Higgs couplings

ATLAS+CMS Combination

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Overview

ATLAS and CMS have combined results to give measurements of the Higgs boson production and decay rates and constraints on its couplings to vector bosons and fermions.

This result was first presented at the LHCP conference in St Petersburg, 1 Sept 2015

ATLAS-CONF-2015-044 or CMS-PAS-HIG-15-002

LHCP: https://indico.cern.ch/event/389531/session/31/contribution/51
CERN Seminar: http://indico.cern.ch/event/442438/

Higgs Couplings @ the LHC

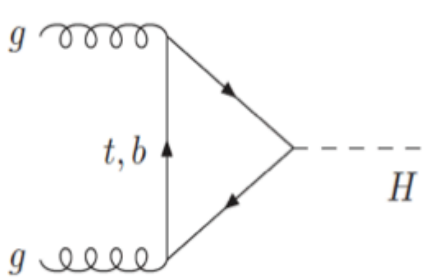
- The production cross sections and decay branching ratios (BR) of the Higgs boson can be precisely calculated once the mass is known.

$$M_H = 125.09 \pm 0.24 \text{ GeV} = \pm 0.21 \text{ (stat.)} \pm 0.11 \text{(syst.)}$$

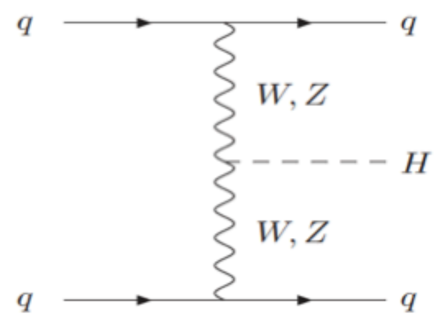
- At the LHC there is direct sensitivity to the couplings of the Higgs boson to W, Z bosons and to τ , b and t fermions+ indirectly to gluons and γ
- Combing ATLAS and CMS adds a factor of almost $\sqrt{2} = 1.4$ in precision (when signal theory systematics do not dominate)
- Many different measurements possible depending on assumptions made (SM BR's, σ's)

Higgs Production

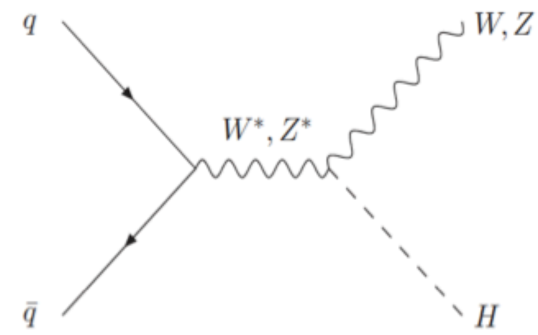
ggH



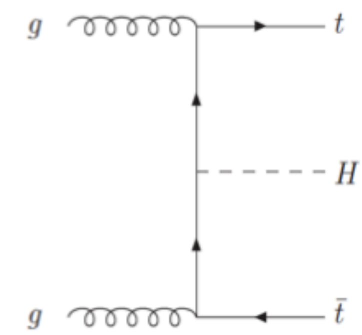
VBF



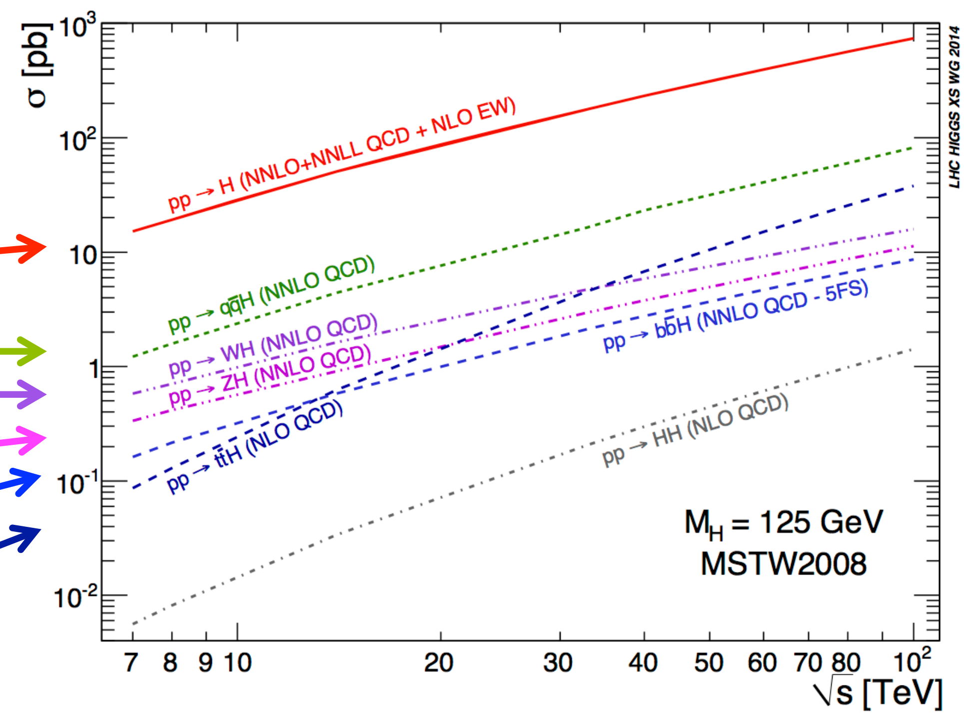
VH



ttH



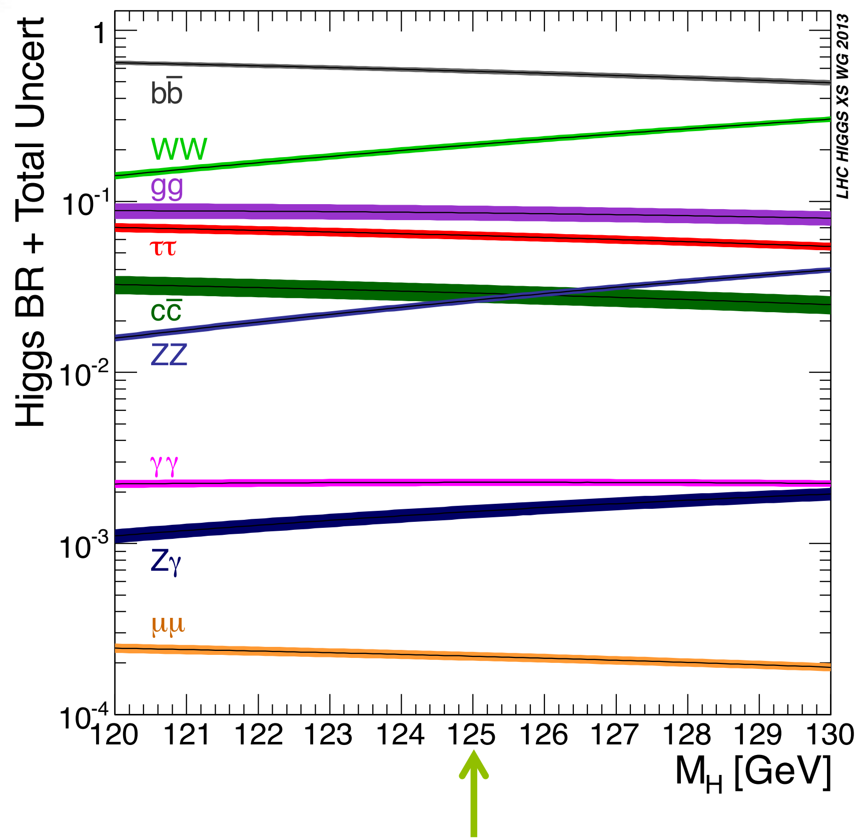
Production process
ggF
VBF
WH
ZH
bbH
ttH



Higgs Decays

Higgs decay

Decay channel	Branching ratio [%]
$H \to bb$	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

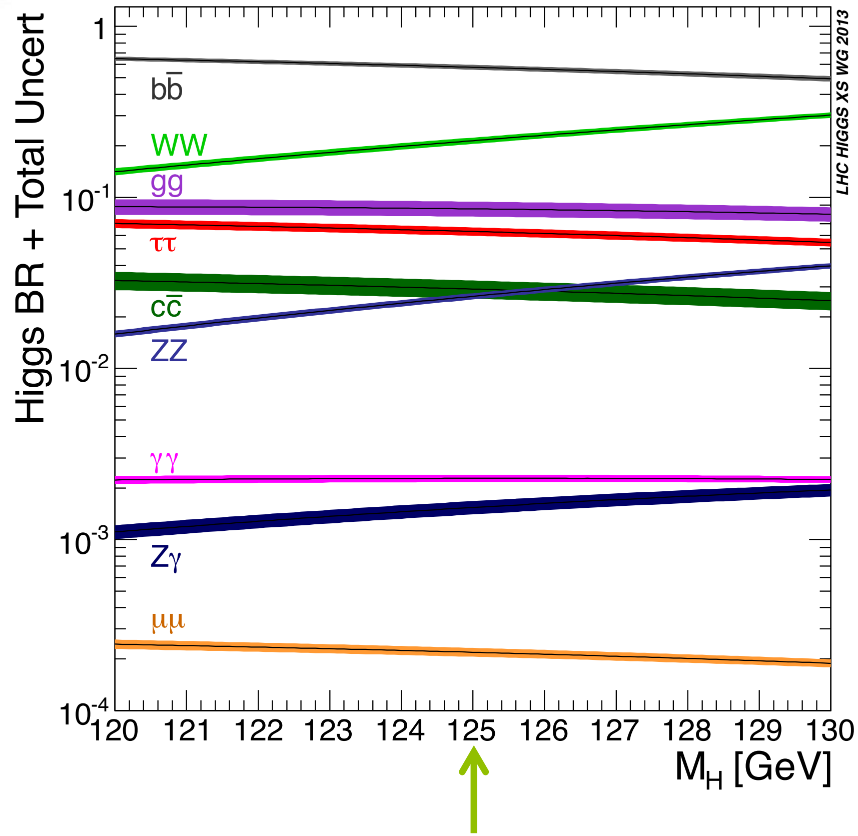


$$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})\ \text{GeV},$$

Higgs Decays

Evidence for Higgs decay at the LHC

Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[51]	[52]	$1.15^{+0.27}_{-0.25}$	$1.12^{+0.25}_{-0.23}$	5.0	5.6
			$\left(^{+0.26}_{-0.24}\right)$	$\left(^{+0.24}_{-0.22}\right)$	(4.6)	(5.1)
$H \to ZZ \to 4\ell$	[53]	[54]	$1.51^{+0.39}_{-0.34}$	$1.05^{+0.32}_{-0.27}$	6.6	7.0
			$\left(^{+0.33}_{-0.27}\right)$	$\left(^{+0.31}_{-0.26}\right)$	(5.5)	(6.8)
$H \to WW$	[55, 56]	[57]	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$	6.8	4.8
			$\left(^{+0.21}_{-0.20}\right)$	$\left(^{+0.23}_{-0.20}\right)$	(5.8)	(5.6)
$H \to \tau\tau$	[58]	[59]	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$	4.4	3.4
			$\left(^{+0.37}_{-0.33}\right)$	$\left(^{+0.31}_{-0.29}\right)$	(3.3)	(3.7)
$H \to bb$	[38]	[39]	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$	1.7	2.0
			$\left(^{+0.39}_{-0.37}\right)$	$\left(^{+0.45}_{-0.43}\right)$	(2.7)	(2.5)
$H \to \mu\mu$	[60]	[61]	-0.7 ± 3.6	0.8 ± 3.5		
			(± 3.6)	(± 3.5)		
ttH production	[28, 62, 63]	[65]	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$	2.7	3.6
			$\left(^{+0.72}_{-0.66}\right)$	$\left(^{+0.88}_{-0.80}\right)$	(1.6)	(1.3)



$$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})\ \text{GeV},$$

Combination Inputs

Inputs are based on the ~5 fb^{-1} of 7 TeV + 20 fb^{-1} 8 TeV data per experiment

	Untagged	**VBF**	**VH**	**ttH**
$H\rightarrow\gamma\gamma$	✓	✓	✓	✓
H→ZZ→llll	✓	✓	✓	✓
H→WW	✓	✓	✓	✓
$H\rightarrow\tau\tau$	✓	✓	✓	✓
H→bb			✓	✓
$H\rightarrow\mu\mu$	*included in tree level fit for H-μ coupling*			

Measurements and Compatibility with the SM

- The ATLAS+CMS coupling combination results include:

  1) Fits of signal strengths (global, by production, by decay) relative to the SM

  2) Fits in the κ-framework, measuring coupling modifiers

  3) Generic parameterizations based on ratios of XS and BR and on coupling modifier ratios

- Common Assumptions:
  - Assume there is only one Higgs boson with Spin Parity 0^+ and with a narrow width such that production and decay are decoupled

Statistical Combination

- The final signal yield is the combination of many individual analyses.
- Each analysis is broken into categories, which generally target a production mode. ~100 categories in final combination.
- There is cross talk between production categories but not (much) between decays

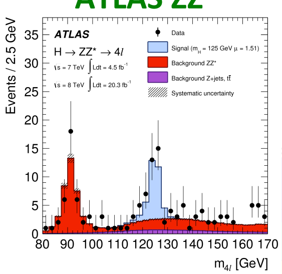
$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{\sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}^f\right\},$$
$$= \mathcal{L}(k) \times \sum_i \sum_f \mu_i \mu^f \left\{\sigma_i^{\text{SM}} \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}^f_{\text{SM}}\right\}$$

Integrated Luminosity

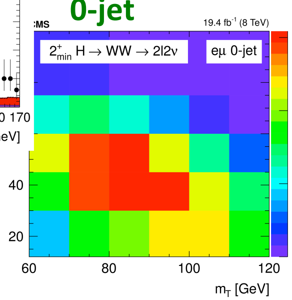
Detector Acceptance

Selection and Analysis Efficiency for Category k

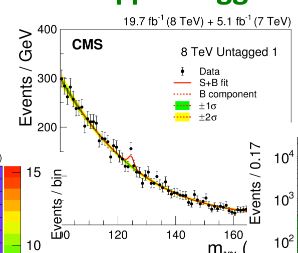
ATLAS ZZ



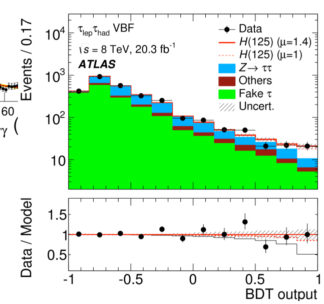
CMS WW 0-jet



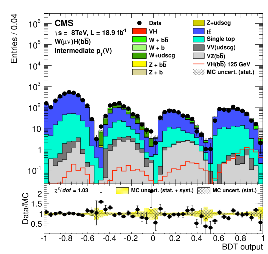
CMS γγ untagged



ATLAS ττ VBF μ-τ$_{had}$



CMS bb



Statistical Combination

Measure parameters of interest, $\vec{\alpha}$

signal strengths (μ),

coupling modifiers (κ),

production cross sections,

branching ratios,

or ratios of these quantities,

with Profile likelihood ratio. A maximum-likelihood fit is performed on all categories simultaneously to extract the parameters of interest

$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

set of nuisance parameter values that maximize the likelihood for a given $\vec{\alpha}$

best fit values for nuisance parameters and parameters of interest

- About 4200 nuisance parameters are incorporated in the combined fits

Statistical Combination: Systematic Uncertainties

- Categorized in four groups:

1) **Statistical** (except for the case of the finite size of MC simulation samples). Including the statistical uncertainties on some background control regions and certain fit parameters used to parameterize backgrounds measured from data ("stat")

2) **Signal Theory** uncertainties ("thsig")

3) **Background Theory** uncertainties, not correlated with any of the signal theory uncertainties ("thbgd")

4) **Experimental:** ("expt"), including the experimental uncertainties and those related to the finite size of the MC simulation samples.

- **The biggest challenge is the correlations between channels and experiments**

Coupling Combination: 1) Signal Strengths

$$i \rightarrow H \rightarrow f$$

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}} \qquad \mu^f = \frac{BR^f}{(BR^f)_{SM}}$$

with σ_i (i=ggF, VBF, WH, ZH, ttH) and BR^f (f =ZZ, WW, $\gamma\gamma$, $\tau\tau$, bb)

Since σ_i and BR^f cannot be separately measured without additional assumptions, only the product of μ_i and μ^f can be extracted experimentally, leading to a signal strength μ_i^f for the combined production and decay:

$$\mu_i^f = \frac{\sigma_i \cdot BR^f}{(\sigma_i)_{SM} \cdot (BR^f)_{SM}} = \mu_i \times \mu^f$$

Coupling Combination: 1) Signal Strengths

$$\mu_i^f = \frac{\sigma_i \cdot BR^f}{(\sigma_i)_{SM} \cdot (BR^f)_{SM}} = \mu_i \times \mu^f$$

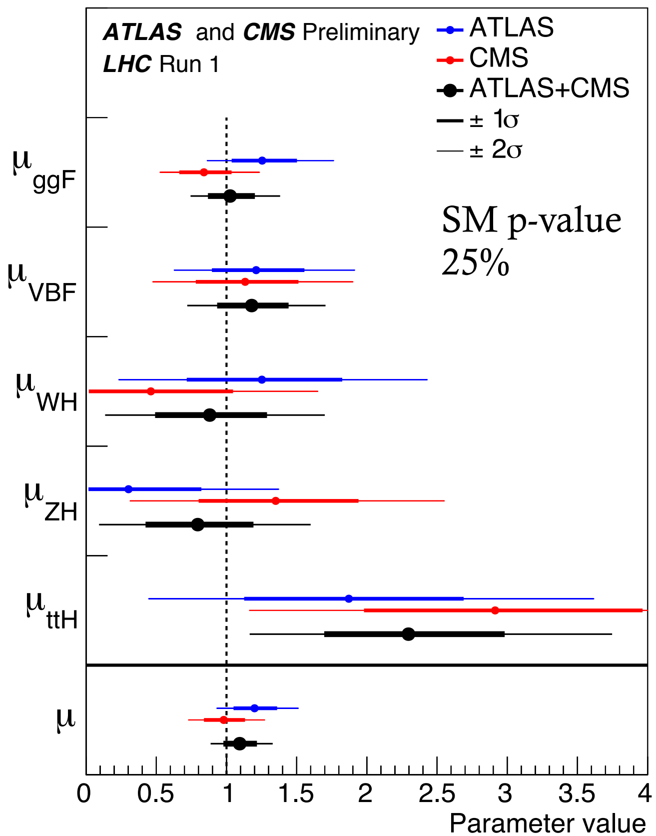
- Most precisely measured H coupling and also most constrained parameterization: Assume μ_i and μ^f are the same for all production processes and decay channels: the SM predictions of signal yields in all categories are scaled by a global signal strength μ .
- A fit to the combined ATLAS and CMS data at $\sqrt{s}$ = 7 and 8 TeV with μ as the parameter of interest results in the best-fit

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

total systematic uncertainty: $^{+0.09}_{-0.08}$

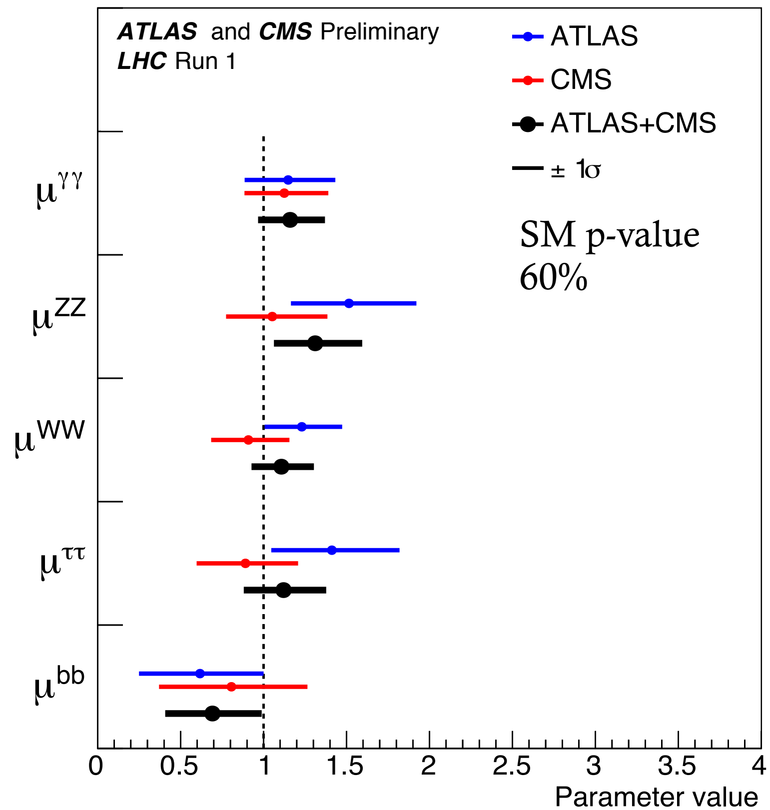
Coupling Combination: 1) Signal Strengths

Production signal strengths
Assume SM BRs



$2.3\,\sigma$

Decay signal strengths
Assume SM Cross Sections



Coupling Combination: 1) Signal Strengths

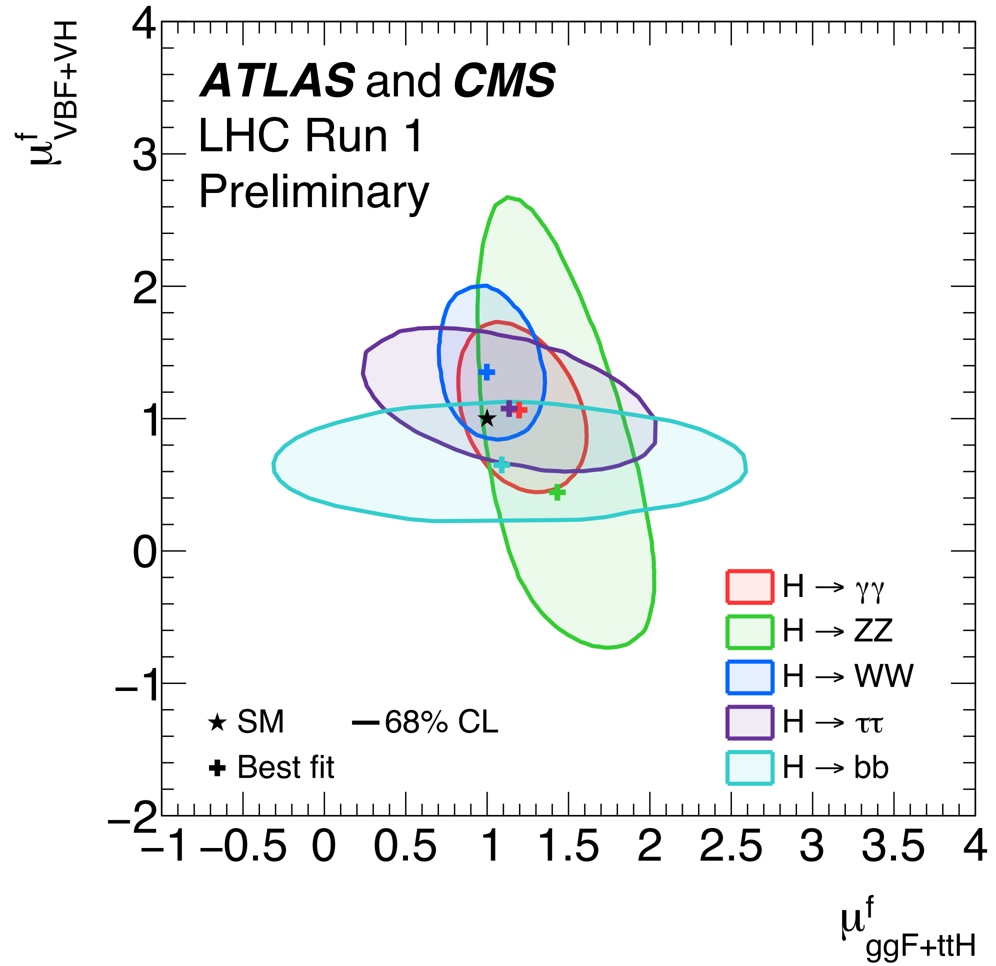
- Comparing likelihood of the best-fit with no signal: $\mu_{\text{prod}}=0$ and $\mu^{\text{decay}}=0$:

Production process	Measured significance (σ)	Expected significance (σ)
> 5 σ VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
> 5 σ $H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

VBF and H→ τ τ now established at 5 σ! Join ggF, H→ γ γ, H→ZZ, H→WW which were already established from single experiments

Coupling Combination: 1) Signal Strengths

- **Fit the bosonic and fermionic productions separately per decay**
- $\mu_{\mathrm{VBF+VH}} / \mu_{\mathrm{ggF+ttH}} = 1.06^{+0.35}_{-0.27}$
- No assumption on the BRs is needed in the combination of the $\mu_{\mathrm{VBF+VH}} / \mu_{\mathrm{ggF+ttH}}$ ratio (benefit of the ratio)



Coupling Combination: 2) The κ Framework– Coupling modifiers

$$i \rightarrow H \rightarrow f$$

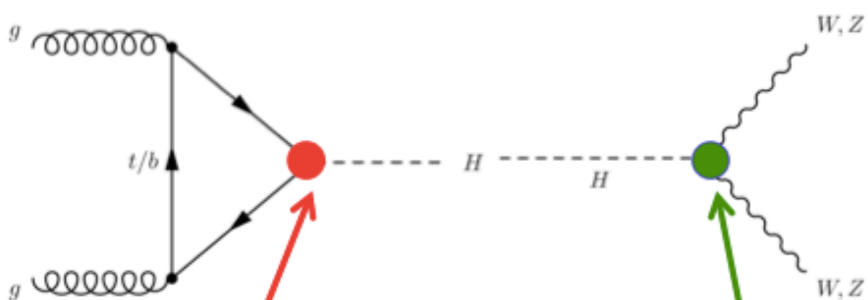
- κ framework developed by LHC Higgs Cross Section WG
- Scale Higgs boson couplings by modifiers, κ, factorizing production and decay

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} \quad or \quad \kappa_j^2 = \frac{\Gamma^j}{\Gamma^j_{SM}} \qquad\qquad \Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$$

- Individual coupling modifiers, correspond to tree-level H couplings to the different particles: κ_W, κ_Z, κ_t, κ_b, κ_τ, κ_μ
- BR_{BSM} includes invisible + undetected H decays

Coupling Combination: 2) Disentangle Branching Ratios and Cross Sections

- Example for ggF production of H→VV



$\sigma_{ggF} = (1.06\,\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_b\kappa_t)\,\sigma_{ggF}(SM)$ $\Gamma_{W,Z} = \kappa^2_{W,Z}\,\Gamma_{W,Z}(SM)$

$$\sigma(i \to H \to f) = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_\mathrm{H}}$$

NB: σ_{ggF}(SM) from NNLO(QCD) + NLO(EW) calculation!

κ -Parameterization

Production	Loops	Interference	Multiplicative factor
$\sigma(gg\mathrm{F})$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(V\mathrm{BF})$	–	–	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim \kappa_W^2$
$\sigma(qq/qg \to ZH)$	–	–	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	–	$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
Partial decay width			
Γ^{ZZ}	–	–	$\sim \kappa_Z^2$
Γ^{WW}	–	–	$\sim \kappa_W^2$
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
Γ^{bb}	–	–	$\sim \kappa_b^2$
$\Gamma^{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
Total width for $\mathrm{BR}_{\mathrm{BSM}} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + {}$ $+ 0.06 \cdot \kappa^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + {}$ $+ 0.0023 \cdot \kappa^2 + 0.0016 \cdot \kappa_Z^2 + {}$ $+ 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa^2$

κ -Parameterization

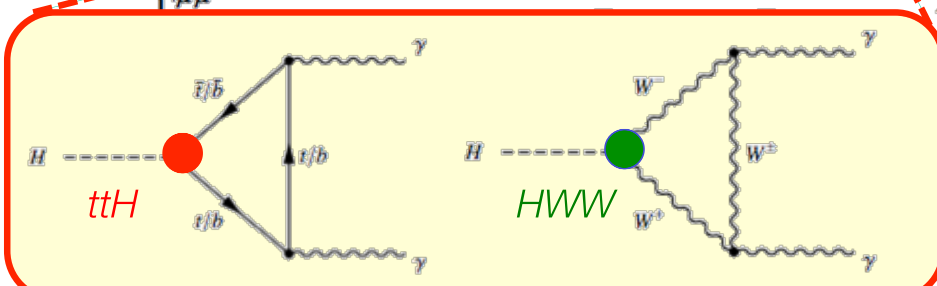
The kappa framework – the dic

Production	Loops	Interference	M	
$\sigma(ggF)$	✓	$b-t$	κ	
$\sigma(VBF)$	–	–		
$\sigma(WH)$	–	–		
$\sigma(qq/qg \to ZH)$	–	–		
$\sigma(gg \to ZH)$	✓	$Z-t$		
$\sigma(ttH)$	–	–		
$\sigma(gb \to WtH)$	–	$W-t$		
$\sigma(qb \to tHq)$	–	$W-t$		
$\sigma(bbH)$	–	–		
Partial decay width				
Γ^{ZZ}	–	–		
Γ^{WW}	–	–	$\sim$	κ_W^2
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim$	κ_τ^2
Γ^{bb}	–	–	$\sim$	κ_b^2
$\Gamma^{\mu\mu}$	–	–	$\sim$	κ_μ^2
			$\sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Processes with **interference** allow (in principle) to measure the relative sign of coupling strengths

Since all interferences considered always involve the top quark, **choose sign of top coupling positive** by construction (no loss of generality)

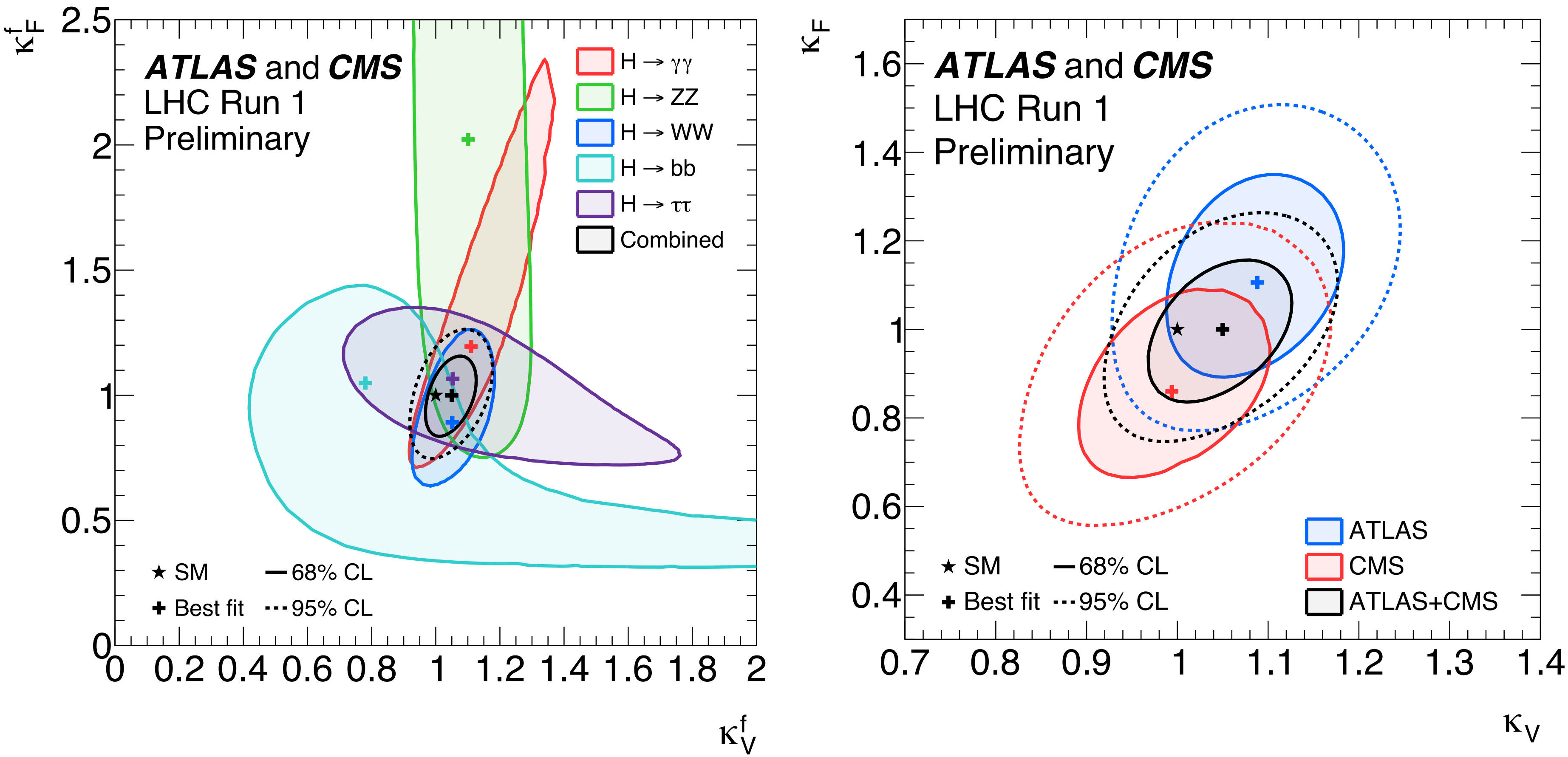
→ can allow data to constrain sign of b,W,Z coupling w.r.t top quark coupling



κ -Parameterization

Assume all fermions scale by κ_F and all vectors by κ_V

Assume no BSM physics enters in Loops, no invisible decays

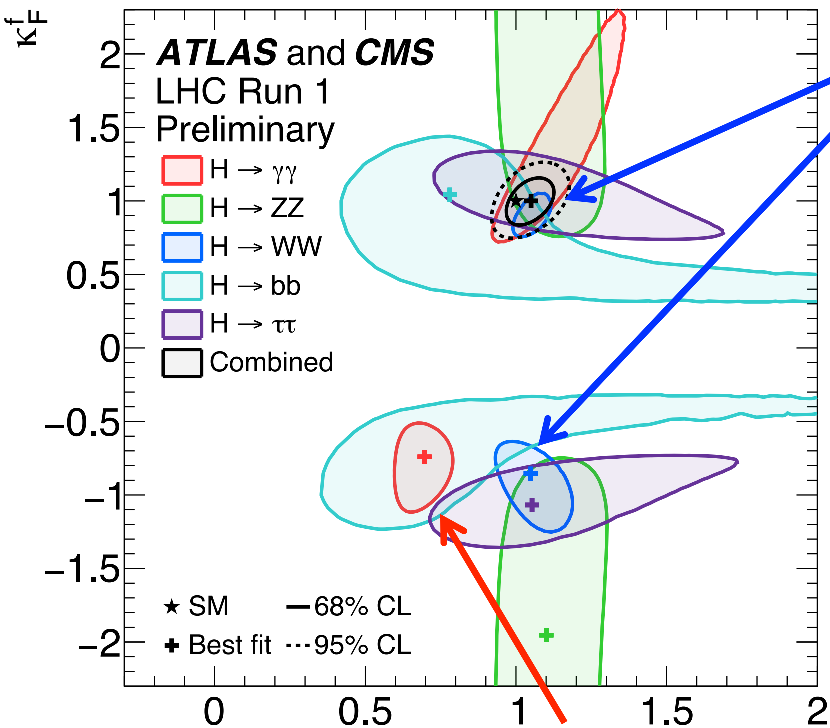


Results agree with the SM within 1 sigma

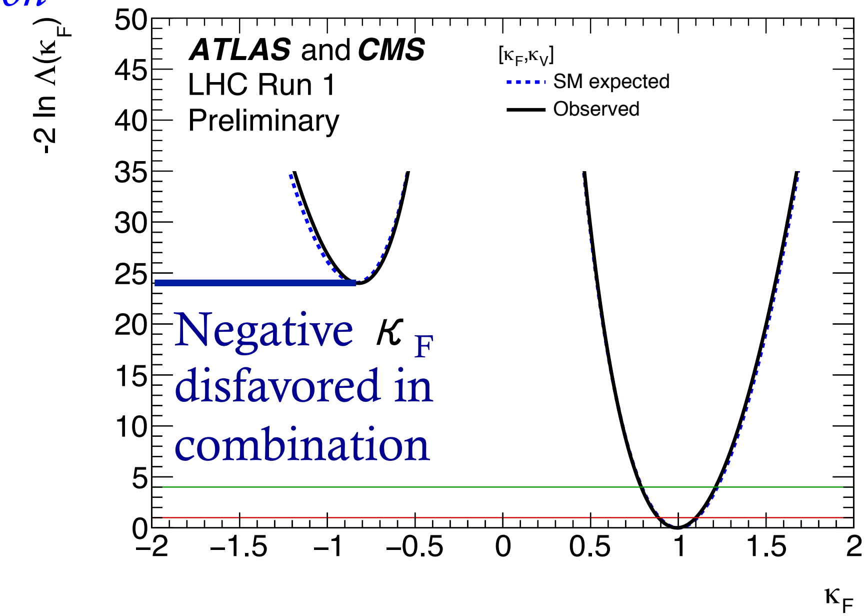
κ -Parameterization

Constraints for H couplings to fermions, bosons

Expanding parameter ranges to include negative couplings



Positive WW contour reduced due to preferred negative solution



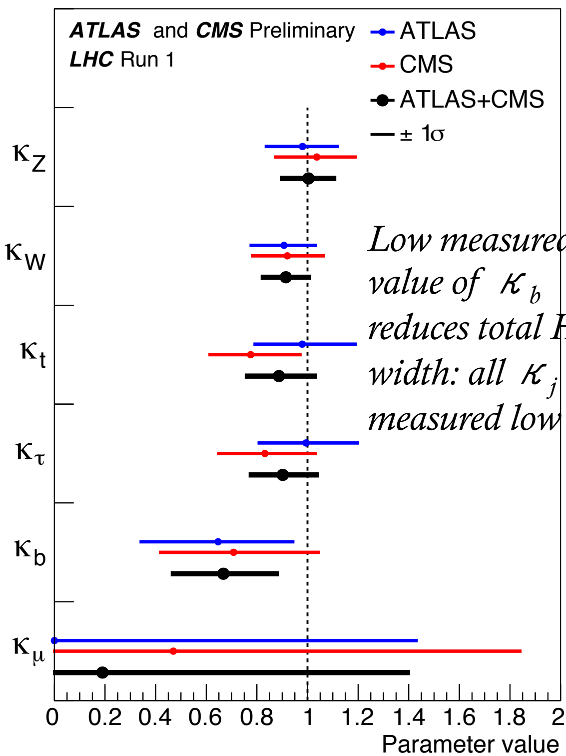
Negative κ_F disfavored in combination

Negative κ_F can only be excluded in a combination of channels due to incompatible negative contours. The negative YY contour is completely incompatible with the negative WW contour, for example.

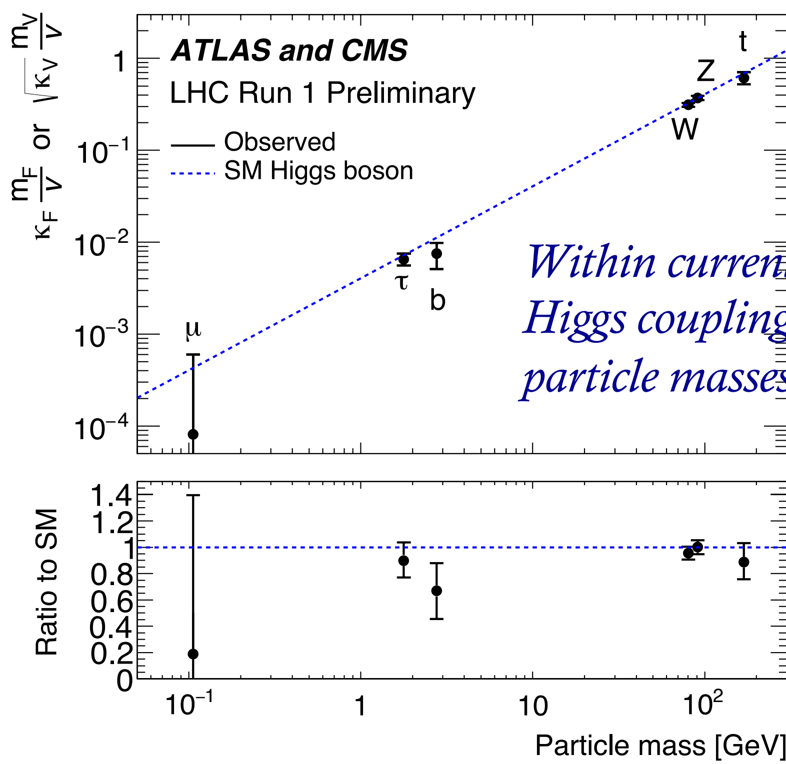
κ -Parameterization
Constraints on tree-level H couplings

Assume only SM physics in loops, no invisible or unseen BSM Higgs decays

Fit for scaling parameters for Higgs couplings to W, Z, b, t, τ , μ



Low measured value of κ_b reduces total H width: all κ_j measured low



Within current precision Higgs couplings scale with particle masses

κ -Parameterization
Allowing for BSM contributions

- Results shown so far have assumed no invisible BSM Higgs decays or BSM contributions to loops. Now drop these assumptions.

1) Represent loop processes (ggF, H→ϒϒ) with effective parameters (κ_g, κ_Υ)

$\mathbf{1.06\,\kappa_t^2 + 0.01\,\kappa_b^2 - 0.07\,\kappa_t\kappa_b}$

$\boldsymbol{\kappa_g^2}$

2) Allow for invisible/undetected BSM Higgs decays to increase the Total H width

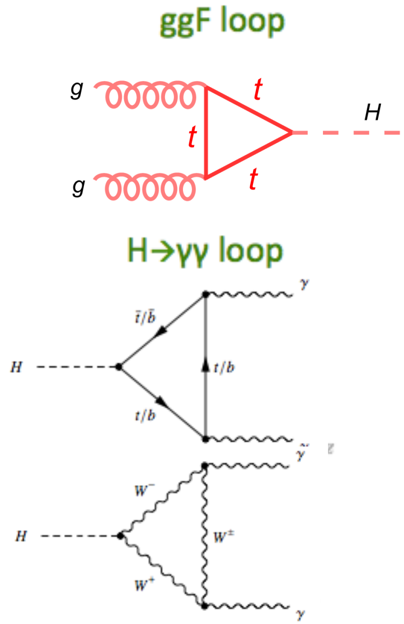
$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$$

3) Constrain Γ_H with off-shell +on-shell coupling strengths. (Not used in combination.) arXiv:1507.04548.

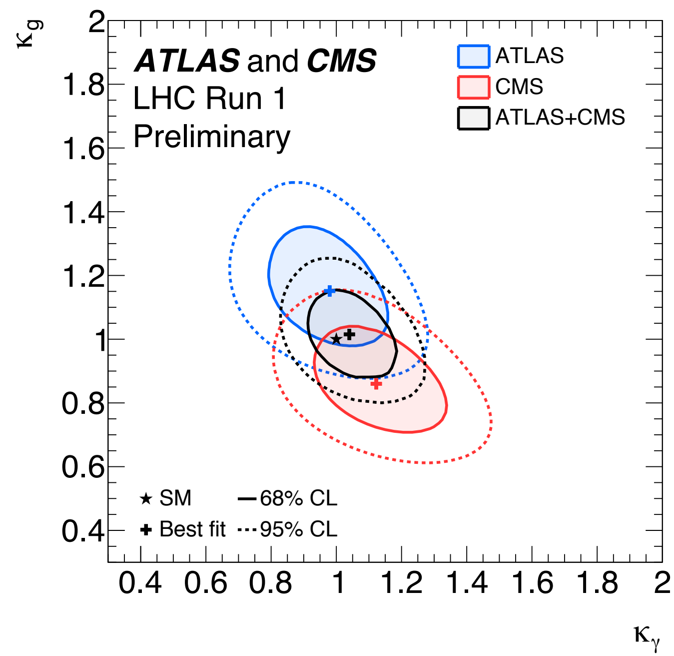
κ -Parameterization
Allowing for BSM contributions

1.

Probe potential BSM contributions to loops. Fix all tree-level Higgs couplings to SM ($\kappa_W, \kappa_Z, \kappa_b, \kappa_t, \kappa_\mu, \kappa_\tau$=1) and BR_{inv}=0 , and only allow modifications to the two main loops of ggF and H$\gamma\gamma$



Additional heavy fermions or charged Higgs boson would modify the effective couplings



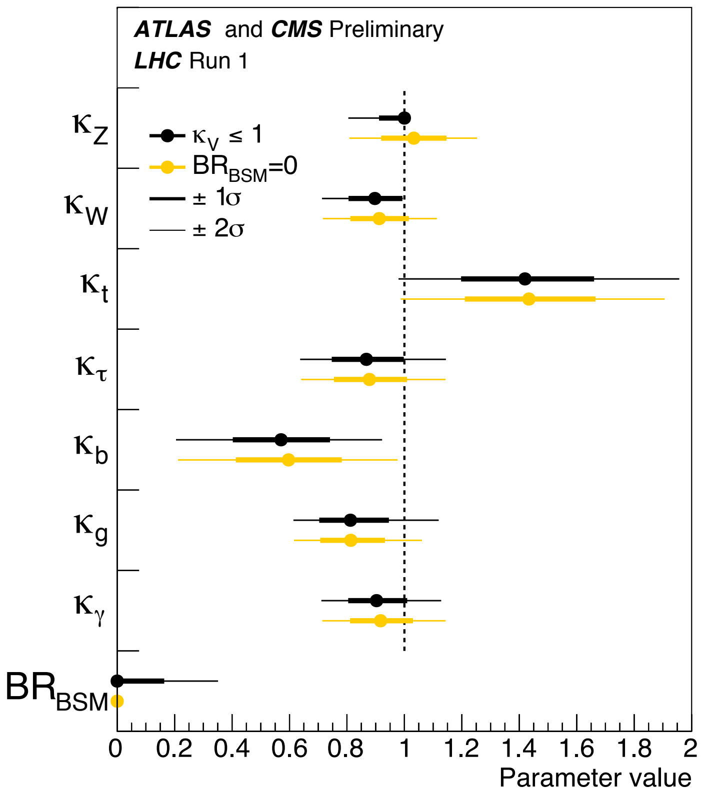
κ -Parameterization
Allowing for BSM contributions

Constraints on Higgs couplings allowing BSM physics in loops & decays

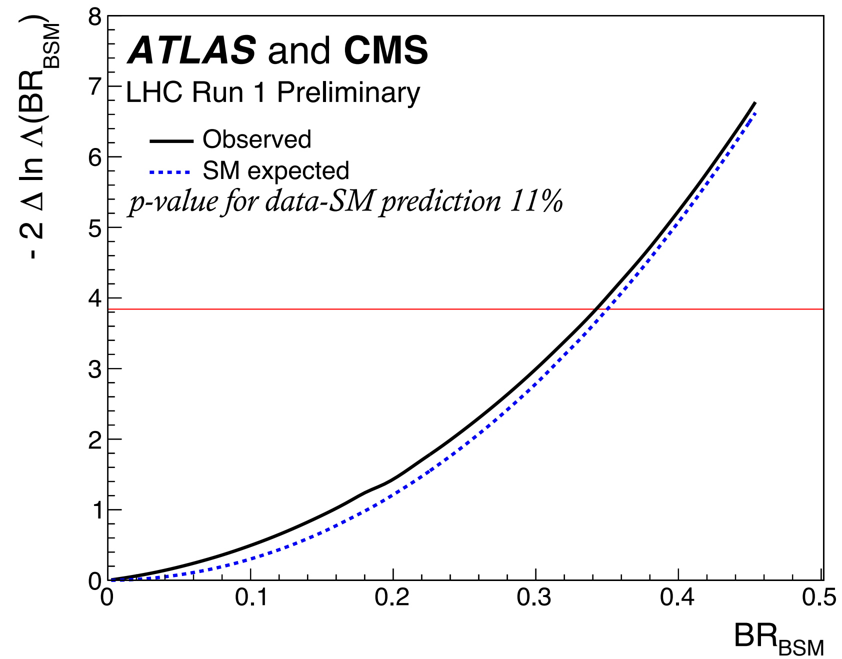
2.

Keep all 6+2 coupling parameters floating, but assume either $BR_{BSM} = 0$ or $\kappa_W, \kappa_Z \leq 1$

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



BRBSM < 0.34 at 95% C.L. (assuming κV≤1)



κ -Parameterization

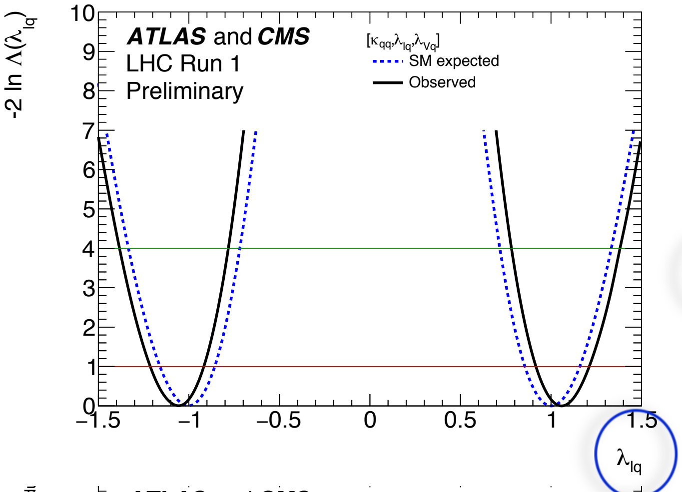
Up/down fermion and lepton/quark symmetries

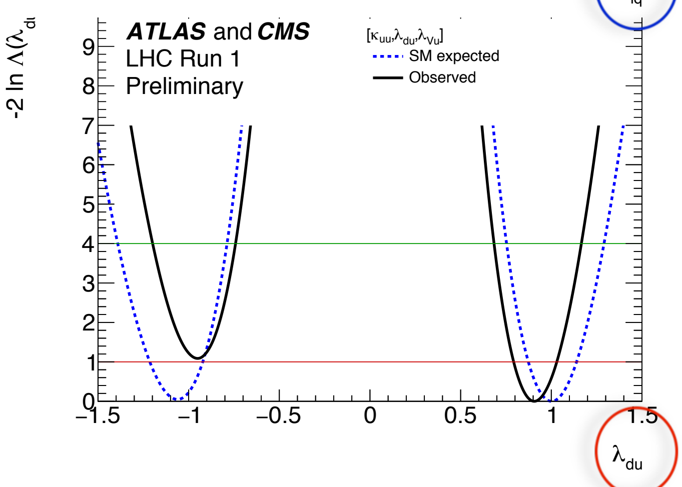
Several BSM physics models (notably 2HDM), predict asymmetries in couplings between up-type and down-type fermion couplings, and between lepton and quark couplings

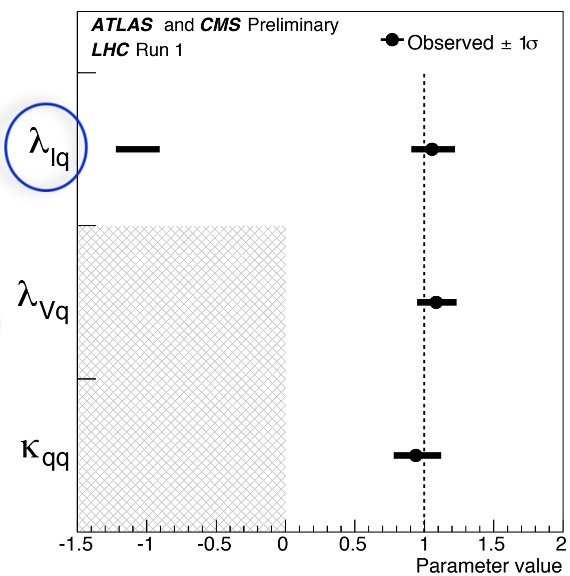
$$\boxed{\lambda_{du} = \kappa_d/\kappa_u} \qquad \boxed{\lambda_{\ell q} = \kappa_\ell/\kappa_q}$$

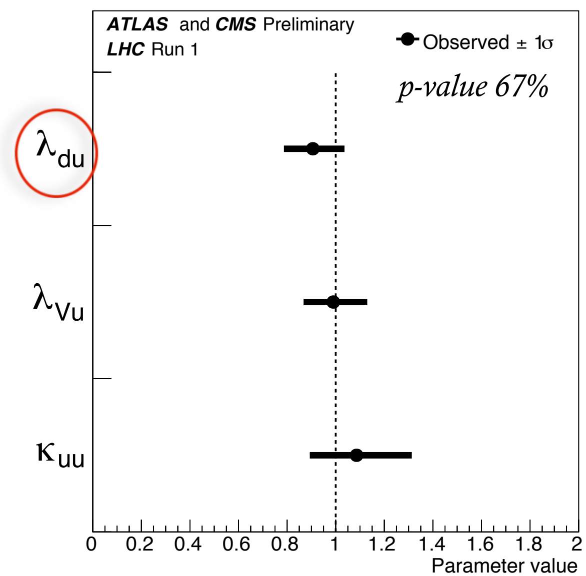
$$\lambda_{Vu} = \kappa_V/\kappa_u \qquad \lambda_{Vq} = \kappa_V/\kappa_q$$

$$\kappa_{uu} = \kappa_u \cdot \kappa_u/\kappa_H . \qquad \kappa_{qq} = \kappa_q \cdot \kappa_q/\kappa_H .$$









Probing Up-type: ggF, $\gamma\gamma$,ttH
Probing Down-type: bb, tautau
Probing Quark coupling: ggF, $\gamma\gamma$, bb, ttH
Probing lepton coupling: tautau

Katy Grimm, Lancaster University

Parameterization using ratios of cross sections and branching ratios

- Take gg→H→ZZ as a reference because of its small systematic uncertainties

- Then use ratios of σ and BR:

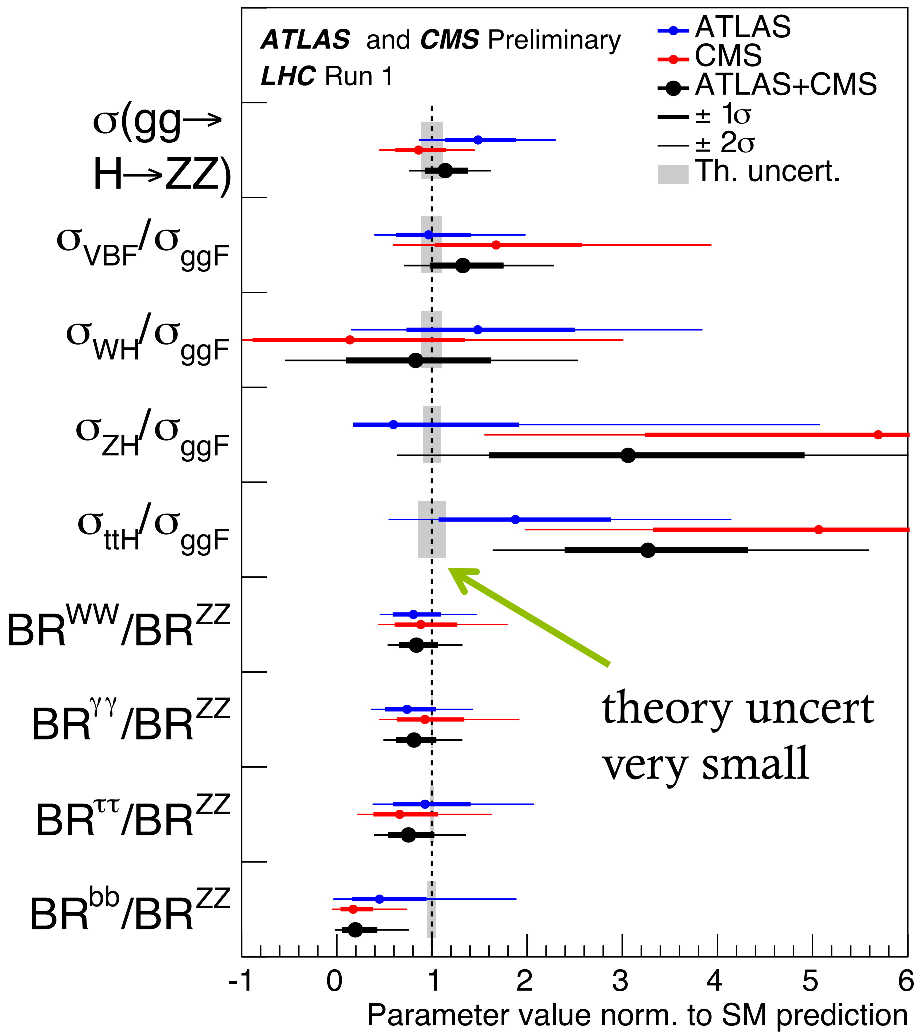
$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right),$$

- The combined fit results can be presented as a function of nine parameters of interest: one reference cross section times branching ratio, $\sigma(gg \to H \to ZZ)$, four ratios of production cross sections, σ_i/σ_{ggF} and four ratios of branching ratios, $\mathrm{BR}^f/\mathrm{BR}^{ZZ}$.

- **The ratios are independent of the theoretical predictions on the Inclusive cross sections and BR's**

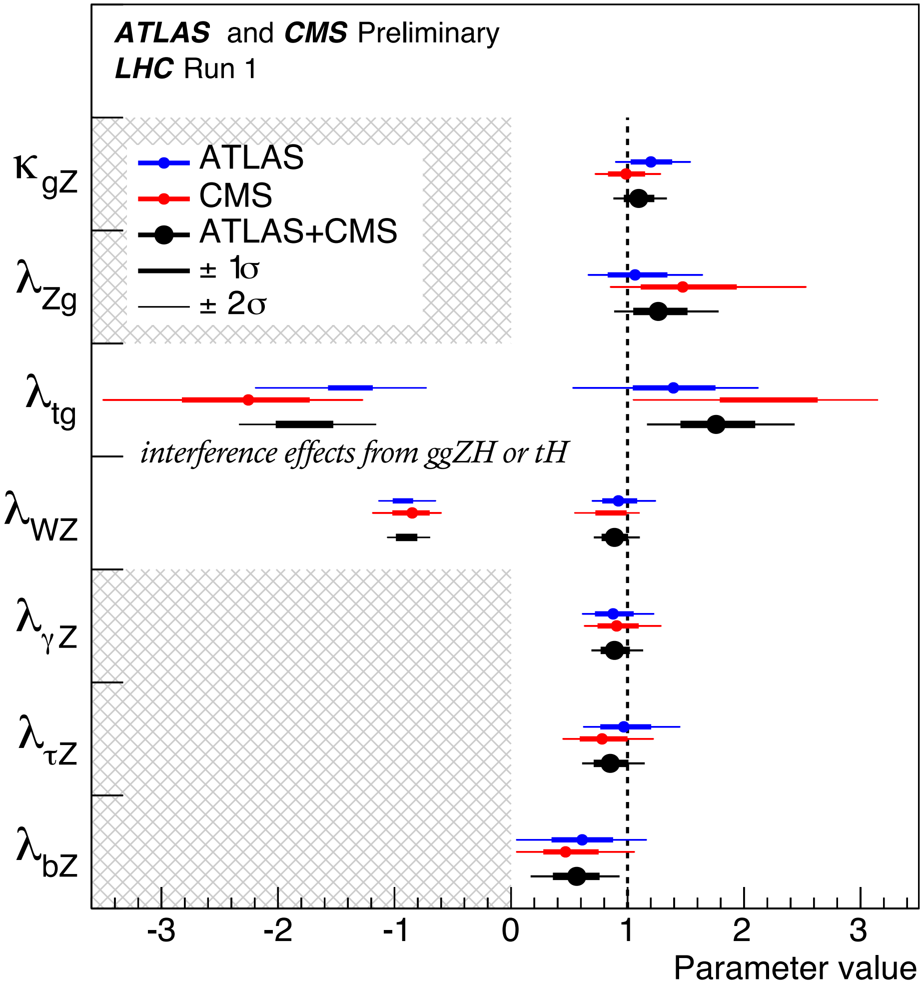
σ and BR ratio model
$\sigma(gg \to H \to ZZ)$
$\sigma_{VBF}/\sigma_{ggF}$
σ_{WH}/σ_{ggF}
σ_{ZH}/σ_{ggF}
$\sigma_{ttH}/\sigma_{ggF}$
$\mathrm{BR}^{WW}/\mathrm{BR}^{ZZ}$
$\mathrm{BR}^{\gamma\gamma}/\mathrm{BR}^{ZZ}$
$\mathrm{BR}^{\tau\tau}/\mathrm{BR}^{ZZ}$
$\mathrm{BR}^{bb}/\mathrm{BR}^{ZZ}$

Parameterization using ratios of cross sections and branching ratios



- Results generally agree with SM
- The p-value of the compatibility between the data and the SM predictions is 16%
- Largest difference is seen in BR_{bb}/BR_{ZZ}, at the level of 2.4 σ
  - Effect mainly coming from large ZH and ttH (both ratios σ_i/σ_{ggF} ~ 3) because Hbb does not contribute to the observed excesses.

Ratios of κ's



Coupling-strength ratio model
$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$
$\lambda_{Zg} = \kappa_Z / \kappa_g$
$\lambda_{tg} = \kappa_t / \kappa_g$
$\lambda_{WZ} = \kappa_W / \kappa_Z$
$\lambda_{Z} = \kappa / \kappa_Z$
$\lambda_{Z} = \kappa_\tau / \kappa_Z$
$\lambda_{bZ} = \kappa_b / \kappa_Z$

- Agreement with SM
- p-value of the compatibility between the data and the SM predictions is 13%
- Similar features as seen in signal strength ratio model

Summary

- **Run 1 ATLAS and CMS Higgs boson coupling measurements have been combined --sensitivity improved by almost √2 in many cases– a range of different measurements are extracted**

- **Higgs to $\tau\tau$ and VBF production established at more that 5σ level**

- The most precise results on Higgs production and decay and constraints on its couplings have been obtained (O(10%) precision):

$$\mu = 1.09^{+0.11}_{-0.10}$$

- Different parameterizations have been studied and all results are consistent with the SM predictions within uncertainties: min. SM p-value of all combined fits $\in$ [10% - 88%]

- LHC Run-2 at 13 TeV, precision will be improved during the coming years thanks to higher energy, larger integrated luminosity and progress in the theory predictions

Backup

Correlated uncertainties in ATLAS/CMS combination

- Full combination describes ~580 signal regions & control regions from both experiments. Grand total of ~4200 nuisance parameters, related to (systematic) uncertainties
- Correlation strategy of nuisance parameters a delicate and complicated task
  - **Detector systematic uncertainties** → follow strategy of ATLAS and CMS internal combinations (**generally correlated within, not between experiments)**
  - **Signal theory uncertainties** (QCD scales, PDF, UEPS) on **inclusive cross-sections** generally **correlated between experiments.**
  - **Signal theory uncertainties on acceptance and selection efficiency** are **uncorrelated between experiments**, as these are small and estimation procedures are generally different.
  - **PDF uncertainties on signal cross-sections** **uncorrelated between channels**, except WH/ZH = correlated (effect of ignoring other correlations is ≤1%)
  - **No correlations assumed** **between Higgs BRs** (except for WW/ZZ). *Effect of ignoring correlations shown to be generally small, except for a few specific measurements, in which case full correlation structure is retained*

Experimental uncertainties

Stefan Gadatsch

- ATLAS and CMS are two different detectors
  - ➥ All experimental uncertainties not correlated
- Except luminosity
  - ➥ Same treatment as in mass combination
  - ➥ Partially correlated through the sub-dominant contribution from the knowledge of the beam currents in accelerator

Main theory signal uncertainties: QCD scales, PDFs, UEPS, H BRs

Signal theory uncertainties – PDF

- PDF uncertainties on the inclusive rates for different Higgs production processes are correlated between the experiments for the same production mode classes but uncorrelated between themselves
  - gg correlates ggH, bbH and is anti-correlated with ttH
  - qq correlates qqH, WH, ZH and is anti-correlated with ggZH
  - gq associated with $gq \to tH$ production
- No correlation between signal and background
- tH (WtH and tHbj) are correlated between $ttH(\gamma\gamma, \text{leptons}, bb)$
- Procedure cross-checked by using full correlation matrix: effect smaller than 1 %

WH and ZH assumed fully correlated
ggF and ttH assumed fully anti-correlated

Signal theory uncertainties – UEPS, QCD scales, BRs

- Treatment of UEPS and QCD scale uncertainties similar to PDF ones:
- ➥ Correlated between the two experiments in the same production channels
- ➥ Uncorrelated between different channels, e.g. VBF or VH enriched categories
- For Higgs boson BRs implement full correlation model based on partial decay width (split in PU and TU) when it matters
  - E.g. uncertainties cancel in ratios of coupling strengths
- Other theory uncertainties on signal acceptance and selection efficiencies are small
  - Different estimate and treatment in experiments, therefor uncorrelated

Specific examples of potential correlations

- Uncertainties on $ttbb$ and ttb backgrounds to $ttH(bb)$ correlated in ATLAS, uncorrelated in CMS
  - ➥ Verify treatment by tossing toys for five different correlation schemes
  - ➥ Maximal difference in combined signal strength less than 10 % compared to a total uncertainty of about 80 %
  - ➥ **No need to include potential bias or a spurious signal**
- Uncertainties on the WW continuum in $H \to WW$
  - ➥ ATLAS uses extrapolation of normalization from CRs to SRs, CMS constrains shape and normalization from extended phase space
  - ➥ Very different systematic uncertainties: ATLAS estimate dominated by two-point generator comparisons (CMS only checks impact), others defined as envelope of two-point comparisons
  - ➥ **Do not correlate normalization factors or uncertainties on estimate**
- Uncertainties on the top background in 1-jet and 2-jet bins in $H \to WW$
  - ➥ Estimate is part of fit (ATLAS) or external (CMS), uses different central values, and is dominated by experimental uncertainties (top-tagging)
  - ➥ **No straightforward correlation**

Modifications for the combination

Differences with respect to individual ATLAS or CMS combinations:

- Some small variations in the results are due to evaluating them in the past at different values of the Higgs boson mass.
- Other differences are expected due to minor modifications to the signal parameterisation and to the handling of systematic uncertainties. These are introduced to implement a fully consistent and correlated treatment of the dominant signal theoretical uncertainties between the two experiments.
- ATLAS now uses the Stewart-Tackmann prescription [78] for the jet bin uncertainties for the $H \rightarrow WW$ channel instead of the jet-veto-efficiency prescription of Ref. [79,80];
- CMS now includes the bbH, tH and ggZH production processes in the signal model for the channels for which they are relevant;
- CMS now adopts the signal cross-section calculations from Ref. [27] for all channels (in earlier analyses, less up-to-date prescriptions had been applied);
- CMS now adopts a unified prescription for the treatment of the Higgs boson *pT,* as described in Section 2.2;
- The cross sections for the dominant backgrounds have been adjusted to the same values in the cases where they are estimated from simulation (ZZ background for the $H \rightarrow ZZ$ channel and ttZ and ttW backgrounds for the ttH channels);
- Both experiments have adopted the same correlation scheme for some of the signal theory uncertainties: for example, the treatment of the PDF uncertainties on the signal production cross sections now follows a common scheme for all decay channels, as described in Section 3.3.

MC Generators

- **ggF and *VBF:*** Powheg event generator interfaced with Pythia 8 (ATLAS) or Pythia 6.4 (CMS) for parton shower, hadronization, underlying event.

- **WH ZH:** leading-order (LO) event generators for all quark-initiated processes, namely Pythia8 in ATLAS and Pythia6.4 in CMS. A prominent exception is the more sensitive $H \rightarrow bb$ decay channel, for which ATLAS uses Powheg/ Pythia8, while CMS uses Powheg/Herwig++ [37].

- ***ttH* production:** ATLAS uses the NLO calculation of the HELAC-Oneloop pack- age [44] interfaced to Powheg (this chain is often referred to as Powhel [45]), while CMS simulates this process with the LO Pythia6 program.