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

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HiggsSignals

Motivation

- Thus far, the discovered **Higgs boson** is in good agreement with the Standard Model (SM) prediction.
- Many well motivated BSM theories feature an extended Higgs sector.
  - ⇒ possible deviations in the couplings/signal rates from the SM Higgs, and additional Higgs states may be discovered in future LHC searches.
  - ⇒ **model-independent** tools to confront:

Theory predictions

$\Longleftrightarrow$

vs. **Experimental results**

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Theo	vs.	Exp
precise predictions of Higgs signal rates and Higgs mass	$\Longleftrightarrow$	**precision measurements** of Higgs signal rates and mass
predictions for additional Higgs states		searches for additional Higgs states

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Theo		Exp
precise predictions of Higgs signal rates and Higgs mass	HiggsSignals	**precision measurements** of Higgs signal rates and mass
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- Current version: HiggsSignals-1.4.0 (HiggsSignals-2.1.0beta)
- Website: `http://higgsbounds.hepforge.org.`
- Documentation: [arXiv:1305.1933], [arXiv:1311.0055]
- Applications: [arXiv:1403.1582], [arXiv:1608.00638], + many more

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 $i \in \{\text{ggH, VBF, WH, ZH, ttH, ...}\}$ 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 ($i \in$ {ggH, VBF, WH, ZH, ttH, ...}).
  σ, BR given via effective couplings or at hadronic level (using the HiggsBounds framework).
- 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!

- Signal strength measurements:

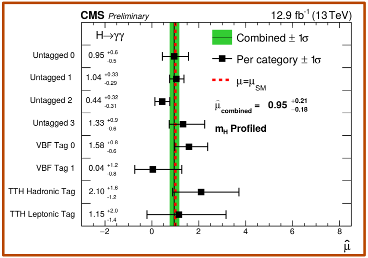
$$\mu_{H_k \to XX} = \frac{\sum_i \epsilon^i_{model} \left[\sigma_i(pp \to H_k) \times \mathrm{BR}(H_k \to XX)\right]_{model}}{\sum_i \epsilon^i_{SM} \left[\sigma_i(pp \to H) \times \mathrm{BR}(H \to XX)\right]_{SM}},$$

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

Examples:

experimental categories

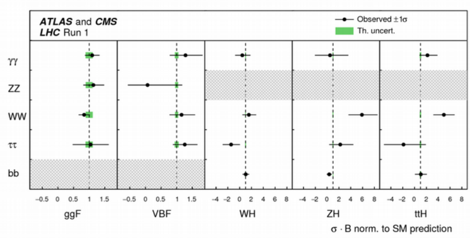
[CMS-PAS-HIG-16-020]



+ signal efficiencies (if given)

'pure' signal channels

[ATLAS+CMS 7/8 TeV, 1606.02266]



+ 20 × 20 correlation matrix

HiggsSignals: Experimental input

- Signal strength measurements:

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

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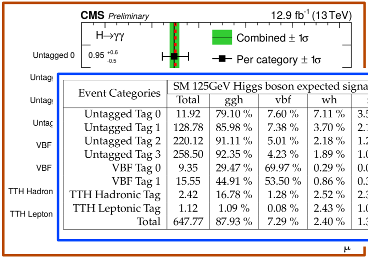
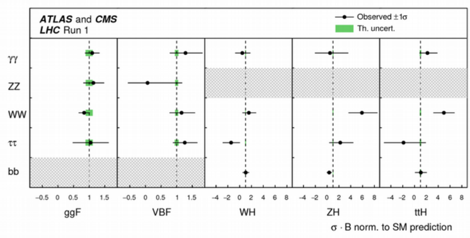


Event Categories	SM 125GeV Higgs boson expected signal					
	Total	ggh	vbf	wh	zh	tth
Untagged Tag 0	11.92	79.10 %	7.60 %	7.11 %	3.59 %	2.60 %
Untagged Tag 1	128.78	85.98 %	7.38 %	3.70 %	2.12 %	0.82 %
Untagged Tag 2	220.12	91.11 %	5.01 %	2.18 %	1.23 %	0.47 %
Untagged Tag 3	258.50	92.35 %	4.23 %	1.89 %	1.06 %	0.47 %
VBF Tag 0	9.35	29.47 %	69.97 %	0.29 %	0.07 %	0.20 %
VBF Tag 1	15.55	44.91 %	53.50 %	0.86 %	0.38 %	0.35 %
TTH Hadronic Tag	2.42	16.78 %	1.28 %	2.52 %	2.39 %	77.02 %
TTH Leptonic Tag	1.12	1.09 %	0.08 %	2.43 %	1.06 %	95.34 %
Total	647.77	87.93 %	7.29 %	2.40 %	1.35 %	1.03 %

Valuable Information! Interface: $\zeta^i = \frac{\epsilon^i_{model}}{\epsilon^i_{SM}}$

'pure' signal channels

[ATLAS+CMS 7/8 TeV, 1606.02266]



$+\ 20 \times 20$ correlation matrix

HiggsSignals: χ^2 Evaluation

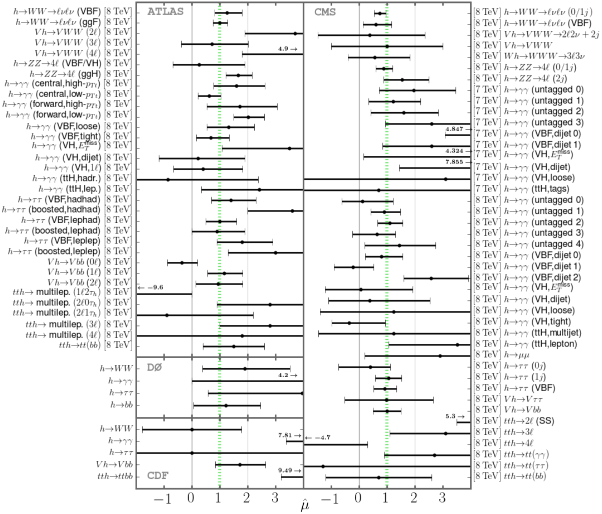
- Global χ^2 for the signal strength measurement is given by

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

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

HiggsSignals: Observables

- **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.



Validation of HiggsSignals with LHC Run 1 data

Validation of HiggsSignals with Run 1 data

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

Coupling scale factors κ's (phenomenological descripton)

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

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

- Profile likelihood fits within the Higgs coupling scale factor parametrization: $\kappa_Z, \kappa_W, \kappa_u, \kappa_d, \kappa_\ell, \kappa_g, \kappa_\gamma$

  up-type (κ_u), down-type (κ_d), leptons (κ_ℓ), loop-induced (κ_g, κ_γ)

- 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)

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Inputs to HiggsSignals

Run-1 Combination Input

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

Validation of HiggsSignals with Run 1 data

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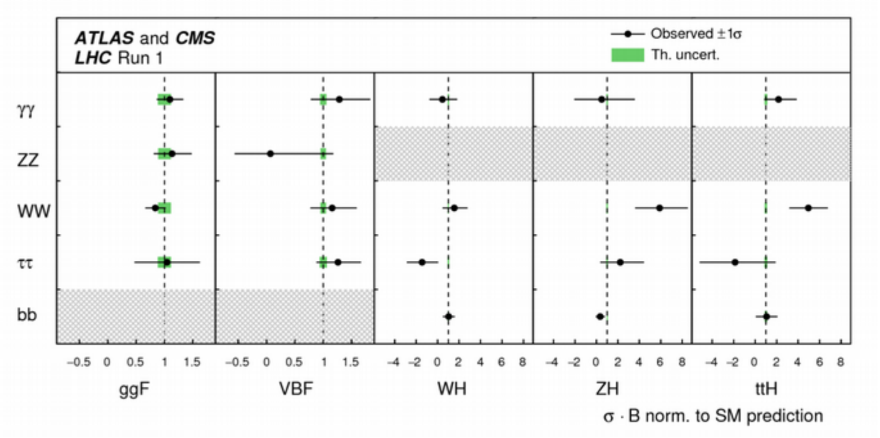


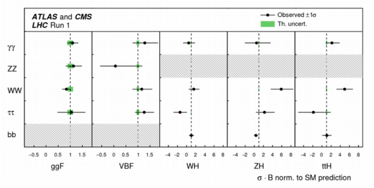
JHEP08(2016)045 [arXiv:1606.02266]

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

Inputs to HiggsSignals

Run-1 Combination Input

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



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JHEP08(2016)045 [arXiv:1606.02266]

Validation of HiggsSignals with Run 1 data

- Try ... com... 1 ...ts.

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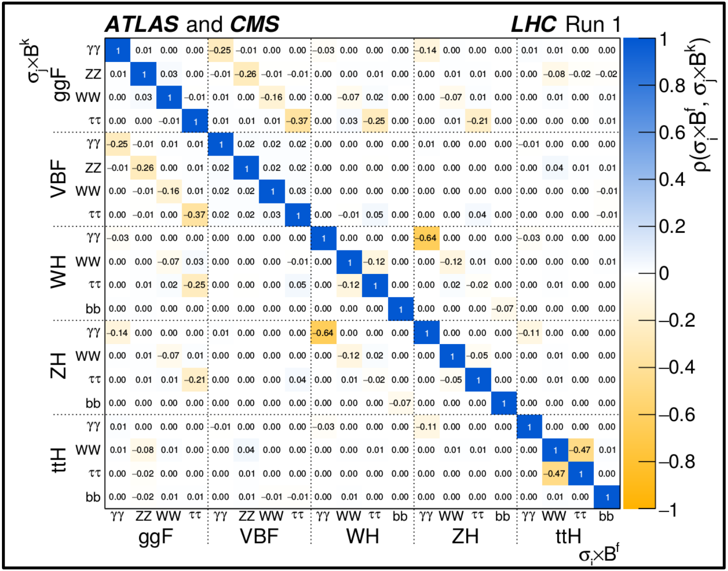

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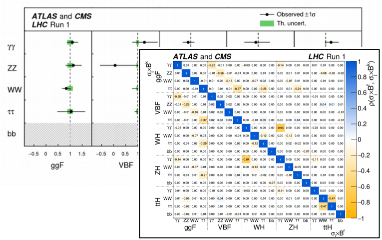

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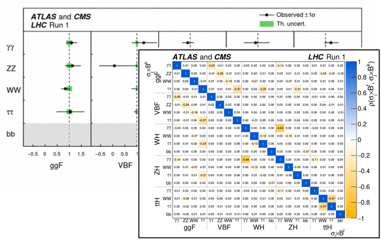

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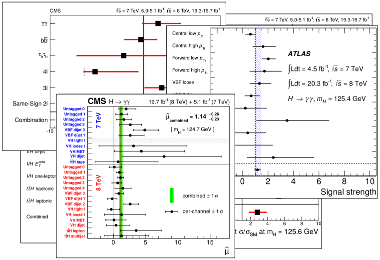

[arXiv:1407.0558,arXiv:1408.7084,arXiv:1408.1682,...]

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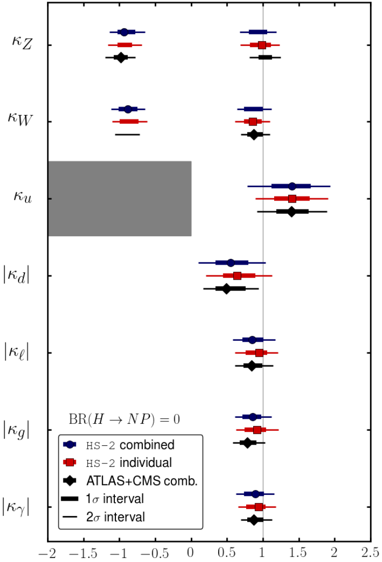
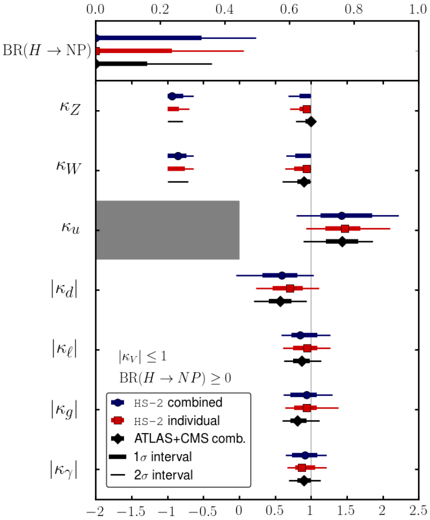


Assumption:
no new Higgs decay modes,
$BR(H \to \mathrm{NP}) = 0$

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



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.

Constraining possible CP mixing of the Higgs boson with Run 1 data

Motivation

Spin 0 particle may be either

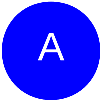
- Pure CP even

SM-like

Spin 0 particle may be either

- Pure CP even
- Pure CP odd

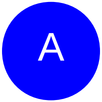
SM-like

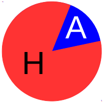


Spin 0 particle may be either

- Pure CP even
- Pure CP odd
- Mixture

SM-like





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

Pure CP even scenario

$$\Phi = H$$

Yukawa Lagrangian:

$$\mathcal{L}_{Yuk}^{SM} = - \quad \overline{u_L} Y_u^{SM} u_R H - \quad \overline{d}_L Y_d^{SM} d_R H - \quad \overline{\ell}_L Y_\ell^{SM} \ell_R H$$

Pure CP even scenario

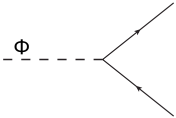
$$\Phi = H$$

Yukawa Lagrangian:

$$\mathcal{L}_{Yuk}^{mod} = - \; \kappa_u \overline{u_L} Y_u^{SM} u_R H - \kappa_d \overline{d_L} Y_d^{SM} d_R H - \; \kappa_\ell \overline{\ell_L} Y_\ell^{SM} \ell_R H$$

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

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



CP mixture scenario

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

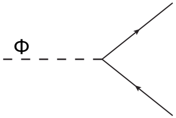
Modified Yukawa Lagrangian: [A.Freitas, P.Schwaller; 1211.1980]

CP even → $\mathcal{L}_{Yuk}^{mod} = - \kappa_{u_s}\overline{u_L}Y_u^{SM}u_R H - \kappa_{d_s}\overline{d_L}Y_d^{SM}d_R H - \kappa_{\ell_s}\overline{\ell_L}Y_\ell^{SM}\ell_R H$

CP odd → $- i\kappa_{u_p}\overline{u_L}Y_u^{SM}u_R A - i\kappa_{d_p}\overline{d_L}Y_d^{SM}d_R A - i\kappa_{\ell_p}\overline{\ell_L}Y_\ell^{SM}\ell_R A + h.c.$

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

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



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

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

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CP odd → $- i\kappa_{u_p}\overline{u_L}Y_u^{SM}u_R A - i\kappa_{d_p}\overline{d_L}Y_d^{SM}d_R A - i\kappa_{\ell_p}\overline{\ell_L}Y_\ell^{SM}\ell_R A + h.c.$

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

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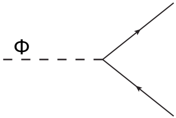
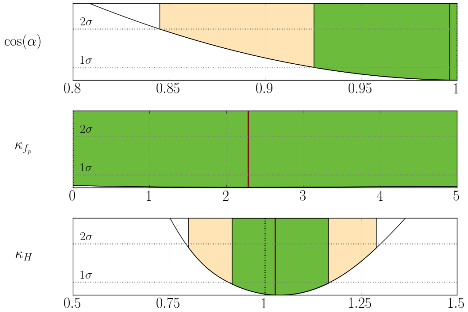


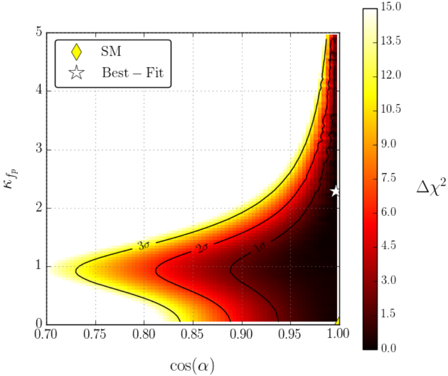
(QCD Corrections $R^{ii} \approx 1$)

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

- Only two free parameters: $\cos\alpha, \kappa_{f_p}$
- $\kappa_V = \kappa_{f_s} = 1$.
- No decays into states of new physics: $\mathrm{BR}(H \to \mathrm{NP}) = 0$.

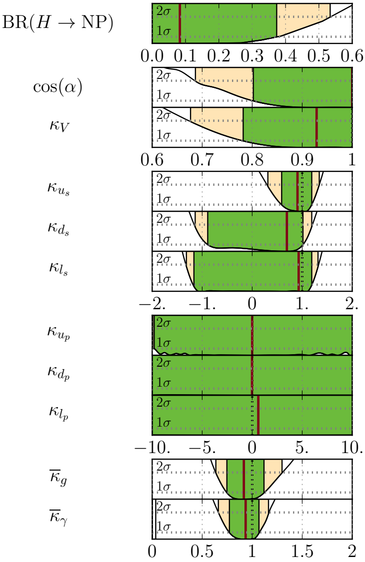




- $\chi^2_{min}/\mathrm{ndf} = 69.3/84 \Rightarrow \mathcal{P} = 87.6\%$.
- flat 1dimensional $\Delta\chi^2$ profile for κ_{f_p}.

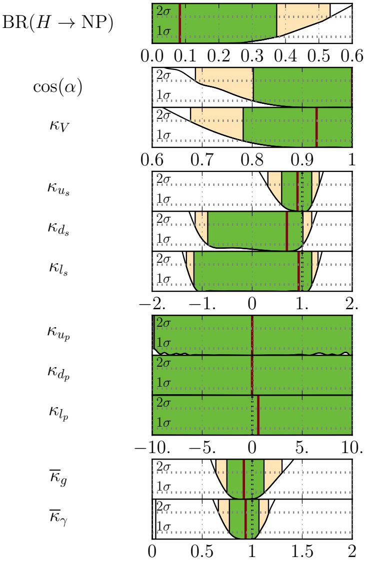
Probing Yukawa structure

- **ATLAS + CMS combination input**
- $\alpha, \mathrm{BR}(H \to \mathrm{NP}), \kappa_V, \kappa_{u_s}, \kappa_{d_s}, \kappa_{\ell_s}, \kappa_{u_p}, \kappa_{d_p}, \kappa_{\ell_p}$
- $|\kappa_V| \leq 1$; κ_g, κ_γ derived



Probing Yukawa structure

- **ATLAS + CMS combination input**
- $\alpha, \mathrm{BR}(H \to \mathrm{NP}), \kappa_V, \kappa_{u_s}, \kappa_{d_s}, \kappa_{\ell_s}, \kappa_{u_p}, \kappa_{d_p}, \kappa_{\ell_p}$
- $|\kappa_V| \leq 1$; κ_g, κ_γ 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.

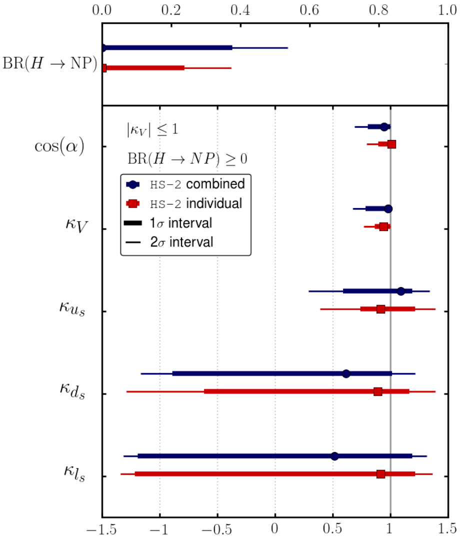


Comparison: Run 1 combination vs. μ input

- Insensitive to pseudoscalar scale factors $\rightarrow$ dropped in plot.
- **up-type**, **down-type** and **lepton** scale factors $\rightarrow$ consistent result!
- **HS** finds tighter constraints on $BR(H \rightarrow \mathrm{NP})$, $\cos\alpha$ and κ_V with individual μ input.

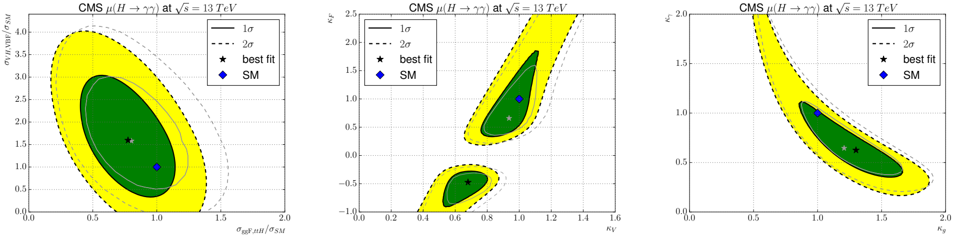
$\Rightarrow$ Compare to pure CP even scenario.

- Constraint on possible CP mixing
  Combination input: $\cos\alpha \geq 0.8(0.68)$
  Individual μ input : $\cos\alpha \geq 0.9(0.81)$
  at 1σ (2σ) CL.



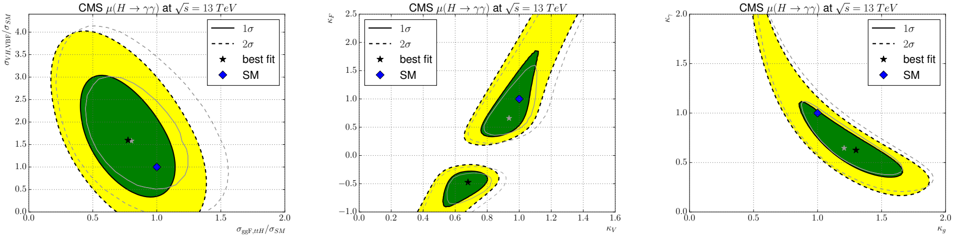
Validation of 13 TeV data

Comparison: HiggsSignals (colored) vs. official (gray) fit results.



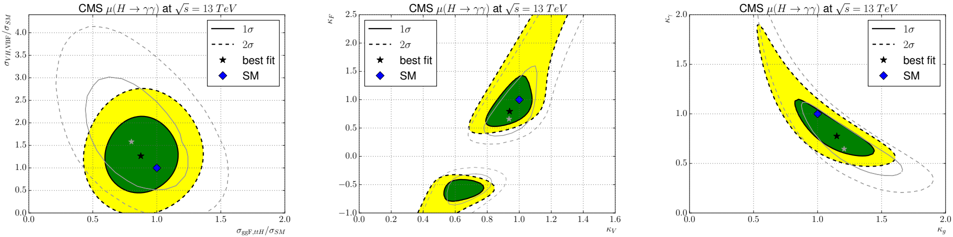
[CMS PAS HIG-16-020]

Comparison: HiggsSignals (colored) vs. official (gray) fit results.



Without Signal efficiencies:

[CMS PAS HIG-16-020]

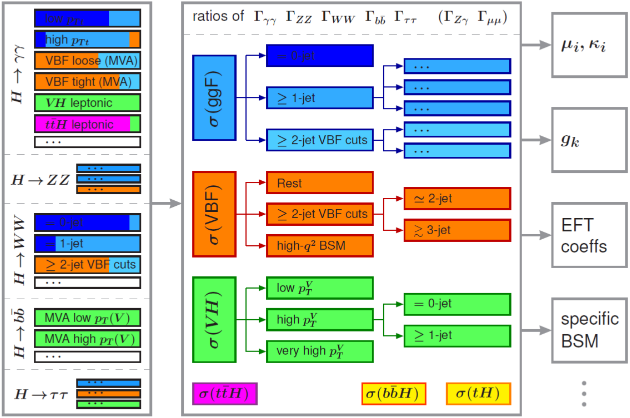


$\Rightarrow$ Signal efficiencies contain very **valuable information**!

Simplified Template Cross Sections (STXS)

- left: **Experimental measurements** (similar to Run1 coupling measurements)
- centre: **STXS** (from experimental categories by global fit)
- right: STXS serve as input for subsequent interpretations.

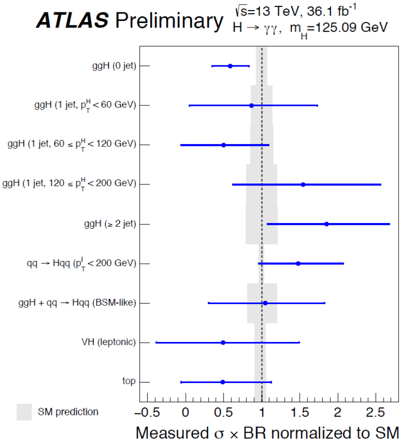
[LHC HXSWG, YR4, 1610.07922]

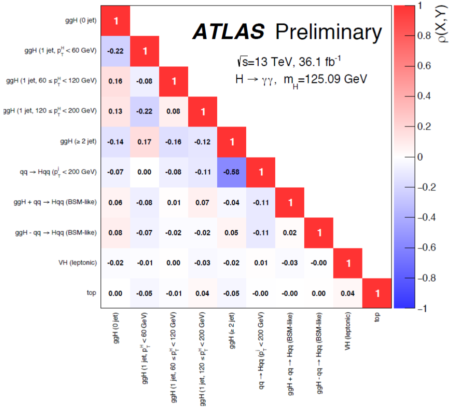


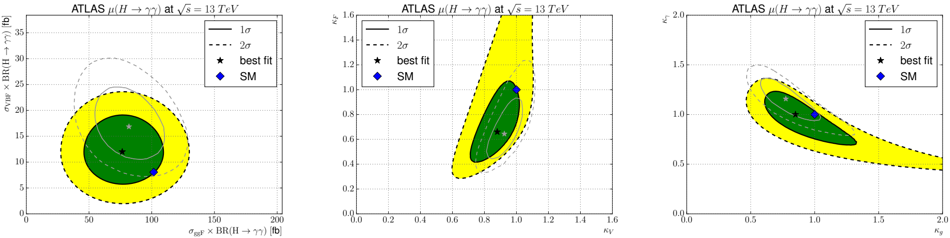
STXS performance of ATLAS $H \to \gamma\gamma$ 13 TeV results

- ATLAS presented 9 STXS together with a correlation matrix.

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

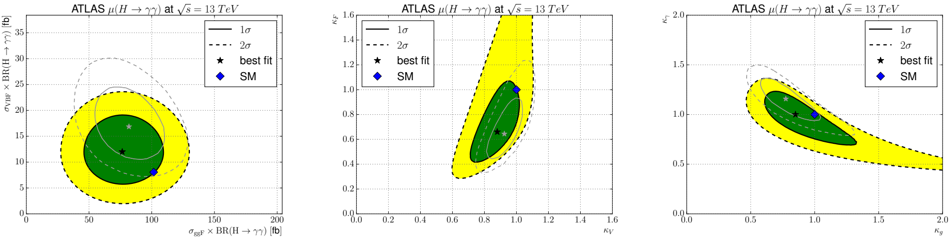






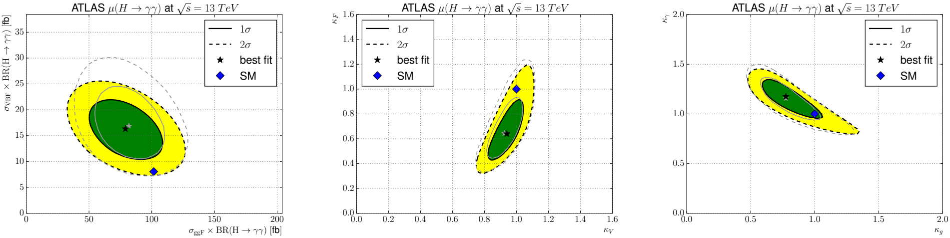
STXS: Cross sections are measured in a given production mode. [ATLAS-CONF-2017-045]

Without correlation!



STXS: Cross sections are measured in a given production mode. [ATLAS-CONF-2017-045]

with correlation matrix (from ATLAS):



$\Rightarrow$ Significant improvement! First results look promising!

Summary

- HiggsBounds and HiggsSignals are excellent tools for confronting theory vs. experiment (also for extended Higgs sectors).
- Good agreement between HS and official ATLAS+CMS result.
- CP mixing scenario:
  - Sizable CP-odd Higgs couplings are still allowed by signal rates.
  - Combination input: $\cos\alpha \geq 0.8(0.68)$
    Individual μ input : $\cos\alpha \geq 0.9(0.81)$ at 1σ (2σ) CL.
- Transparent information about signal efficiencies ϵ_i and correlations of systematic uncertainties is **very valuable**!
- New experimental input (STXS, σ and BR-ratios) is being implemented and first results look promising.

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

Summary

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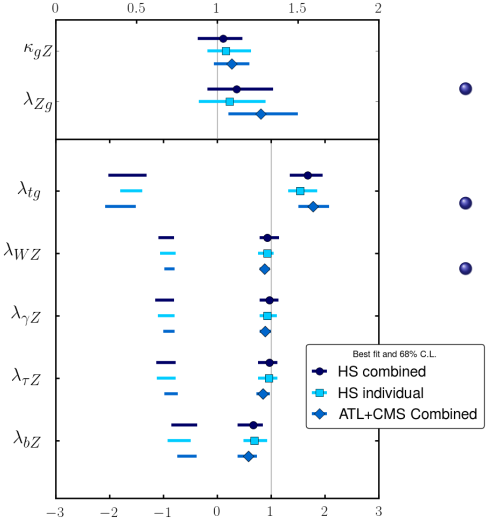
Thanks for your attention!

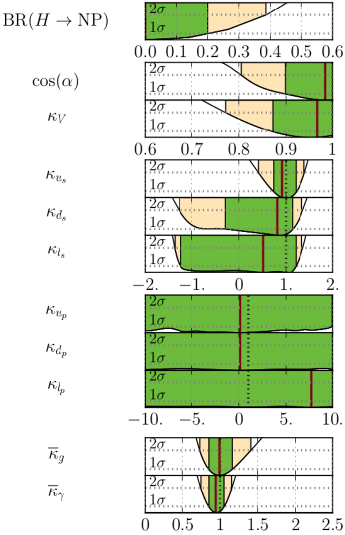
Backup: Fit result: λ parametrization

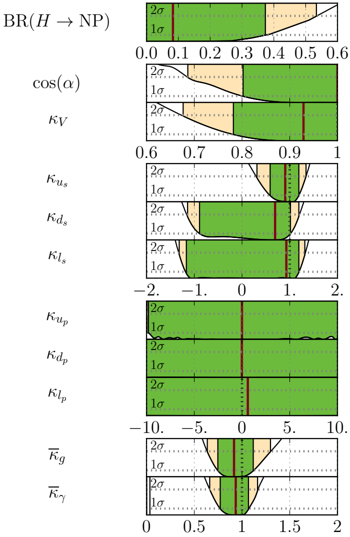


- Reference channel ($\sigma \cdot \mathrm{BR}$) ($gg \to H \to ZZ$): $\kappa_{gZ} = \frac{\kappa_g \cdot \kappa_Z}{\kappa_H}$ (little background and one the smallest overall sys. uncertainties).
- Probe of production measurements: $\lambda_{Zg} = \frac{\kappa_Z}{\kappa_g}$, $\lambda_{tg} = \frac{\kappa_t}{\kappa_g}$
- Decay modes $H \to ii$ ($i = W, \tau, b, \gamma$): $\lambda_{iZ} = \frac{\kappa_i}{\kappa_Z}$

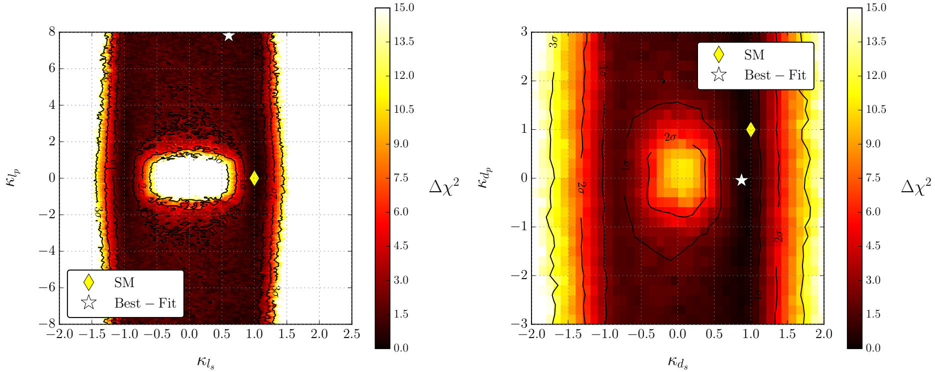
Backup: χ^2 profiles: Individual μ vs. combination input

μ input vs. combination input





Backup: Probing Yukawa structure



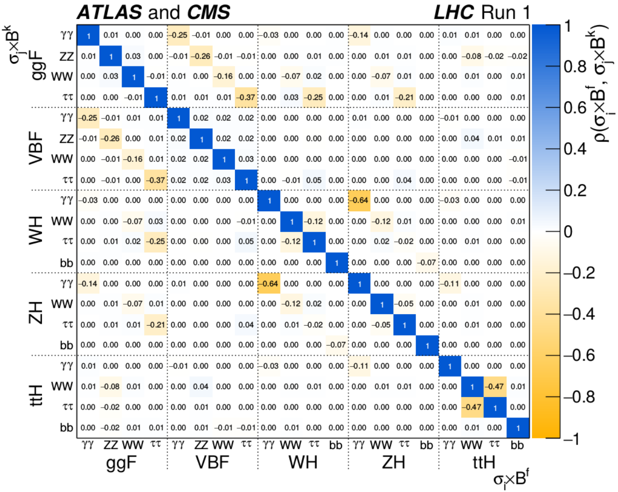
- Vanishing couplings to scalar Higgs component can be compensated by non-vanishing coupling to the pseudoscalar component.

Backup: 'ATLAS+CMS combined' measurement

Production process		Decay mode														
		$H \to \gamma\gamma$ [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	$2.2^{+1.6}_{-1.3}$	$^{+1.6}_{-1.3}$	$^{+0.2}_{-0.1}$	–			$5.0^{+1.8}_{-1.7}$	$^{+1.5}_{-1.5}$	$^{+1.0}_{-0.9}$	$-1.9^{+3.7}_{-3.3}$	$^{+3.2}_{-2.7}$	$^{+1.9}_{-1.8}$	$1.1^{+1.0}_{-1.0}$	$^{+0.5}_{-0.5}$	$^{+0.8}_{-0.8}$

JHEP08(2016)045 [arXiv:1606.02266]

Backup: 'ATLAS+CMS combined' covariance matrix



JHEP08(2016)045 [arXiv:1606.02266]