Constraining new physics from Higgs measurements with Lilith: Update to LHC Run 2 results

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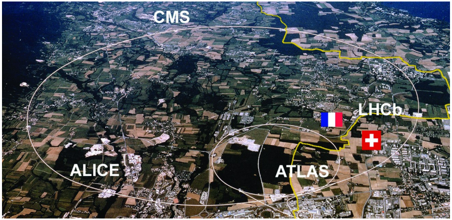
Summary

Motivation

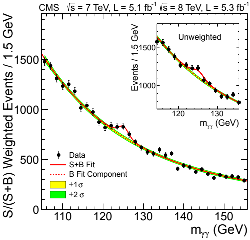
- Higgs physics has become one of the most important programs nowadays in particle physics.
- Higgs couplings are measured to find deviations from the Standard Model (SM) values.
- We therefore need automatic tools to compare measured Higgs couplings with new physics model values.

LHC Run 1 & Run 2

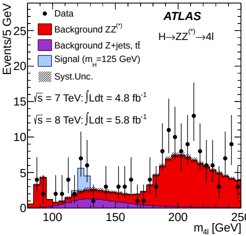


- Large Hadron Collider (LHC) is the world's largest and most powerful collider.
- Run 1 (2009-2013) : Higgs boson was discovered in July 2012, energy scale of 7 & 8 TeV.
- Run 2 (2015–2018) : Upgraded with a combined energy of 13 TeV.

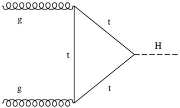
[CMS-HIG-12-028]



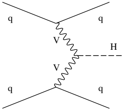
[ATLAS-HIGG-2012-27]



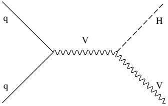
Main Higgs production modes



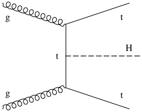
ggH



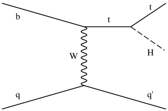
qqH (VBF)



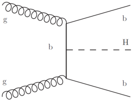
VH



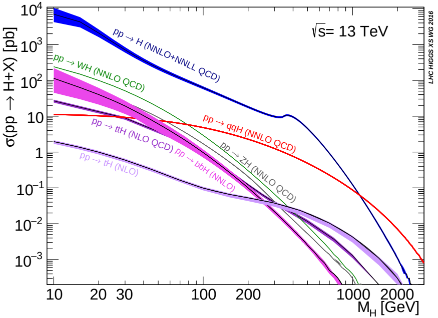
ttH



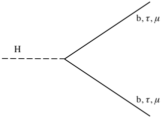
tH



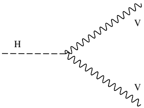
bbH



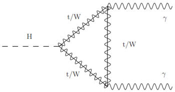
Main Higgs decay modes



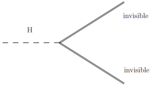
H→ff



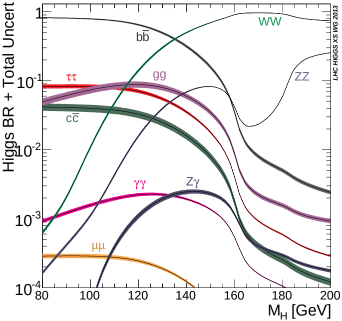
H→VV



H→ γγ



H→ invisible



Higgs Signal Strengths

The Higgs measurements are provided in terms of signal strengths :

$$\mu = \frac{N^{\text{exp}}_{\text{signal}}}{N^{\text{SM}}_{\text{signal}}} = \frac{\sigma \times A \times \epsilon}{[\sigma \times A \times \epsilon]^{SM}}. \quad (1)$$

Under 2 conditions :

1. Observed signal is a sum of SM processes : $\sigma = \sum_{X,Y} \sigma(X)\mathcal{B}(H \to Y)$.
2. Acceptance, efficiency is the same as in SM : $(A \times \epsilon)_{X,Y} = (A \times \epsilon)^{SM}_{X,Y}$.

The signal strengths read :

$$\mu(X, Y) = \frac{\sigma(X)\mathcal{B}(H \to Y)}{\sigma(X)^{\text{SM}}\mathcal{B}(H \to Y)^{\text{SM}}}. \quad (2)$$

$\Rightarrow$ Allow a combination of various channels.
$\Rightarrow$ Be able to perform means of global fits for given models.

Higgs Reduced couplings

Reduced couplings in Lagrangian

$$\mathcal{L} = C_W \underbrace{g m_W W^\mu W_\mu H}_{\text{SM}} + C_Z \underbrace{g \frac{m_Z}{\cos\theta_W} Z^\mu Z_\mu H}_{\text{SM}} - \sum_{f=t,b,c,\tau} C_f \underbrace{g \frac{m_f}{2m_W} f\bar{f} H}_{\text{SM}} . \quad (3)$$

The Reduced couplings :

- Show how the experiments/new physics models deviate from the SM.
- Equal to 1 for the SM, differ from 1 in scenarios of new physics.

Signal Strengths & Reduced Couplings relations

The combined signal strengths could be rewritten :

$$\mu = \sum_{X,Y} \mathrm{eff}_{X,Y} \frac{\sigma(X)\mathcal{B}(H \to Y)}{\sigma(X)^{\mathrm{SM}}\mathcal{B}(H \to Y)^{\mathrm{SM}}} = \frac{\sum_{X,Y} \mathrm{eff}_{X,Y} C_X^2 C_Y^2}{\sum_Y C_Y^2 \mathcal{B}^{\mathrm{SM}}(H \to Y)}. \quad (4)$$

Couplings for production modes involving many SM-liked particles :

$$C_{ggH}^2 = \frac{\sum\limits_{i,j=t,b,c} C_i C_j \sigma_{ij}^{\mathrm{SM}}(\mathrm{ggH})}{\sum\limits_{i,j=t,b,c} \sigma_{ij}^{\mathrm{SM}}(\mathrm{ggH})}, \quad C_{VBF}^2 = \frac{\sum\limits_{i,j=t,b,c} C_i C_j \sigma_{ij}^{\mathrm{SM}}(\mathrm{VBF})}{\sum\limits_{i,j=t,b,c} \sigma_{ij}^{\mathrm{SM}}(\mathrm{VBF})}, \quad (5)$$

Couplings of interest for decay modes :

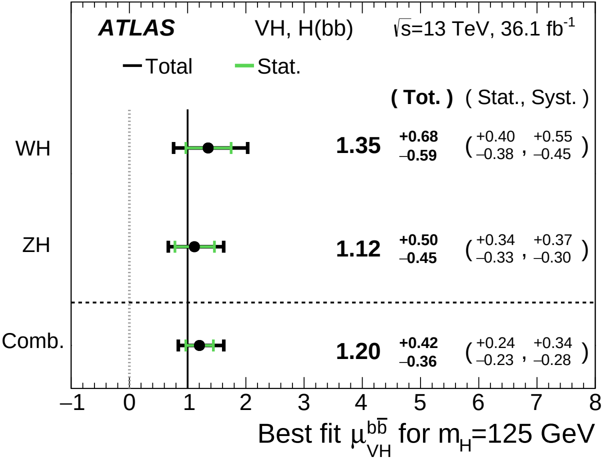
$$C_{gg}^2 = \frac{\sum\limits_{i,j=t,b,c} C_i C_j \Gamma_{ij}^{\mathrm{SM}}(H \to gg)}{\sum\limits_{i,j=t,b,c} \Gamma_{ij}^{\mathrm{SM}}(H \to gg)}, \quad C_{\gamma\gamma,Z\gamma}^2 = \frac{\sum\limits_{i,j=W,t,b,c,\tau} C_i C_j \Gamma_{ij}^{\mathrm{SM}}(H \to \gamma\gamma, Z\gamma)}{\sum\limits_{i,j=W,t,b,c,\tau} \Gamma_{ij}^{\mathrm{SM}}(H \to \gamma\gamma, Z\gamma)}, \quad (6)$$

LHC Dataset

Collaboration	Analysis	Type	Reference
ATLAS	$ggH - VBF - VH - ttH, H \to \gamma\gamma$	4D matrix	[HIGG-2016-21]
	$ggH - VBF, H \to ZZ^*$	2D contour	[HIGG-2016-22]
	$ttH, VH, H \to ZZ^*$	1D interval	[HIGG-2016-22]
	$ggH - VBF, H \to WW^*$	2D contour	[HIGG-2016-07]
	$WH, ZH, H \to b\bar{b}$	1D interval	[HIGG-2016-29]
	$VBF, H \to b\bar{b}$	1D interval	[HIGG-2016-30]
	$ggH - VBF, H \to \tau\bar{\tau}$	2D contour	[HIGG-2017-07]
	$ttH, H \to b\bar{b}, \tau\bar{\tau}, VV^*(WW^* + ZZ^*)$	3D matrix	[HIGG-2017-02]
	$ZH, H \to invisible$	1D grids	[HIGG-2016-28]
CMS	$ggH - VBF - WH - ZH - ttH,$ $H \to \gamma\gamma, ZZ^*, WW^*, b\bar{b}, \tau\bar{\tau}, \mu\bar{\mu}$	24D matrix	[HIG-17-031]

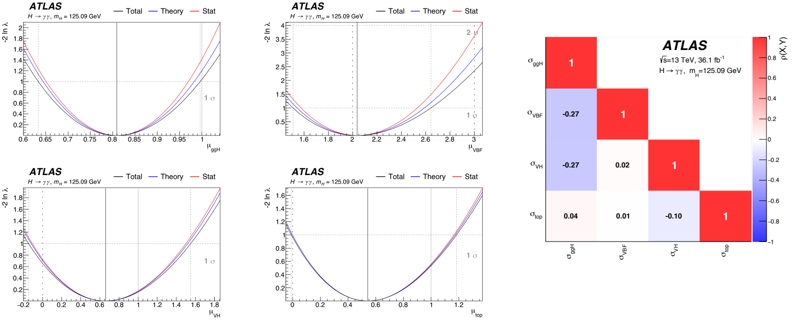
TABLE – Recommended set of experimental results

ATLAS data for $H \to b\bar{b}$



Higgs signal strengths for *VH*, $H \to bb$. arXiv:1708.03299 [hep-ex]

ATLAS data for $H \to \gamma\gamma$



Higgs signal strengths for *ggH* – *VBF* – *VH* – *top*, $H \to \gamma\gamma$. [arXiv:1802.04146 [hep-ex]]

Log-likelihood function of Higgs signal strengths

Log-likelihood function :

- Used when we compare models with data.
- Not fully provided by the ATLAS/CMS due to complexity in fitting process (only best fits, uncertainties, correlation provided).
- Not well approximated by Gaussian distribution, since it is highly asymmetric.

$\Rightarrow$ Need for a multi-variable continuous asymmetric distribution.

Generalized Poisson Log-likelihood distribution

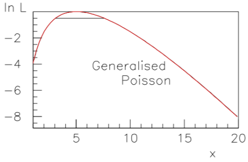
Issues has been overcome :

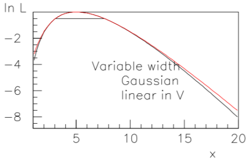
1. Generalize Poisson Log-likelihood to a continuous function of its parameter [arXiv:physics/0406120]
2. Incorporate negative correlation in bi-variable cases. [Statistica Neerlandica (2004) Vol. 58, nr. 3, pp. 349–364]

Drawbacks :

1. Complicated and may slow down computation process.
2. Restricted to only 1D and 2D cases.

Variable Gaussian Log-likelihood distribution





1D Gaussian Log-likelihood :

$$-2\log L(\mu) = \frac{(\mu - \hat{\mu})^2}{\sigma^2}, \quad (\mathrm{Var} = \sigma^2) \tag{7}$$

Define 1D Variable Gaussian linear in Var :

$$\mathrm{Var}(\mu) = \sigma^+\sigma^- + (\sigma^+ - \sigma^-)(\mu - \hat{\mu}) \tag{8}$$

$$-2\log L(\mu) = \frac{(\mu - \hat{\mu})^2}{\sigma^+\sigma^- + (\sigma^+ - \sigma^-)(\mu - \hat{\mu})}. \tag{9}$$

Extended to n-dimension, where the best fit point $\hat{\boldsymbol{\mu}} = (\hat{\mu}_1, \ldots, \hat{\mu}_n)$ and the covariance matrix :

$$C = \boldsymbol{\Sigma}(\boldsymbol{\mu}).\rho.\boldsymbol{\Sigma}(\boldsymbol{\mu}), \quad \boldsymbol{\Sigma}(\boldsymbol{\mu}) = \mathrm{diag}(\Sigma_1, \ldots, \Sigma_n), \tag{10}$$

$$-2\log L(\boldsymbol{\mu}) = (\boldsymbol{\mu} - \hat{\boldsymbol{\mu}})^T C^{-1} (\boldsymbol{\mu} - \hat{\boldsymbol{\mu}}), \tag{11}$$

with

$$\Sigma_i = \sqrt{\sigma_i^+\sigma_i^- + (\sigma_i^+ - \sigma_i^-)(\mu_i - \hat{\mu}_i)}, \quad i = 1, \ldots, n. \tag{12}$$

Meet Lilith 2

Lilith

Light **Li**kelihood Fi**t** for the **H**iggs

http://lpsc.in2p3.fr/projects-th/

- A public Python tool for applying the Higgs constraints on new physics models' signal strengths or reduced couplings.
- Based on version 1 by Jérémy Bernon and Béranger Dumont (2015)
- Version 2 with :
  1. Update LHC Run 2 data with luminosity $36fb^{-1}$, energy scale 13 TeV.
  2. Take into account signal strengths' asymmetric uncertainties, extended to N-dimension Log-likelihood.
  3. Added new production modes tHq, tHW, ggZH, bbH.

Experimental XML data

```xml
<expmu dim="4" type="vn">
  <experiment>ATLAS</experiment>
  <source type="published">HIGG-2016-21</source>
  <sqrts>13</sqrts>
  <mass>125.09</mass>
  <CL>68%</CL> <!-- optional -->

  <eff axis="d1" prod="ggH" decay="gammagamma">1.0</eff>
  <eff axis="d2" prod="VBF" decay="gammagamma">1.0</eff>
  <eff axis="d3" prod="VH" decay="gammagamma">1.0</eff>
  <eff axis="d4" prod="top" decay="gammagamma">1.0</eff>

  <bestfit>
    <d1>0.80936</d1>
    <d2>2.03724</d2>
    <d3>0.65912</d3>
    <d4>0.54081</d4>
  </bestfit>

  <param>
    <uncertainty axis="d1" side="left">-0.17614</uncertainty>
    <uncertainty axis="d1" side="right">+0.18695</uncertainty>
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    <uncertainty axis="d3" side="right">+0.89033</uncertainty>
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    <uncertainty axis="d4" side="right">+0.64205</uncertainty>

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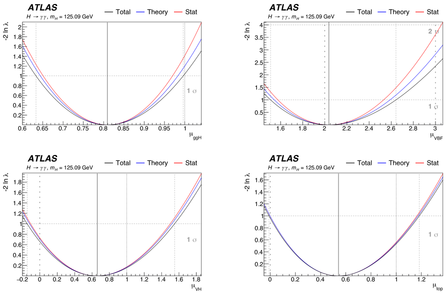

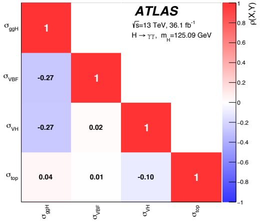

ggH − *VBF* − *VH* − *top*, $H \to \gamma\gamma$ arXiv:1802.04146 [hep-ex].

User XML Input (Signal strengths)


```xml
<?xml version="1.0"?>

<lilithinput>
 <signalstrengths part="h">
    <mass>125</mass>

    <mu prod="ggH" decay="gammagamma">1.0</mu>
    <mu prod="ggH" decay="VV">1.0</mu>
    <mu prod="ggH" decay="bb">1.0</mu>
    <mu prod="ggH" decay="tautau">1.0</mu>
    <mu prod="ggH" decay="mumu">1.0</mu>

    <mu prod="VVH" decay="gammagamma">1.0</mu>
    <mu prod="VVH" decay="VV">1.0</mu>
    <mu prod="VVH" decay="bb">1.0</mu>
    <mu prod="VVH" decay="tautau">1.0</mu>
    <mu prod="VVH" decay="mumu">1.0</mu>

    <mu prod="ttH" decay="gammagamma">1.0</mu>
    <mu prod="ttH" decay="VV">1.0</mu>
    <mu prod="ttH" decay="bb">1.0</mu>
    <mu prod="ttH" decay="tautau">1.0</mu>
    <mu prod="ttH" decay="mumu">1.0</mu>

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    <redxsBR prod="VBF" decay="invisible">0.0</redxsBR>
  </signalstrengths>
</lilithinput>
```

User XML Input (Reduced couplings)

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    <C to="cc">2.0</C>
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    <C to="tautau">1.0</C>
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    <C to="ZZ">1.3</C>

    <C to="gammagamma">1.0</C>
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    <precision>BEST-QCD</precision>

    <extraBR>
      <BR to="invisible">0.0</BR>
      <BR to="undetected">0.0</BR>
    </extraBR>
  </reducedcouplings>
</lilithinput>
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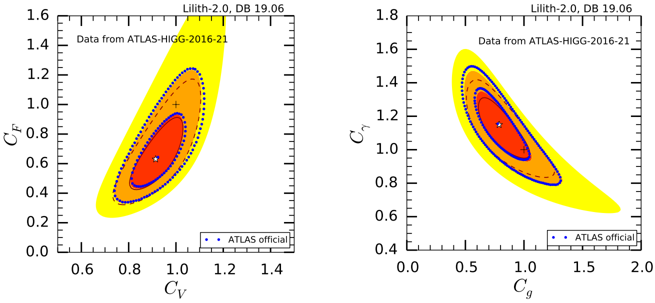
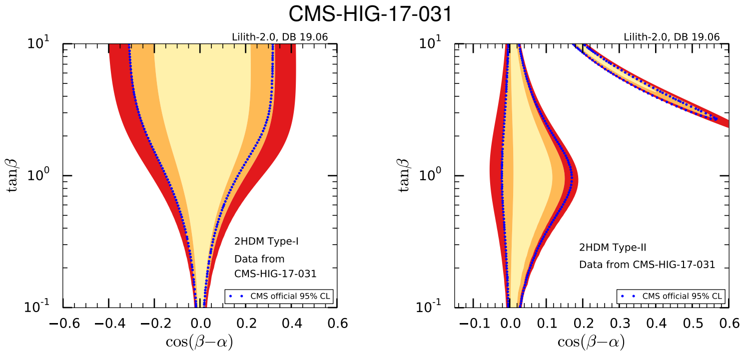
ATLAS Validations for Reduced Couplings

ATLAS-HIGG-2016-21



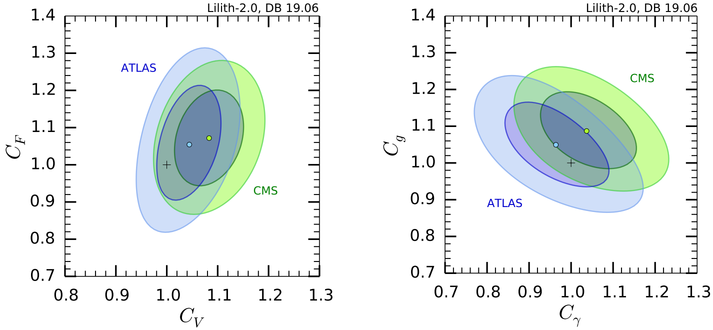
Reduced Couplings Validation
(assumed that $C_F \equiv C_t = C_b = C_\mu$ and $C_V \equiv C_Z = C_W$)

CMS Validations for 2 Higgs Doublet Model (2HDM)



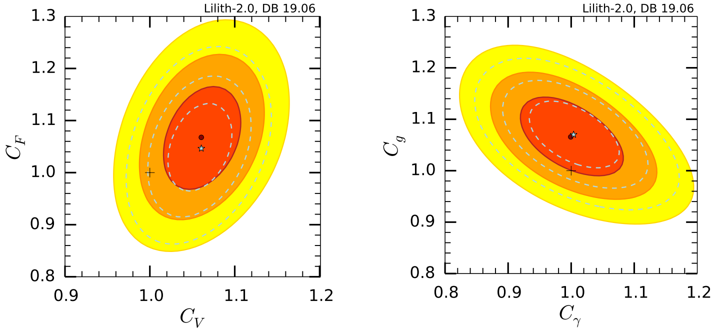
Validations for 2 Higgs Doublet Model (2HDM)

Compare Higgs coupling fits between ATLAS vs CMS dataset



Overlap between ATLAS vs CMS Reduced couplings fits

Higgs coupling fits for Run 2 and Run 2 + Run 1 dataset



	C_F		C_V		C_g		C_γ	
Run 2	1.066		1.062		1.066		0.999	
	+0.066	-0.065	+0.030	-0.030	+0.051	-0.050	+0.055	-0.053
Run 2+1	1.048		1.059		1.070		1.004	
	+0.056	-0.055	+0.025	-0.025	+0.043	-0.043	+0.048	-0.047

Reduced Couplings best fits and uncertainties
from Combined ATLAS-CMS Run 2 (and Run 2 + Run 1) dataset.

Conclusion

- Investigated the Higgs Reduced Couplings scheme.
- Incorporated ATLAS-CMS Run 2 data on Higgs Signal Strengths to constrain Higgs Reduced Couplings.
- Introduced Lilith, a Python tool that constrains new physics models as well as compares and combines ATLAS-CMS, Run 2 & Run 1 results.

Further information about Lilith : http://lpsc.in2p3.fr/projects-th/lilith/

Acknowledgments :

This research is funded by the Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 103.01-2017.78.

Thank you for your attention !

Backup Slides

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  <mass>125</mass>

  <eff prod="ZH">1</eff>

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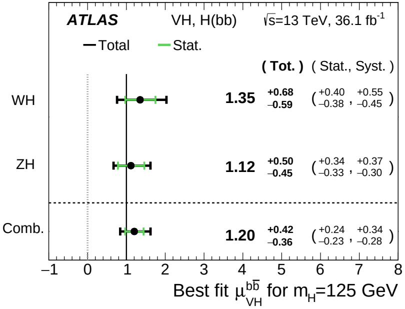

A need for generalized Poisson Log-likelihood

Poisson probability mass function :

$$f(k;\lambda) = \frac{\lambda^k e^{-\lambda}}{k!}. \tag{13}$$

Poisson Log-likelihood function :

$$\log[f(k;\lambda)] = -\lambda + k\log\lambda - \log k!. \tag{14}$$

Issues :

1. Generalize Poisson Log-likelihood to a continuous function of its parameter [arXiv:physics/0406120]
2. Incorporate negative correlation in multi-variable cases. [Statistica Neerlandica (2004) Vol. 58, nr. 3, pp. 349–364]

```xml
<expmu dim="4" type="vn">
  <experiment>ATLAS</experiment>
  <source type="published">HIGG-2016-21</source>
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  <mass>125.09</mass>
  <CL>68%</CL> <!-- optional -->

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  <eff axis="d2" prod="VBF" decay="gammagamma">1.0</eff>
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  <eff axis="d4" prod="top" decay="gammagamma">1.0</eff>

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    <d1>0.80936</d1>
    <d2>2.03724</d2>
    <d3>0.65912</d3>
    <d4>0.54081</d4>
  </bestfit>

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    <uncertainty axis="d4" side="left">-0.55073</uncertainty>
    <uncertainty axis="d4" side="right">+0.64205</uncertainty>

    <correlation entry="d1d2">-0.27</correlation>
    <correlation entry="d1d3">-0.27</correlation>
    <correlation entry="d1d4">0.04</correlation>
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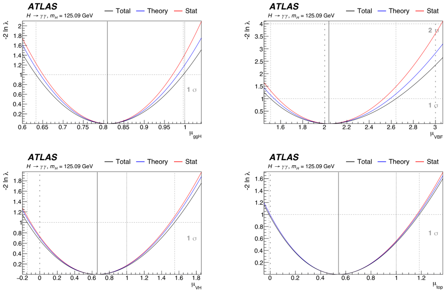


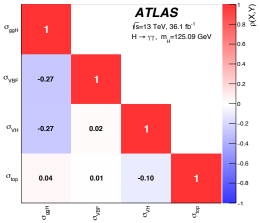
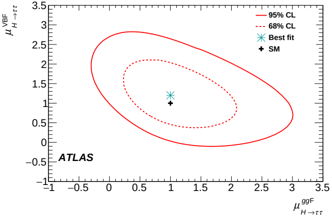
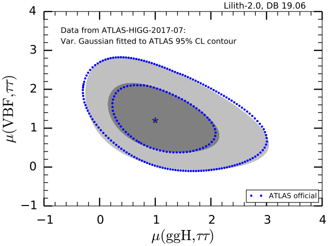


TABLE – Recommended set of experimental results



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  <CL>68%</CL> <!-- optional -->

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</expmu>
```

TABLE – Recommended set of experimental results

$$\log L(\mu_X, \mu_Y) = \log L(\mu_X) + \log L(\mu_Y|\mu_X), \tag{15}$$

where the marginal likelihood for the channel X is given by

$$\log L(\mu_X) = -\nu_X\gamma_X(\mu_X - \hat{\mu}_X) + \nu_X \log\left[1 + \gamma_X\left(\mu_X - \hat{\mu}_X\right)\right], \tag{16}$$

and the conditional likelihood for the channel Y given the channel X

$$\log L(\mu_Y|\mu_X) = f(\mu_X, \mu_Y) - f(\hat{\mu}_X, \hat{\mu}_Y) + \nu_Y \log\frac{f(\mu_X, \mu_Y)}{f(\hat{\mu}_X, \hat{\mu}_Y)}. \tag{17}$$

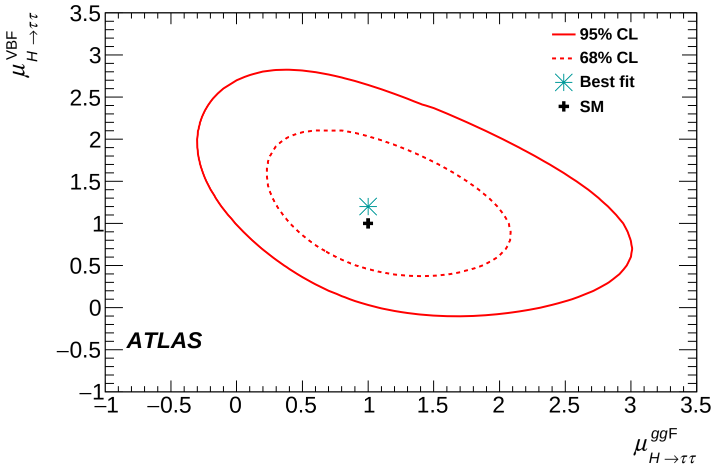
Here the function f reads

$$f(a, b) = -\nu_Y\gamma_Y\left(b - \hat{\mu}_Y + \frac{1}{\gamma_Y}\right)\exp\left[\nu_X\alpha - \left(e^{\alpha} - 1\right)\nu_X\gamma_X(a - \hat{\mu}_X + \frac{1}{\gamma_X})\right], \tag{18}$$

where α is solved numerically from the correlation expression

$$\rho = \frac{\nu_X\nu_Y\left(e^{\alpha} - 1\right)}{\sqrt{\nu_X\nu_Y\left[1 + \nu_Y\left(e^{\nu_X(e^{\alpha}-1)^2} - 1\right)\right]}}, \tag{19}$$

ATLAS HIGG-2017-07



Higgs signal strengths for $ggH - VBF, H \to WW^*$. [HIGG-2017-07]

CMS HIG-17-031

Decay mode	Production process																			
	ggH				VBF				WH				ZH				ttH			
	Best fit value		Uncertainty stat	Uncertainty syst	Best fit value		Uncertainty stat	Uncertainty syst	Best fit value		Uncertainty stat	Uncertainty syst	Best fit value		Uncertainty stat	Uncertainty syst	Best fit value		Uncertainty stat	Uncertainty syst
$H \to bb$	2.51	$^{+2.43}_{-2.01}$	$^{+1.96}_{-1.92}$	$^{+1.44}_{-0.59}$	—				1.73	$^{+0.70}_{-0.68}$	$^{+0.53}_{-0.51}$	$^{+0.46}_{-0.45}$	0.99	$^{+0.47}_{-0.45}$	$^{+0.41}_{-0.40}$	$^{+0.23}_{-0.20}$	0.91	$^{+0.45}_{-0.43}$	$^{+0.24}_{-0.23}$	$^{+0.38}_{-0.36}$
		$\left(^{+2.06}_{-1.86}\right)$	$\left(^{+1.85}_{-1.83}\right)$	$\left(^{+0.89}_{-0.33}\right)$	—					$\left(^{+0.69}_{-0.67}\right)$	$\left(^{+0.52}_{-0.51}\right)$	$\left(^{+0.45}_{-0.44}\right)$		$\left(^{+0.46}_{-0.44}\right)$	$\left(^{+0.40}_{-0.39}\right)$	$\left(^{+0.23}_{-0.20}\right)$		$\left(^{+0.44}_{-0.42}\right)$	$\left(^{+0.23}_{-0.23}\right)$	$\left(^{+0.37}_{-0.35}\right)$
$H \to \tau\tau$	1.05	$^{+0.53}_{-0.47}$	$^{+0.25}_{-0.25}$	$^{+0.46}_{-0.40}$	1.12	$^{+0.45}_{-0.43}$	$^{+0.37}_{-0.35}$	$^{+0.25}_{-0.25}$	—				—				0.23	$^{+1.03}_{-0.88}$	$^{+0.80}_{-0.71}$	$^{+0.65}_{-0.52}$
		$\left(^{+0.45}_{-0.41}\right)$	$\left(^{+0.23}_{-0.23}\right)$	$\left(^{+0.38}_{-0.34}\right)$		$\left(^{+0.45}_{-0.43}\right)$	$\left(^{+0.37}_{-0.35}\right)$	$\left(^{+0.25}_{-0.24}\right)$	—				—					$\left(^{+0.98}_{-0.87}\right)$	$\left(^{+0.80}_{-0.73}\right)$	$\left(^{+0.56}_{-0.47}\right)$
$H \to WW$	1.35	$^{+0.21}_{-0.19}$	$^{+0.12}_{-0.12}$	$^{+0.17}_{-0.15}$	0.28	$^{+0.64}_{-0.60}$	$^{+0.58}_{-0.53}$	$^{+0.28}_{-0.28}$	3.91	$^{+2.26}_{-2.01}$	$^{+1.89}_{-1.72}$	$^{+1.24}_{-1.05}$	0.96	$^{+1.81}_{-1.46}$	$^{+1.74}_{-1.44}$	$^{+0.50}_{-0.22}$	1.60	$^{+0.65}_{-0.59}$	$^{+0.40}_{-0.39}$	$^{+0.52}_{-0.45}$
		$\left(^{+0.17}_{-0.16}\right)$	$\left(^{+0.10}_{-0.10}\right)$	$\left(^{+0.13}_{-0.12}\right)$		$\left(^{+0.62}_{-0.58}\right)$	$\left(^{+0.57}_{-0.53}\right)$	$\left(^{+0.26}_{-0.25}\right)$		$\left(^{+1.47}_{-1.19}\right)$	$\left(^{+1.32}_{-1.06}\right)$	$\left(^{+0.64}_{-0.54}\right)$		$\left(^{+1.67}_{-1.37}\right)$	$\left(^{+1.61}_{-1.35}\right)$	$\left(^{+0.45}_{-0.20}\right)$		$\left(^{+0.56}_{-0.53}\right)$	$\left(^{+0.38}_{-0.38}\right)$	$\left(^{+0.41}_{-0.37}\right)$
$H \to ZZ$	1.22	$^{+0.23}_{-0.21}$	$^{+0.20}_{-0.19}$	$^{+0.12}_{-0.10}$	−0.09	$^{+1.02}_{-0.76}$	$^{+1.00}_{-0.72}$	$^{+0.21}_{-0.22}$	0.00	$^{+2.33}_{+0.00}$	$^{+2.31}_{-0.00}$	$^{+0.30}_{-0.00}$	0.00	$^{+4.26}_{+0.00}$	$^{+4.19}_{-0.00}$	$^{+0.80}_{-0.00}$	0.00	$^{+1.50}_{+0.00}$	$^{+1.47}_{-0.00}$	$^{+0.30}_{-0.00}$
		$\left(^{+0.22}_{-0.20}\right)$	$\left(^{+0.20}_{-0.19}\right)$	$\left(^{+0.10}_{-0.07}\right)$		$\left(^{+1.27}_{-0.99}\right)$	$\left(^{+1.25}_{-0.97}\right)$	$\left(^{+0.23}_{-0.21}\right)$		$\left(^{+4.46}_{-0.99}\right)$	$\left(^{+4.42}_{-0.99}\right)$	$\left(^{+0.57}_{-0.00}\right)$		$\left(^{+7.57}_{-1.00}\right)$	$\left(^{+7.45}_{-1.00}\right)$	$\left(^{+1.33}_{-0.00}\right)$		$\left(^{+2.95}_{-0.99}\right)$	$\left(^{+2.89}_{-0.99}\right)$	$\left(^{+0.59}_{-0.00}\right)$
$H \to \gamma\gamma$	1.16	$^{+0.21}_{-0.18}$	$^{+0.17}_{-0.15}$	$^{+0.13}_{-0.10}$	0.67	$^{+0.59}_{-0.46}$	$^{+0.49}_{-0.42}$	$^{+0.32}_{-0.18}$	3.76	$^{+1.48}_{-1.35}$	$^{+1.45}_{-1.33}$	$^{+0.33}_{-0.24}$	0.00	$^{+1.14}_{+0.00}$	$^{+1.14}_{-0.00}$	$^{+0.09}_{-0.00}$	2.18	$^{+0.88}_{-0.75}$	$^{+0.82}_{-0.74}$	$^{+0.32}_{-0.14}$
		$\left(^{+0.17}_{-0.16}\right)$	$\left(^{+0.14}_{-0.14}\right)$	$\left(^{+0.11}_{-0.08}\right)$		$\left(^{+0.59}_{-0.48}\right)$	$\left(^{+0.48}_{-0.43}\right)$	$\left(^{+0.34}_{-0.21}\right)$		$\left(^{+1.28}_{-1.16}\right)$	$\left(^{+1.27}_{-1.16}\right)$	$\left(^{+0.13}_{-0.06}\right)$		$\left(^{+2.51}_{-1.04}\right)$	$\left(^{+2.50}_{-1.04}\right)$	$\left(^{+0.25}_{-0.00}\right)$		$\left(^{+0.74}_{-0.63}\right)$	$\left(^{+0.72}_{-0.63}\right)$	$\left(^{+0.16}_{-0.06}\right)$
$H \to \mu\mu$	0.31	$^{+1.80}_{-1.79}$	$^{+1.79}_{-1.78}$	$^{+0.19}_{-0.19}$	2.72	$^{+7.12}_{-7.03}$	$^{+7.12}_{-7.04}$	$^{+0.26}_{-0.00}$	—				—				—			
		$\left(^{+1.69}_{-1.65}\right)$	$\left(^{+1.67}_{-1.67}\right)$	$\left(^{+0.28}_{-0.00}\right)$		$\left(^{+7.02}_{-6.94}\right)$	$\left(^{+7.01}_{-6.93}\right)$	$\left(^{+0.38}_{-0.50}\right)$	—				—				—			

Combined results for Higgs signal strengths [HIG-17-031].

CMS HIG-17-031

CMS *Supplementary* $35.9\ \mathrm{fb}^{-1}$ (13 TeV)

Rows and columns: μ_i^f; colour scale: ρ (from –1 to 1)

μ_i^f	ggH γγ	ggH ZZ	ggH WW	ggH ττ	ggH bb	ggH μμ	VBF γγ	VBF ZZ	VBF WW	VBF ττ	VBF μμ	WH γγ	WH ZZ	WH WW	WH bb	ZH γγ	ZH ZZ	ZH WW	ZH bb	ttH γγ	ttH ZZ	ttH WW	ttH bb	ttH ττ
ggH γγ	1.00	0.12	0.16	0.08	0.00	0.00	-0.28	0.00	0.00	0.00	0.00	-0.15	0.00	0.00	0.00	-0.08	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
ggH ZZ	0.12	1.00	0.14	0.04	0.00	0.00	0.00	-0.41	0.00	0.00	0.00	0.00	-0.09	0.00	0.00	0.00	-0.20	0.00	0.00	0.00	0.00	0.02	0.00	0.00
ggH WW	0.16	0.14	1.00	0.05	0.00	0.00	0.00	0.00	-0.21	0.02	0.00	0.00	0.00	-0.11	0.00	0.00	0.00	-0.02	0.02	0.00	0.00	0.00	0.00	0.00
ggH ττ	0.08	0.04	0.05	1.00	0.00	0.00	0.06	0.05	0.03	-0.32	0.00	0.05	0.00	0.02	0.00	0.00	0.00	0.00	0.02	0.02	-0.02	0.00	0.00	0.00
ggH bb	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.02	-0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ggH μμ	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	-0.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
VBF γγ	-0.28	0.00	0.00	0.06	0.00	0.00	1.00	0.03	0.02	0.00	0.00	0.03	0.00	0.00	0.00	0.02	0.00	0.00	0.00	-0.02	0.00	0.00	0.00	0.00
VBF ZZ	0.00	-0.41	0.00	0.05	0.00	0.00	0.03	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.02	0.00	0.00	0.00
VBF WW	0.00	0.00	-0.21	0.03	0.00	0.00	0.02	0.00	1.00	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
VBF ττ	0.00	0.00	0.02	-0.32	0.00	0.00	0.00	0.00	-0.03	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.02	0.00	0.00	0.00
VBF μμ	0.00	0.00	0.00	0.00	0.00	-0.54	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WH γγ	-0.15	0.00	0.00	0.05	0.00	0.00	0.03	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	-0.20	0.00	0.00	0.00	-0.08	0.00	0.00	0.00	0.00
WH ZZ	0.00	-0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	-0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WH WW	0.00	0.00	-0.11	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	-0.05	0.00	0.00	0.00	0.00	0.00	0.00
WH bb	0.00	0.00	0.00	0.00	-0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	-0.03	0.00	0.00	0.00	0.00	0.00
ZH γγ	-0.08	0.00	0.00	0.00	-0.02	0.00	0.02	0.00	0.00	0.00	0.00	-0.20	0.00	0.00	0.00	1.00	0.00	0.00	0.00	-0.03	0.00	0.00	0.00	0.00
ZH ZZ	0.00	-0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	-0.30	0.00	0.00	0.00	1.00	0.00	0.00	0.00	-0.02	0.00	0.00	0.00
ZH WW	0.00	0.00	-0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.05	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
ZH bb	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.03	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
ttH γγ	0.02	0.00	0.00	0.02	0.00	0.00	-0.02	0.00	0.00	0.00	0.00	-0.08	0.00	0.00	0.00	-0.03	0.00	0.00	0.00	1.00	0.00	0.05	0.04	0.00
ttH ZZ	0.00	0.00	0.00	-0.02	0.00	0.00	0.00	-0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	-0.02	0.00	0.00	0.00	1.00	-0.08	0.00	-0.04
ttH WW	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	-0.08	1.00	0.03	-0.42
ttH bb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.03	1.00	0.00
ttH ττ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.04	-0.42	0.00	1.00

Sources of uncertainties

Source of uncertainties [CMS-NOTE-2011-005 ; ATL-PHYS-PUB-2011-11] :

- Experimental uncertainties :
  Reconstruction of the same final state, luminosity uncertainty
- Theoretical uncertainties :
  PDF, QCD scale, . . .

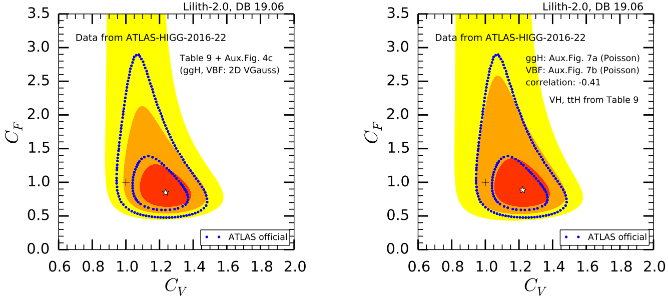
Causes of asymmetric uncertainties [arXiv:physics/0406120] :

- Nonlinear dependency of μ on some nuisance parameters (systematic rather than statistical).
- Extraction of results due to limitation in number of events recorded.

$\Rightarrow$ Need for a multi-variable continuous asymmetric distribution.

ATLAS Validations

ATLAS-HIGG-2016-22



Constraints in the 2HDM

Using the Run 2 (Run 2 + Run 1) results of DB 19.06, assuming that no contribution from new particles, as well as invisible or undetected decays, we find

$$C_F = 1.066^{+0.066}_{-0.065}\ (1.048^{+0.056}_{-0.055}), \quad C_V = 1.062 \pm 0.030\ (1.059 \pm 0.025) \tag{20}$$

with a correlation of 0.31.

$$C_g = 1.066^{+0.051}_{-0.050}\ (1.070^{+0.043}_{-0.043}), \quad C_\gamma = 0.999^{+0.055}_{-0.053}\ (1.004^{+0.048}_{-0.047}) \tag{21}$$

with correlation -0.52 (-0.51) from Run 2 (combining Run 2 and Run 1) results.