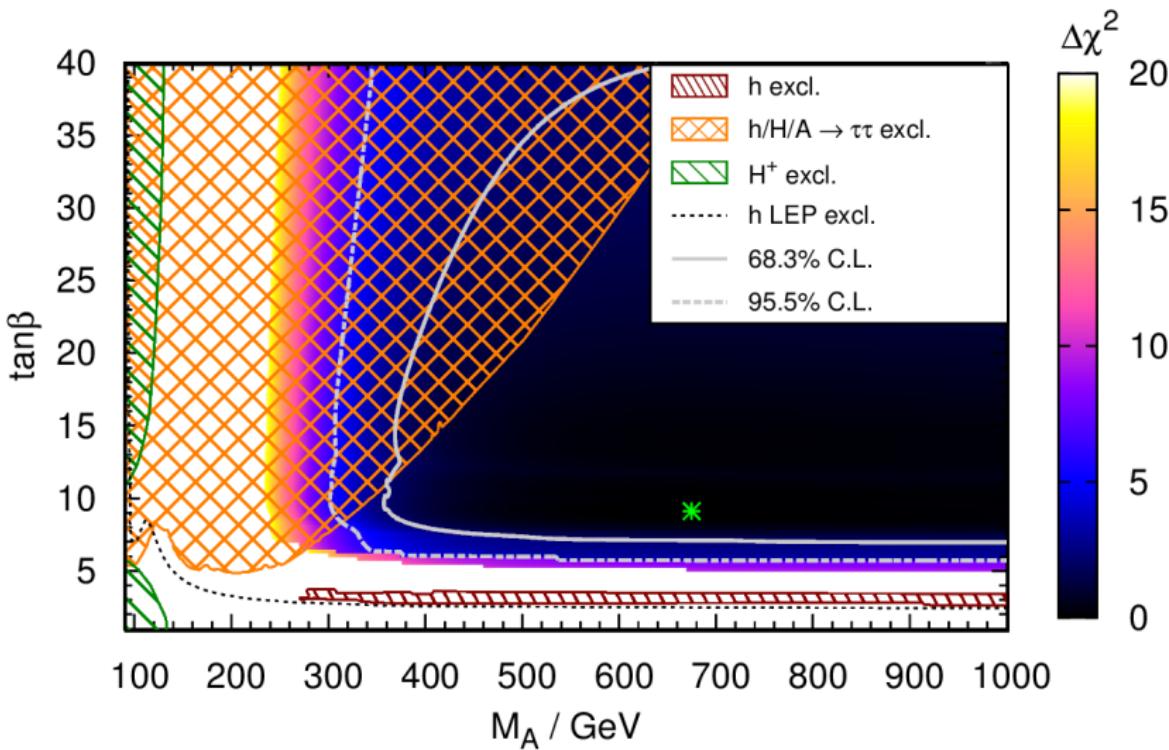


(+ HiggsBounds LEP χ^2 extension)

$\chi^2/\text{ndf} = 70.2/66$

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

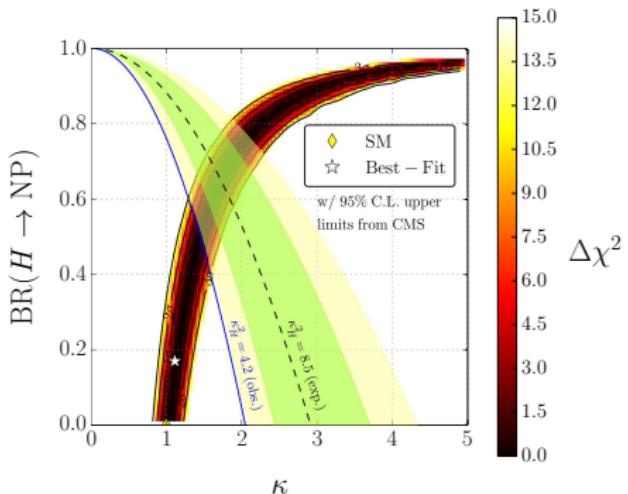
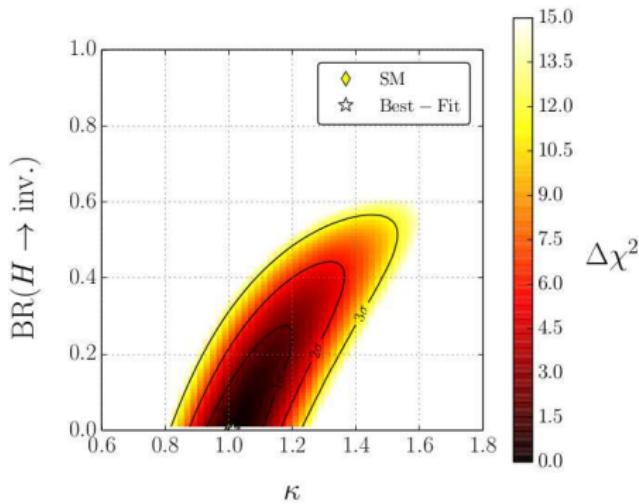
Carena, Heinemeyer, Stål, Wagner, Weiglein '13, [arXiv:1302.7033]



(+ HiggsBounds LEP χ^2 extension)

$$\chi^2/\text{ndf} = 70.6/66$$

Example: Minimal Visible Rate



using CMS-PAS-HIG-14-002

$$\kappa_{H,\text{limit}}^2 = 40 \text{ (10)} \quad \rightarrow \quad \kappa \leq 2.51 \text{ (1.78)} \quad \text{and} \quad \mathcal{B}(h \rightarrow \text{NP}) \leq 84\% \text{ (68\%)}$$

Example: 7-dimensional scale factor (κ) fit

- Additional decay mode:

$$\text{BR}(H \rightarrow \text{NP})$$

$$\text{BR}(H \rightarrow \text{NP}) \equiv \text{BR}(H \rightarrow \text{inv.})$$

- Independent scale factors:

$$\kappa_V^2 = \frac{\sigma_{\text{VBF}}}{\sigma_{\text{VBF}}^{\text{SM}}} = \frac{\sigma_{VH}}{\sigma_{VH}^{\text{SM}}} = \frac{\Gamma_{VV^{(*)}}}{\Gamma_{VV^{(*)}}^{\text{SM}}}$$

$$\kappa_u^2 = \frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{\text{SM}}} = \frac{\Gamma_{cc,tt}}{\Gamma_{cc,tt}^{\text{SM}}}$$

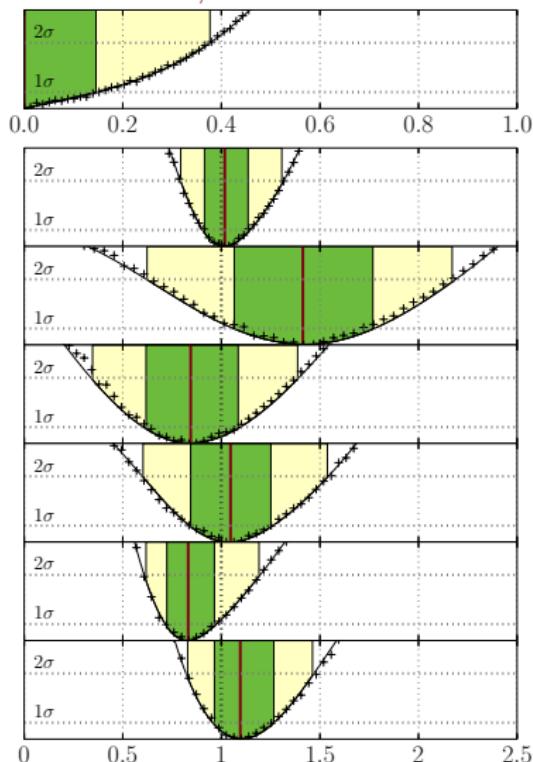
$$\kappa_d^2 = \frac{\Gamma_{ss,bb}}{\Gamma_{ss,bb}^{\text{SM}}}$$

$$\kappa_\ell^2 = \frac{\Gamma_{\mu\mu,\tau\tau}}{\Gamma_{\mu\mu,\tau\tau}^{\text{SM}}}$$

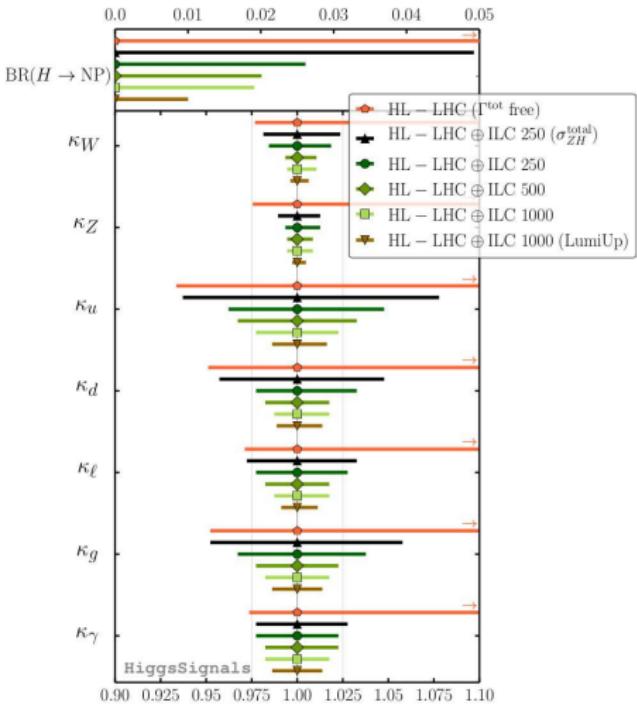
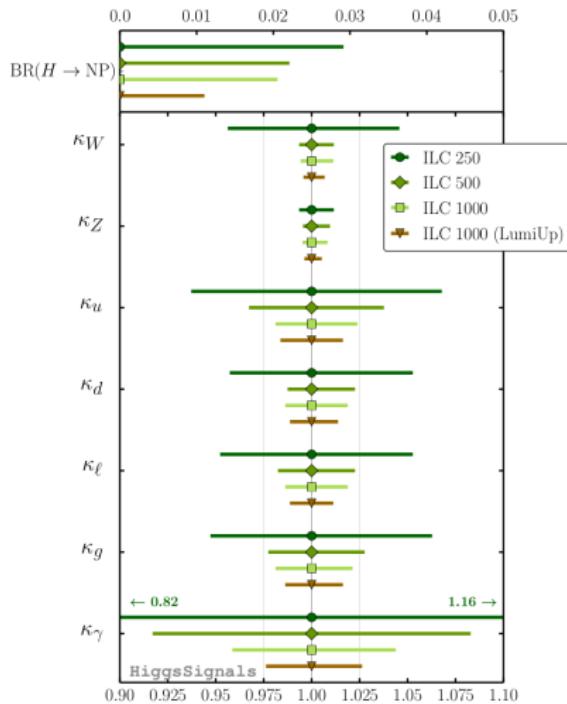
$$\kappa_g^2 = \frac{\sigma_{ggH}}{\sigma_{ggH}^{\text{SM}}} = \frac{\Gamma_{gg}}{\Gamma_{gg}^{\text{SM}}}$$

$$\kappa_\gamma^2 = \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\text{SM}}}$$

current LHC/Tevatron data

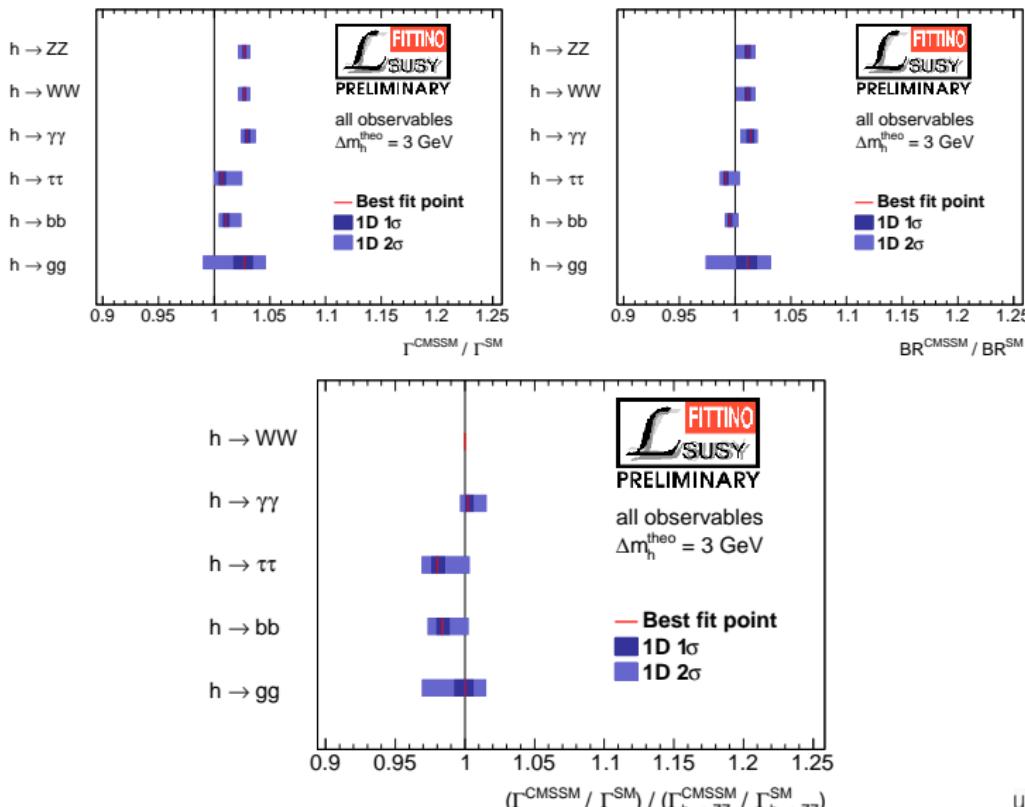


Example: Ultimate Precision at the ILC



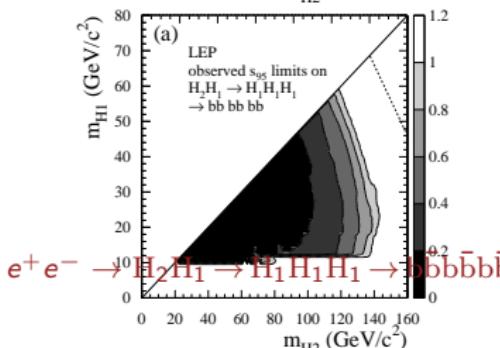
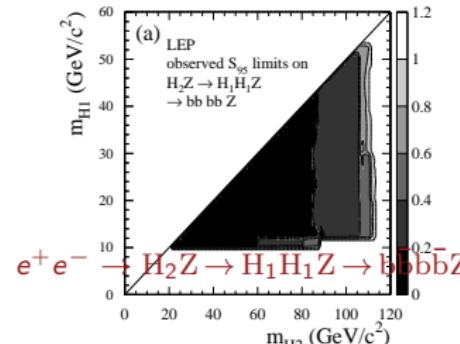
CMSSM application: Predicted Higgs properties

- Using HS + other input (see e.g. arXiv:1204.4199,arXiv:1310.3045)

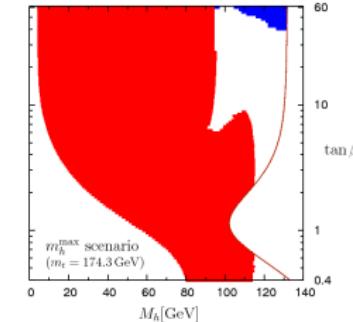
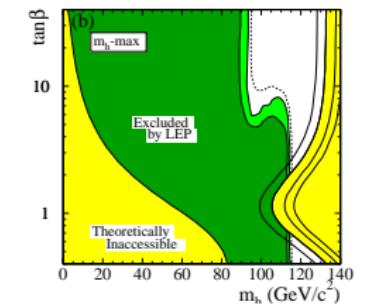


HiggsBounds: Higgs Searches in Arbitrary Models

- HiggsBounds project ARXIV:0811.4169 [HEP-PH], ARXIV:1102.1898 [HEP-PH]
- Use the model independent results from LEP/TeV/LHC statistically correctly interpreted in arbitrary models (but NOT combined)



Test using the MSSM:



Have to add a third dimension to these plots

Conclusions

- HiggsSignals and HiggsBounds are tools available for interpretations of the Higgs mass and rate measurements, and exclusions, in **every** model with **any** Higgses
- Thus they maybe are interesting for you to make sure your preferred model for studies at the ILC is in full agreement with the LHC results
- It could be interesting to feed results from a few different staging and running scenarios into a benchmark model in HiggsSignals and optimize
- The agreement between HiggsSignals and HiggsBounds and the official results from the experimental LHC collaborations is thoroughly tested and documented
- The agreement should be more than good enough for phenomenological studies using any model with Higgs(es)
- Can make detailed projections for future experiments

Backup Slides