Probing Higgs CP properties with Higgs signal rates using HiggsSignals-2

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Motivation

- The discovery of a Higgs boson by **ATLAS** and **CMS** ($m \approx 125\,\text{GeV}$) has opened new era in particle physics!
- Thus far, it is in good agreement with the **Standard Model (SM) Higgs boson**.

  $\Rightarrow$ Standard model finally complete!

- Many well motivated BSM theories feature an extended Higgs sector.

  $\Rightarrow$ possible deviations in the couplings/signal rates from the SM Higgs, and/or additional Higgs states may be discovered in future LHC searches.

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  $\Rightarrow$ possible deviations in the couplings/signal rates from the SM Higgs, and/or additional Higgs states may be discovered in future LHC searches.

  $\Rightarrow$ **model-independent** tools to confront:

Theory predictions vs. **Experimental results**

Motivation

precise predictions of Higgs signal rates and Higgs mass

predictions for additional Higgs states

Theo. $\Longleftrightarrow$ vs. **Exp.**

precision measurements of Higgs signal rates and Higgs mass

searches for additional Higgs states

precise predictions of Higgs signal rates and Higgs mass

HiggsSignals

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precise predictions of Higgs signal rates and Higgs mass

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precision measurements of Higgs signal rates and Higgs mass

Theo. $\Longleftrightarrow$ vs. **Exp.**

predictions for additional Higgs states

HiggsBounds

searches for additional Higgs states

The HiggsSignals code

- Current version: HiggsSignals-1.4.0 (HiggsSignals-2.1.0beta)
- Website: `http://higgsbounds.hepforge.org.`
- Documentation:
  Eur.Phys.J. C74 (2014) 2711 [arXiv:1305.1933]
  Eur.Phys.J. C74 (2014) 2693 [arXiv:1311.0055]
- Applications: [arXiv:1403.1582], [arXiv:1608.00638], + many more

HiggsSignals

HiggsSignals: Basic Idea

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

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

for each neutral Higgs boson $k = 1, ..., N$ and production cross-section $(i \in \{\mathrm{ggH, VBF, WH, ZH, ttH}, ...\})$ as user input.

2. Calculate the predicted signal strength μ for every observable

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

(zero-width approximation $(\sigma \cdot \mathrm{BR})(i \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_{tot}}$ assumed)

3. χ^2 test of model predictions against available data from signal rate and mass measurements from the Tevatron and LHC.

HiggsSignals: Theoretical input

- Predictions for physical quantities of given Higgs sector:

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

  with $k = 1, ..., N$ and $(i \in \{\text{ggH, VBF, WH, ZH, ttH, ...}\})$.
  σ, BR given via **effective couplings** or **at hadronic level**.
- Optional: Uncertainties for $m_k, \sigma_i(pp \to H_k), BR(H_k \to XX)$.
- Input for specific models can be provided by other tools (e.g. FeynHiggs, CPsuperH, 2HDMC, SARAH/SPheno, ...)
- Many example programs provided!

HiggsSignals: Experimental input

- Signal strength measurements:

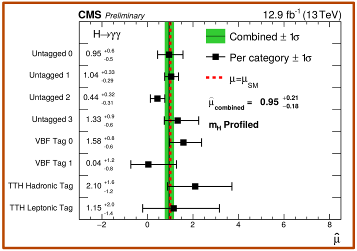
$$\mu_{H_k \to XX} = \frac{\sum_i \epsilon^i_{model} \left[\sigma_i(pp \to H_k) \times \mathrm{BR}(H_k \to XX)\right]_{model}}{\sum_i \epsilon^i_{SM} \left[\sigma_i(pp \to H) \times \mathrm{BR}(H \to XX)\right]_{SM}},$$

with Efficiencies ϵ_i and ($i \in$ {ggH, VBF, WH, ZH, ttH, ...}).

Examples:

experimental categories

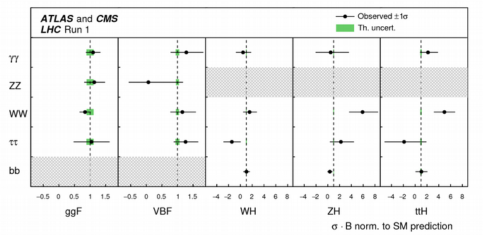
[CMS-PAS-HIG-16-020]



+ signal efficiencies (if given)

pure signal channels

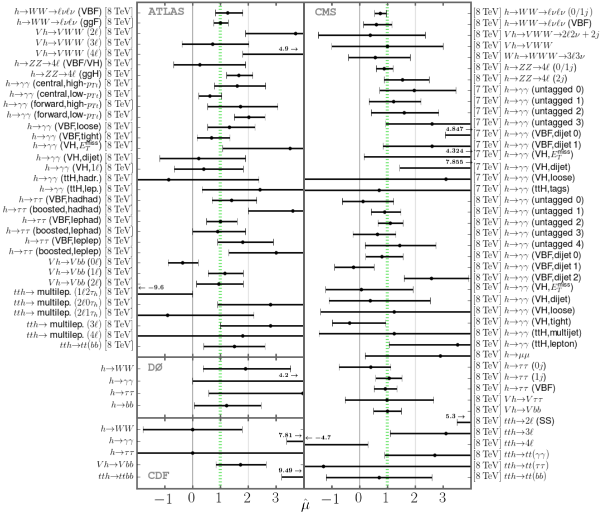
[ATLAS+CMS 7/8 TeV, 1606.02266]



+ 20 × 20 correlation matrix

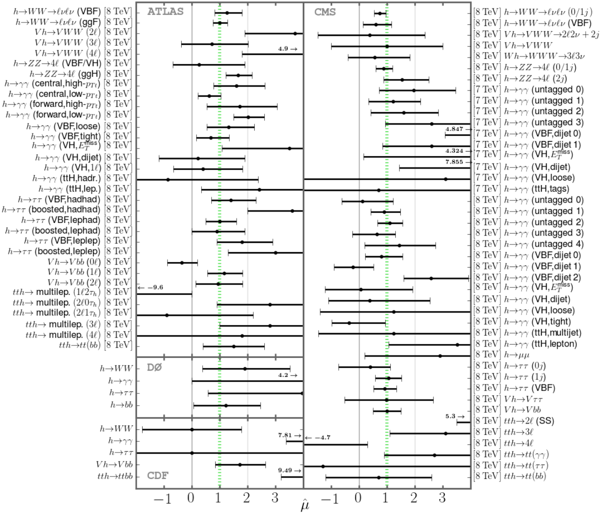
Observables included in HiggsSignals

- **HS-1.4.0:** Latest $\sqrt{s} = 7 + 8\,\text{TeV}$ measurements from the LHC + Tevatron.



Observables included in HiggsSignals

- **HS-1.4.0:** Latest $\sqrt{s} = 7 + 8$ TeV measurements from the LHC + Tevatron.
- **HS-2.1.0beta:** First $\sqrt{s} = 13$ TeV results included.



HiggsSignals: χ^2 Evaluation

- Global χ^2 for the signal strength measurement is given by

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

- Correlations of major systematic uncertainites are taken into account (if publicly known):
  - $\Delta\sigma_i^{theo.}$
  - $\Delta\mathrm{BR}(H_k \to XX)^{theo}$
  - $\Delta\mathcal{L}$
  - ...
- If correlation matrices are provided directly, they can easily be easily inserted in `HiggsSignals`.

Validation of HiggsSignals with LHC Run 1 ($7 + 8\,\text{TeV}$) data

Probing deviations in the Higgs couplings

- Profile likelihood fits within the Higgs coupling scale factor parametrization

Coupling scale factors κ's (phenomenological descripton)

$$\sigma_{ii} = \kappa_i^2 \cdot \sigma_{ii}^{SM}, \qquad \Gamma_{ff} = \kappa_f^2 \cdot \Gamma_{ff}^{SM}$$

$$\Rightarrow (\sigma \cdot \mathrm{BR})(ii \to H \to ff) = (\sigma \cdot \mathrm{BR})^{SM}(ii \to H \to ff) \cdot \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

- Tree-Level Couplings:

$$\kappa_Z, \kappa_W, \kappa_u, \kappa_d, \kappa_\ell$$

- Loop-induced couplings:

$$\kappa_\gamma, \kappa_g$$

- No model independent determination of κ_H at the LHC.

  $\rightarrow$ Additional assumption to remove one dof:
  - No decays into states of new physics (NP)
  - $|\kappa_V| \leq 1$ (well motivated by many BSM models)

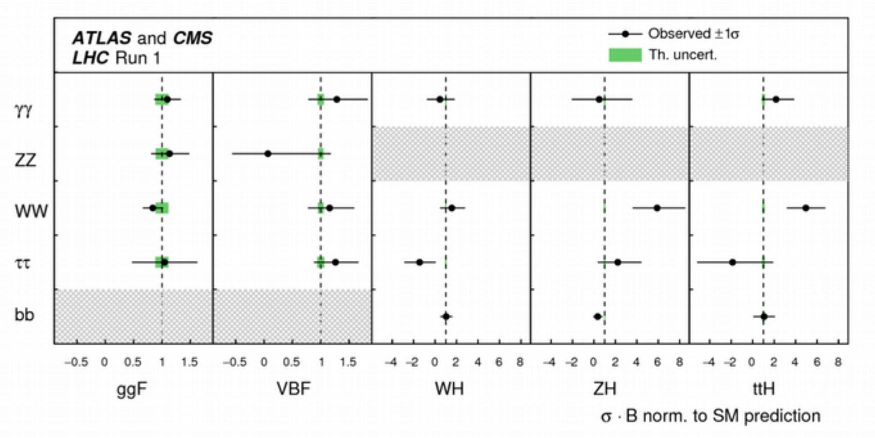
Validation of HiggsSignals with Run 1 data

Inputs to HiggsSignals

Run-1 Combination Input

All μ measurements (Run-1) from ATLAS and CMS

Validation of HiggsSignals with Run 1 data



JHEP08(2016)045 [arXiv:1606.02266]

Validation of HiggsSignals with Run 1 data

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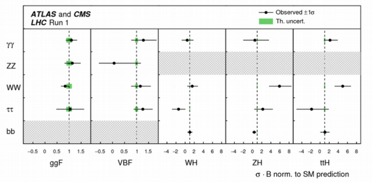
- combined $\sigma_i \cdot \mathrm{BR}^f$ measurements.



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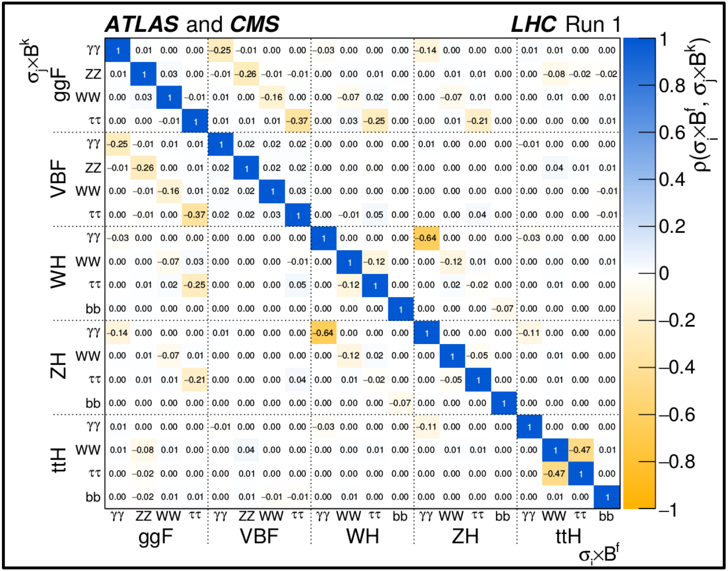
All μ measurements (Run-1) from ATLAS and CMS

Validation of HiggsSignals with Run 1 data



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JHEP08(2016)045 [arXiv:1606.02266]

Validation of HiggsSignals with Run 1 data

Inputs to HiggsSignals

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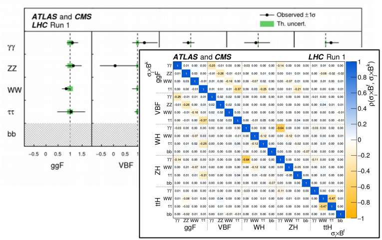
- Corr. matrix from combined fit.



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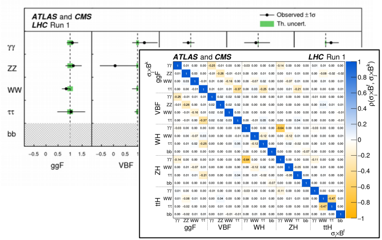

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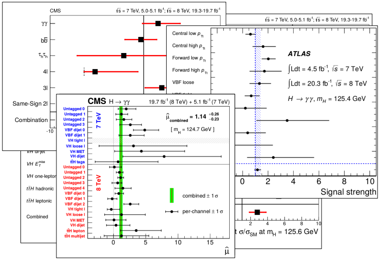
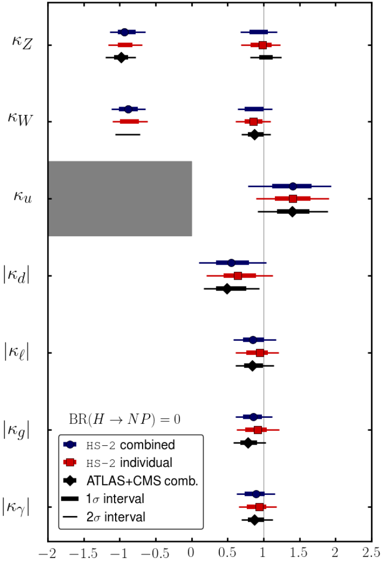


[arXiv:1407.0558,arXiv:1408.7084,arXiv:1408.1682,...]

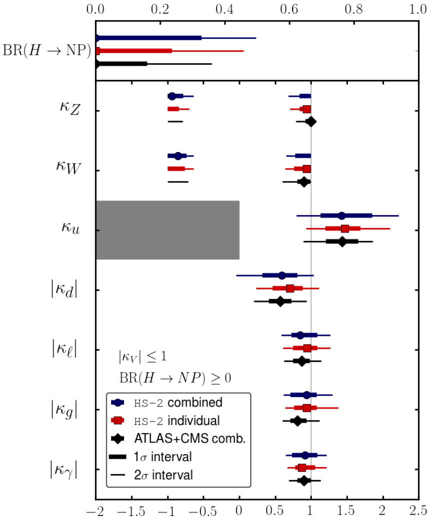
Validation of HiggsSignals with Run 1 data



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

- Very good agreement to the official ATLAS + CMS result.
- Official 1 and 2σ intervals are slightly smaller in almost all parameters.

Validation of HiggsSignals with Run 1 data



Assumption:
Upper limit on κ_V, $|\kappa_V| \leq 1$
($V = W, Z$)

- Very good agreement to the official ATLAS + CMS result.
- Official 1 and 2σ intervals are slightly smaller in almost all parameters.
- ATLAS + CMS find tighter constraints on $BR(H \to \mathrm{NP})$

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

CP mixing scenario
LHC Run-1 ($7+8$ TeV)+ Tevatron

Spin 0 particle my be either

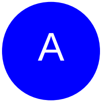
- Pure CP even

SM-like

Spin 0 particle my be either

- Pure CP even
- Pure CP odd

SM-like



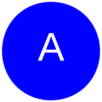
Motivation

Spin 0 particle my be either

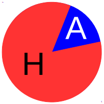
- Pure CP even

SM-like

- Pure CP odd



- Mixture



- CP mixing in the Higgs Sector can appear in many extension of the SM, e.g.
  - 2HDM
  - SUSY

Higgs couplings and CP properties

- SM predicts the couplings of the Higgs to massive particles

$$\mathcal{L}_{Yuk}^{SM} = -\overline{q_L} Y_u u_R \tilde{H} - \overline{q_L} Y_d d_R H - \overline{\ell_L} Y_\ell \ell_R H + h.c.$$

- Example: SM coupling to τ: $\overline{\tau_L} Y_\ell \tau_R H$

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- Example: SM coupling to τ: $\overline{\tau_L} Y_\ell^s \tau_R H$

H

- CP-odd Higgs coupling to τ: $\overline{\tau_L} Y_\ell^p \tau_R A$

A

Higgs couplings and CP properties

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$+$

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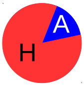


Parametrization

- Φ can be a mixture of a **CP even scalar H** and a **CP odd pseudoscalar A**

$$\Phi = \cos\alpha H + \sin\alpha A$$

Modified Yukawa Lagrangian: [arXiv:1211.1980]

CP even $\rightarrow$
CP odd $\rightarrow$

$$\begin{aligned}\mathcal{L}_{Yuk} = - & \kappa_{u_s}\overline{u_L}Y_u u_R H - \kappa_{d_s}\overline{d_L}Y_d d_R H - \kappa_{\ell_s}\overline{\ell_L}Y_\ell \ell_R H \\ & - i\kappa_{u_p}\overline{u_L}Y_u u_R A - i\kappa_{d_p}\overline{d_L}Y_d d_R A - i\kappa_{\ell_p}\overline{\ell_L}Y_\ell \ell_R A \\ & + h.c.\end{aligned}$$

κ's: Strengths of the couplings relative to the SM

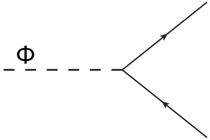
- SM corresponds to: $\alpha = \kappa_{u_p} = \kappa_{d_p} = \kappa_{\ell_p} = 0$ and $\kappa_{u_s} = \kappa_{d_s} = \kappa_{\ell_s} = 1$

Modifications to tree-level partial decay widths

Pure CP even scenario

$$\Phi = H$$

Examples for **tree-level** partial decay widths



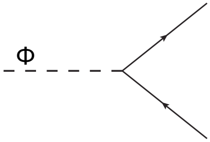
- $\frac{\Gamma_{VV}}{\Gamma_{VV}^{SM}} = \kappa_V^2$
- $\frac{\Gamma_{\tau\tau}}{\Gamma_{\tau\tau}^{SM}} = \kappa_\ell^2$
- $\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_u^2$
- $\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_d^2$

[arXiv:1211.1980]

CP mixture scenario

$$\Phi = \cos\alpha H + \sin\alpha A$$

Examples for **tree-level** partial decay widths



- $\frac{\Gamma_{VV}}{\Gamma_{VV}^{SM}} = \kappa_V^2 \cdot \cos^2\alpha$
- $\frac{\Gamma_{\tau\tau}}{\Gamma_{\tau\tau}^{SM}} = \kappa_{\ell_s}^2 \cdot \cos^2\alpha + \kappa_{\ell_p}^2 \cdot \sin^2\alpha$
- $\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_{u_s}^2 \cdot \cos^2\alpha + R^{cc}\kappa_{u_p}^2 \cdot \sin^2\alpha$
- $\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_{d_s}^2 \cdot \cos^2\alpha + R^{bb}\kappa_{d_p}^2 \cdot \sin^2\alpha$

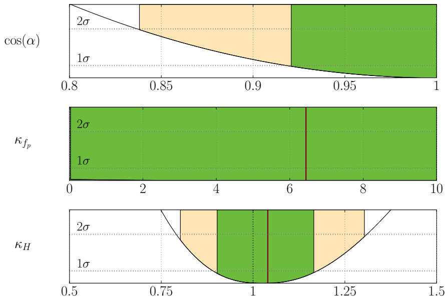
[arXiv:1211.1980]

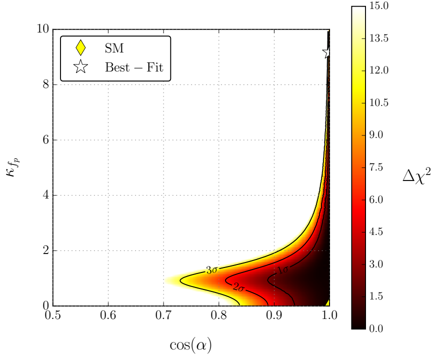
(QCD Corrections $R^{ii} \approx 1$)

$\Rightarrow$ fit parameters: $BR(H \to NP), \alpha, \kappa_V, \kappa_{\ell_s}, \kappa_{\ell_p}, \kappa_{u_s}, \kappa_{u_p}, \kappa_{d_s}, \kappa_{d_p}$

Simple example with SM scalar couplings

- Using individual μ measurements from LHC $(7+8\,\text{TeV})$ + Tevatron as input to `HiggsSignals`
- Free parameters: $\cos\alpha, \kappa_{f_p}$, $\kappa_V = \kappa_{f_s} = 1$.
- No decays into states of new physics: $\mathrm{BR}(H \to \mathrm{NP}) = 0$.

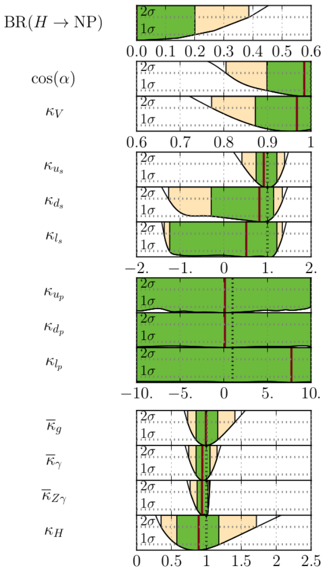




- $\chi^2_{min}/\text{ndf} = 69.3/84 \Rightarrow \mathcal{P} = 87.6\%$
- flat 1dimensional $\Delta\chi^2$ profile for κ_{f_p}

Probing Yukawa structure

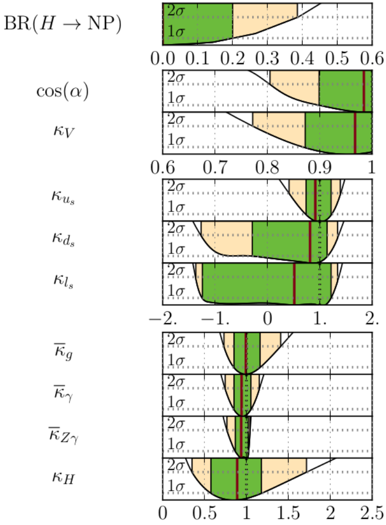
- $\alpha, \mathrm{BR}(H \to \mathrm{NP}), \kappa_V, \kappa_{u_s}, \kappa_{d_s}, \kappa_{\ell_s}, \kappa_{u_p}, \kappa_{d_p}, \kappa_{\ell_p}$
- Assumption: $|\kappa_V| \leq 1$
- $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$ derived
  - Couplings to pseudoscalar component flat.



- $\alpha, \mathrm{BR}(H \to \mathrm{NP}), \kappa_V, \kappa_{u_s}, \kappa_{d_s}, \kappa_{\ell_s}, \kappa_{u_p}, \kappa_{d_p}, \kappa_\ell$
- Assumption: $|\kappa_V| \leq 1$
- $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$ derived

  - Couplings to pseudoscalar component flat.
  - Deviation from pure CP even Higgs still compatible with data.
  - Negative values for κ_{u_s} strongly disfavored (H-γ effective coupling ($\kappa_V > 0$)).
  - Sign degeneracy of κ_{d_s} slightly broken (κ_g is sensitive to relative sign of κ_t, κ_b).
  - Vanishing κ_{ℓ_s}, κ_{d_s} compatible with data.

$\Rightarrow$ $\chi^2_{min}/\mathrm{ndf} = 68.6/77 \Rightarrow \mathcal{P} = 74.2\%$



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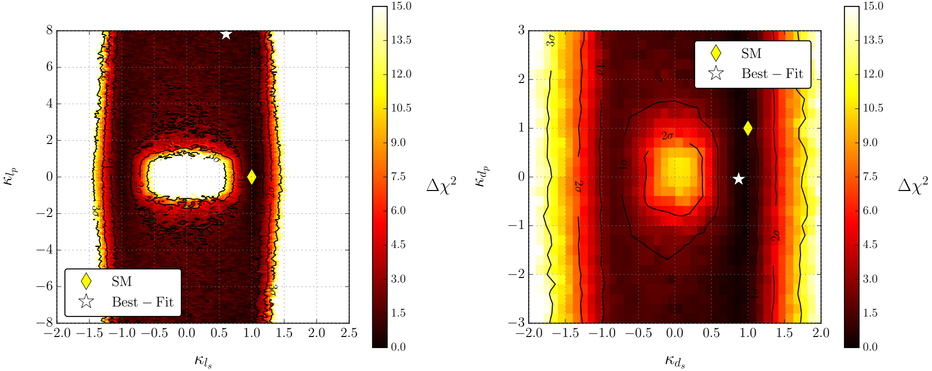
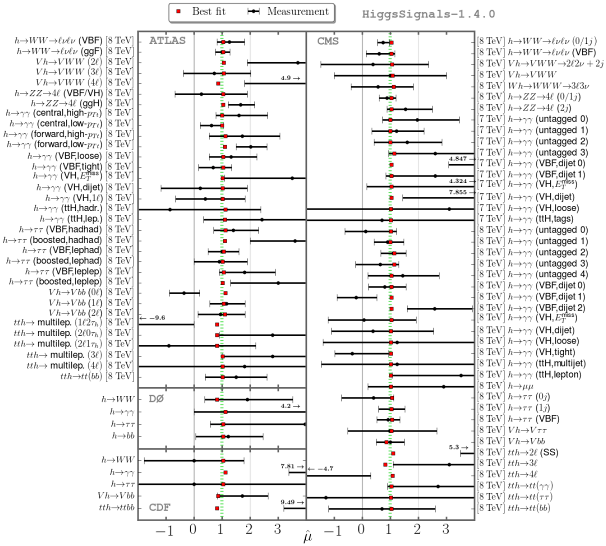


- Vanishing couplings to scalar Higgs component can be compensated by non-vanishing coupling to the pseudoscalar component.

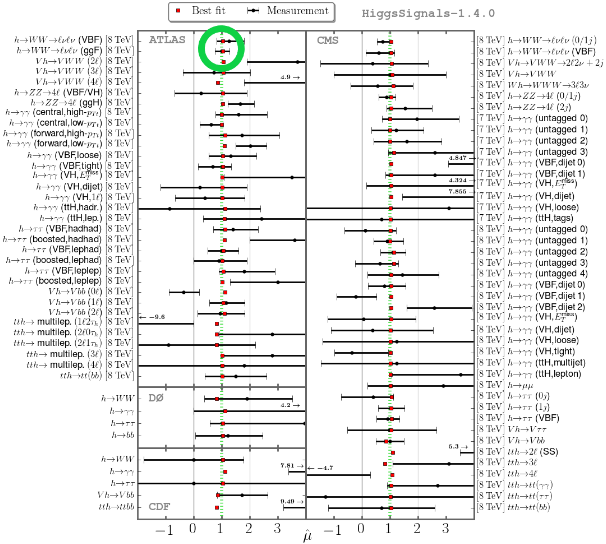
Predicted signals rates of the **best-fit** point.



Fit parameter	best-fit
$\mathrm{BR}(H \to \mathrm{NP})$	0.0
$\cos(\alpha)$	0.984
κ_V	0.967
κ_u^s	0.915
κ_d^s	0.815
κ_ℓ^s	0.514
κ_u^p	0.125
κ_d^p	0.125
κ_ℓ^p	7.744
χ^2	**68.6**

Comparison: predicted signal rates ↔ measurements

Predicted signals rates of the **best-fit** point.



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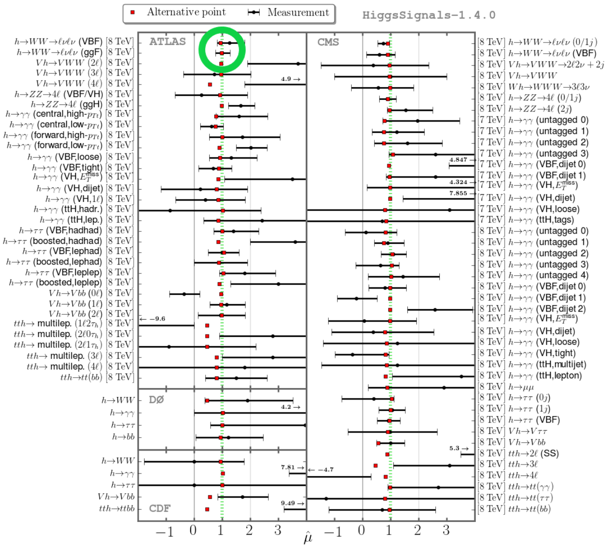
χ^2	**68.6**

Predicted signals rates of an **alternative (non SM-like)** point.



Fit parameter	alternative
$\mathrm{BR}(H \to \mathrm{NP})$	0.166
$\cos(\alpha)$	0.891
κ_V	0.990
κ_u^s	1.080
κ_d^s	0.0
κ_ℓ^s	0.0
κ_u^p	−0.046
κ_d^p	−1.472
κ_ℓ^p	1.957
χ^2	**72.6**

Summary

- HiggsBounds and HiggsSignals are excellent tools for confronting theory vs. experiment (also for extended Higgs sectors).
- Transparent information about signal efficiencies ϵ_i and correlations of systematic uncertainties is **very valuable**!
- Good agreement between HS-1 and official ATLAS+CMS result.
- Non-vanishing CP-odd component of the Higgs is still allowed by signal rates. At 2σ $cos(\alpha)$ down to 0.8 is still compatible.

Next Steps:

- Redo CP fits using ATLAS+CMS combined input(+ additional parametrizations)!

Available at `http://higgsbounds.hepforge.org`!

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Available at `http://higgsbounds.hepforge.org`!

Thanks for your attention!

Backup: Lagrangian explizit

$$\mathcal{L}_{Yuk}^{SM} = -Y_{ij}^{d}\overline{Q_{Li}}Hd_{Rj} - Y_{ij}^{u}\overline{Q_{Li}}\tilde{H}u_{Rj} - Y^{\ell}\overline{L_{Li}}H\ell_{Rj} + h.c.$$

$$Y_{ij}^{d}\overline{Q_{Li}}Hd_{Rj} =$$

with $\tilde{H} = -i\tau_2 H^*$ and

$$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Backup: Combined measurements

Production process		$H \to \gamma\gamma$ [fb]			$H \to ZZ$ [fb]			$H \to WW$ [pb]			$H \to \tau\tau$ [fb]			$H \to bb$ [pb]		
		Best fit value	Uncertainty Stat	Syst	Best fit value	Uncertainty Stat	Syst	Best fit value	Uncertainty Stat	Syst	Best fit value	Uncertainty Stat	Syst	Best fit value	Uncertainty Stat	Syst
ggF	Measured	$48.0^{+10.0}_{-9.7}$	$^{+9.4}_{-9.4}$	$^{+3.2}_{-2.3}$	580^{+170}_{-160}	$^{+170}_{-160}$	$^{+40}_{-40}$	$3.5^{+0.7}_{-0.7}$	$^{+0.5}_{-0.5}$	$^{+0.5}_{-0.5}$	1300^{+700}_{-700}	$^{+400}_{-400}$	$^{+500}_{-500}$	–		
		$\left(^{+9.7}_{-9.5}\right)$	$\left(^{+9.4}_{-9.4}\right)$	$\left(^{+2.5}_{-1.6}\right)$	$\left(^{+150}_{-130}\right)$	$\left(^{+140}_{-130}\right)$	$\left(^{+30}_{-20}\right)$	$\left(^{+0.7}_{-0.7}\right)$	$\left(^{+0.5}_{-0.5}\right)$	$\left(^{+0.5}_{-0.5}\right)$	$\left(^{+700}_{-700}\right)$	$\left(^{+400}_{-400}\right)$	$\left(^{+500}_{-500}\right)$	–		
	Predicted	44 ± 5			510 ± 60			4.1 ± 0.5			1210 ± 140			11.0 ± 1.2		
	Ratio	$1.10^{+0.23}_{-0.22}$	$^{+0.22}_{-0.21}$	$^{+0.07}_{-0.05}$	$1.13^{+0.34}_{-0.31}$	$^{+0.33}_{-0.30}$	$^{+0.09}_{-0.07}$	$0.84^{+0.17}_{-0.17}$	$^{+0.12}_{-0.12}$	$^{+0.12}_{-0.11}$	$1.0^{+0.6}_{-0.6}$	$^{+0.4}_{-0.4}$	$^{+0.4}_{-0.4}$	–		
VBF	Measured	$4.6^{+1.9}_{-1.8}$	$^{+1.8}_{-1.7}$	$^{+0.6}_{-0.5}$	3^{+46}_{-26}	$^{+46}_{-25}$	$^{+7}_{-7}$	$0.39^{+0.14}_{-0.13}$	$^{+0.13}_{-0.12}$	$^{+0.07}_{-0.05}$	125^{+39}_{-37}	$^{+34}_{-32}$	$^{+19}_{-18}$	–		
		$\left(^{+1.8}_{-1.6}\right)$	$\left(^{+1.7}_{-1.6}\right)$	$\left(^{+0.5}_{-0.4}\right)$	$\left(^{+60}_{-39}\right)$	$\left(^{+60}_{-39}\right)$	$\left(^{+8}_{-5}\right)$	$\left(^{+0.15}_{-0.13}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.07}_{-0.06}\right)$	$\left(^{+39}_{-37}\right)$	$\left(^{+34}_{-32}\right)$	$\left(^{+19}_{-18}\right)$	–		
	Predicted	3.60 ± 0.20			42.2 ± 2.0			0.341 ± 0.017			100 ± 6			0.91 ± 0.04		
	Ratio	$1.3^{+0.5}_{-0.5}$	$^{+0.5}_{-0.5}$	$^{+0.2}_{-0.1}$	$0.1^{+1.1}_{-0.6}$	$^{+1.1}_{-0.6}$	$^{+0.2}_{-0.2}$	$1.2^{+0.4}_{-0.4}$	$^{+0.4}_{-0.3}$	$^{+0.2}_{-0.2}$	$1.3^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$	$^{+0.2}_{-0.2}$	–		
WH	Measured	$0.7^{+2.1}_{-1.9}$	$^{+2.1}_{-1.8}$	$^{+0.3}_{-0.3}$	–			$0.24^{+0.18}_{-0.16}$	$^{+0.15}_{-0.14}$	$^{+0.10}_{-0.08}$	-64^{+64}_{-61}	$^{+55}_{-50}$	$^{+32}_{-34}$	$0.42^{+0.21}_{-0.20}$	$^{+0.17}_{-0.16}$	$^{+0.12}_{-0.11}$
		$\left(^{+1.9}_{-1.8}\right)$	$\left(^{+1.9}_{-1.8}\right)$	$\left(^{+0.1}_{-0.1}\right)$	–			$\left(^{+0.16}_{-0.14}\right)$	$\left(^{+0.14}_{-0.13}\right)$	$\left(^{+0.08}_{-0.07}\right)$	$\left(^{+67}_{-64}\right)$	$\left(^{+60}_{-54}\right)$	$\left(^{+30}_{-32}\right)$	$\left(^{+0.22}_{-0.21}\right)$	$\left(^{+0.18}_{-0.17}\right)$	$\left(^{+0.12}_{-0.11}\right)$
	Predicted	1.60 ± 0.09			18.8 ± 0.9			0.152 ± 0.007			44.3 ± 2.8			0.404 ± 0.017		
	Ratio	$0.5^{+1.3}_{-1.2}$	$^{+1.3}_{-1.1}$	$^{+0.2}_{-0.2}$	–			$1.6^{+1.2}_{-1.0}$	$^{+1.0}_{-0.9}$	$^{+0.6}_{-0.5}$	$-1.4^{+1.4}_{-1.4}$	$^{+1.2}_{-1.1}$	$^{+0.7}_{-0.8}$	$1.0^{+0.5}_{-0.5}$	$^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$
ZH	Measured	$0.5^{+2.9}_{-2.4}$	$^{+2.8}_{-2.3}$	$^{+0.5}_{-0.2}$	–			$0.53^{+0.23}_{-0.20}$	$^{+0.21}_{-0.19}$	$^{+0.10}_{-0.07}$	58^{+56}_{-47}	$^{+52}_{-44}$	$^{+20}_{-16}$	$0.08^{+0.09}_{-0.09}$	$^{+0.08}_{-0.08}$	$^{+0.04}_{-0.04}$
		$\left(^{+2.3}_{-1.9}\right)$	$\left(^{+2.3}_{-1.9}\right)$	$\left(^{+0.1}_{-0.1}\right)$	–			$\left(^{+0.17}_{-0.14}\right)$	$\left(^{+0.16}_{-0.14}\right)$	$\left(^{+0.05}_{-0.04}\right)$	$\left(^{+49}_{-40}\right)$	$\left(^{+46}_{-38}\right)$	$\left(^{+16}_{-12}\right)$	$\left(^{+0.10}_{-0.09}\right)$	$\left(^{+0.09}_{-0.08}\right)$	$\left(^{+0.05}_{-0.04}\right)$
	Predicted	0.94 ± 0.06			11.1 ± 0.6			0.089 ± 0.005			26.1 ± 1.8			0.238 ± 0.012		
	Ratio	$0.5^{+3.0}_{-2.5}$	$^{+3.0}_{-2.5}$	$^{+0.5}_{-0.2}$	–			$5.9^{+2.6}_{-2.2}$	$^{+2.3}_{-2.1}$	$^{+1.1}_{-0.8}$	$2.2^{+2.2}_{-1.8}$	$^{+2.0}_{-1.7}$	$^{+0.8}_{-0.6}$	$0.4^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$	$^{+0.2}_{-0.2}$
ttH	Measured	$0.64^{+0.48}_{-0.38}$	$^{+0.48}_{-0.38}$	$^{+0.07}_{-0.04}$	–			$0.14^{+0.05}_{-0.05}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	-15^{+30}_{-26}	$^{+26}_{-22}$	$^{+15}_{-15}$	$0.08^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.06}_{-0.06}$
		$\left(^{+0.45}_{-0.34}\right)$	$\left(^{+0.44}_{-0.33}\right)$	$\left(^{+0.10}_{-0.05}\right)$	–			$\left(^{+0.04}_{-0.04}\right)$	$\left(^{+0.04}_{-0.04}\right)$	$\left(^{+0.02}_{-0.02}\right)$	$\left(^{+31}_{-26}\right)$	$\left(^{+26}_{-22}\right)$	$\left(^{+16}_{-13}\right)$	$\left(^{+0.07}_{-0.06}\right)$	$\left(^{+0.04}_{-0.04}\right)$	$\left(^{+0.06}_{-0.05}\right)$
	Predicted	0.294 ± 0.035			3.4 ± 0.4			0.0279 ± 0.0032			8.1 ± 1.0			0.074 ± 0.008		
	Ratio	$2.2^{+1.6}_{-1.3}$	$^{+1.6}_{-1.3}$	$^{+0.2}_{-0.1}$	–			$5.0^{+1.8}_{-1.7}$	$^{+1.5}_{-1.5}$	$^{+1.0}_{-0.9}$	$-1.9^{+3.7}_{-3.3}$	$^{+3.2}_{-2.7}$	$^{+1.9}_{-1.8}$	$1.1^{+1.0}_{-1.0}$	$^{+0.5}_{-0.5}$	$^{+0.8}_{-0.8}$

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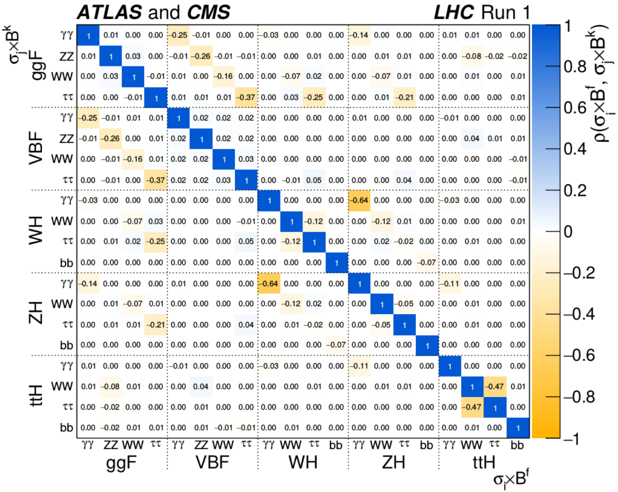
Backup: Covariance matrix



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Backup: 2D Plots