HiggsSignals:

Testing BSM physics with LHC Higgs Measurements

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http://higgsbounds.hepforge.org

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Introduction

The LHC discovery in 2012 of a Higgs boson with mass $\sim 125\ \mathrm{GeV}$ has opened a new era in particle physics!

⇒ Particle content of the Standard Model seems complete!

⇒ Thus far, its measured properties agree with the SM predictions.

Well motivated BSM theories often feature an *extended* Higgs sector.

⇒ expect deviations in the signal rates / couplings of the discovered Higgs,

⇒ additional Higgs states may be discovered in future LHC searches.

Experiment	Theory (BSM)
precision measurements of Higgs signal rates and Higgs mass	*precise predictions* of Higgs signal rates and Higgs mass
collider searches for additional Higgs states	predictions/model building for additional Higgs states

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collider searches for additional Higgs states	HiggsBounds	predictions/model building for additional Higgs states

The HiggsSignals code

Authors: P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein

Programming Language: `Fortran 90` (based on `HiggsBounds` code)

First release: 9 May 2013

Current version: `HiggsSignals-1.4.0` (released 24 July 2015)

Website: `http://higgsbounds.hepforge.org`.

Documentation and useful references:

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

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

JHEP 1411 (2014) 039 [arXiv:1403.1582]

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HiggsSignals: The basic idea

1. Take model-predictions for *physical quantities* of given Higgs sector:

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

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

$$\mu_{H\to XX} = \frac{\sum_i \epsilon^i_{\text{model}} \, [\sigma_i(pp \to H) \times \text{BR}(H \to XX)]_{\text{model}}}{\sum_i \epsilon^i_{\text{SM}} \, [\sigma_i(pp \to H) \times \text{BR}(H \to XX)]_{\text{SM}}}.$$

   (narrow width approximation assumed)

3. Perform a χ^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.

Theoretical Input

- Model-predictions for *physical quantities* of given Higgs sector,

$$m_k, \quad \Gamma_k^{\rm tot}, \quad \sigma_i(pp \to H_k), \quad \mathrm{BR}(H_k \to XX),$$

  with $k = 1, \ldots, N$, $\quad i \in \{\mathrm{ggH}, \mathrm{VBF}, WH, ZH, t\bar{t}H\}$.

  σ, BR given via effective couplings or at partonic/hadronic level using the HiggsBounds framework:

  - SLHA (requires two HiggsBounds specific Blocks),
  - HiggsBounds specific input data-files, or
  - Fortran 90 subroutines.

- Input for specific models can be provided by other tools, e.g., FeynHiggs, CPsuperH, 2HDMC, SARAH/SPheno, NMSSMTools,. . .

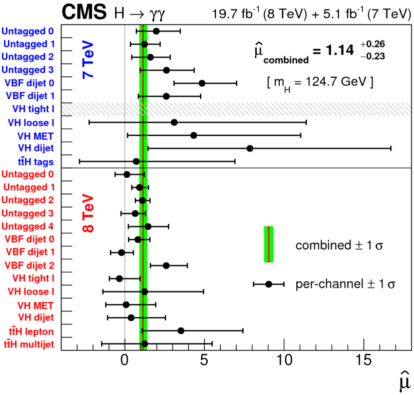
- Many example programs provided.

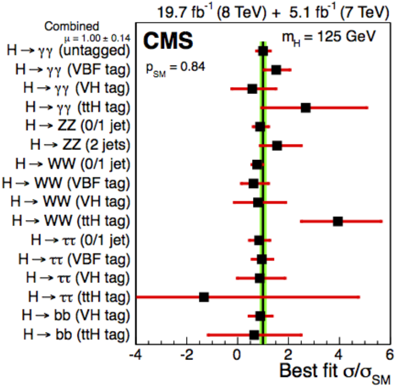
Experimental input

- Signal strength measurements:

$$\mu_{H\to XX} = \frac{\sum_i \epsilon^i_{\rm model}\,[\sigma_i(pp\to H)\times \mathrm{BR}(H\to XX)]_{\rm model}}{\sum_i \epsilon^i_{\rm SM}\,[\sigma_i(pp\to H)\times \mathrm{BR}(H\to XX)]_{\rm SM}},$$

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





Efficiencies

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

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

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

HiggsSignals: 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: $\Delta\sigma_i$, $\Delta\mathrm{BR}_i$.
  (assume inclusive rate uncertainties given by the LHC Higgs XS WG)
  [LHC HXSWG, YR3, 1307.1347]

Other correlations of systematics can be incorporated if publicly known (see later).

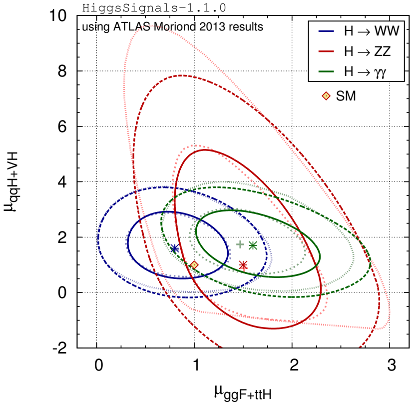
The global χ^2 for the signal strength measurements is then given by

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

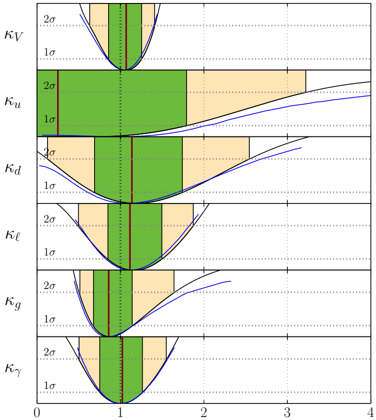
A similar calculation is done for the mass observables $\Rightarrow \chi^2_m$.

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,. . .

Incorporating correlations of systematic uncertainties

Systematics will become more important with increasing statistics!

With assumption that systematic uncertainties are Gaussian, their correlations between different μ measurements can be included in the covariance matrix.

Need to know from experimentalists:

"By how much (and in which direction) does a 1σ variation of a common source of systematic uncertainty affect the measured μ values?"

Simple example:

- 2 measurements μ_1, μ_2 with total uncertainties $\Delta\mu_1$, $\Delta\mu_2$
- one common systematic uncertainty, affecting μ_1 by 15% and μ_2 by -5%.

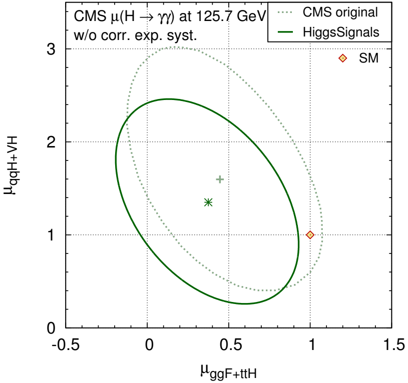
$$\Rightarrow \quad \mathbf{C}_\mu = \begin{pmatrix} (\Delta\mu_1)^2 & 0.15\mu_1 \cdot (-0.05)\mu_2 \\ 0.15\mu_1 \cdot (-0.05)\mu_2 & (\Delta\mu_2)^2 \end{pmatrix}.$$

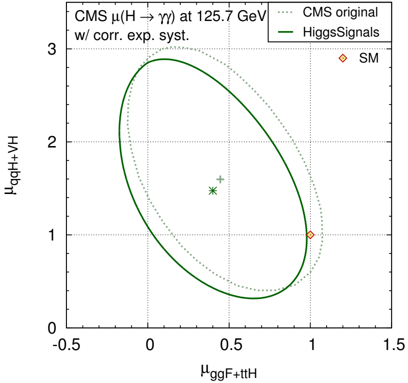
Formalism can be generalized for systematics that affect differently the individual signal components (e.g. anti-correlation between ggF and VBF components),

Similar procedure as used in Higgs search combinations by LEP.

Impact of including correlations of systematic uncertainties

Using CMS $H \to \gamma\gamma$ measurements from *before* Summer 2014.

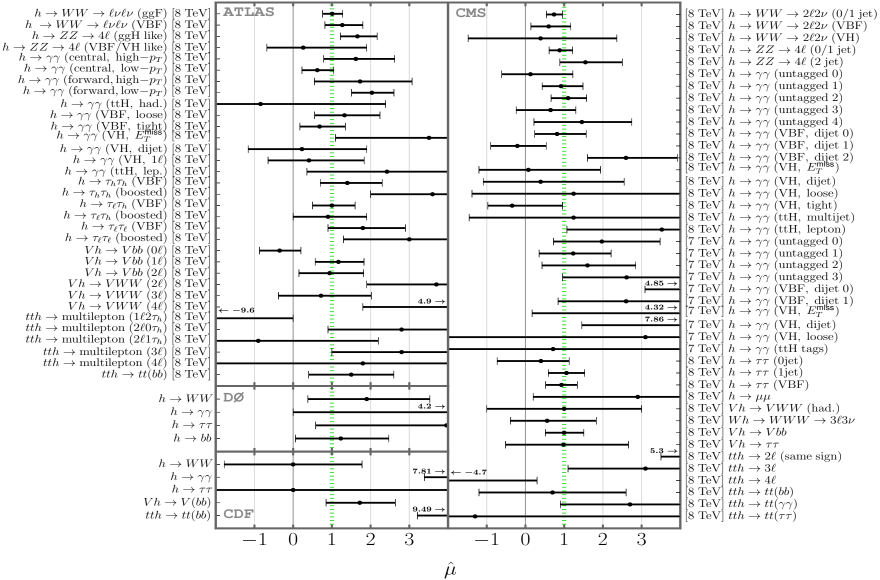




- Event migration of 12.5% (15%) between neighboring untagged categories (loose and tight dijet categories),
- Dijet tagging efficiency $\to$ anti-correlated uncertainties between ggH and VBF of $\sim$ 15% in dijet categories, etc...

Observables included in HiggsSignals-1.4.0

in total: 85 signal rate + 4 mass measurements (July 2015)



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).

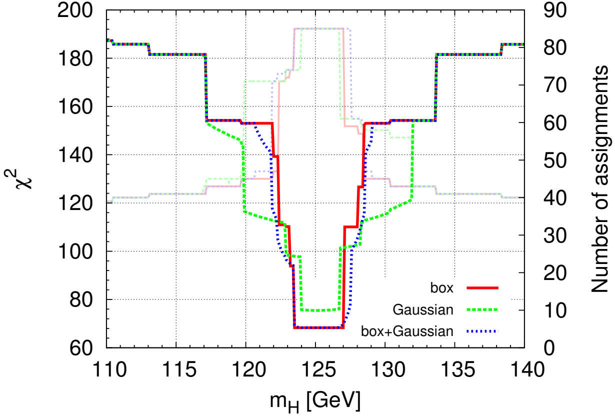
- If multiple Higgs bosons are assigned, their signal strengths are added incoherently: $\mu_\alpha = \sum_i \mu_{\alpha,i}$. In case of a mass measurement, a signal-strength weighted mass average is used in the χ^2_m evaluation.

- If no Higgs boson is assigned to an observable α, its χ^2 contribution is evaluated for zero predicted signal strength, $\mu_\alpha = 0$.

Mass dependence of total χ^2 for 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 Higgs boson with $\Delta m = 2$ GeV (and $\Lambda = 1$)

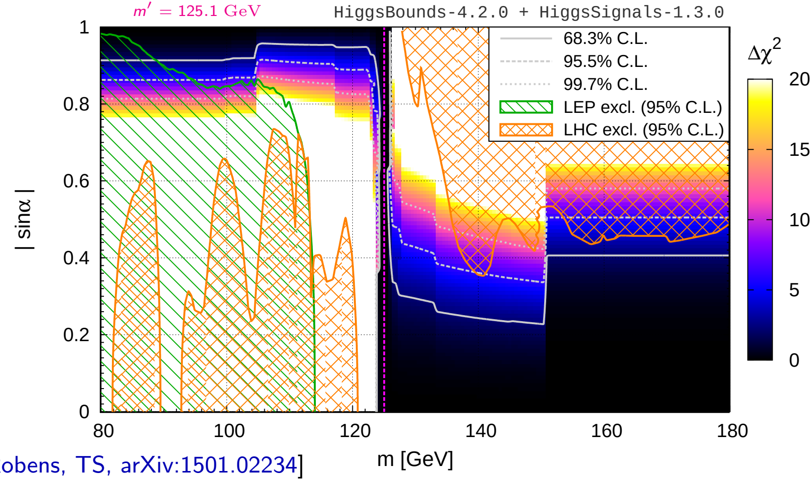


Example: Real Higgs singlet extension of the SM

- consider SM extended by a real Higgs singlet with vev $\neq 0$.

$\Rightarrow$ doublet-singlet mixing to physical states (h, H)

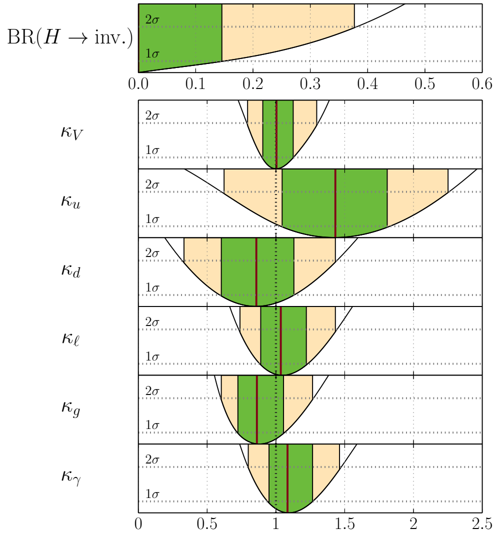
$$g_{hXX} = \cos\theta\, g^{\mathrm{SM}}_{HXX}, \qquad g_{HXX} = \sin\theta\, g^{\mathrm{SM}}_{HXX}$$



[T. Robens, TS, arXiv:1501.02234]

Example: κ scale factors

ATLAS $\oplus$ CMS $\oplus$ CDF $\oplus$ DØ combined (March 2014)



- very general fit with high freedom to adjust Higgs signal rates.
- 1σ precision of scale factors $\sim \mathcal{O}(10 - 30\%)$.

$\Rightarrow$ Still plenty of room for possible deviations!

Future prospects:

- LHC: $\sim \mathcal{O}(3 - 10\%)$ (14 TeV, 3 ab^{-1})
- ILC: $\sim \mathcal{O}(1 - 2.5\%)$ ('baseline' incl. 1 TeV)

[Bechtle, Heinemeyer, Stål, TS, Weiglein, arXiv:1403.1582]

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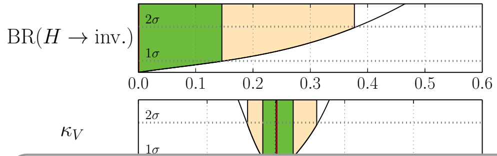
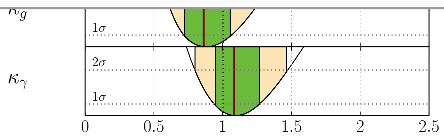


More HiggsBounds/HiggsSignals applications:

- M. Hamer (`Fittino`) — CMSSM analysis Thursday 2:00pm
- M. Dolan (`MasterCode`) — pMSSM10 analysis Thursday 2:40pm
- TS — pMSSM7 analysis Thursday 3:00pm



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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.

Take-home messages for experimentalists:

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

Take-home messages for phenomenologists:

- accurate and validated tool for testing your model,
- works well also for extended Higgs sectors,
- requires physical quantities as input ⇒ (almost) model-independent
- interfaces to many model building tools exist.

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Thanks for your attention!

Backup Slides

Probing deviations in the Higgs couplings

- What is the compatibility of the present data with the SM?
- Are there tendencies for deviations from the SM prediction?
- What is the allowed range for possible deviations?

Strategy: Profile likelihood fits of simplified models with scale factors (κ) parametrizing the relevant Higgs couplings. [LHC Higgs XS WG, 1307.1347]

$$\kappa_u, \kappa_d, \kappa_\ell, \kappa_W, \kappa_Z, \kappa_g, \kappa_\gamma, \ldots$$

Partial widths and cross sections are scaled with relevant scale factor. E.g.:

$$\kappa_V^2 = \frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \frac{\sigma_{VH}}{\sigma_{VH}^{SM}} = \frac{\Gamma_{H\to VV^*}}{\Gamma_{H\to VV^*}^{SM}}, \quad \kappa_g^2 = \frac{\sigma_{ggF}}{\sigma_{ggF}^{SM}} = \frac{\Gamma_{H\to gg}}{\Gamma_{H\to gg}^{SM}}$$

Loop-induced coupling scale factors (κ_g, κ_γ) either derived or free parameters.

We allow additional decay modes to "new physics": $\mathrm{BR}(H \to \mathrm{NP})$