HiggsSignals

Testing BSM physics with LHC Higgs precision data

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Higgs Couplings 2017, Heidelberg

November 8th, 2017

http://higgsbounds.hepforge.org

HiggsBounds

A common question...

BSM theorist: "Is my model consistent with the Higgs data?"

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5. Test your model against them in a statistically well-defined way;
6. Interpret your result (95% $\mathrm{C.L.}$ allowed/excluded or χ^2).

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Run `HiggsBounds` and `HiggsSignals`.

6. Interpret your result (95% $\mathrm{C.L.}$ allowed/excluded or χ^2).

HiggsBounds and HiggsSignals: Code overview

Team: P. Bechtle, D. Dercks, S. Heinemeyer, T. Klingl, TS, G. Weiglein

http://higgsbounds.hepforge.org

HiggsBounds

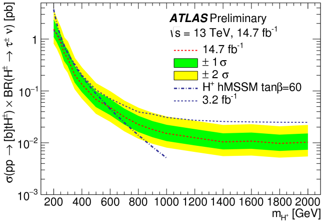
Confronts BSM Higgs sectors with exclusion limits from LEP, Tevatron and LHC Higgs searches

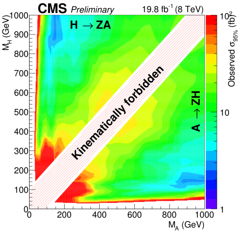
$\Rightarrow$ excluded/allowed at 95% C.L.

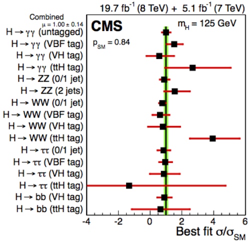
HiggsSignals

Confronts BSM Higgs sectors with LHC (& Tevatron) Higgs signal rate and mass measurements

$\Rightarrow \chi^2$ (sep. for rates and mass)







HiggsSignals: The basic idea

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

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

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

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

(narrow width approximation assumed)

3. Perform a χ^2 test of model predictions against all available signal rate and mass measurements from Tevatron and LHC.

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

Theoretical Input

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

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

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

  σ, BR given via effective couplings or at 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:

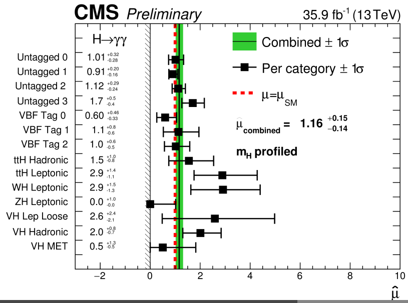
$$\mu_{H\to XX} = \frac{\sum_i \epsilon^i_{\mathrm{model}}\ [\sigma_i(pp\to H)\times \mathrm{BR}(H\to XX)]_{\mathrm{model}}}{\sum_i \epsilon^i_{\mathrm{SM}}\ [\sigma_i(pp\to H)\times \mathrm{BR}(H\to XX)]_{\mathrm{SM}}},$$

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

Examples:

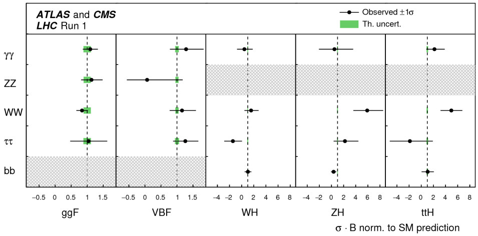
experimental categories

[CMS-PAS-HIG-16-040]



“pure” signal channels

[ATLAS+CMS 7/8 TeV, 1606.02266]



$+\ 20 \times 20$ correlation matrix

Signal efficiencies

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

Event Categories	SM 125 GeV Higgs boson expected signal								
	Total	ggH	VBF	ttH	bbH	tHq	tHW	WH lep	ZH
Untagged 0	45.83	80.19 %	11.75 %	1.83 %	0.40 %	0.47 %	0.22 %	0.41 %	0.1
Untagged 1	480.56	86.81 %	7.73 %	0.56 %	1.15 %	0.13 %	0.02 %	0.47 %	0.2
Untagged 2	670.45	89.76 %	5.48 %	0.44 %	1.18 %	0.08 %	0.01 %	0.51 %	0.3
Untagged 3	610.07	91.13 %	4.51 %	0.48 %	1.07 %	0.07 %	0.01 %	0.55 %	0.3
VBF 0	10.01	21.69 %	77.09 %	0.34 %	0.35 %	0.29 %	0.03 %	0.03 %	0.0
VBF 1	8.64	33.58 %	64.64 %	0.39 %	0.52 %	0.36 %	0.04 %	0.13 %	0.0
VBF 2	27.76	50.14 %	46.46 %	0.81 %	0.73 %	0.53 %	0.07 %	0.20 %	0.0
ttH Hadronic	5.85	10.99 %	0.70 %	77.54 %	2.02 %	4.13 %	2.02 %	0.09 %	0.0
ttH Leptonic	3.81	1.90 %	0.05 %	87.48 %	0.08 %	4.73 %	3.04 %	1.53 %	1.1
ZH Leptonic	0.49	0.00 %	0.00 %	2.56 %	0.00 %	0.02 %	0.13 %	0.00 %	97.3
WH Leptonic	3.61	1.26 %	0.59 %	5.18 %	0.18 %	3.03 %	0.73 %	84.48 %	4.3
VH LeptonicLoose	2.75	9.16 %	2.70 %	2.34 %	0.57 %	1.81 %	0.13 %	63.62 %	18.8
VH Hadronic	9.69	57.38 %	3.68 %	3.61 %	0.35 %	1.39 %	0.27 %	0.17 %	0.4
VH Met	4.25	23.63 %	2.46 %	14.45 %	0.41 %	2.00 %	1.14 %	25.17 %	28.6
Total	1883.77	86.96 %	7.09 %	1.00 %	1.09 %	0.15 %	0.04 %	0.81 %	0.4

It is possible to insert *relative efficiency scale factors* $\zeta^i \equiv \epsilon^i_{\mathrm{model}}/\epsilon^i_{\mathrm{SM}}$ per tested parameter point and measurement.

The χ^2 evaluation for the signal rates

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

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

Include correlations of major systematic uncertainties (if publicly known):

$$\Delta\sigma_i^{\mathrm{theo}}, \quad \Delta\mathrm{BR}(H_k \to XX)^{\mathrm{theo}}, \quad \Delta\mathcal{L}, \quad \ldots \quad \to \quad \mathbf{Cov}$$

(assume inclusive rate uncertainties given by the LHC Higgs XS WG)

[LHC HXSWG, YR4, 1610.07922]

Ideally, correlation matrices are provided directly by the experiment, which can then be easily inserted in `HiggsSignals`.

Validation with LHC Run 1 (7/8 TeV) data

[ATLAS+CMS 7/8 TeV, 1606.02266]

Try to reproduce 7 or 8-dimensional κ-fit of ATLAS+CMS Run 1 combination with `HiggsSignals`, using two different experimental inputs:

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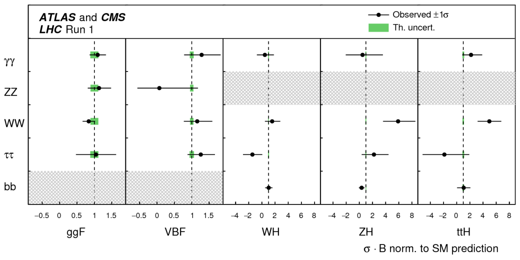
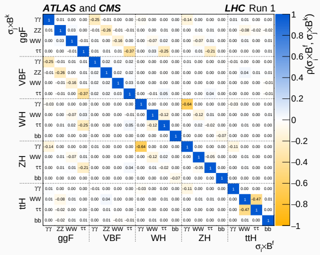
1) Run-1 combination input





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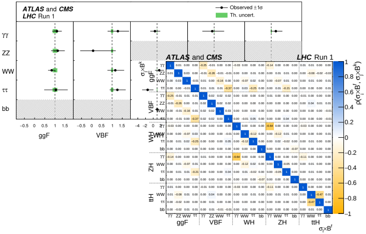
[ATLAS+CMS 7/8 TeV, 1606.02266]

Try to reproduce 7 or 8-dimensional κ-fit of ATLAS+CMS Run 1 combination with HiggsSignals, using two different experimental inputs:

1) Run-1 combination input

- $\sigma_i \cdot \mathrm{BR}^f$ measurements
- 20×20 correlation matrix



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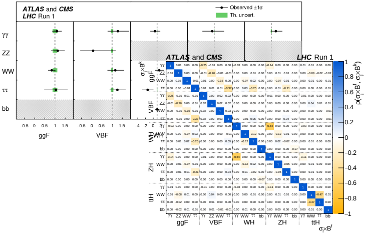
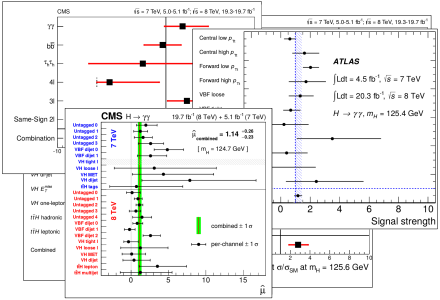


2) All individual μ measurements (total: 76)



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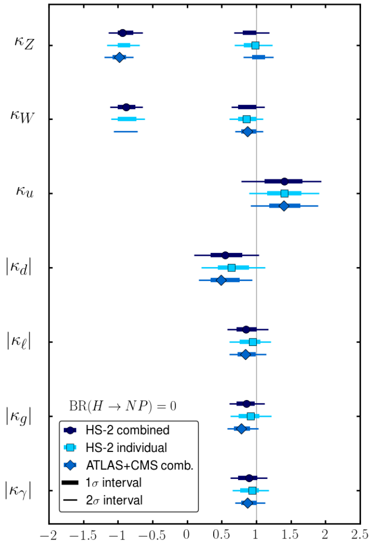
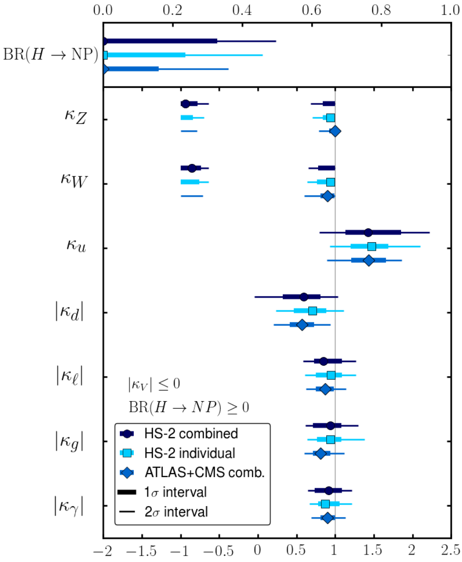


assumption:
no new Higgs decay modes,
$\mathrm{BR}(H \to \mathrm{NP}) = 0$.

- Both HiggsSignals results are well consistent with official ATLAS+CMS results;
- Official 1σ and 2σ intervals are slightly tighter in all parameters.

Validation with LHC Run 1 (7/8 TeV) data



assumption:
upper limit on Higgs-vector boson coupling scale factors:
$|\kappa_V| \leq 1 \quad (V = W, Z)$

- Both HiggsSignals results are well consistent with official ATLAS+CMS results;
- Official 1σ and 2σ intervals are slightly tighter in all parameters.
- ATLAS+CMS find tighter constraints on BR($H \to$ NP).

$\Rightarrow$ *Possible explanation*:
HiggsSignals assumes Gaussian uncertainties.

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).

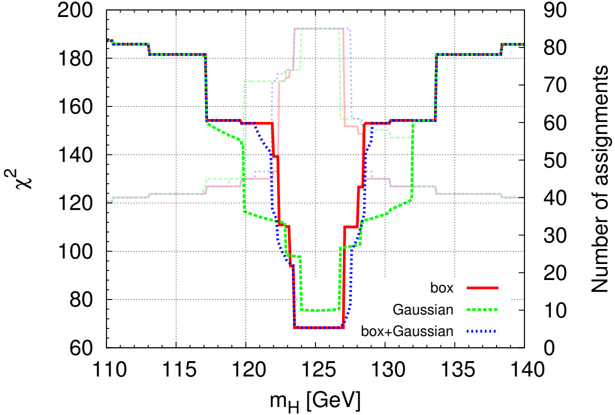
- If multiple Higgs bosons are assigned, their signal strengths are added incoherently: $\mu_\alpha = \sum_i \mu_{\alpha,i}$. In case of a mass measurement, a signal-strength weighted mass average is used in the χ^2_m evaluation.

- 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 $\Delta m = 2\ \mathrm{GeV}$ (and $\Lambda = 1$)

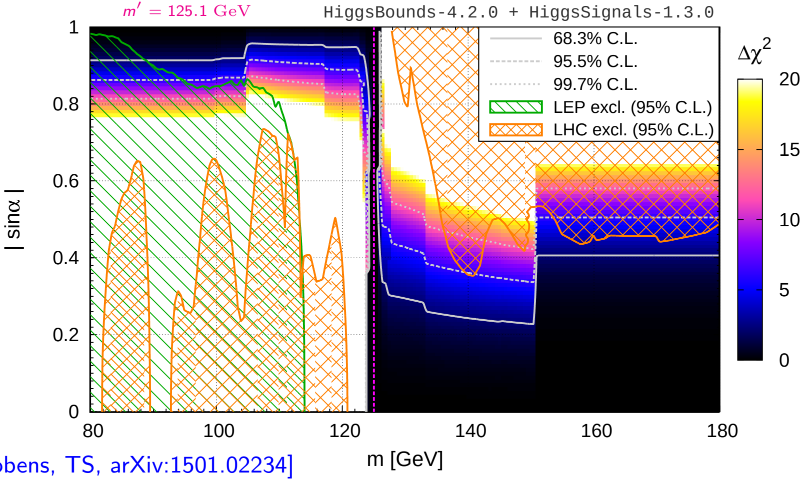


Example: Real Higgs singlet extension of the SM

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

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

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

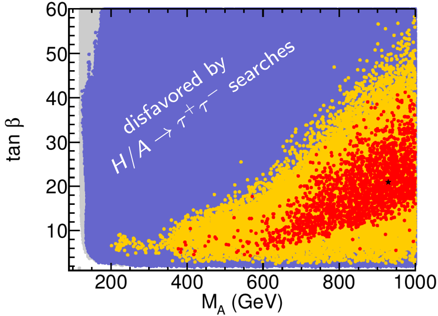


[T. Robens, TS, arXiv:1501.02234]

Example: pMSSM

[P. Bechtle, H. Haber, S. Heinemeyer, O. Stål, TS, G. Weiglein, L. Zeune, 1608.00638]

- Combine HiggsSignals χ^2 with other constraints ($b \to s\gamma$, $B_s \to \mu\mu$, $B_u \to \tau\nu$, $(g-2)_\mu$, M_W; Higgs & SUSY limits)
- Study pMSSM with 8 parameters (relevant for Higgs sector)



■ All points
■ HiggsBounds allowed
■ $\Delta\chi^2 < 2.30$
■ $\Delta\chi^2 < 5.99$
⋆ Best fit point

	only Higgs data	all observables
SM:	$\chi^2/\mathrm{ndf} = 70.2/86$	83.7/91
MSSM:	$\chi^2/\mathrm{ndf} = 67.9/86$	68.5/91

- Found allowed points in *decoupling limit* and in *alignment without decoupling* region.

Current status

Current versions, HiggsBounds-5.1.1beta and HiggsSignals-2.1.0beta, contain the 13 TeV LHC results, extended input quantities and several new features.

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Some new developments und future directions:

- Possibility to insert signal rates directly [e.g. $\sigma(gg \to \phi \to f\bar{f})$] without assumption of narrow width approximation (i.e. factorization of XS and BR).
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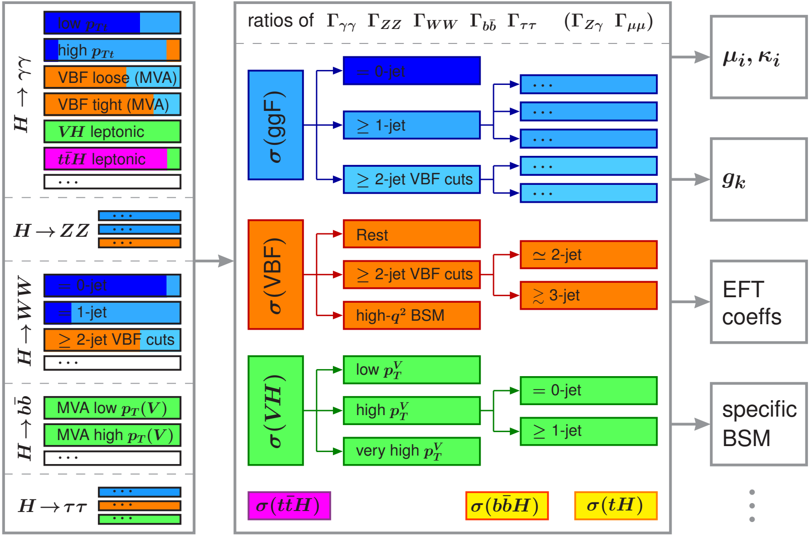
- Enable & transition to new form of experimental input:
  - Simplified Template Cross Sections (STXS): maximize model discrimination power while minimizing model-dependence;
  - σ and BR ratio parameters: cancellation of theoretical uncertainties;

$$\sigma(gg \to H \to ZZ),\ \sigma_{\mathsf{VBF}}/\sigma_{\mathsf{ggF}}, \ldots\ \mathrm{BR}^{WW}/\mathrm{BR}^{ZZ}, \ldots$$

Note: This experimental input is useless unless it comes with a correlation matrix!

Simplified Template Cross Sections (STXS)

[LHC HXSWG, YR4, 1610.07922]

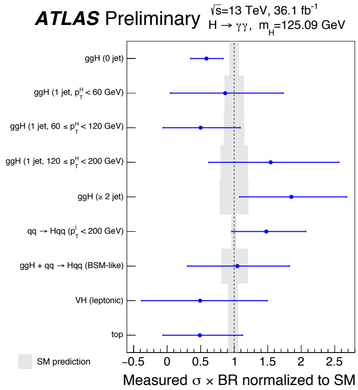


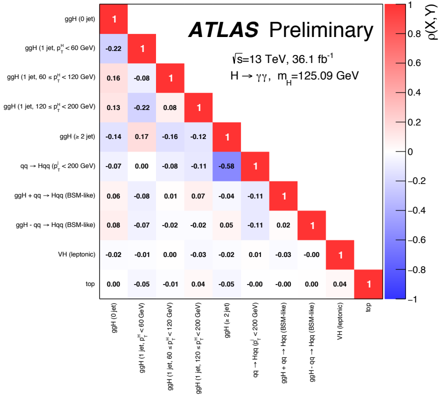
STXS performance of ATLAS $H \to \gamma\gamma$ 13 TeV results

[ATLAS-CONF-2017-045]

- ATLAS presented 9 STXS together with a correlation matrix.

$\Rightarrow$ Use with HiggsSignals and compare with official fit results!





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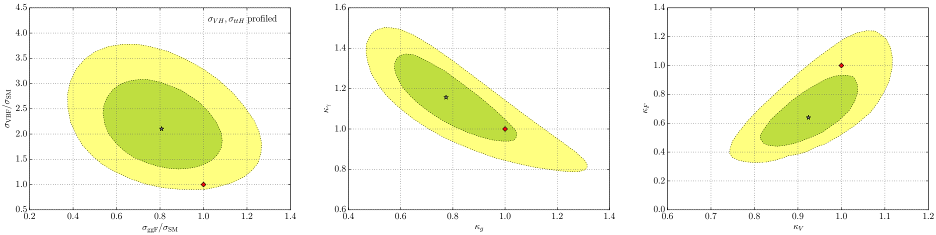

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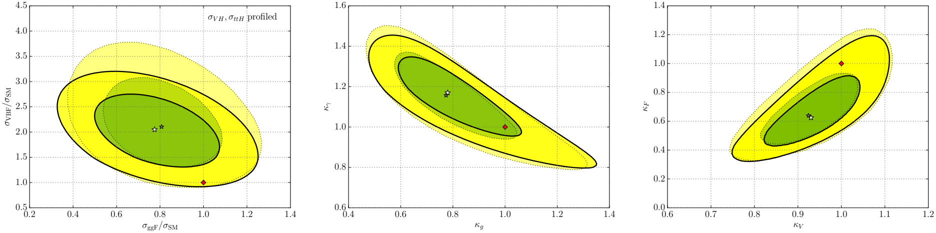

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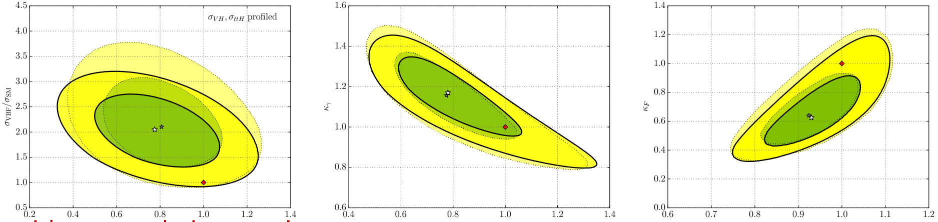
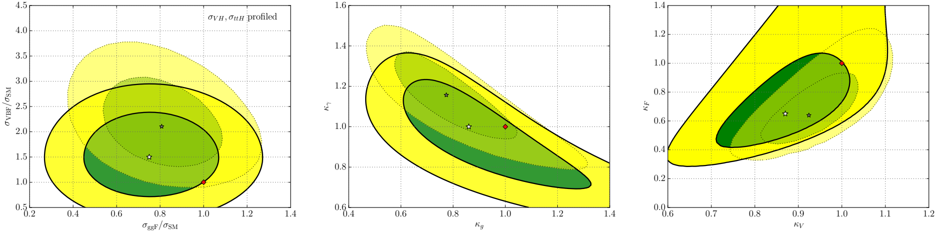


without correlation matrix $\Rightarrow$



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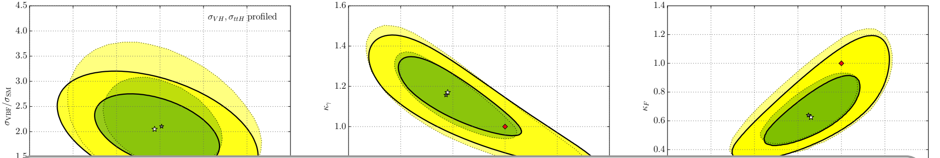
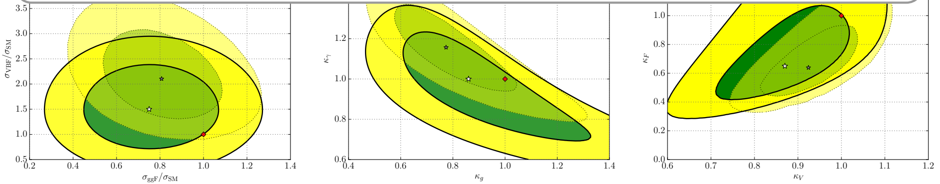


First tests with STXS in HiggsSignals very successful!

But: Correlations need to be included!



Summary

HiggsBounds and HiggsSignals provide an interface between experiment and theory. They test the compatibility of BSM theories with latest Higgs data:

- accurate and validated tool for testing your model,
- works well also for extended Higgs sectors,
- requires physical quantities as input $\Rightarrow$ (almost) model-independent,
- interfaces to many model building tools exist,
- complete information on rate measurements is crucial for implementation: signal efficiencies, correlation matrices,...
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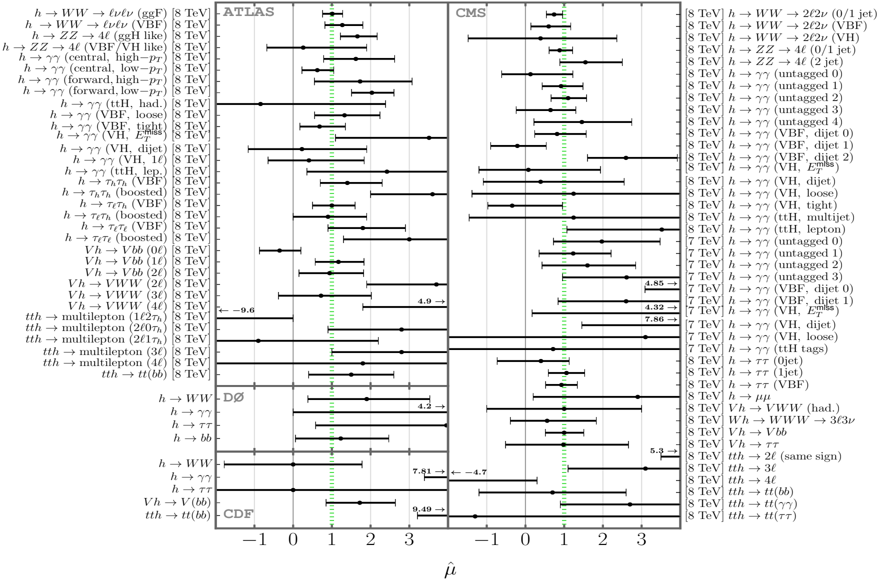
Thanks for your attention!

Backup Slides

Observables included in `HiggsSignals-1.4.0`

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



Global fit of the pMSSM: The setup

Perform a random scan over 8 MSSM parameters ($\sim 10^7$ points):

$$M_A,\ \tan\beta,\ \mu,\ M_{\tilde{q}_3},\ M_{\tilde{\ell}_3},\ M_{\tilde{\ell}_{1,2}},\ A_t = A_b = A_\tau,\ M_2 = 2M_1,\ (+\ m_{top})$$

using `FeynHiggs` and `SuperIso` for MSSM predictions.
(fix other parameters, e.g. $m_{\tilde{q}_{1,2}} = m_{\tilde{g}} = 1.5\ \mathrm{TeV}$)

Observables and limits:

$$\chi^2_{\mathrm{total}} = \frac{(M_{h/H} - \hat{M})^2}{\sigma_M^2} + \chi^2_{\mathrm{HS}} + \sum \frac{(O_i - \hat{O}_i)^2}{\sigma_i^2} - 2\ln\mathcal{L}_{\mathrm{limits}}$$

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$$\chi^2_{\text{total}} = \frac{(M_{h/H} - \hat{M})^2}{\sigma_M^2} + \chi^2_{\text{HS}} + \sum \frac{(O_i - \hat{O}_i)^2}{\sigma_i^2} - 2\ln\mathcal{L}_{\text{limits}}$$

Higgs mass
($\sigma_M^{\text{theo}} = 3\ \mathrm{GeV}$)

Global fit of the pMSSM: The setup

Perform a random scan over 8 MSSM parameters ($\sim 10^7$ points):

$$M_A,\ \tan\beta,\ \mu,\ M_{\tilde{q}_3},\ M_{\tilde{\ell}_3},\ M_{\tilde{\ell}_{1,2}},\ A_t = A_b = A_\tau,\ M_2 = 2M_1,\ (+\ m_{top})$$

using `FeynHiggs` and `SuperIso` for MSSM predictions.
(fix other parameters, e.g. $m_{\tilde{q}_{1,2}} = m_{\tilde{g}} = 1.5\ \mathrm{TeV}$)

Observables and limits:

$$\chi^2_{\text{total}} = \frac{(M_{h/H} - \hat{M})^2}{\sigma_M^2} + \chi^2_{\text{HS}} + \sum \frac{(O_i - \hat{O}_i)^2}{\sigma_i^2} - 2\ln\mathcal{L}_{\text{limits}}$$

Higgs signal rates
(`HiggsSignals`)

Global fit of the pMSSM: The setup

Perform a random scan over 8 MSSM parameters ($\sim 10^7$ points):

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Observables and limits:

$$\chi^2_{\text{total}} = \frac{(M_{h/H} - \hat{M})^2}{\sigma_M^2} + \chi^2_{\text{HS}} + \sum \frac{(O_i - \hat{O}_i)^2}{\sigma_i^2} - 2\ln\mathcal{L}_{\text{limits}}$$

Low energy observables (LEO)

$$O_i \in \{b \to s\gamma, B_s \to \mu\mu, B_u \to \tau\nu_\tau, (g-2)_\mu, M_W\}$$

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Perform a random scan over 8 MSSM parameters ($\sim 10^7$ points):

$$M_A,\ \tan\beta,\ \mu,\ M_{\tilde{q}_3},\ M_{\tilde{\ell}_3},\ M_{\tilde{\ell}_{1,2}},\ A_t = A_b = A_\tau,\ M_2 = 2M_1,\ (+\ m_{top})$$

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Higgs exclusion likelihoods
(LEP, $h/H/A \to \tau^+\tau^-$)

Global fit of the pMSSM: The setup

Perform a random scan over 8 MSSM parameters ($\sim 10^7$ points):

$$M_A,\ \tan\beta,\ \mu,\ M_{\tilde{q}_3},\ M_{\tilde{\ell}_3},\ M_{\tilde{\ell}_{1,2}},\ A_t = A_b = A_\tau,\ M_2 = 2M_1,\ (+\ m_{top})$$

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Observables and limits:

$$\chi^2_{\text{total}} = \frac{(M_{h/H} - \hat{M})^2}{\sigma_M^2} + \chi^2_{\text{HS}} + \sum \frac{(O_i - \hat{O}_i)^2}{\sigma_i^2} - 2\ln\mathcal{L}_{\text{limits}}$$

Hard cuts:

+ 95% CL limits from Higgs searches (`HiggsBounds`)
+ Limits from LHC SUSY searches (`Herwig++/CheckMATE`)
+ require neutral lightest supersymmetric particle (LSP)

Best-fit points

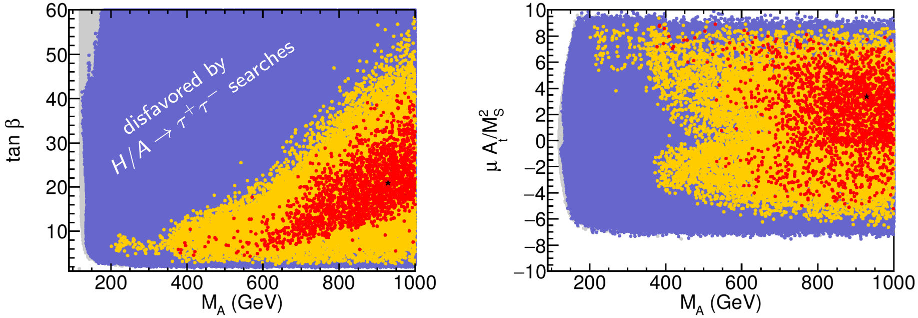
	Higgs data			Higgs data + LEO		
	χ^2/ν	χ^2_ν	$\mathcal{P}$	χ^2/ν	χ^2_ν	$\mathcal{P}$
SM ($m_h = 125.1$ GeV)	70.2/86	0.82	0.89	83.7/91	0.92	0.69
MSSM light Higgs h	67.9/79	0.86	0.81	68.5/84	0.82	0.89
MSSM heavy Higgs H	70.0/80	0.88	0.78	73.7/85	0.87	0.80

number degrees of freedom: $\nu = n_{\text{obs}} - n_{\text{param}}$

- SM and both MSSM cases provide similar fit to the Higgs data.
- Including LEOs, SM fit becomes worse, mainly due to $(g-2)_\mu$.

	M_A (GeV)	$\tan\beta$	μ (GeV)	A_0 (GeV)	$M_{\tilde{q}_3}$ (GeV)	$M_{\tilde{\ell}_3}$ (GeV)	$M_{\tilde{\ell}_{1,2}}$ (GeV)	M_2 (GeV)
MSSM h	929	21.0	7155	4138	2957	698	436	358
MSSM H	172	6.6	4503	-71	564	953	262	293

Favored parameter regions



- Bulk of favored points have $M_A \gtrsim 350\ \mathrm{GeV}$ ⇒ *decoupling limit*.
- points with $M_A \gtrsim 200\ \mathrm{GeV}$ possible ⇒ *alignment w/o decoupling*.

Recall: alignment condition → $\tan\beta \sim \left[\frac{\mu A_t}{M_S^2}\left(\frac{A_t^2}{M_S^2} - 6\right)\right]^{-1}$

⇒ Alignment occurs at small $\tan\beta$ values if $\mu A_t/M_S^2$ is large.

The κ-framework

- 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.:

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

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

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