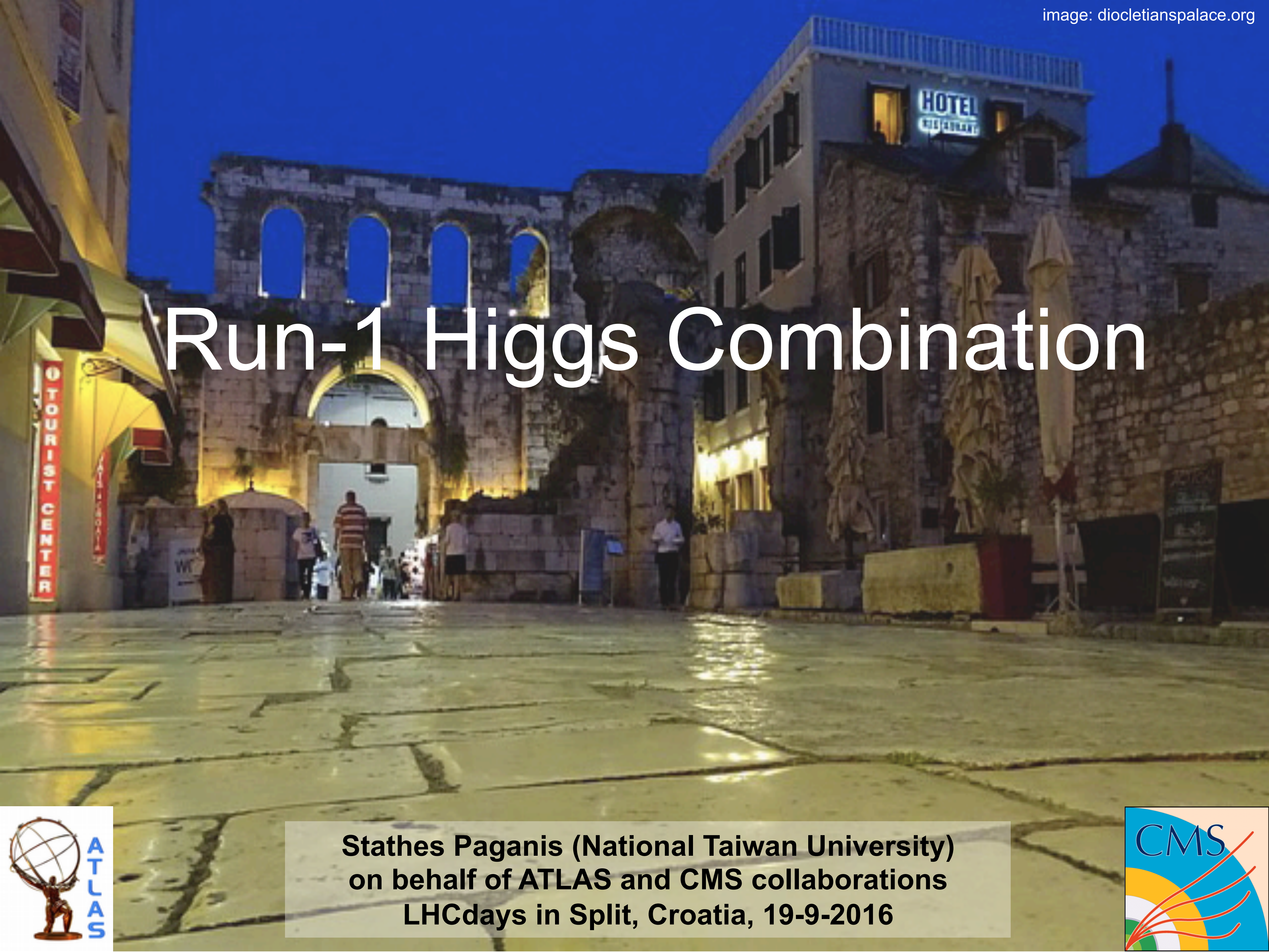


image: diocletianspalace.org

Run-1 Higgs Combination

Stathes Paganis (National Taiwan University)
on behalf of ATLAS and CMS collaborations
LHCdays in Split, Croatia, 19-9-2016

Outline

- Introduction / Assumptions
- Cross sections and Branching Ratios
- Signal Strengths
- Couplings
- Summary

Goals and assumptions

- ATLAS-CMS measurements [1,2] try to answer certain questions:
  - Is the 125 GeV Higgs-like particle the SM Higgs boson?
  - Are all the Higgs boson properties (couplings, decay rates, etc) compatible with the SM predictions?
  - Is there any new physics? For instance, in the loop-induced Higgs-gluon, Higgs-photon processes.
- Run 1 luminosity: ~5 fb^{-1} at $\sqrt{s}$ = 7 TeV , ~20 fb^{-1} at $\sqrt{s}$ = 8 TeV.

<u>Assumptions:</u>

- Higgs mass fixed at the measured value (125.09 GeV) from ATLAS-CMS combination [3]. Small impact of mass uncertainty (±0.24 GeV) to the coupling measurements.
- Higgs width below ~2 GeV (SM prediction ~0.004 GeV).
- Only signal normalizations allowed to vary. Kinematics assumed to be close to SM predictions.

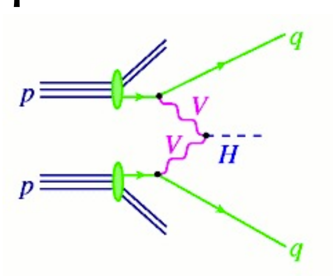
[1] CMS-PAS-HIG-15-002 / ATLAS-CONF-2015-044
[2] JHEP 08 (2016) 045
[3] PRL 114 (2015) 191803

Higgs Production Channels

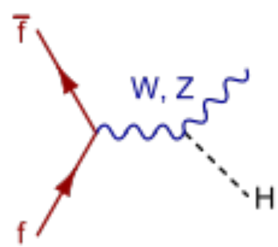
Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD) + NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW) + APPROX. NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD) + NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD) + NLO(EW)
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

Main Higgs production mechanisms depend on V-H or fermion-H couplings

V-H couplings

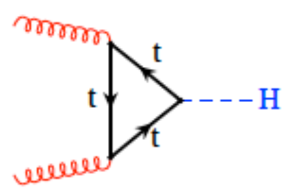


VBF

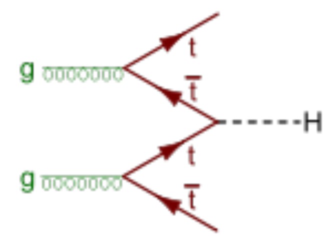


VH

top-H couplings



ggF



ttH

Higgs Decay Channels

Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

H→gg, cc, Zγ not included in the measurement but their contribution is included in the total width.

Strengths/Couplings

Signal Strengths

for a specific process $i \to H \to f$

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}} \quad \text{and} \quad \mu^f = \frac{B^f}{(B^f)_{SM}}$$

$$\mu_i^f = \mu_i \cdot \mu^f$$

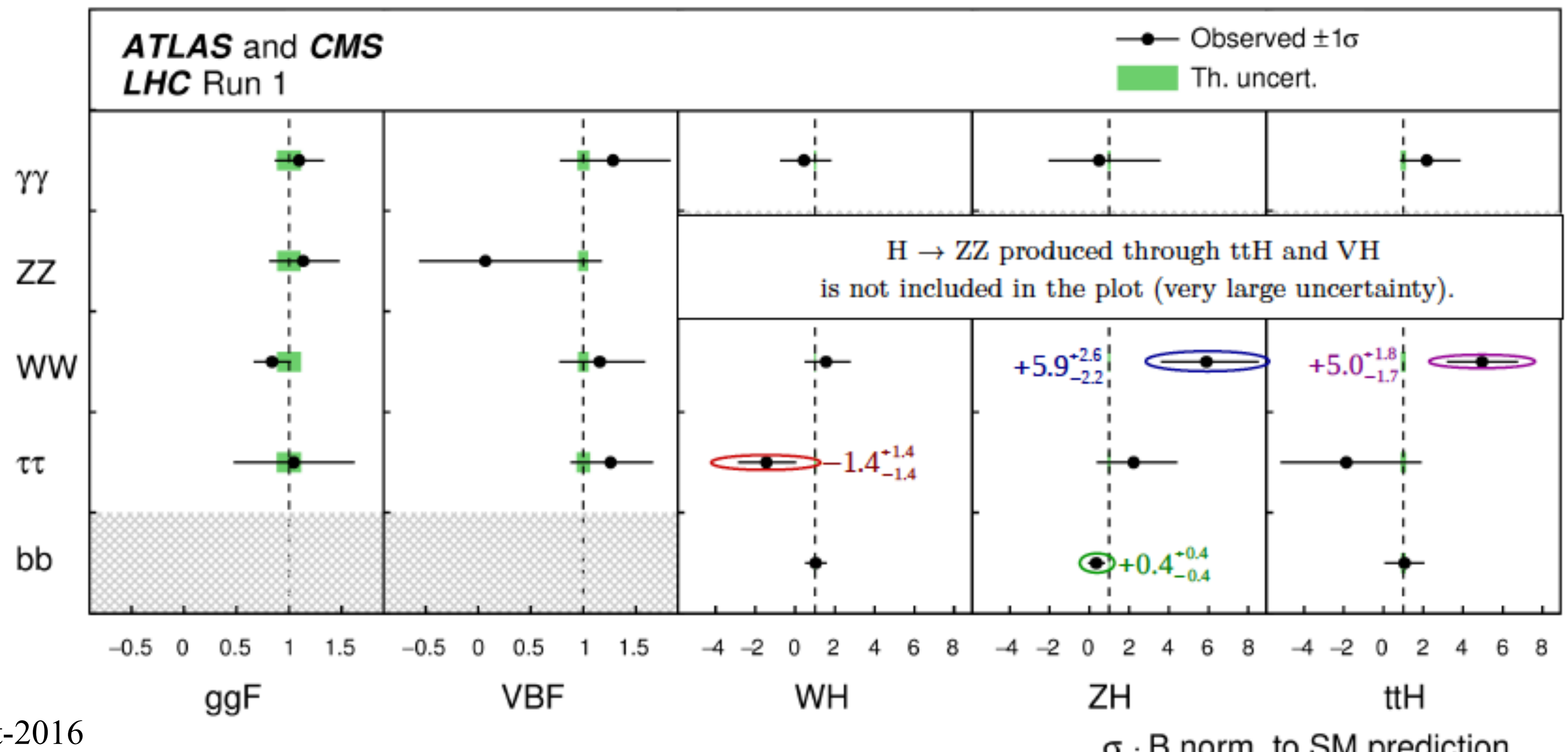
Coupling Modifiers

$$\kappa_j^2 = \sigma_j / \sigma_j^{SM} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma^j_{SM}$$

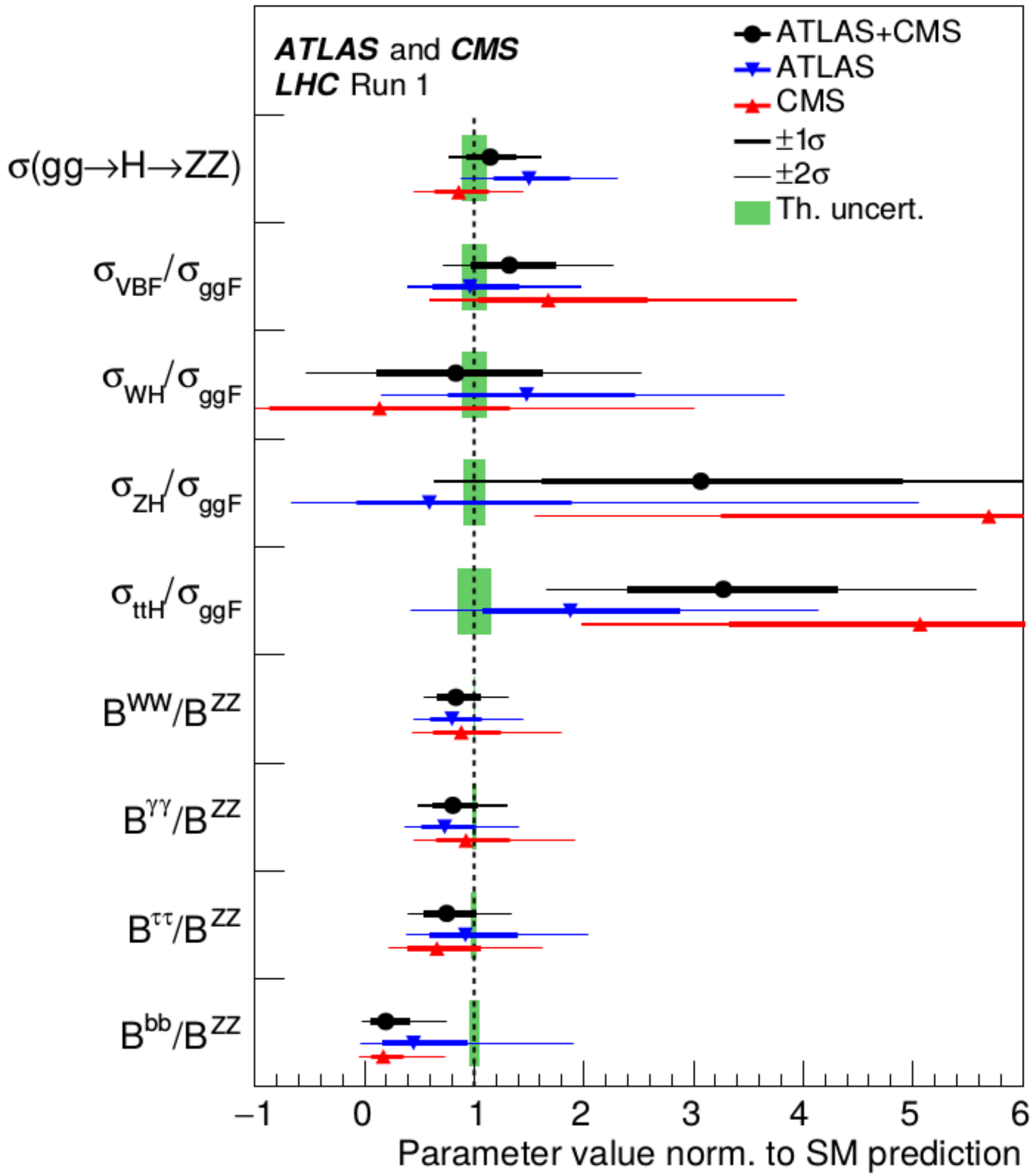
Production × BR fit

σ×BR fit: 25-2 parameters

Production process	Decay channel				
	$H \to \gamma\gamma$	$H \to ZZ$	$H \to WW$	$H \to \tau\tau$	$H \to bb$
ggF	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{gg\mathrm{F}}$	$(\sigma \cdot \mathrm{B})^{ZZ}_{gg\mathrm{F}}$	$(\sigma \cdot \mathrm{B})^{WW}_{gg\mathrm{F}}$	$(\sigma \cdot \mathrm{B})^{\tau\tau}_{gg\mathrm{F}}$	–
VBF	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{\mathrm{VBF}}$	$(\sigma \cdot \mathrm{B})^{ZZ}_{\mathrm{VBF}}$	$(\sigma \cdot \mathrm{B})^{WW}_{\mathrm{VBF}}$	$(\sigma \cdot \mathrm{B})^{\tau\tau}_{\mathrm{VBF}}$	–
WH	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{WH}$	$(\sigma \cdot \mathrm{B})^{ZZ}_{WH}$	$(\sigma \cdot \mathrm{B})^{WW}_{WH}$	$(\sigma \cdot \mathrm{B})^{\tau\tau}_{WH}$	$(\sigma \cdot \mathrm{B})^{bb}_{WH}$
ZH	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{ZH}$	$(\sigma \cdot \mathrm{B})^{ZZ}_{ZH}$	$(\sigma \cdot \mathrm{B})^{WW}_{ZH}$	$(\sigma \cdot \mathrm{B})^{\tau\tau}_{ZH}$	$(\sigma \cdot \mathrm{B})^{bb}_{ZH}$
ttH	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{ttH}$	$(\sigma \cdot \mathrm{B})^{ZZ}_{ttH}$	$(\sigma \cdot \mathrm{B})^{WW}_{ttH}$	$(\sigma \cdot \mathrm{B})^{\tau\tau}_{ttH}$	$(\sigma \cdot \mathrm{B})^{bb}_{ttH}$



Higgs production and decay



- Assuming a single Higgs boson, σ_i and B^f can be fitted with respect to a reference gg→H→ZZ:

$$\sigma_i \cdot B^f = \sigma(gg \to H \to ZZ)\left(\frac{\sigma_i}{\sigma_{ggF}}\right)\left(\frac{B^f}{B^{ZZ}}\right)$$

- Results compatible with SM (p-value 16%) with outliers (>2σ):

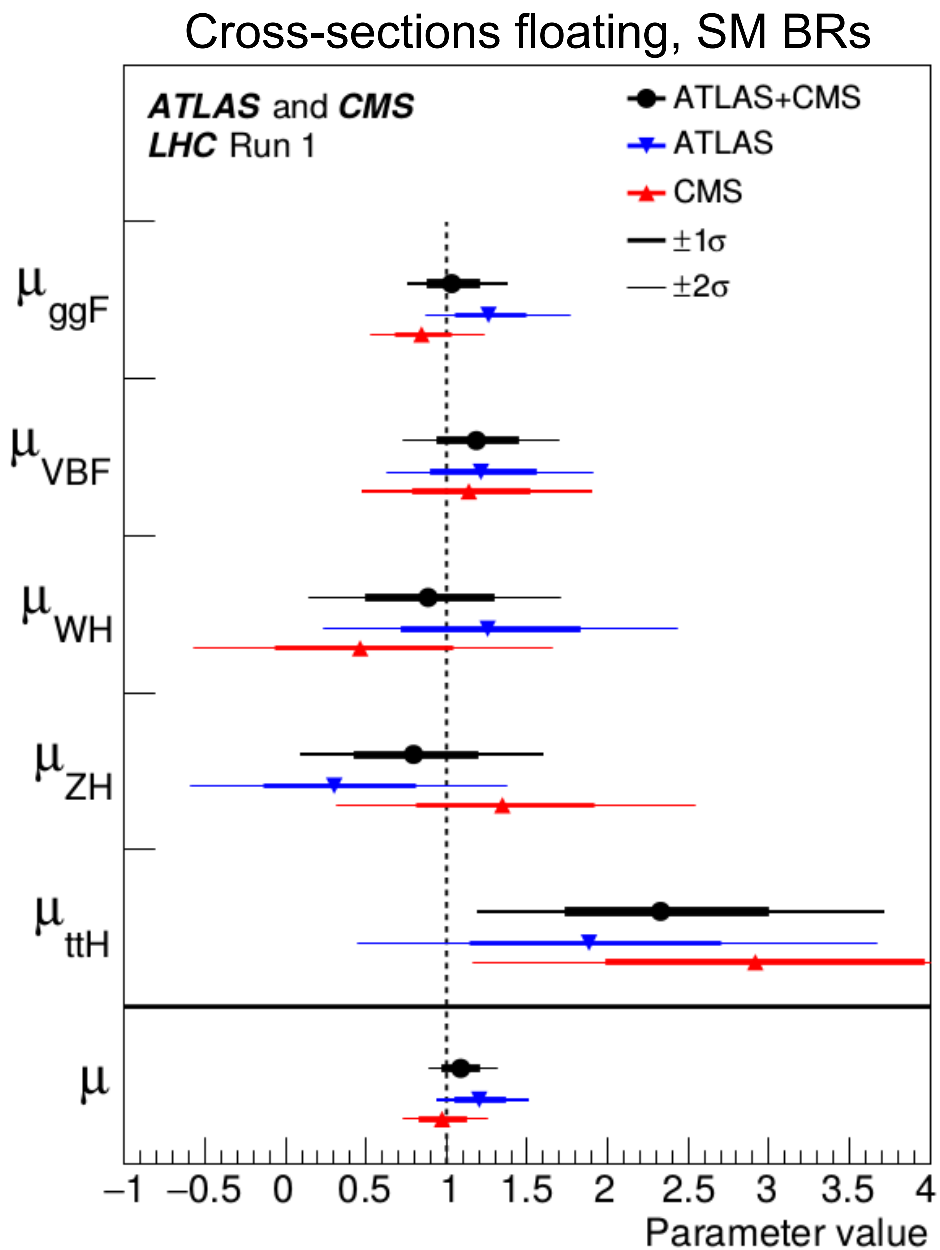
$$\sigma_{ttH}/\sigma_{ggF} = 3.3^{+1.0}_{-0.9}$$

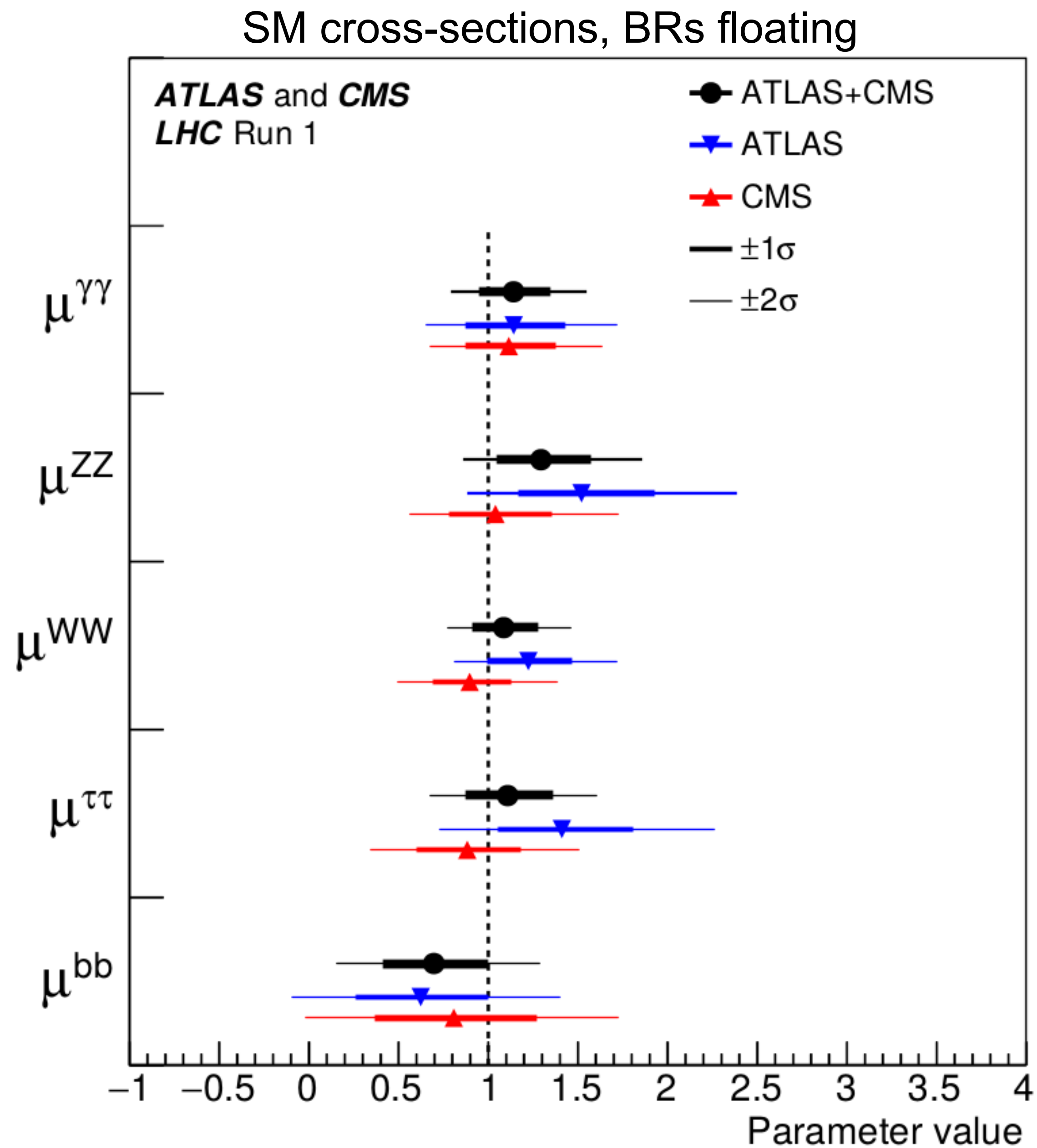
$$B^{bb}/B^{ZZ} = 0.2^{+0.2}_{-0.1}$$

(Normalized to SM predictions)

Signal Strength

Higgs signal strengths





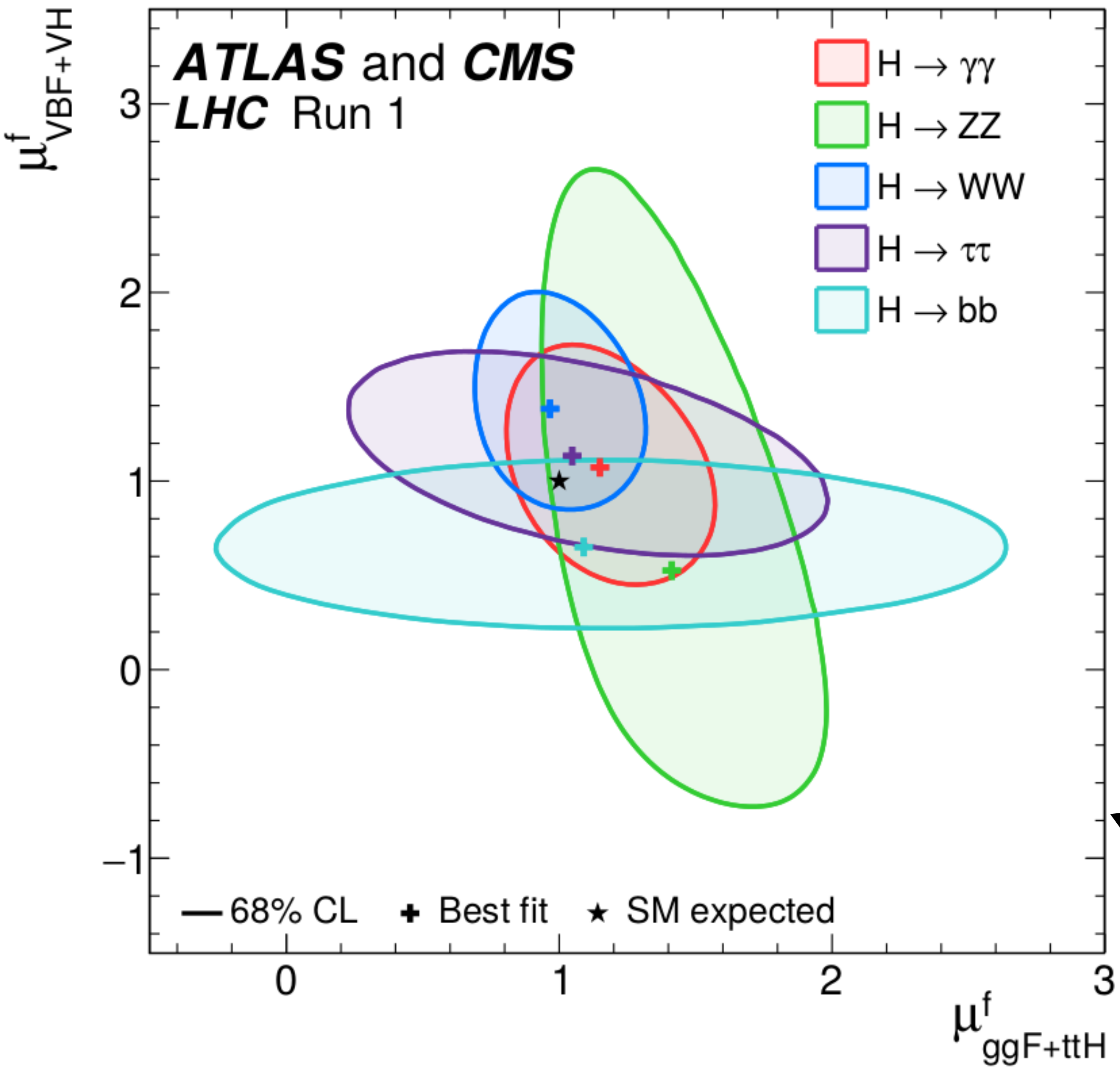
$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

VBF production and H→ττ channel

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

- Combination of ATLAS and CMS measurements leads to a higher than 5 sigma observation of the VBF production process and the H→ττ decay channel.

Production Asymmetry



- Deviation from the SM in the boson vs fermion mediated production is searched by fitting the signal strengths using the VBF+VH/ggF+ttH ratio with the 5 Branching Ratios floating.

$$\frac{\mu^{f}_{\mathrm{VBF+VH}}}{\mu^{f}_{\mathrm{ggF+ttH}}} = 1.09^{+0.36}_{-0.28}$$

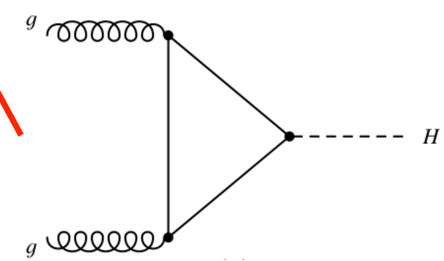
- We also allow for different ratio per decay channel (10 parameter fit). The result is still compatible with SM.

Higgs Couplings

Higgs couplings

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z\kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t\kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t\kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{BSM} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

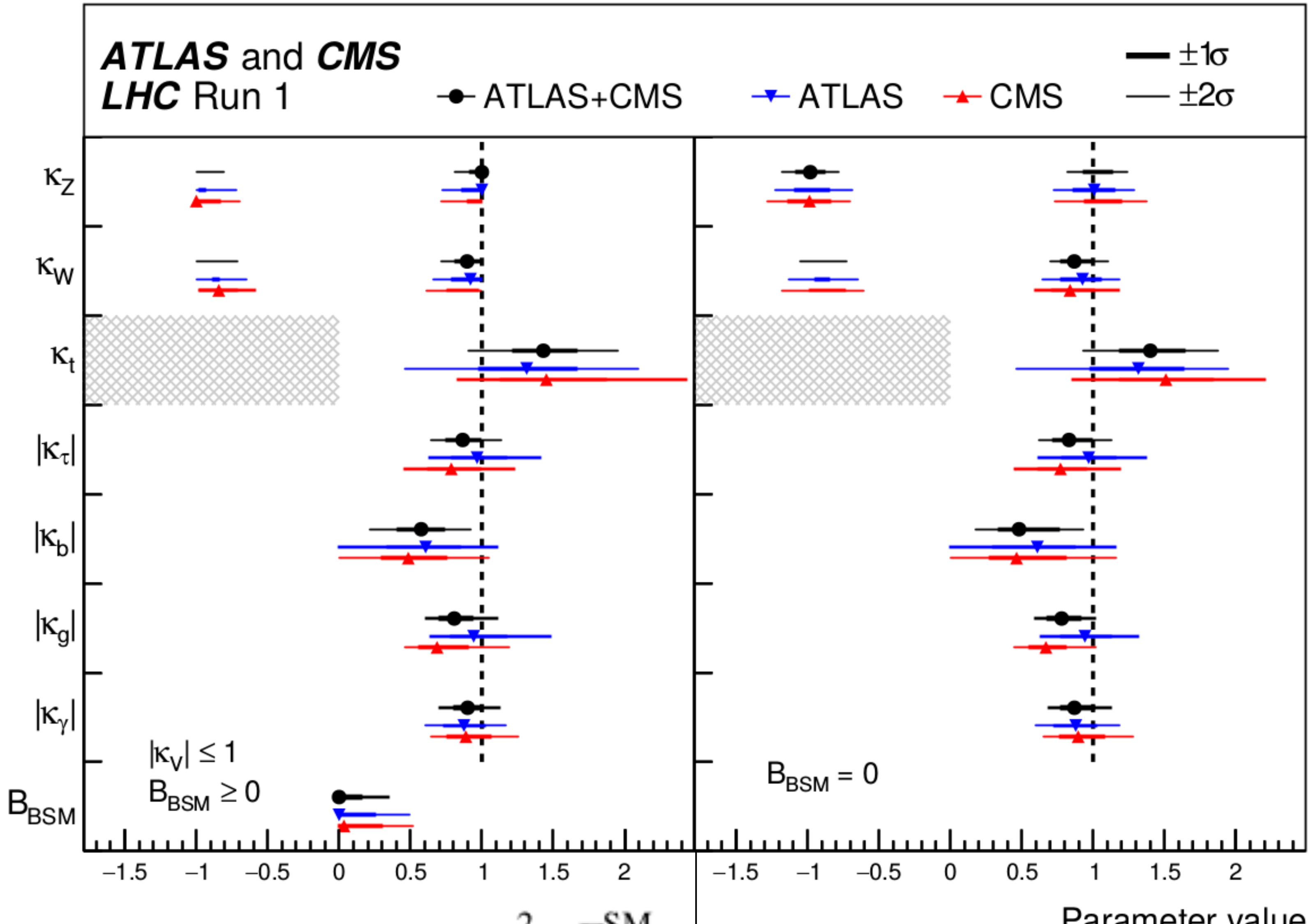
- The σ_i and B^f have been resolved in terms of the k_i Higgs coupling modifiers.



$= k_g^2$

- For gluon-Higgs and Higgs-photon loops, effective coupling modifiers k_g, k_γ are used to search for new physics present in these loops.

Couplings for BSM physics contributing to the Higgs width

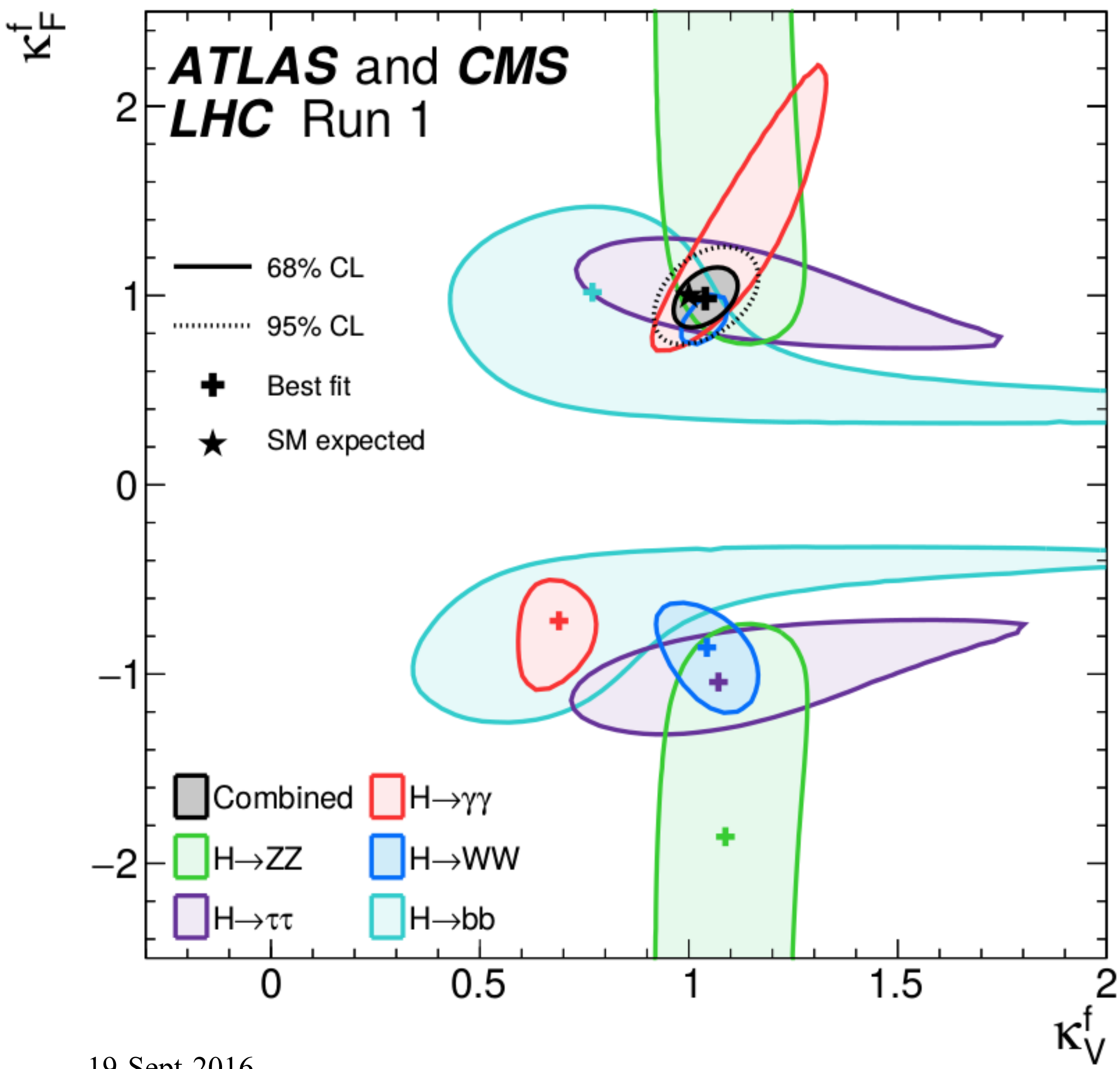


Allow Higgs to have BSM decays → increase of the total width.

$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - B_{BSM}}$$

No BSM Higgs decays.
(BSM can still enter in couplings)

Fermion vs Vector-Boson couplings



Fit two couplings.
A Fermion coupling:

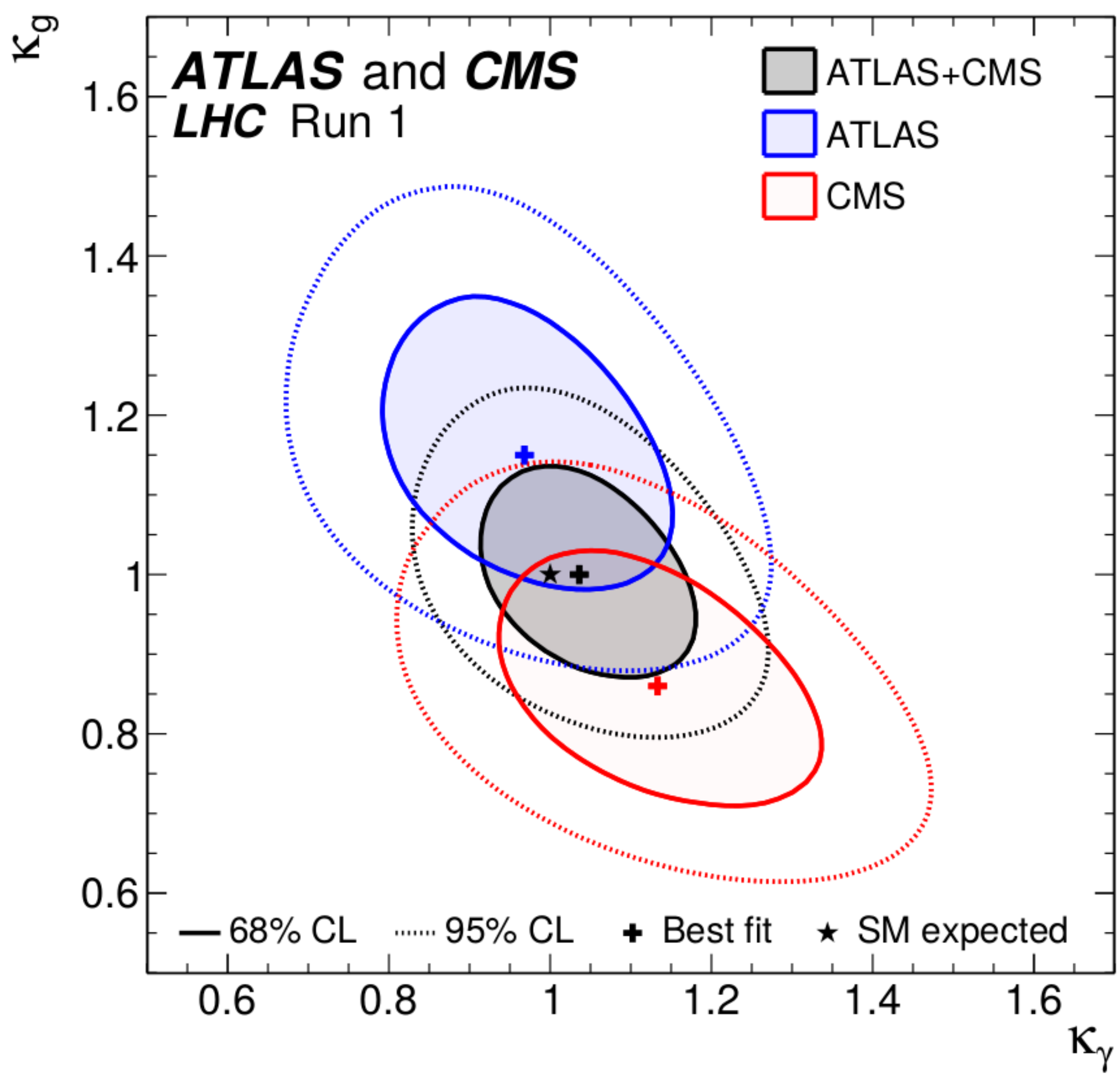
$$k_F = k_t = k_b = k_\tau = k_\mu$$

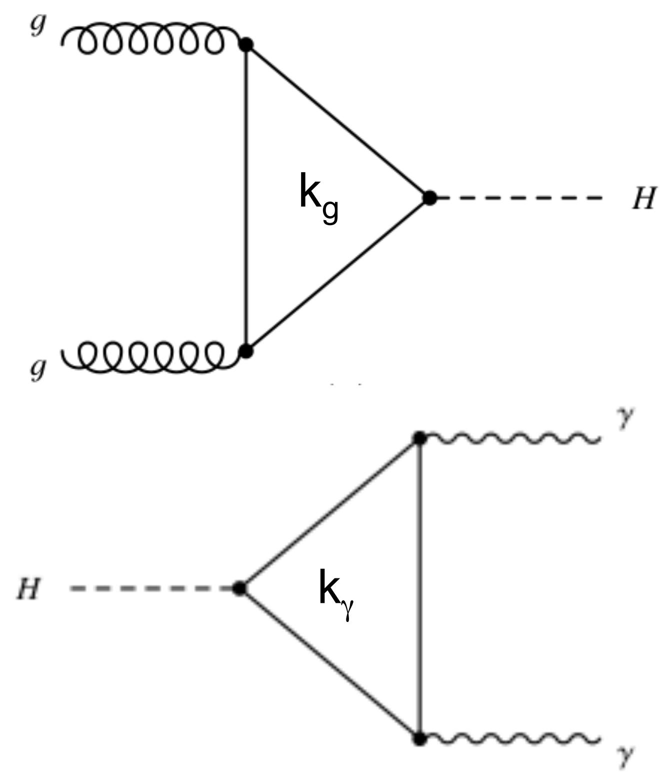
and a Vector-Boson coupling:

$$k_V = k_W = k_Z$$

Results for all decays and combined compatible with the SM (p-value 64%).

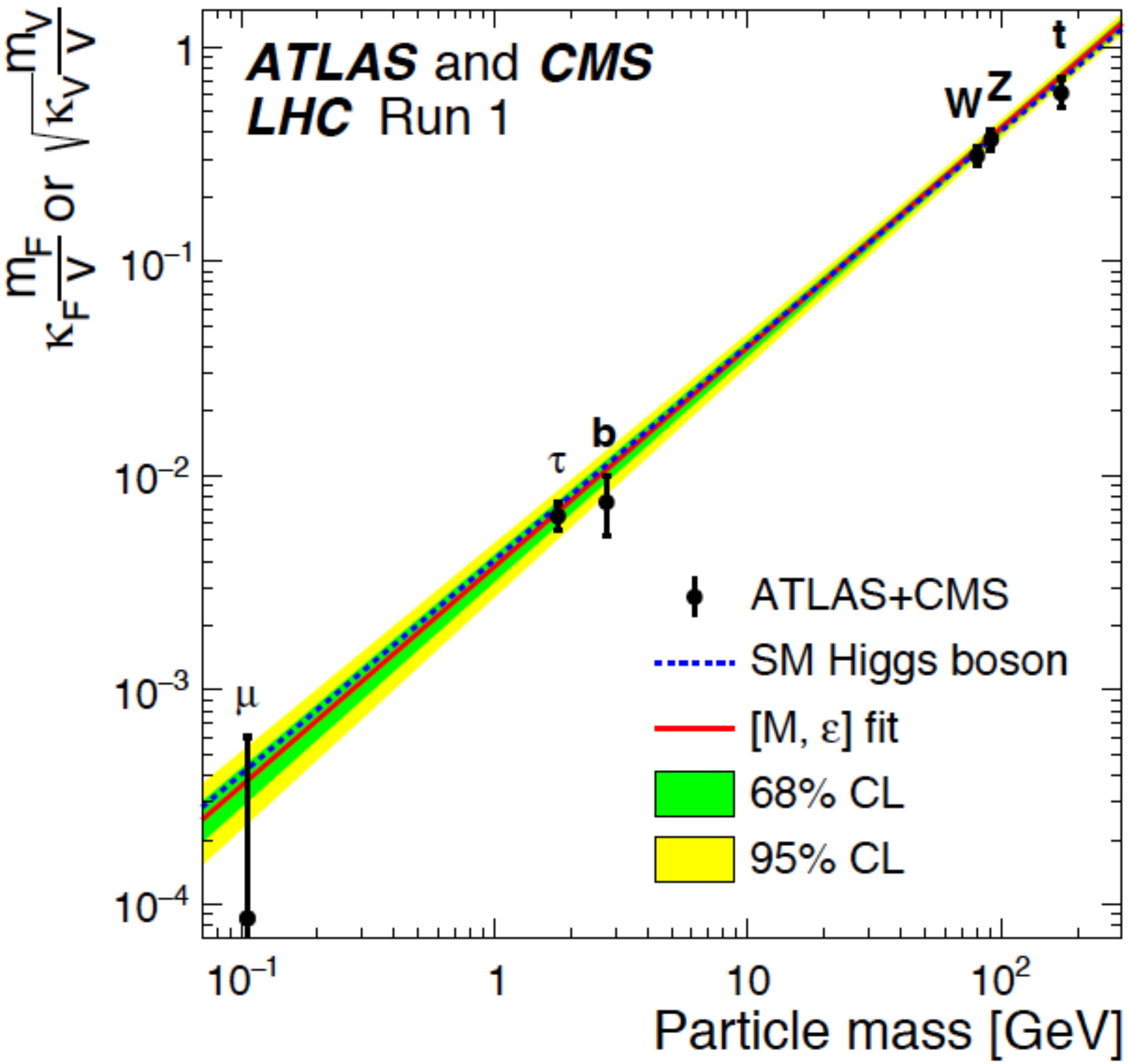
BSM physics in loops: k_g, k_γ





- Fit effective couplings with all other parameters fixed to their SM values.
- k_g, k_γ compatible with SM.

Vector and fermion couplings vs mass



1. Fit the 1/v dependence of couplings to mass

$$\lambda_F = k_F \frac{m_F}{\upsilon}, \quad \lambda_V = \sqrt{k_V}\frac{m_V}{\upsilon}$$

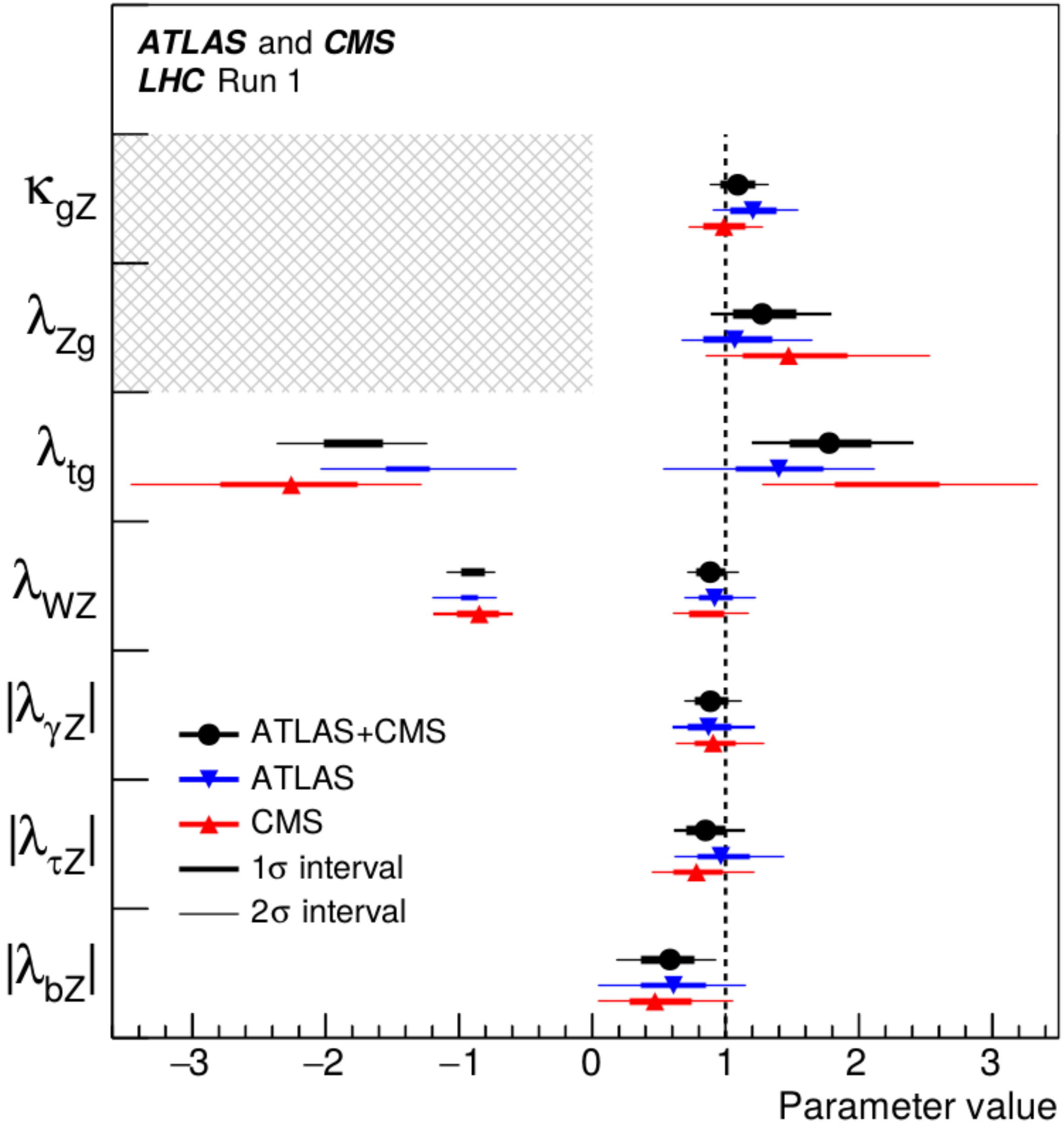
2. Fit data using two degrees of freedom ε and M [1]

$$\kappa_{F,i} = \upsilon \cdot m_{F,i}^{\epsilon}/M^{1+\epsilon}$$
$$\kappa_{V,i} = \upsilon \cdot m_{V,i}^{2\epsilon}/M^{1+2\epsilon}.$$

Couplings scale with the masses as SM predicts.

[1] JHEP **06** (2013) 103

Coupling ratios (norm to gg→H→ZZ)



Coupling modifier ratio parameterisation
$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$
$\lambda_{Zg} = \kappa_Z / \kappa_g$
$\lambda_{tg} = \kappa_t / \kappa_g$
$\lambda_{WZ} = \kappa_W / \kappa_Z$
$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$
$\lambda_{\tau Z} = \kappa_\tau / \kappa_Z$
$\lambda_{bZ} = \kappa_b / \kappa_Z$

- 13% compatibility with SM
- Outliers (>2σ):

$$\lambda_{tg} = 1.78^{+0.30}_{-0.27}$$

$$\left|\lambda_{bZ}\right| = 0.58^{+0.16}_{-0.20}$$

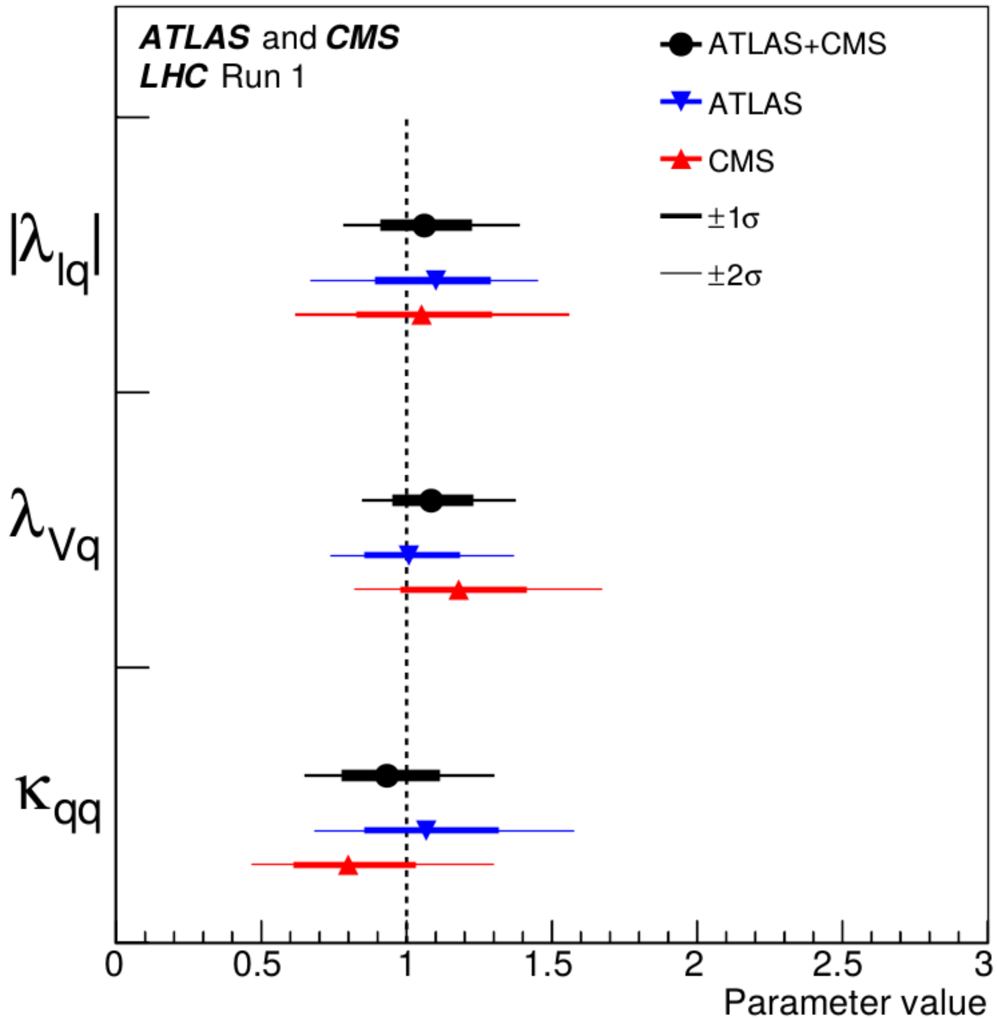
Summary

- A combination of ATLAS and CMS Run-1 (7/8TeV) measurements of Higgs boson production and decay rates has been presented.
- No deviations from the SM have been observed.
- Higgs couplings were measured using different models and found to be compatible with the SM.
- The global Higgs signal strength measured is: 1.09±0.1
- The VBF production and $H \rightarrow \tau\tau$ decay processes were observed with a combined significance of 5.5σ and 5.4σ respectively.
- Run-2 is in progress, with ~30 fb^{-1} already delivered by LHC.

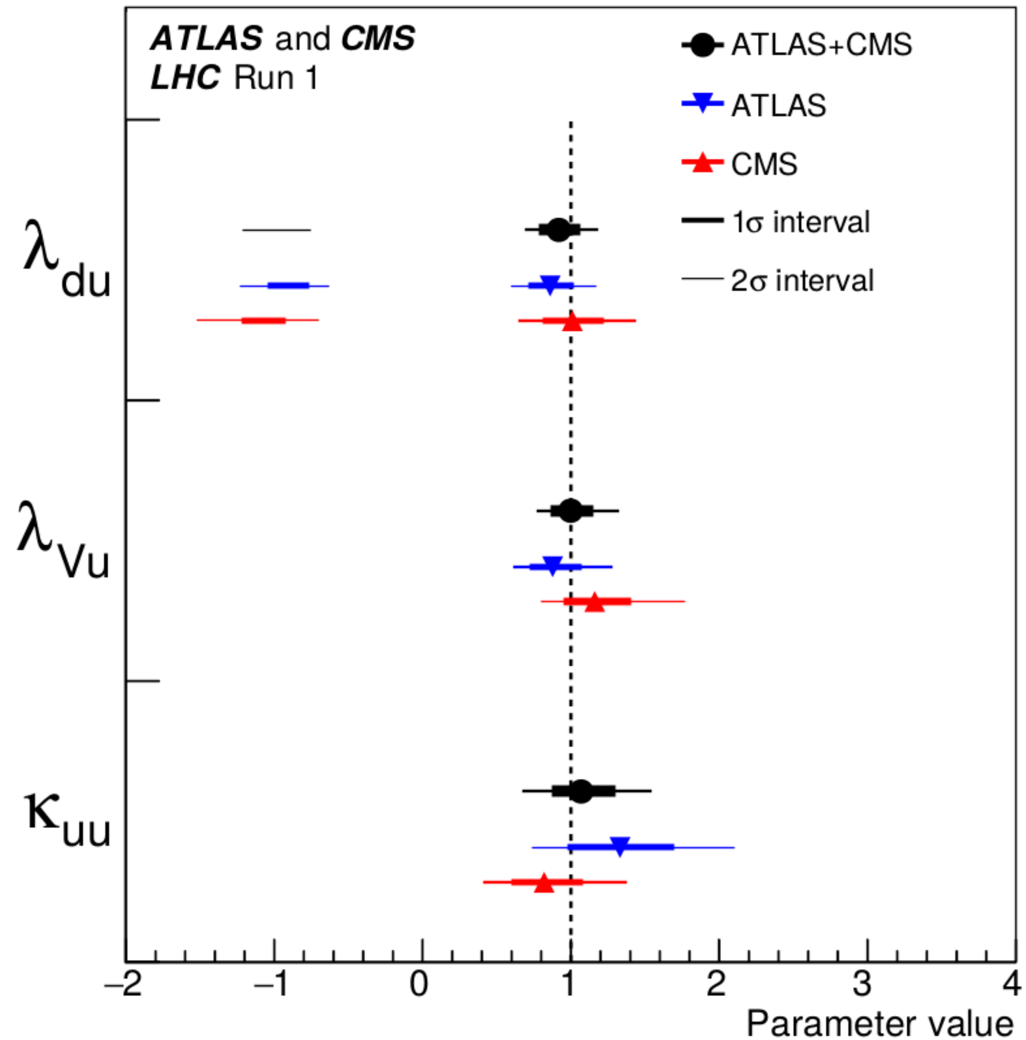
Backup

Fermion asymmetry

Lepton-quark symmetry



up-down quark symmetry



Lepton-quark and up-down quark asymmetry was probed using a 3-parameter fit. Measurements consistent with SM.

Global signal strength: ATLAS vs CMS

Table 11: Measured global signal strength μ and its total uncertainty, together with the breakdown of the uncertainty into its four components as defined in Section 3.3. The results are shown for the combination of ATLAS and CMS, and separately for each experiment. The expected uncertainty, with its breakdown, is also shown.

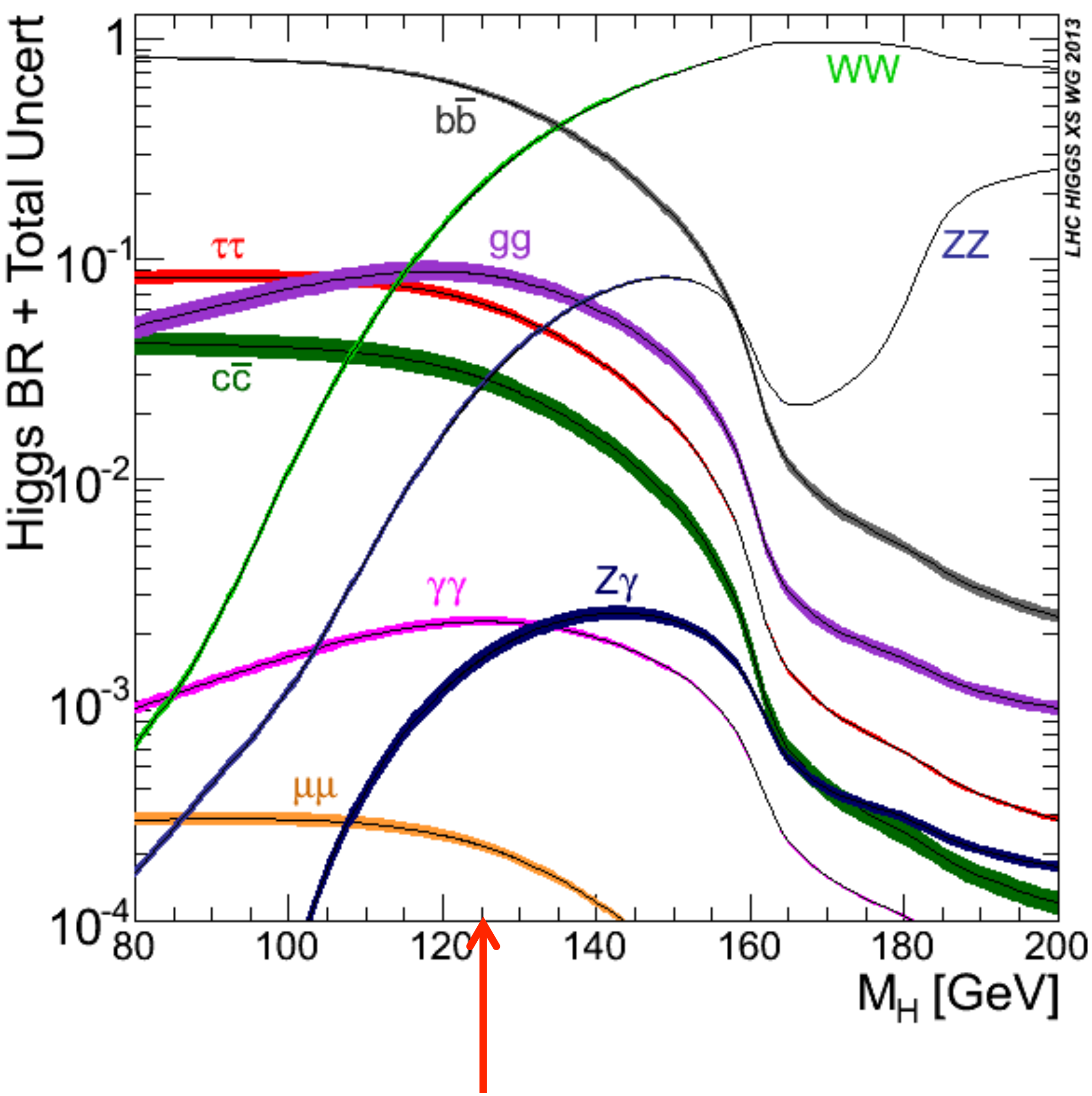
	Best fit μ	Uncertainty				
		Total	Stat	Expt	Thbgd	Thsig
ATLAS + CMS (measured)	1.09	$^{+0.11}_{-0.10}$	$^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	$^{+0.07}_{-0.06}$
ATLAS + CMS (expected)		$^{+0.11}_{-0.10}$	$^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	$^{+0.07}_{-0.06}$
ATLAS (measured)	1.20	$^{+0.15}_{-0.14}$	$^{+0.10}_{-0.10}$	$^{+0.06}_{-0.06}$	$^{+0.04}_{-0.04}$	$^{+0.08}_{-0.07}$
ATLAS (expected)		$^{+0.14}_{-0.13}$	$^{+0.10}_{-0.10}$	$^{+0.06}_{-0.05}$	$^{+0.04}_{-0.04}$	$^{+0.07}_{-0.06}$
CMS (measured)	0.97	$^{+0.14}_{-0.13}$	$^{+0.09}_{-0.09}$	$^{+0.05}_{-0.05}$	$^{+0.04}_{-0.03}$	$^{+0.07}_{-0.06}$
CMS (expected)		$^{+0.14}_{-0.13}$	$^{+0.09}_{-0.09}$	$^{+0.05}_{-0.05}$	$^{+0.04}_{-0.03}$	$^{+0.08}_{-0.06}$

Signal strength per production process

Table 12: Measured signal strengths μ and their total uncertainties for different Higgs boson production processes. The results are shown for the combination of ATLAS and CMS, and separately for each experiment, for the combined $\sqrt{s}$ = 7 and 8 TeV data. The expected uncertainties in the measurements are displayed in parentheses. These results are obtained assuming that the Higgs boson branching fractions are the same as in the SM.

Production process	ATLAS+CMS	ATLAS	CMS
μ_{ggF}	$1.03^{+0.16}_{-0.14}$ $\left(^{+0.16}_{-0.14}\right)$	$1.26^{+0.23}_{-0.20}$ $\left(^{+0.21}_{-0.18}\right)$	$0.84^{+0.18}_{-0.16}$ $\left(^{+0.20}_{-0.17}\right)$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$ $\left(^{+0.24}_{-0.23}\right)$	$1.21^{+0.33}_{-0.30}$ $\left(^{+0.32}_{-0.29}\right)$	$1.14^{+0.37}_{-0.34}$ $\left(^{+0.36}_{-0.34}\right)$
μ_{WH}	$0.89^{+0.40}_{-0.38}$ $\left(^{+0.41}_{-0.39}\right)$	$1.25^{+0.56}_{-0.52}$ $\left(^{+0.56}_{-0.53}\right)$	$0.46^{+0.57}_{-0.53}$ $\left(^{+0.60}_{-0.57}\right)$
μ_{ZH}	$0.79^{+0.38}_{-0.36}$ $\left(^{+0.39}_{-0.36}\right)$	$0.30^{+0.51}_{-0.45}$ $\left(^{+0.55}_{-0.51}\right)$	$1.35^{+0.58}_{-0.54}$ $\left(^{+0.55}_{-0.51}\right)$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$ $\left(^{+0.5}_{-0.5}\right)$	$1.9^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$

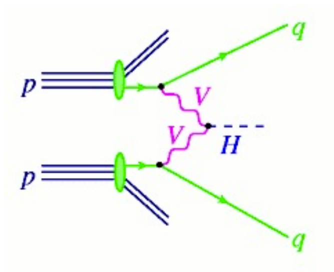
SM Higgs branching ratios

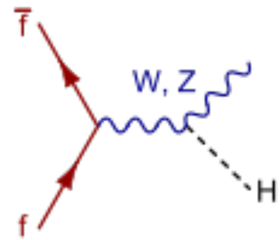


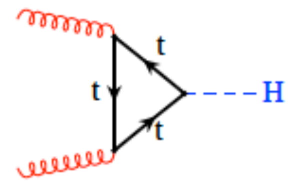
SM Higgs production modes

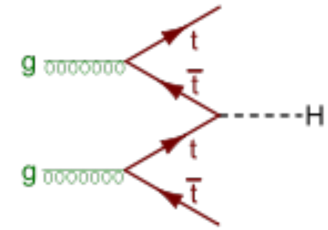
The main Higgs production mechanisms depend on V-H or top-H couplings

V-H couplings









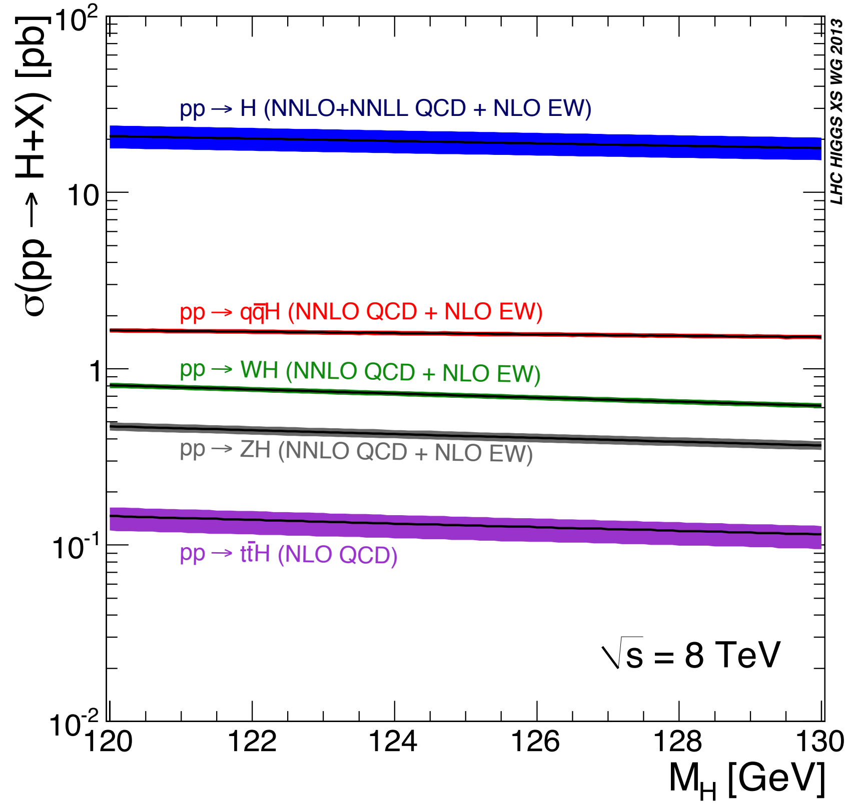
top-H couplings

VBF

VH

ggF

ttH



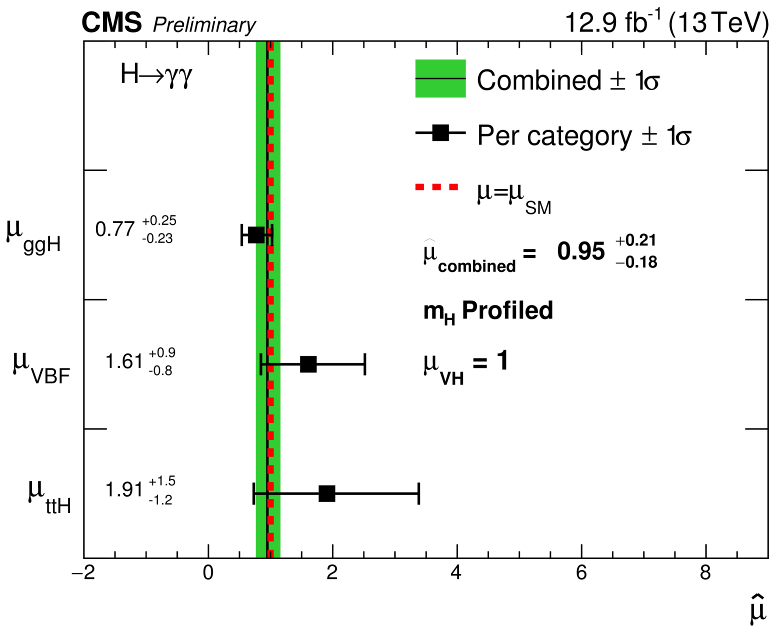
ggF ~ 90%

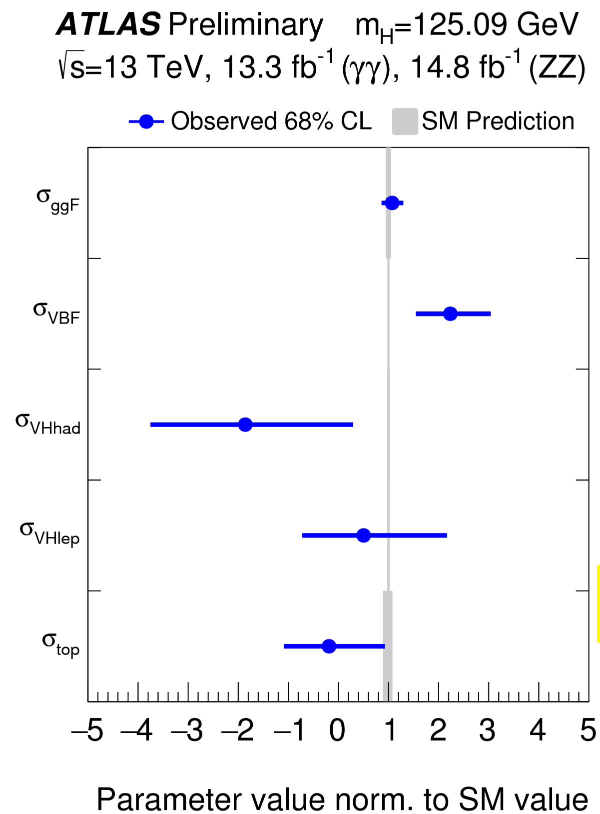
VBF~ 7-8%

VH ~ 3-4%

ttH ~ 0.5-0.8%

Run-2 2016 μ's

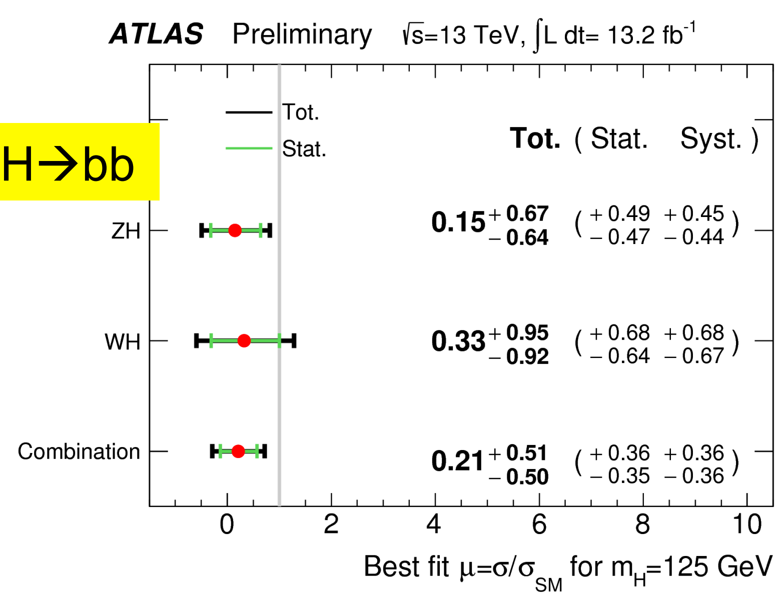


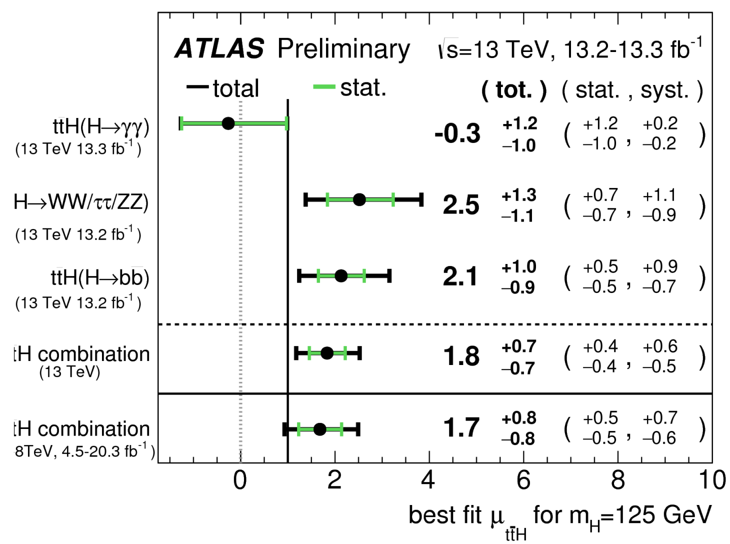


ATLAS-CONF-2016-091
ATLAS-CONF-2016-081
ATLAS-CONF-2016-068
CMS-PAS-HIG-16-020

H→γγ, H→ZZ

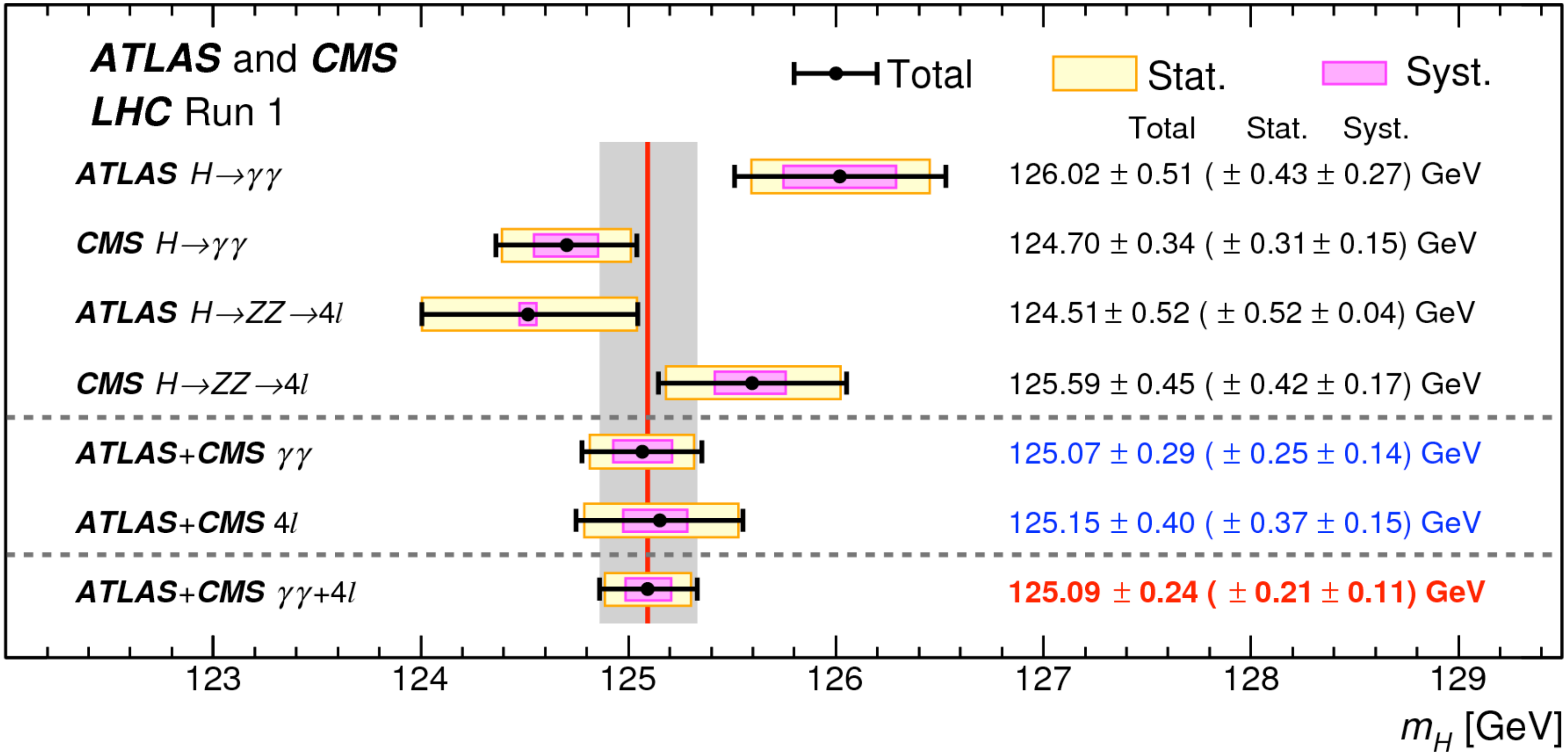
VH→bb





ttH

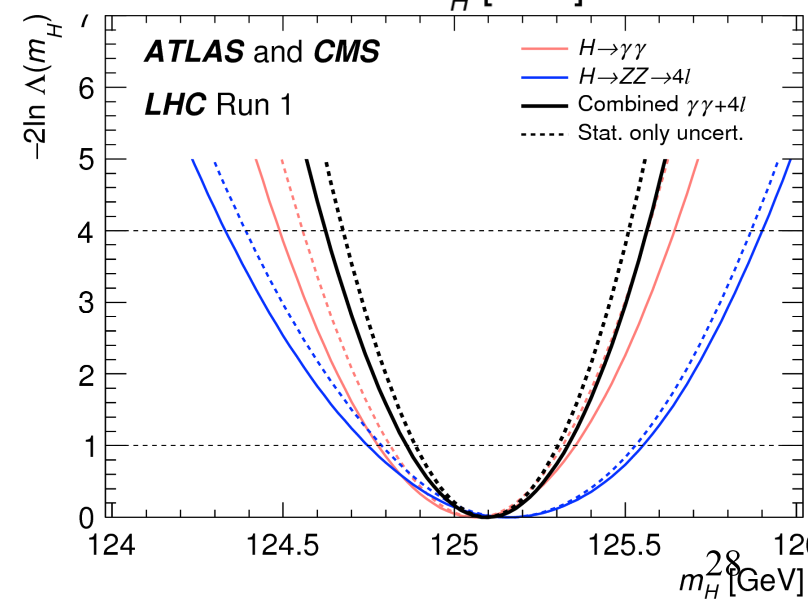
ATLAS/CMS combination: mass



$M_H = 125.09 \pm 0.24$ GeV

$= \pm 0.21$ (stat.) ± 0.11(syst.) GeV

$\delta m_H/m_H$=0.2%



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