Combined Higgs boson coupling constraints

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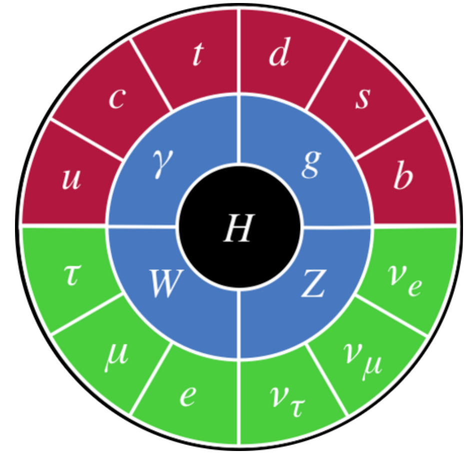
Imperial College London - HEPH Seminar – 18/01/2017

The Higgs boson in the SM

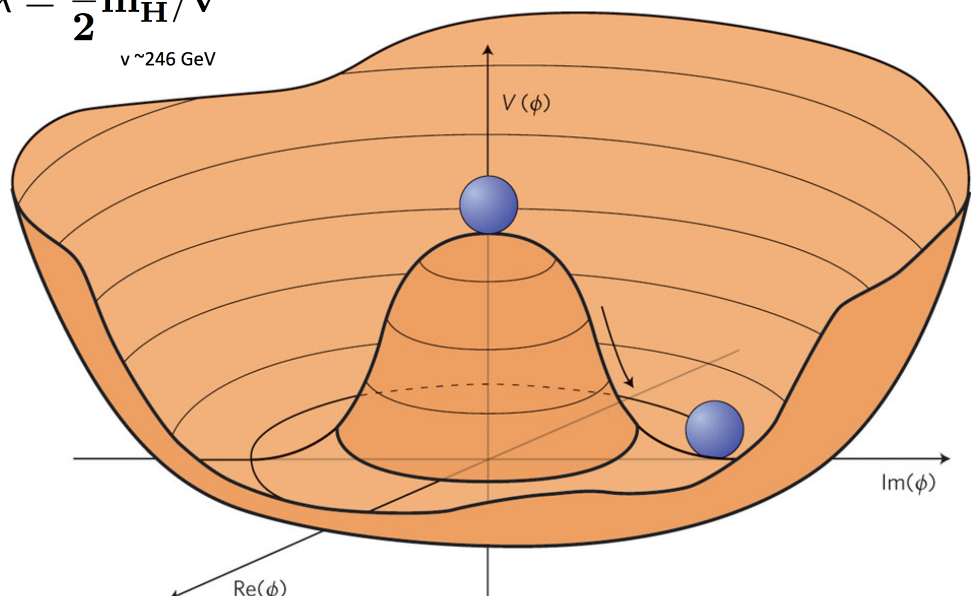


The Higgs boson plays a major role in the standard model…

W and Z bosons acquire mass via **spontaneous symmetry breaking**

$$\lambda = \frac{1}{2}\mathbf{m_H^2/v^2}$$

v ~246 GeV



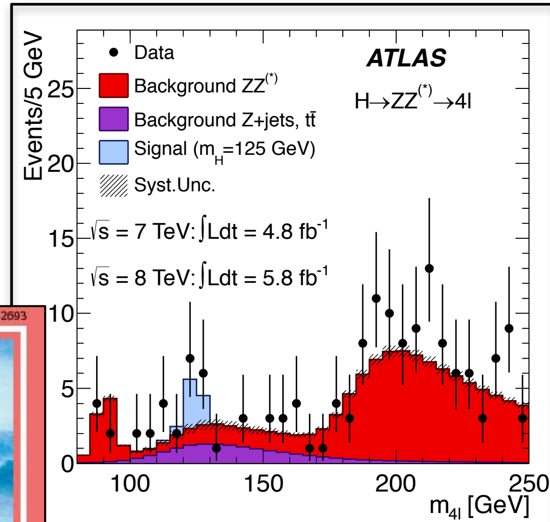
$$\mathscr{L}_\phi = (\hat{D}_\mu\phi)^\dagger(\hat{D}^\mu\phi) + \mu^2\phi^\dagger\phi - \frac{\lambda}{4}(\phi^\dagger\phi)^2,$$

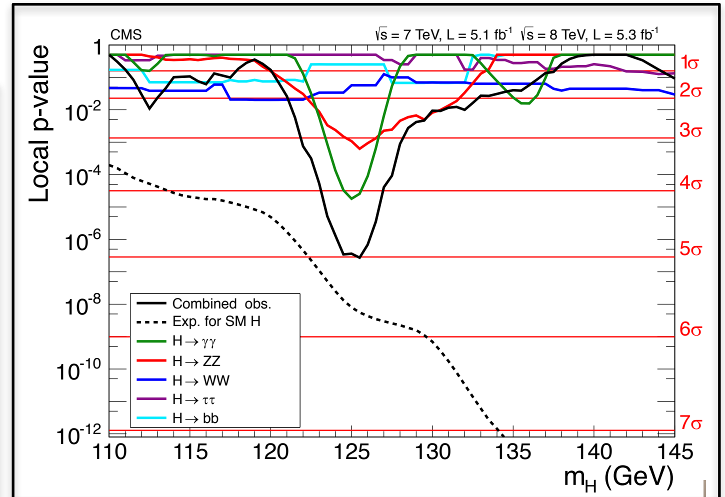
After **SSB**, remaining degrees of freedom manifest as a massive boson … **The Higgs**

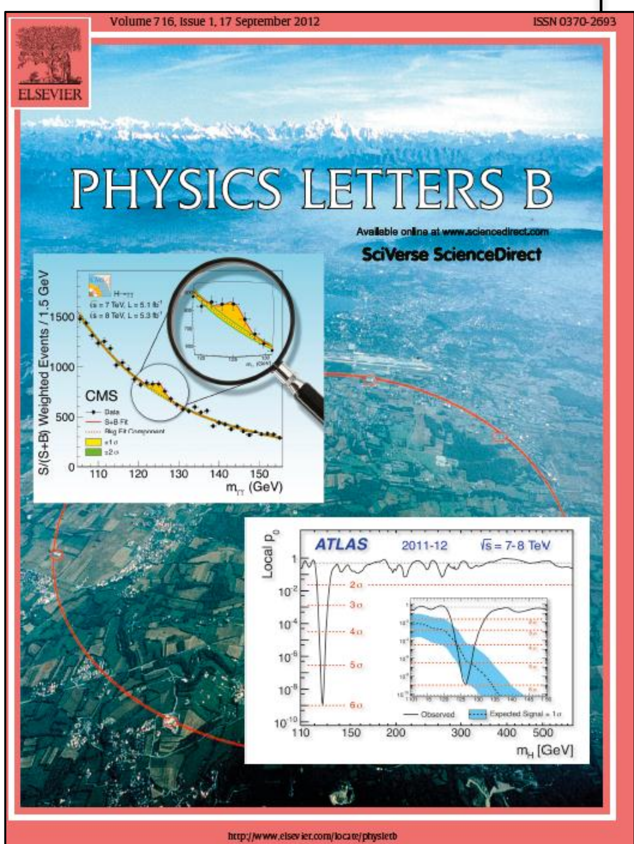
Yukawa couplings provide masses for fermions

Higgs couplings to fermions and bosons are proportional to their mass.

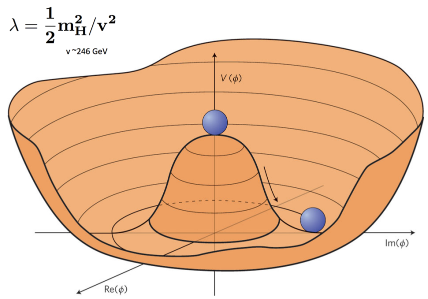
Discovery of a New Particle!







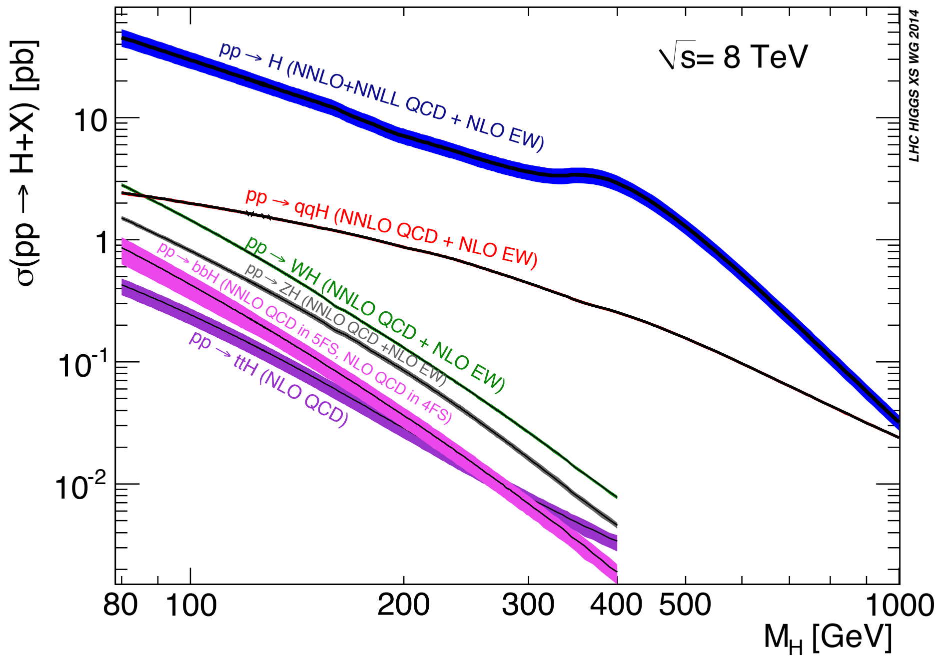
A Massive Problem

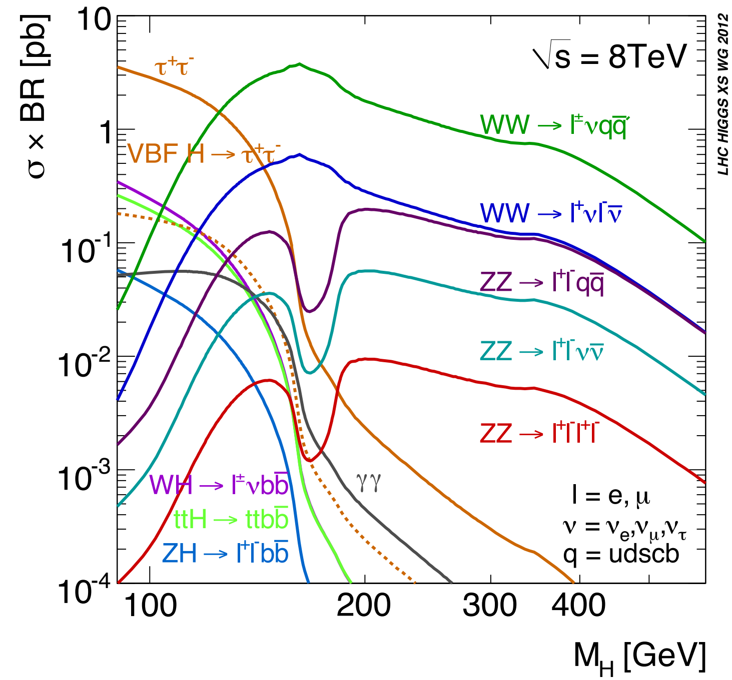


The mass of the Higgs boson is not predicted in the SM

→ **It's a free parameter of the theory**

If we know the mass, all of the Higgs boson couplings to SM particles (and hence **production x-sections** and **decay rates**) are defined …

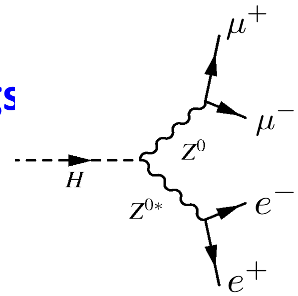


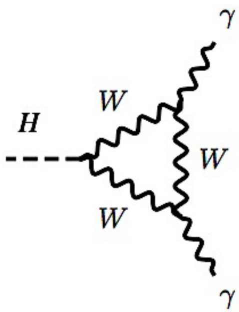


Measuring the mass allows for a precision test of the SM

A Massive Achievement

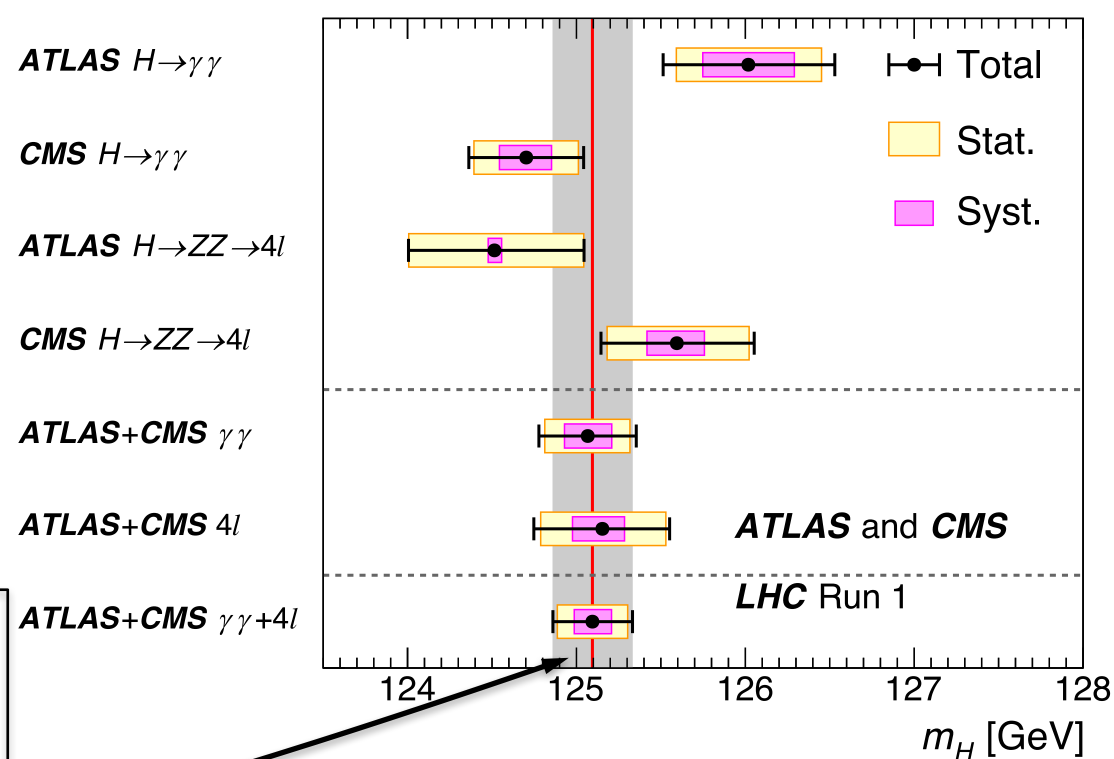
The mass of the Higgs boson is not predicted in the SM
→ **It's the only thing we really "measure" in the SM Higgs sector**





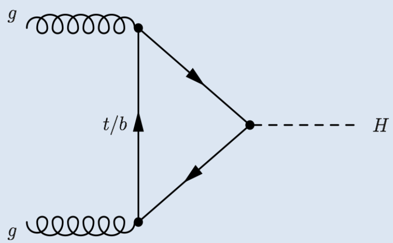
ATLAS and CMS combined measurement of the Higgs boson mass **<0.2% precision!**

M_H = 125.09 ± 0.24 GeV (±0.21 (stat) ±0.11(syst))

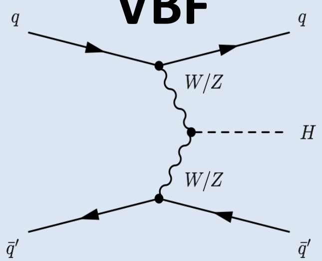


Higgs Production

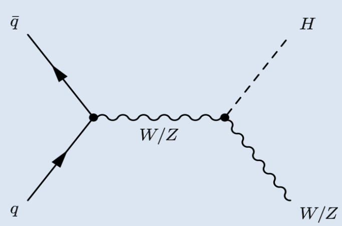
ggF

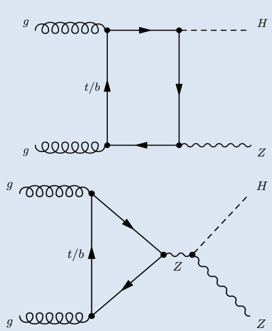


VBF



WH / ZH



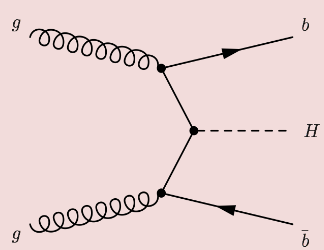


gg→ZH

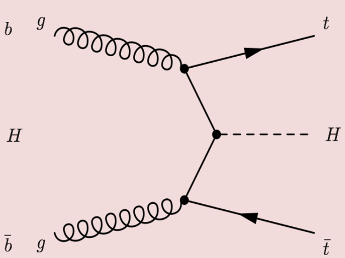
Decreasing cross-section

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)+~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)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

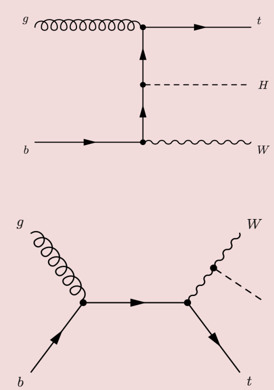
bbH



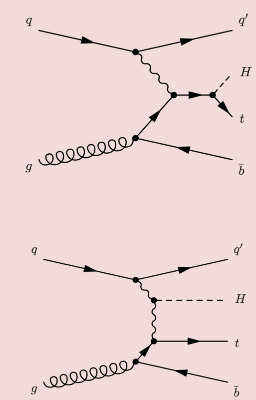
ttH



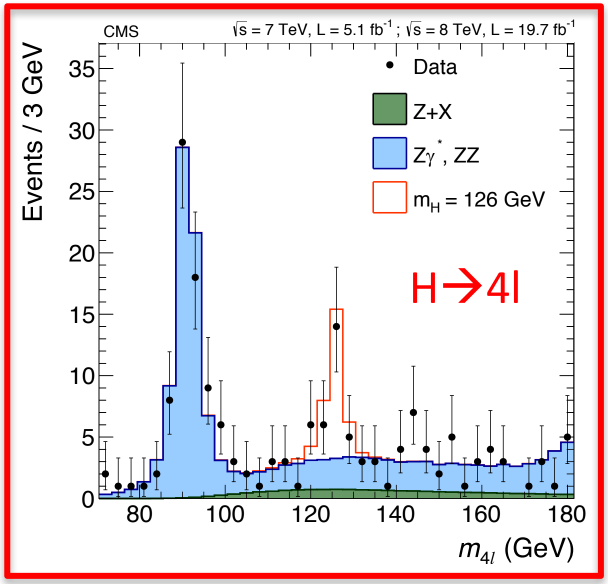
gb→tHW

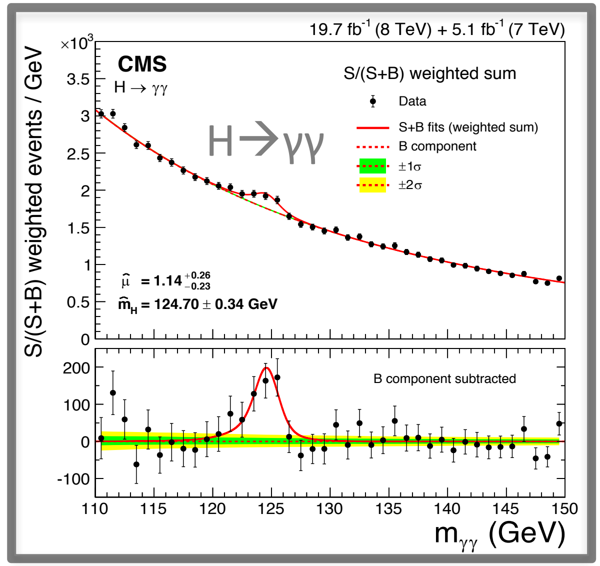


qg→tHq

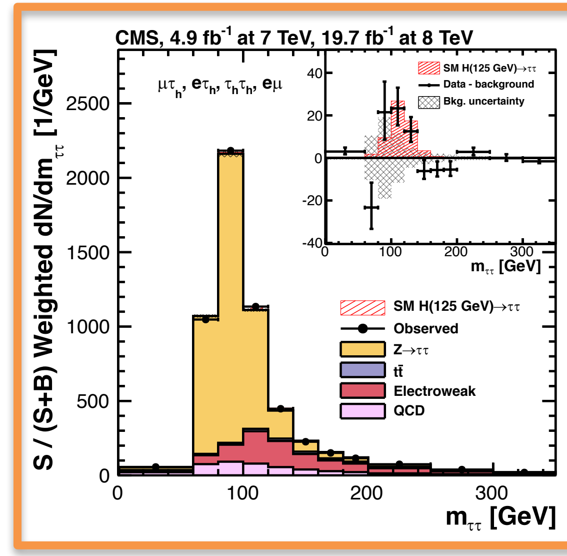


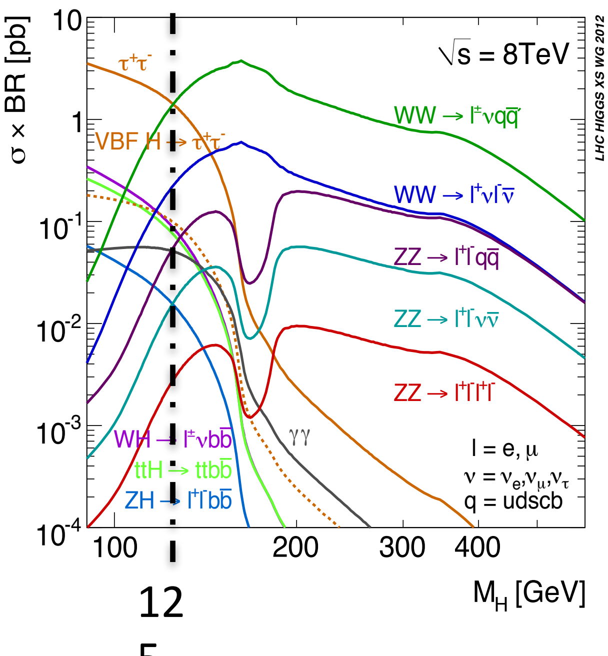
And Decay



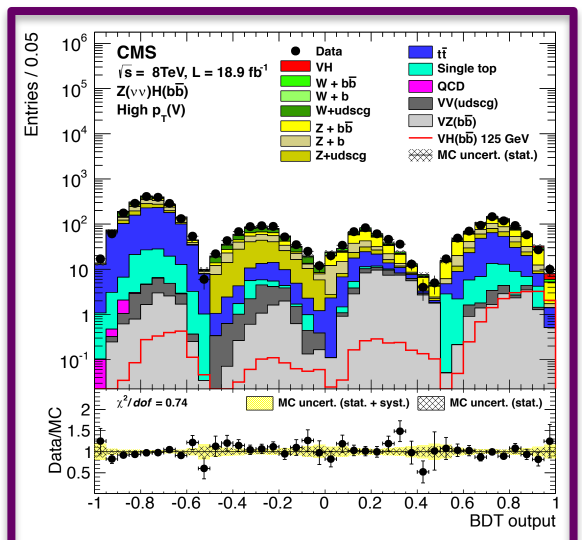


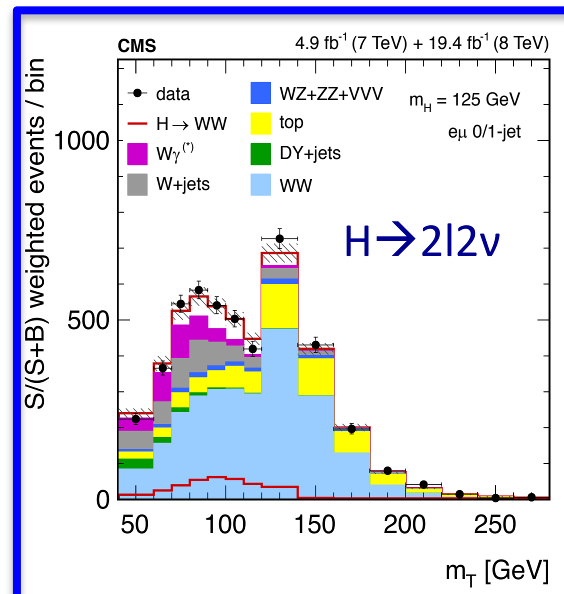
H→ττ





H→bb

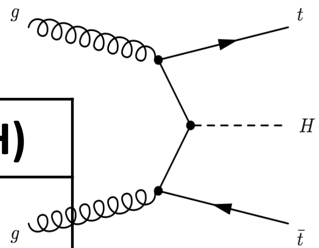




Inputs to the combination

Combination based on inputs from individual combination papers,
~5 fb^{-1} (7TeV) + 20 fb^{-1} (8TeV)

Analyses targeting specific production/decay tagging additional final state particles



	Untagged	VBF	VH	ttH(+tH)
H→γγ	✓	✓	✓	✓
H→ZZ→4l	✓	✓	✓	✓
H→WW→2l2ν	✓	✓	✓	✓
H→ττ	✓	✓	✓	✓
H→bb	✗	✗	✓	✓
H→μμ	✓	✓	✗	✗

ATLAS : ***arXiv:1507.04548***
CMS : ***EPJC 75 (2015) 212***

Note// expect small changes from individual analyses due to small updates and change in m_H

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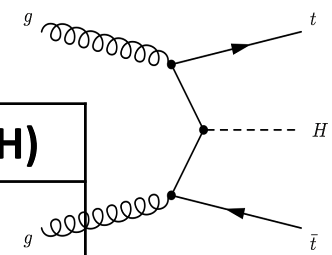

Backgrounds too large (CMS VBF H→bb out too late for combination)

		VBF	VH	ttH(+tH)
		✓	✓	✓
H→ZZ→4l	✓	✓	✓	
H→WW→2l2ν	✓	✓	✓	
H→ττ	✓	✓	✓	✓
H→bb	✗	✗	✓	✓
H→μμ	✓	✓	✗	✗

Signal rate too low with current luminosity

H→Zγ (ATLAS) and H→inv (CMS) included in individual combinations but not this combination

ATLAS : ***arXiv:1507.04548***
CMS : ***EPJC 75 (2015) 212***

Note// expect small changes from individual analyses due to small updates and change in m_H

Breaking down the Likelihood

We use the **Likelihood** formalism to interpret the combined datasets from all channels ….

$$L(D|\boldsymbol{\mu},\boldsymbol{\theta}) = \prod_{n} Prob\left(d_n|\sum_{i,f}\mu_i\mu^f S^f_{i,n}(\boldsymbol{\theta}) + \sum_{k} B_k(\boldsymbol{\theta})\right) \times Gauss(\tilde{\boldsymbol{\theta}}|\theta)$$

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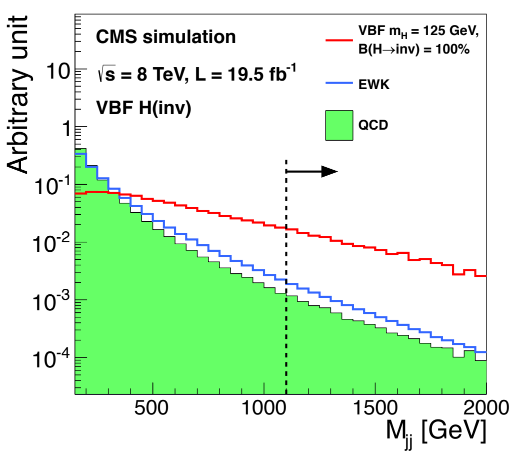
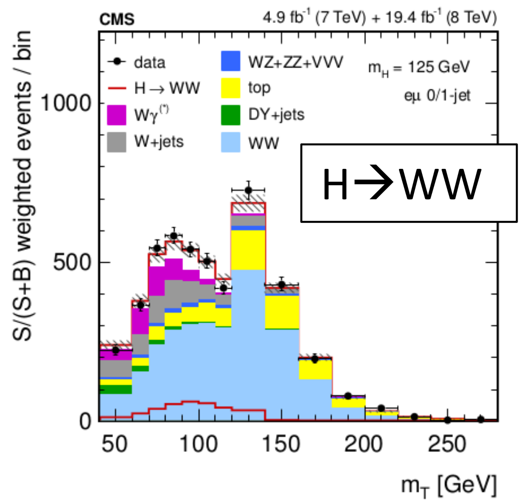
Likelihood defined for a given dataset. Each data point can be …

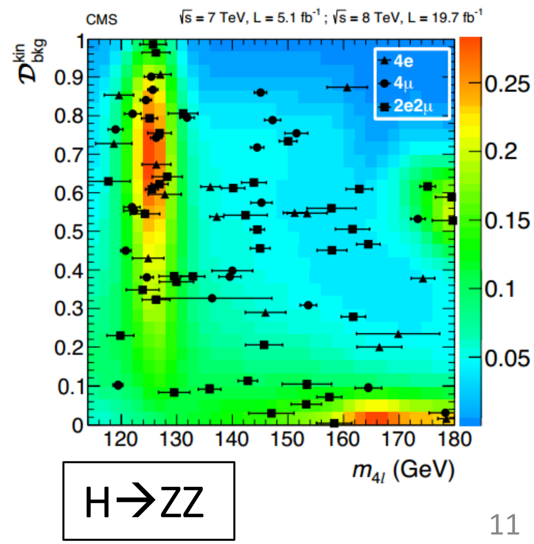
Event counts after some selection





Number of events in a given bin of some distribution

Values of the observables used to separate signal and background



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Parameters of interest are "**signal strengths**":

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

Standard model defined by: $\boldsymbol{\mu}_i = \boldsymbol{\mu}^f = 1$

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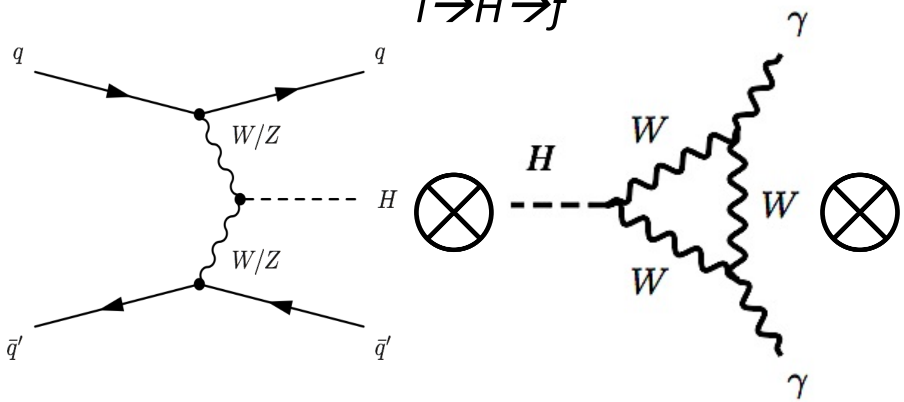
i→H→f



Theory inputs for the production cross-sections (NNLO(QCD)+NLO(EWK) for major processes) and decay (+uncertainties as norm scale-factors)

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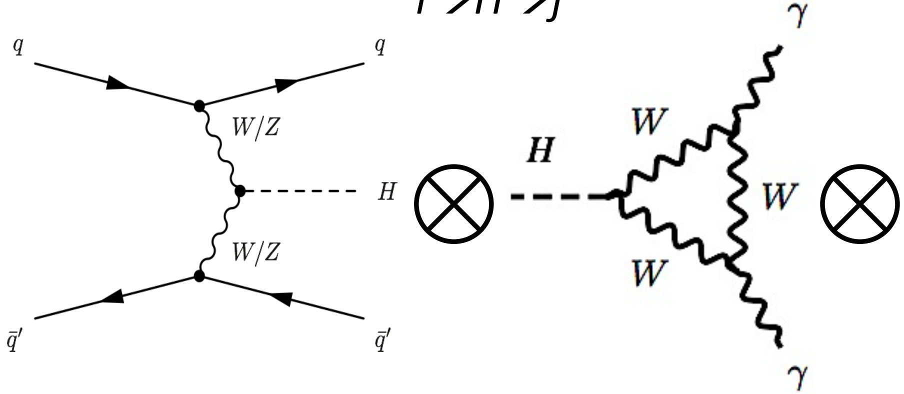
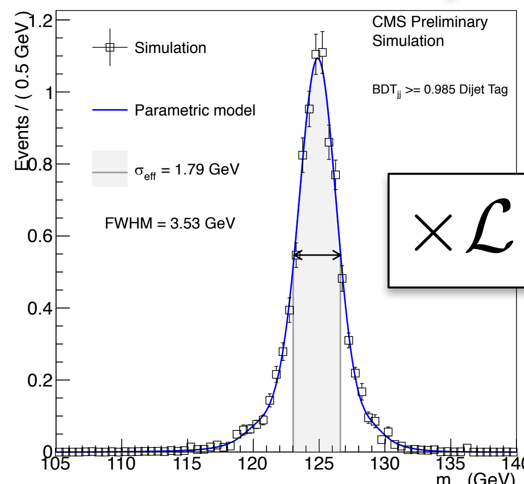
$i \rightarrow H \rightarrow f$





$$\times \mathcal{L} \times \varepsilon \times A$$

Theory inputs for the production cross-sections (NNLO(QCD)+NLO(EWK) for major processes) and decay (+uncertainties as norm scale-factors)

Input from experiment; luminosity, efficiencies and acceptances, energy resolution…

Breaking down the Likelihood

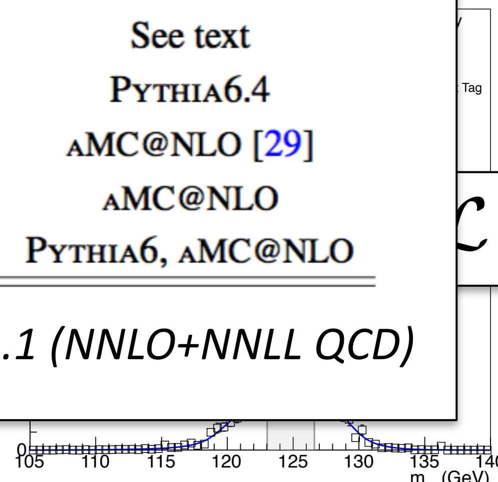
SM Higgs MC to calculate acceptance in each channel (V-p_T, n-jets etc)

Production process	Event generator	
	ATLAS	CMS
ggF*	POWHEG [30–34]	POWHEG
VBF	POWHEG	POWHEG
WH	PYTHIA8 [35]	PYTHIA6.4 [36]
ZH ($qq \to ZH$ or $qg \to ZH$)	PYTHIA8	PYTHIA6.4
$ggZH$ ($gg \to ZH$)	POWHEG	See text
ttH	POWHEL [44]	PYTHIA6.4
tHq ($qb \to tHq$)	MADGRAPH [46]	aMC@NLO [29]
tHW ($gb \to tHW$)	aMC@NLO	aMC@NLO
bbH	PYTHIA8	PYTHIA6, aMC@NLO

**Higgs pT distribution for ggF production with HRes2.1 (NNLO+NNLL QCD)*

all channels ....

$$\times\ Gauss(\tilde{\boldsymbol{\theta}}|\theta)$$



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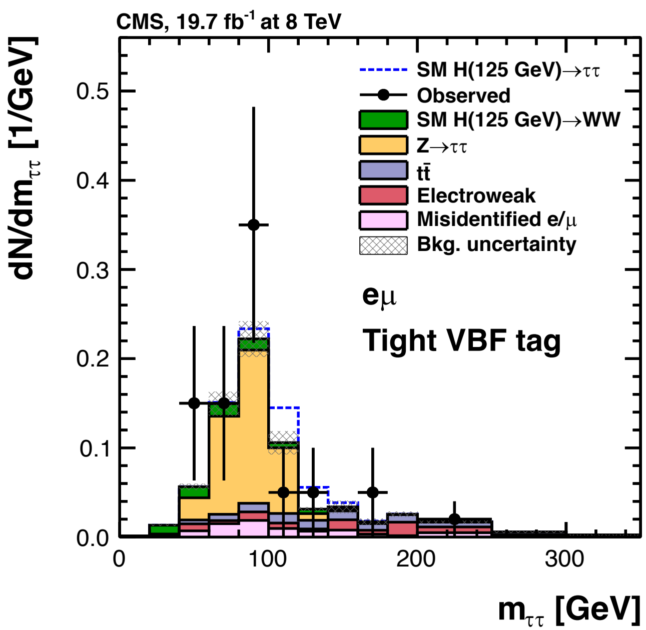
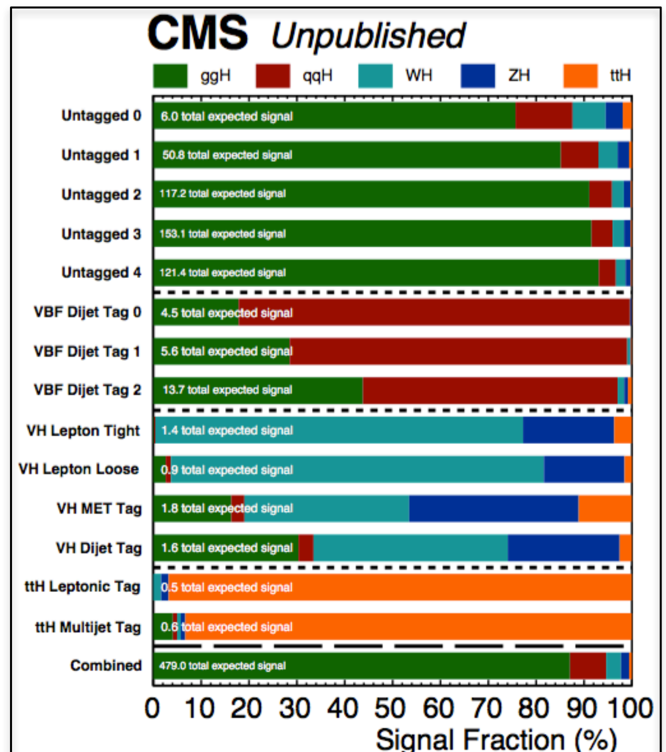
Categorization is never 100% pure
→ Sum over different production and decays which contribute in a given bin/category



CMS H→ττ analysis

CMS H→γγ analysis



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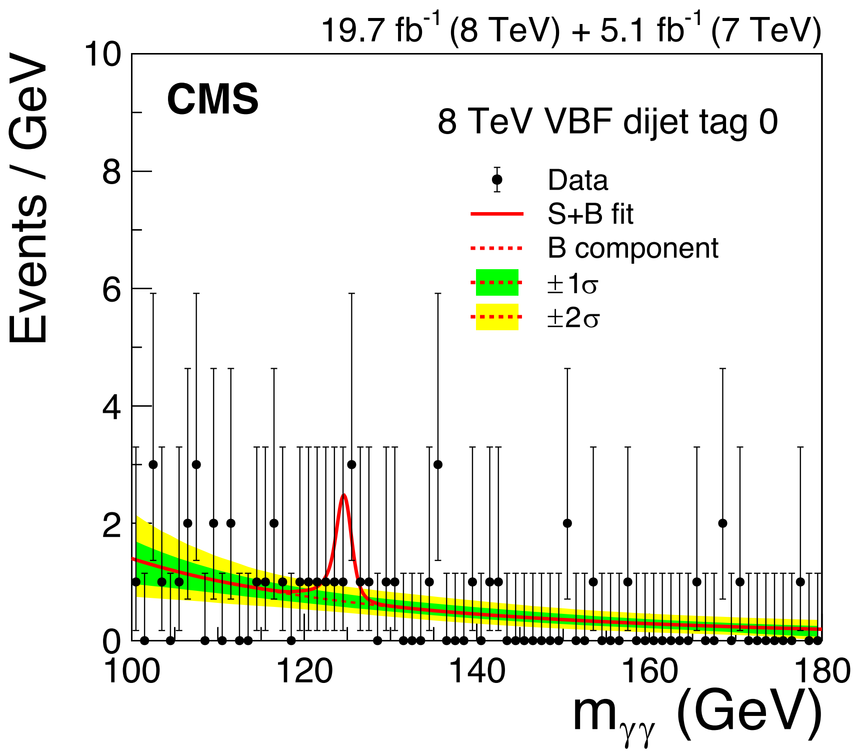
Majority of backgrounds are data-driven (control regions, sidebands…)

For channels using an "unbinned" likelihood …

$$B_k(\boldsymbol{\theta}) \rightarrow B_k(\boldsymbol{x},\boldsymbol{\theta}),$$
$$S^f_{i,n}(\boldsymbol{\theta}) \rightarrow S^f_i(\boldsymbol{x},\boldsymbol{\theta})$$



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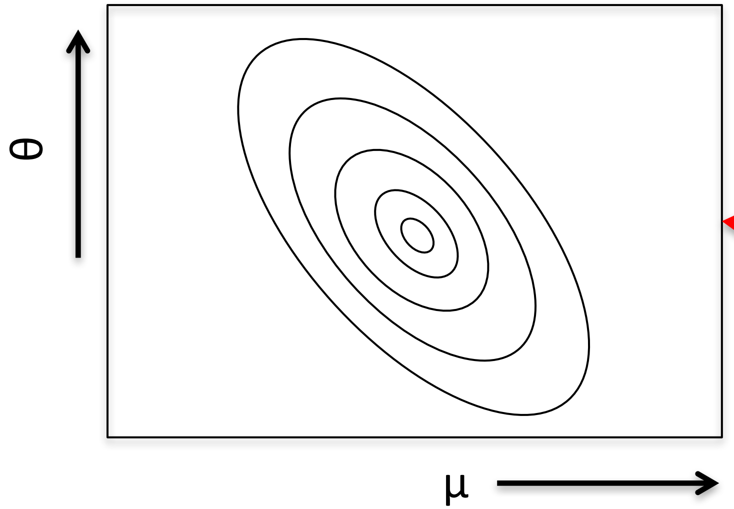

Systematic uncertainties are accounted for via (un-)constrained nuisance parameters in the likelihood…

Majority of (signal theory) systematics treated as log-normal scale-factors on the nominal yields, eg QCD scale.

$$S(\theta) = S_0(1+\frac{\delta S}{S_0})^{\theta}$$

Other systematics can be more complex, varying shapes or propagated through to signal yield
Eg uncertainties on partial widths → BR uncerts

$$BR^f(\boldsymbol{\theta}) = \Gamma^f(\boldsymbol{\theta})/\sum_f \Gamma^f(\boldsymbol{\theta})$$

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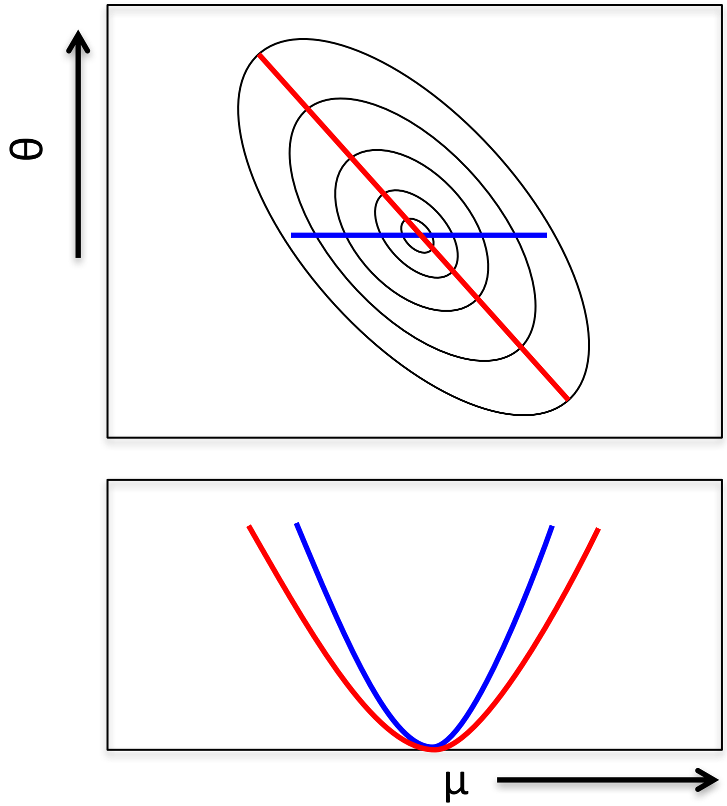


$$L(D|\boldsymbol{\mu},\boldsymbol{\theta}) \rightarrow L(D|\boldsymbol{\mu},\hat{\hat{\boldsymbol{\theta}}})$$

Systematic uncertainties are accounted for via (un-)constrained nuisance parameters in the likelihood…

These nuisance parameters are “profiled” (fit) when scanning the physics parameters.

Nuisances uncorrelated with physics measurements naturally have no effect.

Experimental and theoretical systematics treated under same paradigm

Breaking down the Likelihood

Profiled likelihood test-statistic used to report measurements with uncertainties

$$q_{\boldsymbol{\mu}} = -2Log(\Lambda)$$

$$\Lambda = \frac{L(D|\boldsymbol{\mu}, \hat{\hat{\boldsymbol{\theta}}})}{L(D|\hat{\boldsymbol{\mu}}, \hat{\boldsymbol{\theta}})}$$

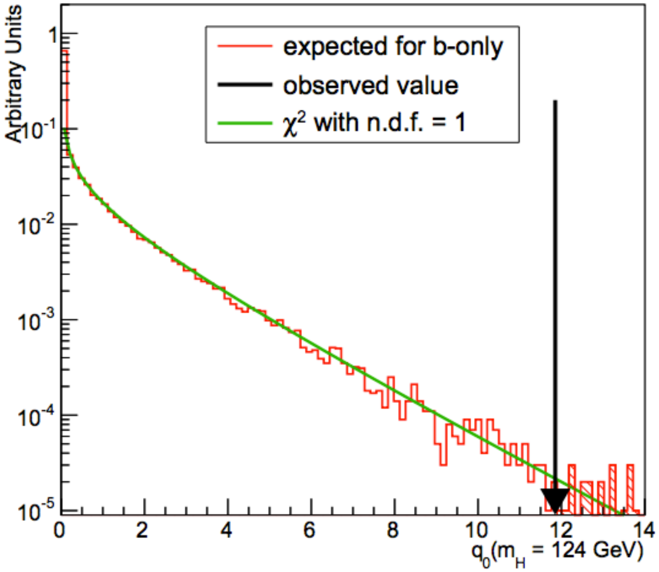
Central values from values of $\boldsymbol{\mu}$ which maximize the likelihood.

$\boldsymbol{q_\mu}$ is distributed according to χ^2 with # d.o.f = number of POI* under the null hypothesis (**μ**)

→ 1D(2D), 68% intervals determined as values for which $\boldsymbol{q_\mu}$**=1(2.3)**

→ $\boldsymbol{q_0}$ distributed as $\delta(0) + \chi^2(1\text{ dof})$ under μ=0. Significance calculations,

$$Z = \sqrt{q_0}$$



*in the asymptotic regime G. Cowan, K. Cramner, E. Gross, O. Vitells

Breaking down the Likelihood

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$$q_{\mu} = -2Log(\Lambda)$$

$$\Lambda = \frac{L(D|\boldsymbol{\mu}, \hat{\hat{\boldsymbol{\theta}}})}{L(D|\hat{\boldsymbol{\mu}}, \hat{\boldsymbol{\theta}})}$$

☺ Powerful test-statistic, best use of data to constrain unknowns (θ)

→ Use control regions / sidebands in data to simultaneously constrain nuisance parameters and parameters of interest

☺ Easy to combine many channels across both experiments

→ Around 600 channels in ATLAS+CMS combination, product of likelihoods gives combined likelihood

☺ Nice Asymptotic properties

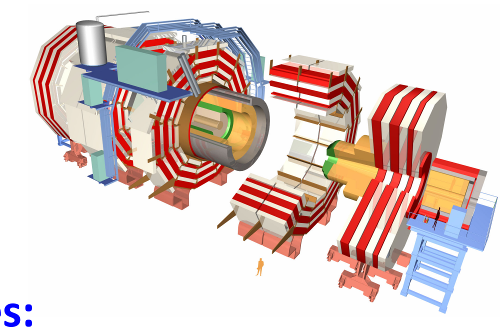
→ P-values, confidence intervals obtained without throwing toys

☹ Extremely intensive CPU

→ This combination has >4200 parameters! Takes some time to understand all of our fits

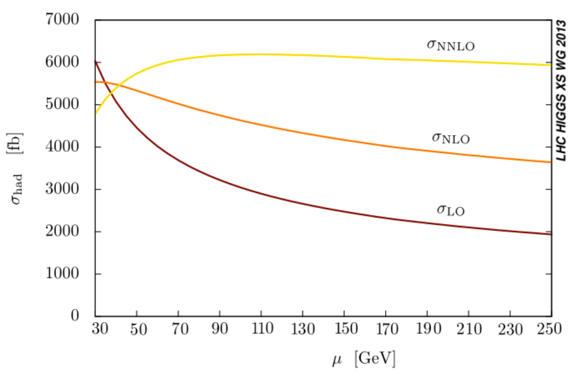
Systematic uncertainties

Combination consists of nearly 600 categories with a total of around **4200** nuisance parameters describing the composition of the different signal and backgrounds



Experimental/Detector systematics:

- Object efficiencies, energy scales, luminosity
- Largely uncorrelated between ATLAS and CMS*

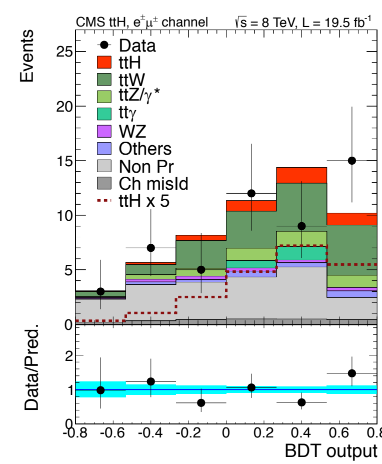


Signal theory uncertainties:

- Correlate inclusive x-section uncertainties, QCD scale, pdf, UEPS, Branching ratios, jet counting**
- De-correlate effects on object acceptance as these are often data-driven/estimation procedures generally differ

Background theory uncertainties:

- Often rather different phase-spaces considered for two experiments or data-driven estimates
- Mostly uncorrelated with few exceptions (gg/qqZZ continuum, ttW, ttZ X-sections)



*Partial correlation of common luminosity measurement
** Follow the recommendations of the LHC-HXSWG

One μ to scale them all

Simplest model (discovery model) is one overall scaling parameter

$$\mu := \mu_i = \mu_f$$
$$\forall i, f \in \{ttH, qqH, H \to ZZ, \ldots\}$$

	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)		$^{+0.14}_{-0.13}$	$^{+0.09}_{-0.09}$	$^{+0.05}_{-0.05}$	$^{+0.04}_{-0.03}$	$^{+0.08}_{-0.06}$

Fixing related nuisance parameters in scans reveals contributions from groups of systematic uncertainties

Theory uncert dominated by ggF incl. x-section

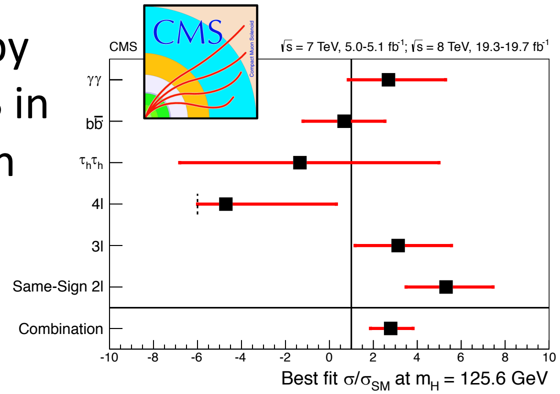
Uncertainty in theoretical calculations and statistical uncertainty similar in magnitude!

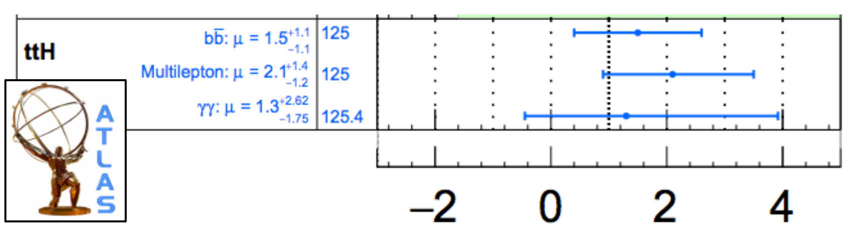
Signal strength by production

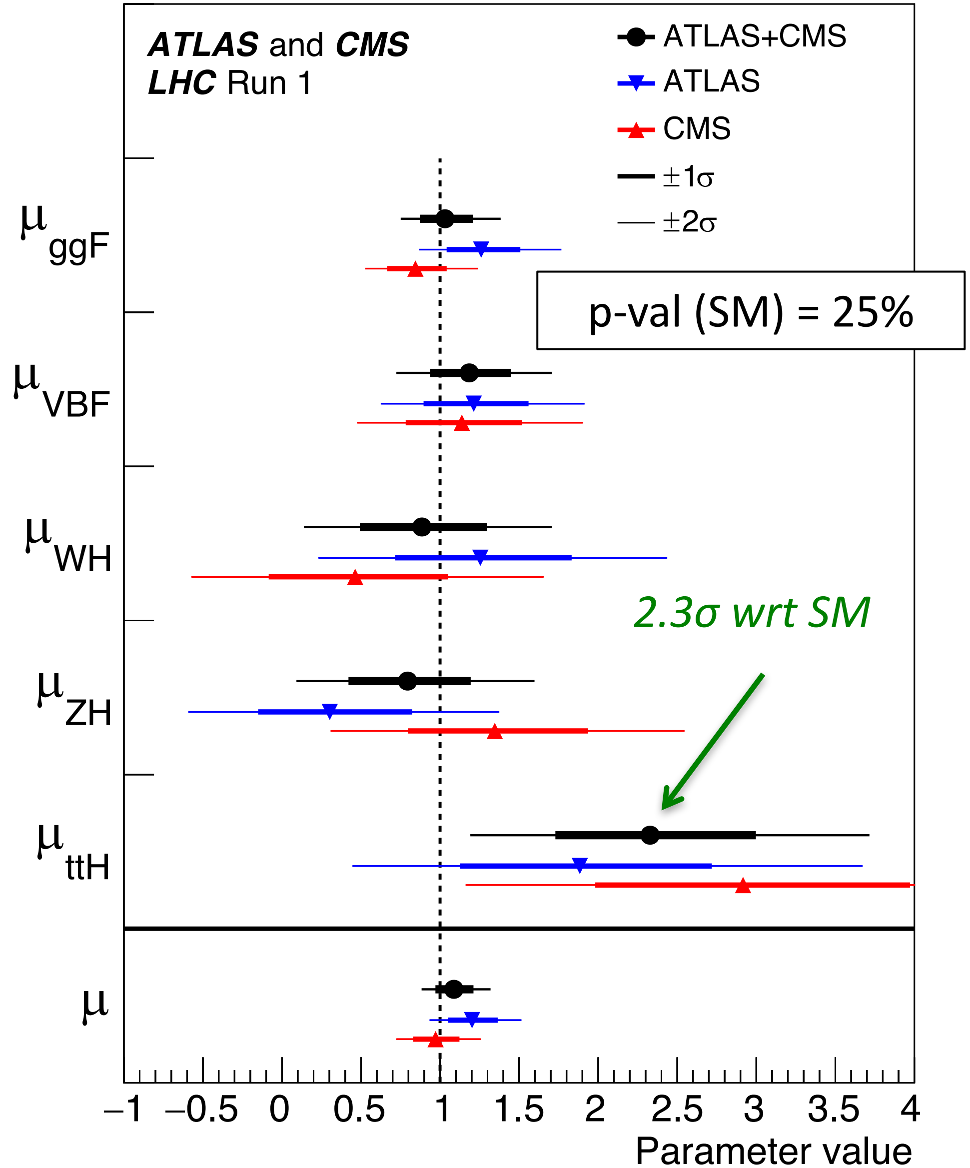
Individual signal strengths by major production modes

- bbH tied to ggF
- tH tied to ttH
- Fix BR to SM values

Excesses seen by ATLAS and CMS in ttH multi-lepton channel



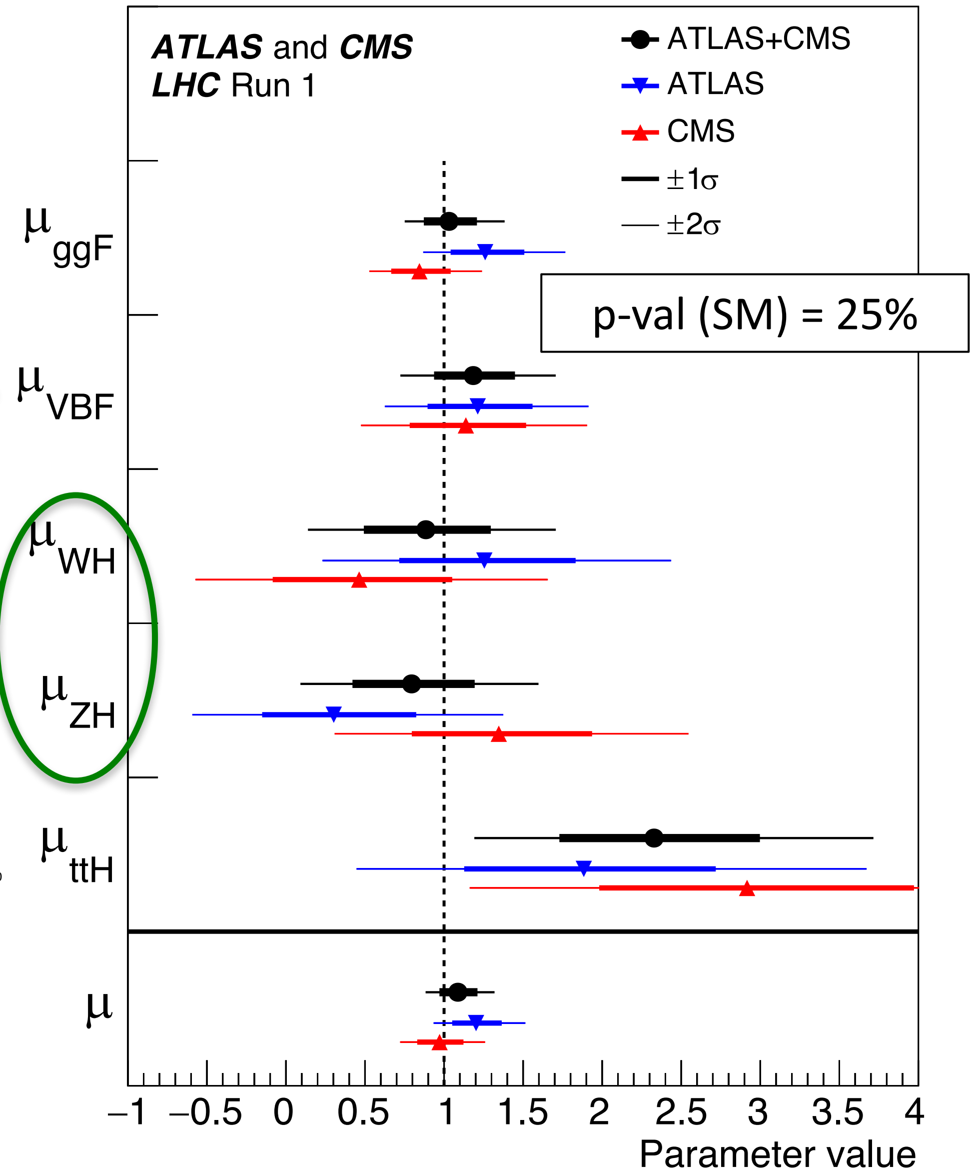




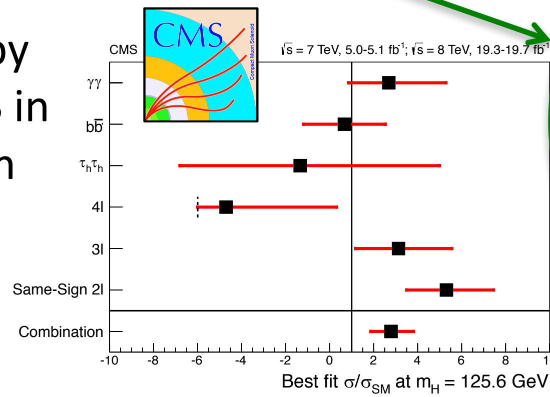
Signal strength by production

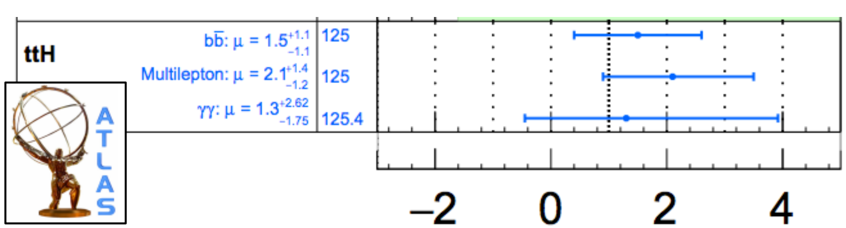
5.4σ for VBF production

>3σ for VH (W+Z) production

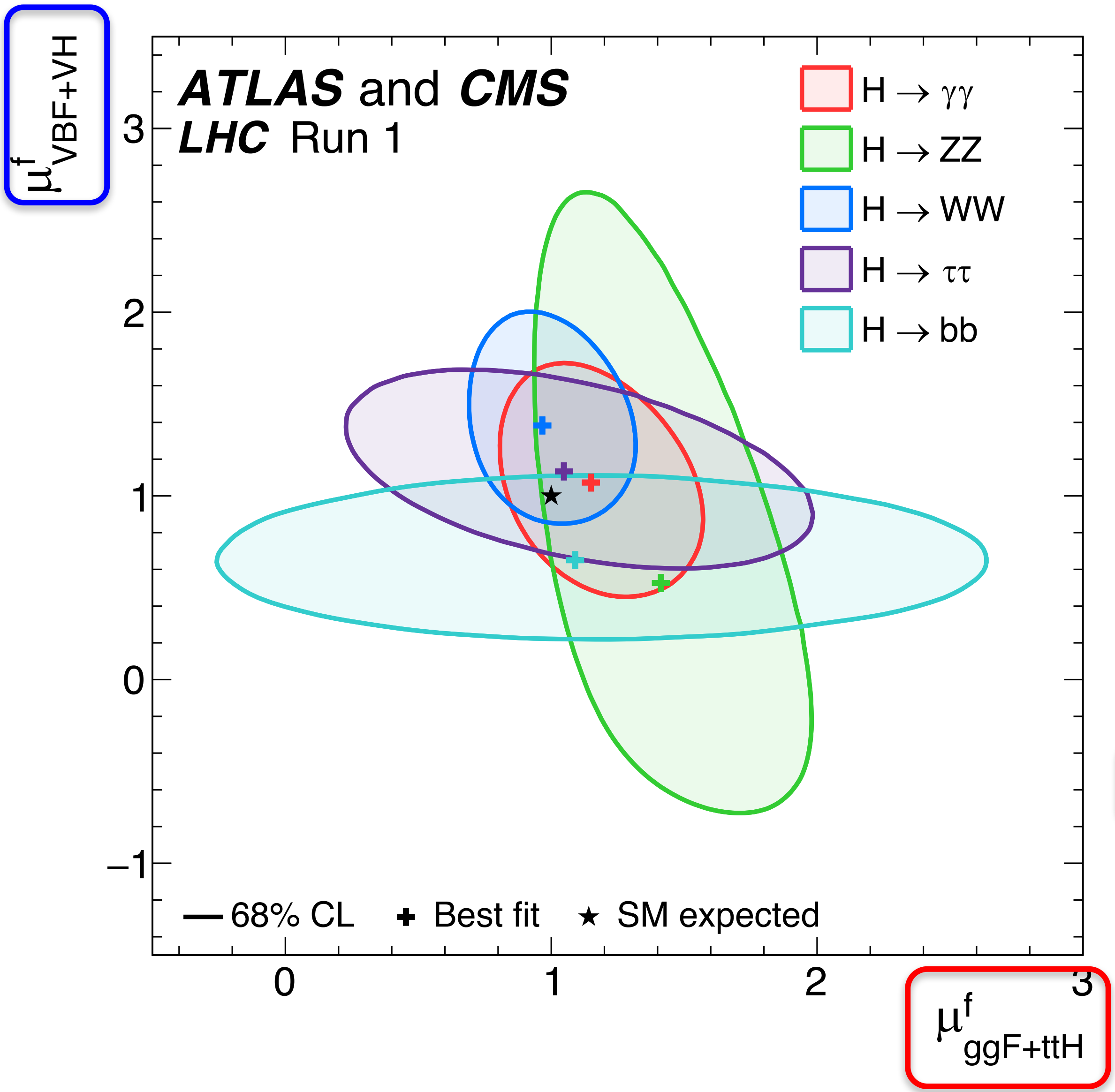


Excesses seen by ATLAS and CMS in ttH multi-lepton channel





Signal strength by production



Group fermionic and bosonic production and **fit by decay mode**

Relax assumptions on cross-sections and individual BRs

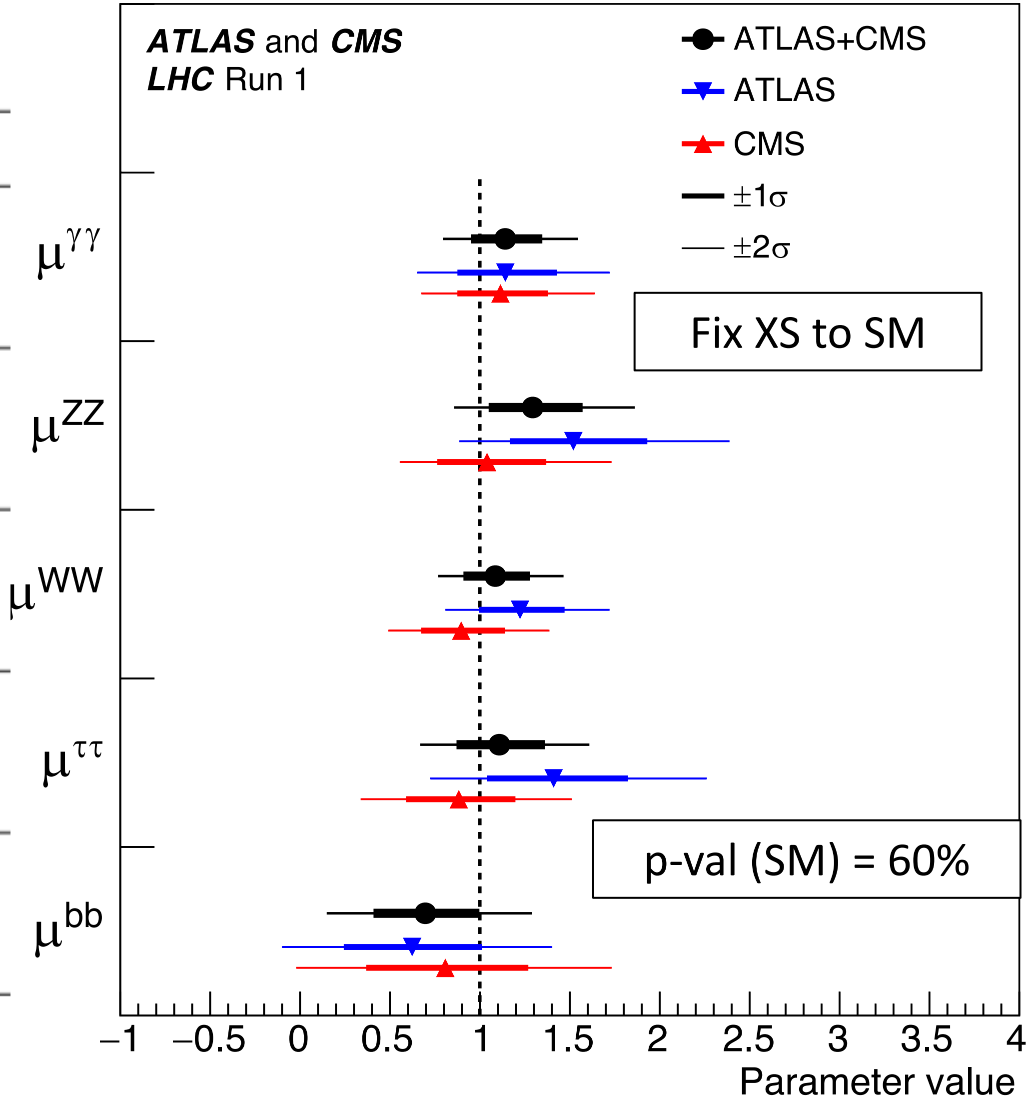
Measure the ratio of fermion to vector modes in combination **without** assumptions on individual decay modes

$$\mu_{\mathrm{VBF+VH}}/\mu_{\mathrm{ggF+ttH}} = 1.06^{+0.35}_{-0.27}$$

Signal strengths by decay

Observed (Expected) significances calculated by comparing likelihood at $\mu^f=0$ to best fit….

ATLAS	CMS
5.0 (4.6)	5.6 (5.1)
7.6 (5.6)	7.0 (6.8)
6.8 (5.8)	4.8 (5.6)
4.4 (3.3)	3.4 (3.7)
1.7 (2.7)	2.0 (2.5)



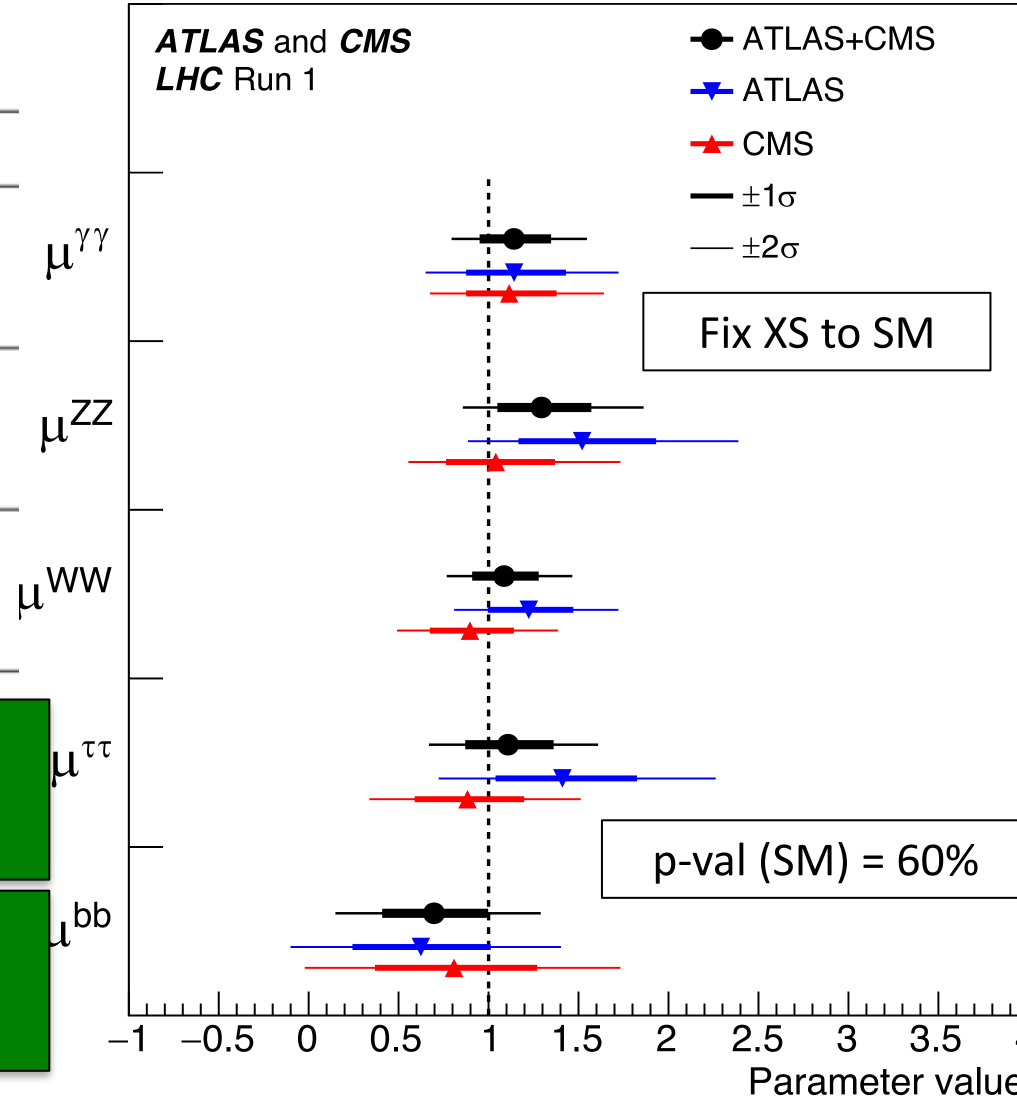
Signal strengths by decay

Combination gives >5σ for Higgs decay to taus!

ATLAS	CMS
5.0 (4.6)	5.6 (5.1)
7.6 (5.6)	7.0 (6.8)
6.8 (5.8)	4.8 (5.6)

5.5 (5.0)

2.6 (3.7)

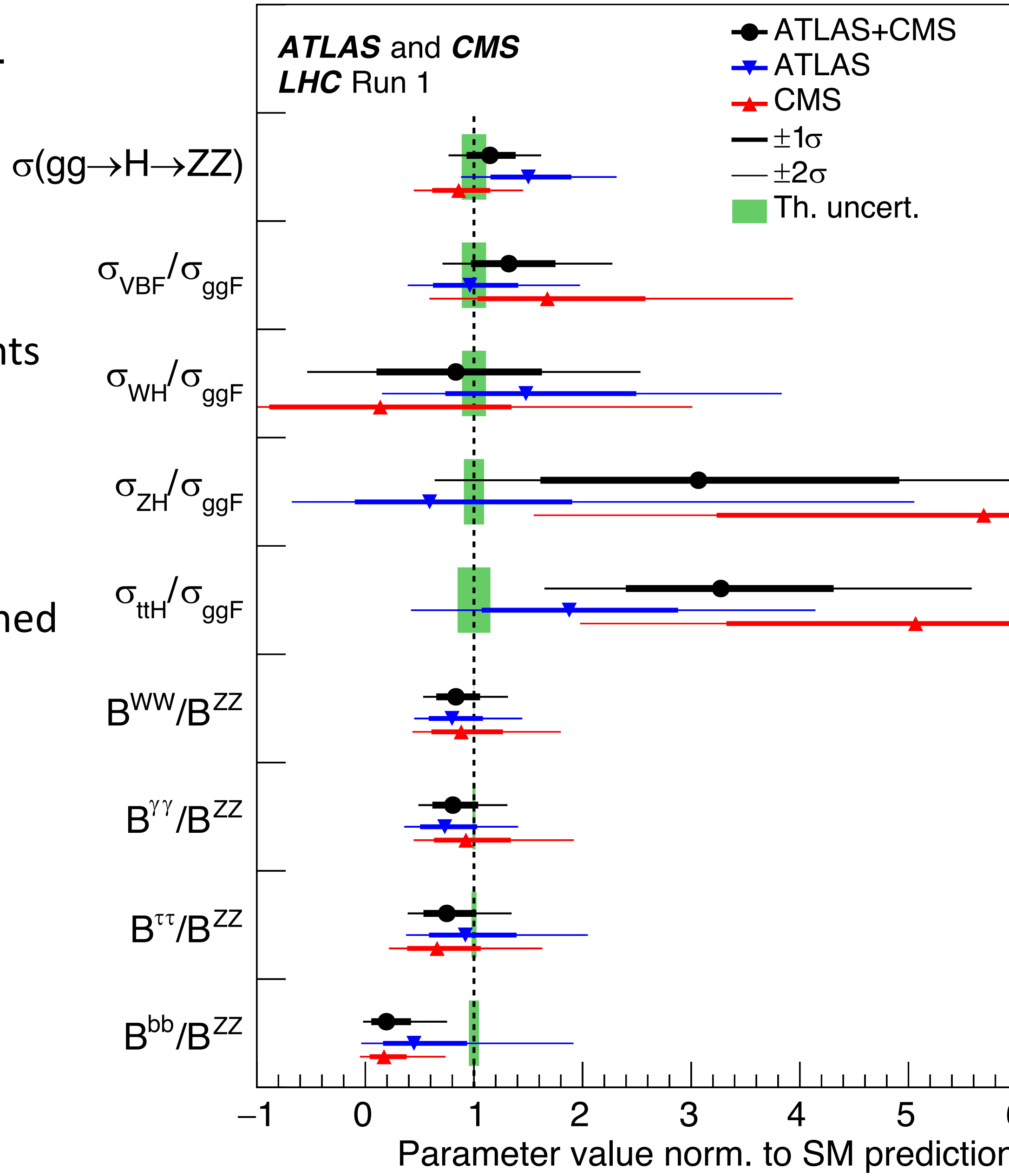


Generic Model

Generic model in terms of ratios of cross-sections and branching ratios

Provides summary of Higgs constraints with **minimal assumptions** and maximal cancellation of theoretical uncertainties.

Allow for re-interpretation of combined data with improved theoretical calculations*

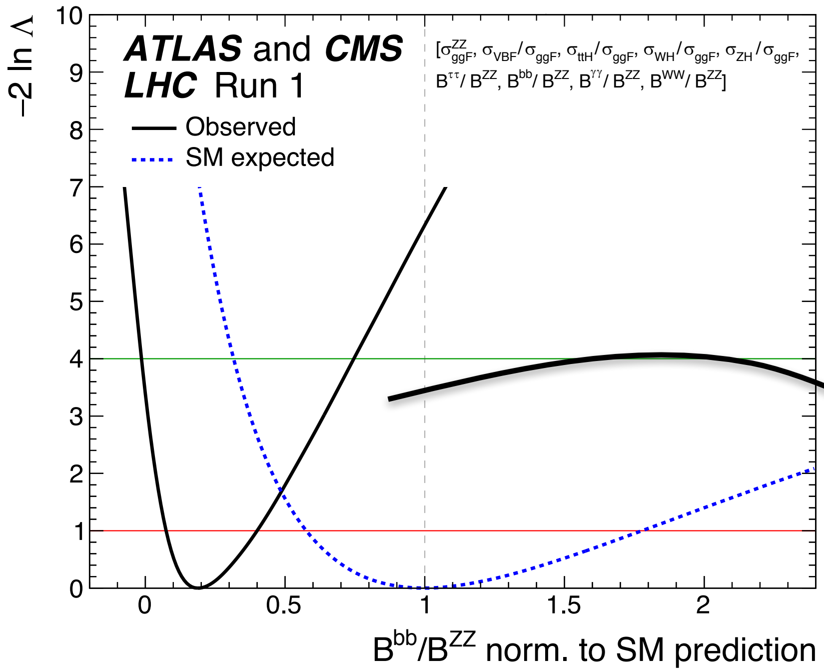


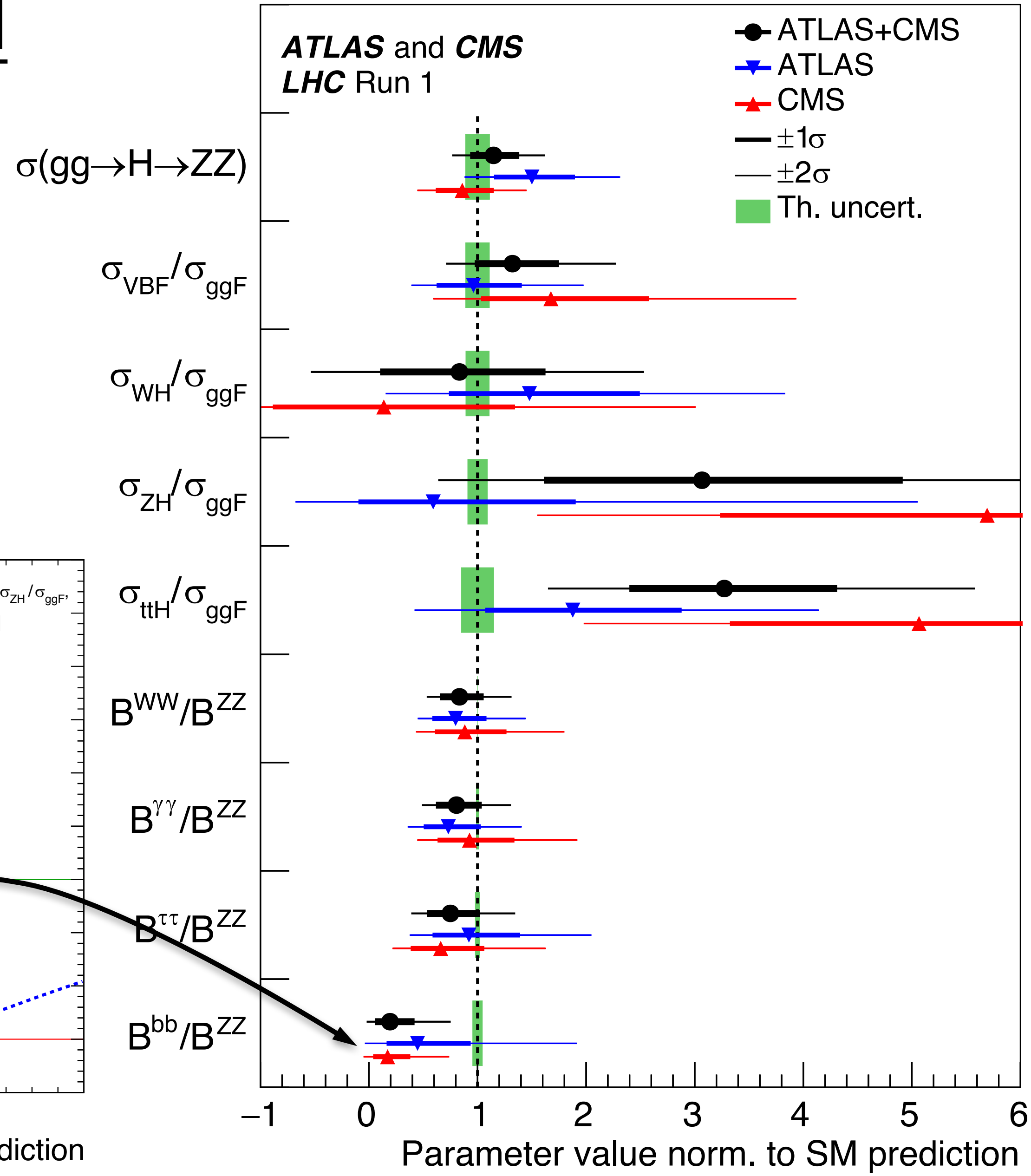
**Covariance matrix provided*

Generic Model

Largest discrepancy seen in BR(bb)/BR(ZZ) at 2.4σ wrt SM

Driven by combination of high ttH→leptons + ZH→ZZ, low VH→bb (while ttH→bb is not high)





Covariance matrix to be provided with paper submission

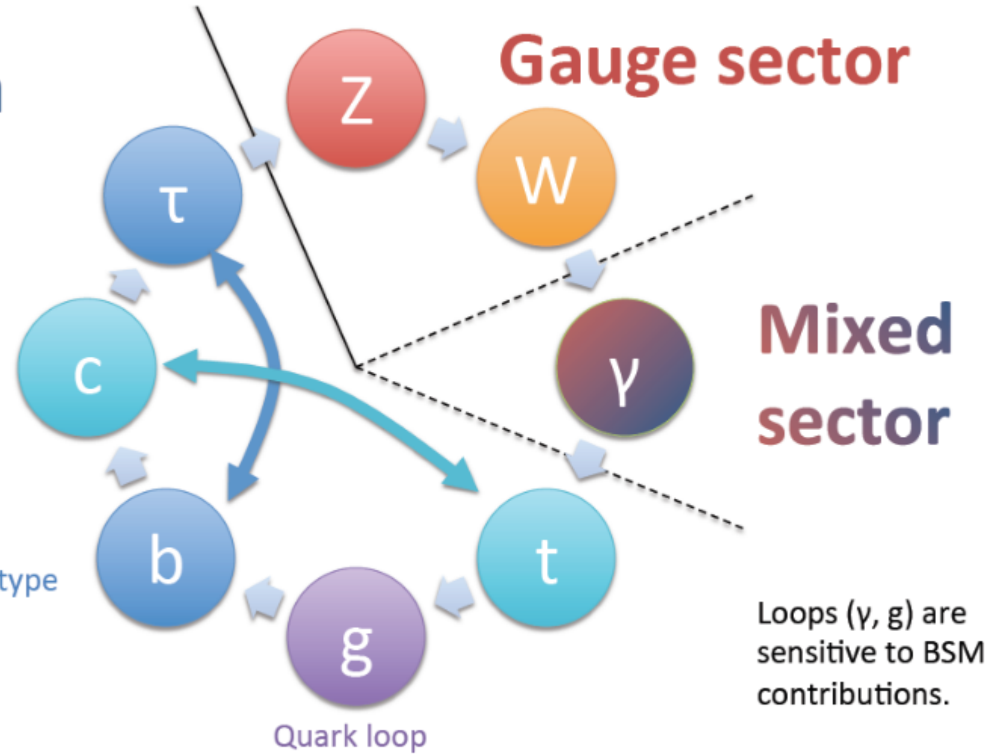
Couplings Framework

Production and decay rates connected through LO coupling modifier framework...

Scale Higgs boson (tree level) couplings by modifiers **κ**

$$\mu \to \mu(\boldsymbol{\kappa})$$

Loop induced processes can either be **resolved** or treated as **effective couplings**



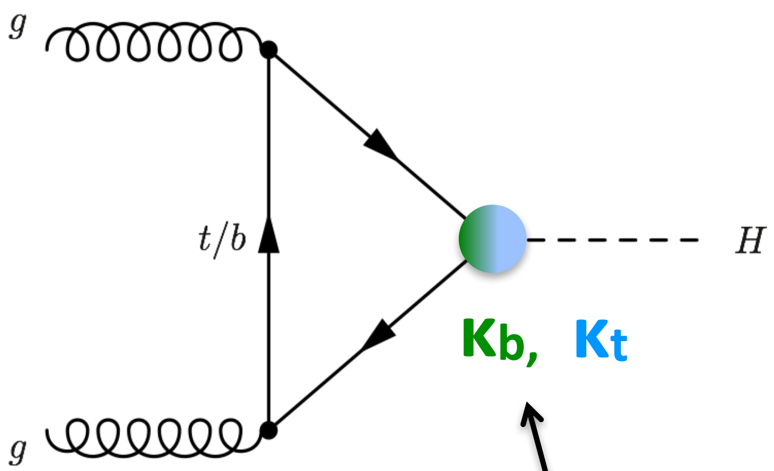
We don't measure the couplings of the SM (they aren't inputs to the theory) but we can test compatibility ⟶ **SM: =** $\boldsymbol{\kappa} = 1$

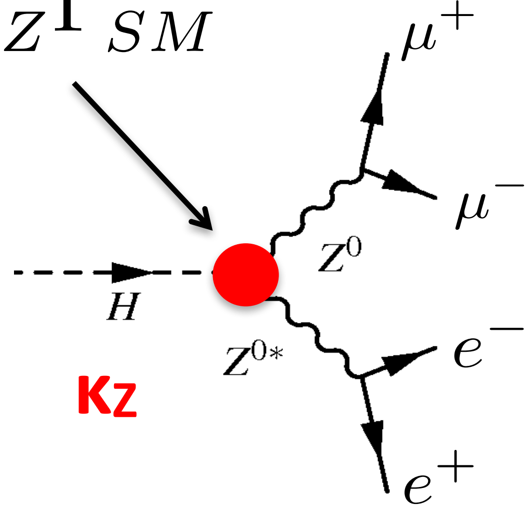
Couplings Framework

Scale production cross-sections and partial widths according to coupling modifiers

Example, ggF production H→ZZ

$$\Gamma^{ZZ} = \kappa_Z^2 \Gamma^{ZZ}_{SM}$$





$$\sigma_{ggF} = (1.06\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_b\kappa_t) \times \sigma_{ggF}^{SM}$$

Coefficients depend on mH and kinematic selection

Couplings Framework

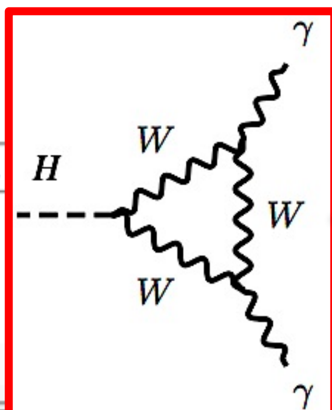
Production	Loops	Interference	Multiplicative factor	
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim$	κ_W^2
$\sigma(qq/qg \to ZH)$	–	–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

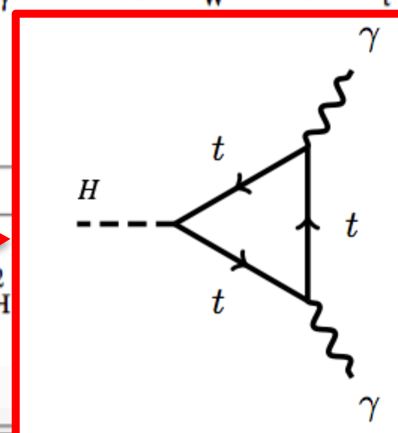
Couplings Framework

Production	Loops	Interference	Multiplicative factor
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
		–	$\sim \kappa_W^2$
		–	$\sim \kappa_Z^2$
		$Z-t$	$\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
		–	$\sim \kappa_t^2$
		$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
		$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
Partial decay width			
Γ^{ZZ}	–	–	$\sim \kappa_Z^2$
Γ^{WW}	–	–	$\sim \kappa_W^2$
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$		–	
Γ^{bb}		–	
$\Gamma^{\mu\mu}$		–	
Total width			
Γ_H		–	κ_H^2 … $+ 0.09 \cdot \kappa_g^2 +$ … $+ 0.03 \cdot \kappa_c^2 +$ … $6 \cdot \kappa_{Z\gamma}^2 +$ … $22 \cdot \kappa_\mu^2$

Interference in some processes gives sensitivity to relative signs

Since all interferences involve the t-quark, we choose $k_t>0$ w.l.o.g





Couplings Framework

Total width (Γ) scales all observed cross-sections.

$$\sigma(i \to H \to f) = \sigma_i(\boldsymbol{\kappa}) \cdot \frac{\Gamma^f(\boldsymbol{\kappa})}{\Gamma_H}$$

Direct constraints on Γ_H are too weak* to be meaningful so need to make assumptions in order to interpret cross-sections in terms of couplings. Introduce total width modifier $\boldsymbol{\kappa_H}$

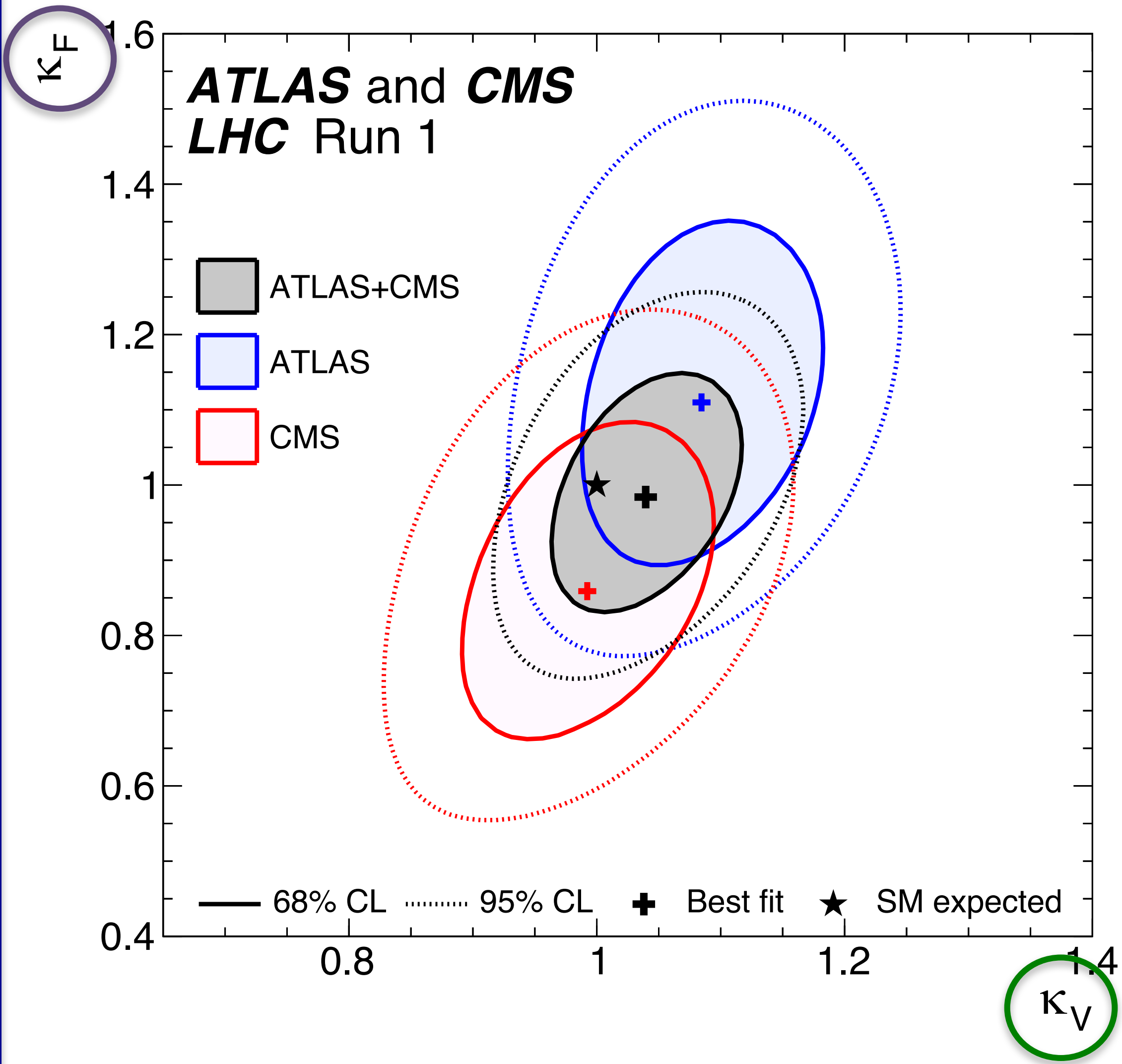
Eg, in absence of BSM decays, assume overall scaling of SM width

$$\Gamma_H^f(\boldsymbol{\kappa}) = \kappa_H^2(\boldsymbol{\kappa}) \cdot \Gamma_H^{SM}$$

Production	Loops	Interference	Multiplicative factor
Γ^{bb}	–	–	$\sim \kappa_b^2$
$\Gamma^{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
Total width for $BR_{BSM} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

*NB, upper limit on width ~2. GeV from direct measurements

Couplings to fermions and bosons



Extended Higgs sector models allow for non-SM couplings to fermions and bosons.

Assume universal coupling modifiers for vector boson (k_V) and fermion (k_F) couplings

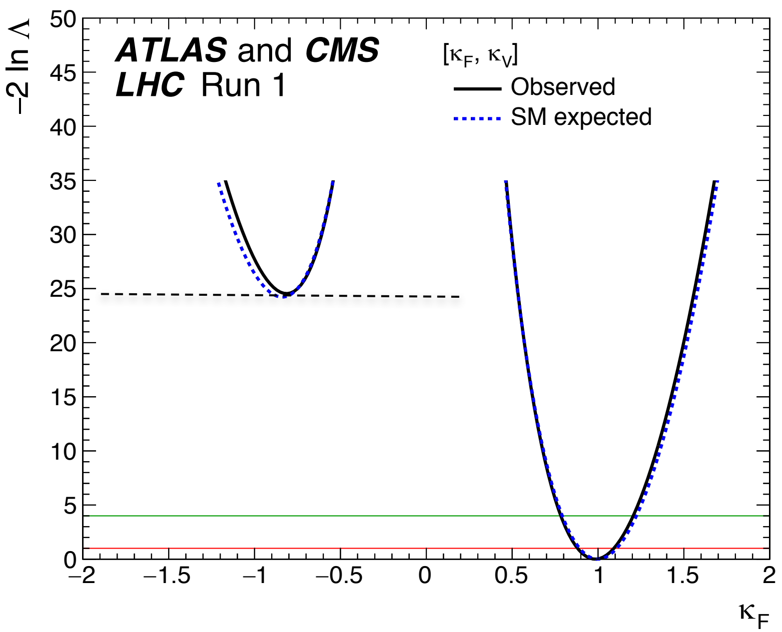
In 2HDM (type-1) tree level couplings scale with mixing angles

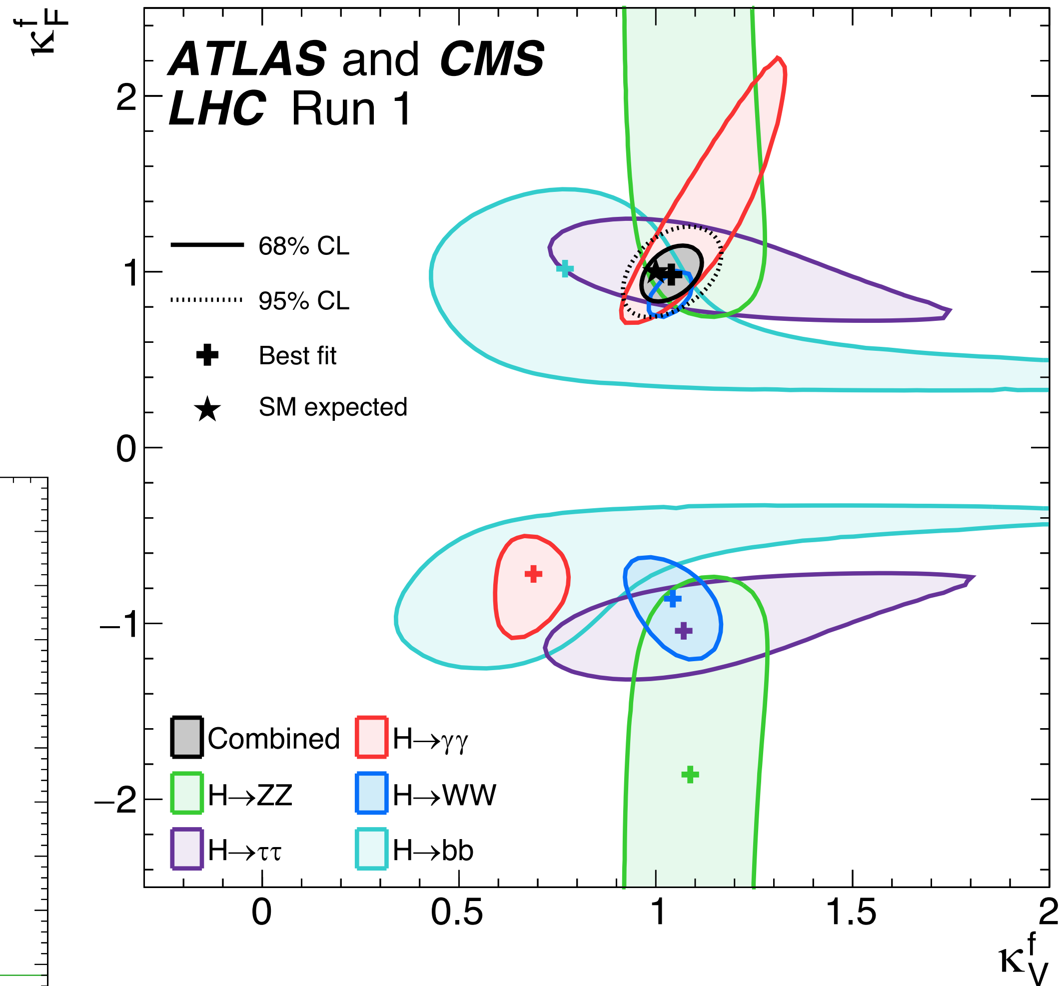
$$\kappa_V = \sin(\beta - \alpha)$$
$$\kappa_F = \cos\alpha / \sin\beta$$

Couplings to fermions and bosons

Individual decay channels are largely insensitive to relative sign of fermion coupling

- ggZH/qqZH interference can be seen in H→bb channel
- Combination resolves sign. Negative sign dis-favoured at nearly 5σ





Tree Level Higgs couplings

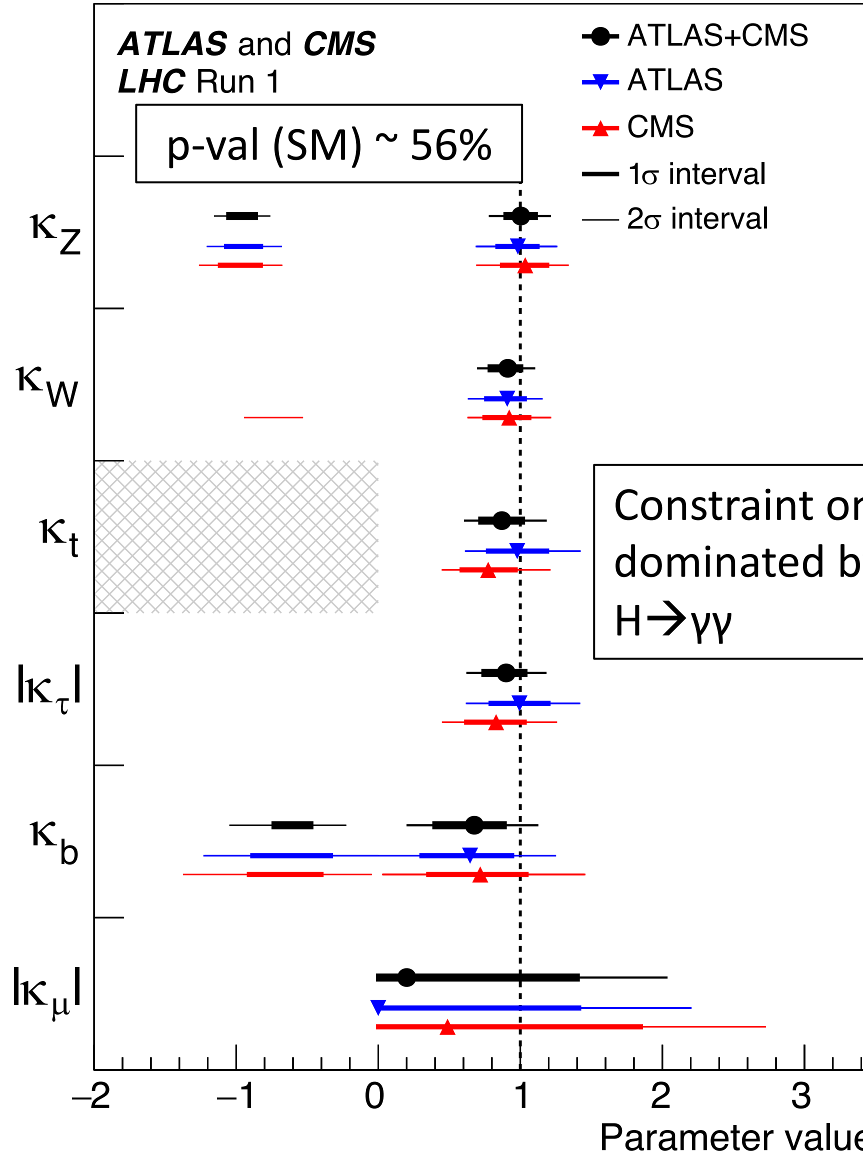
Assume no BSM decays and loops resolved as in the SM

Small measured valued of $\mathbf{k_b}$ reduces total width:

$$\kappa_H^2 \sim \begin{array}{l} 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + \\ + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + \\ + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + \\ + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2 \end{array}$$

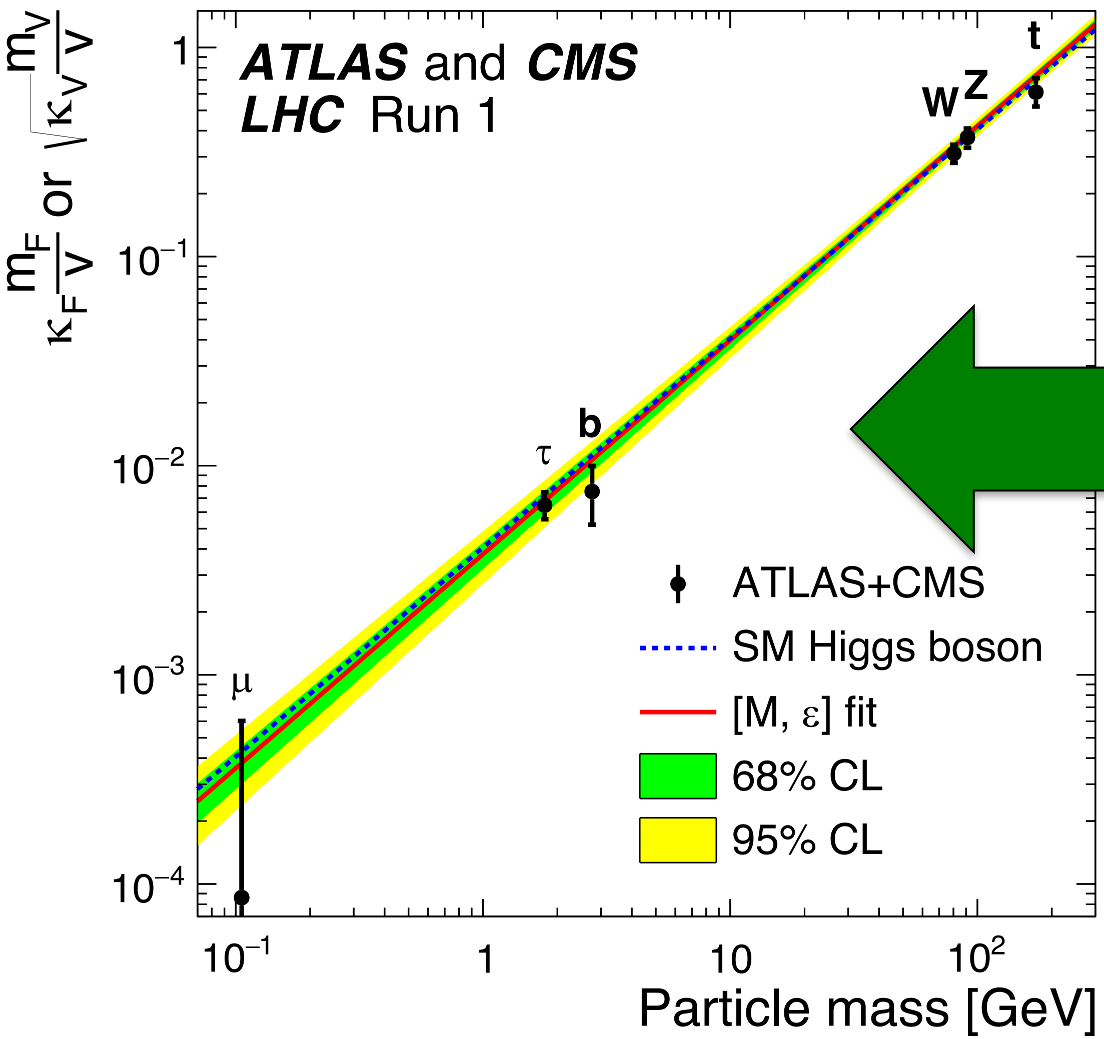
→ All measured k are <1 even though overall signal strength > 1

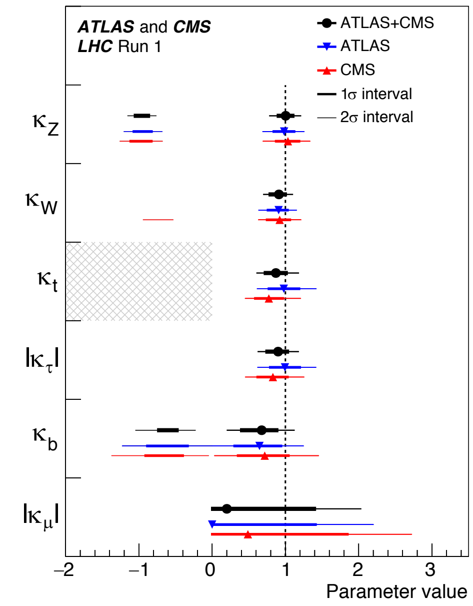
Overall good agreement with SM



Constraint on $\mathbf{k_t}$ dominated by H→γγ

Tree Level Higgs couplings





$$y_{V,i} = \sqrt{\kappa_{V,i}\frac{g_{V,i}}{2v}} = \sqrt{\kappa_{V,i}}\frac{m_{V,i}}{v},$$

$$y_{F,i} = \kappa_{F,i}\frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i}\frac{m_{F,i}}{v},$$

v=246 GeV, m_b evaluated with Higgs mass 125.09 GeV

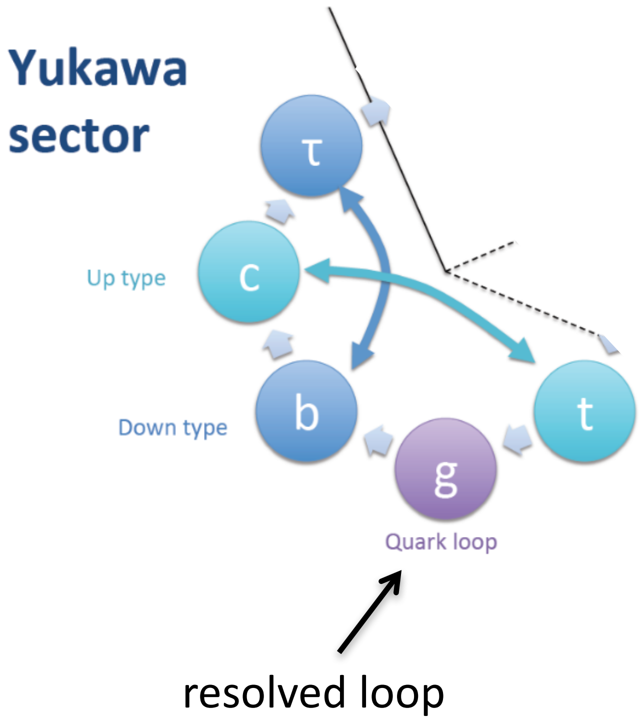
Fermion sector

Extended Higgs sector models allow for asymmetries in couplings between up and down type and between leptons and quarks, eg MSSM, 2HDM type-2(L)

2HDM Type-2 models

$$\kappa_V = \sin(\beta - \alpha)$$
$$\kappa_q = \cos\alpha / \sin\beta$$
$$\kappa_l = -\sin\alpha / \cos\beta$$

$$\kappa_V = \sin(\beta - \alpha)$$
$$\kappa_u = \cos\alpha / \sin\beta$$
$$\kappa_d = -\sin\alpha / \cos\beta$$



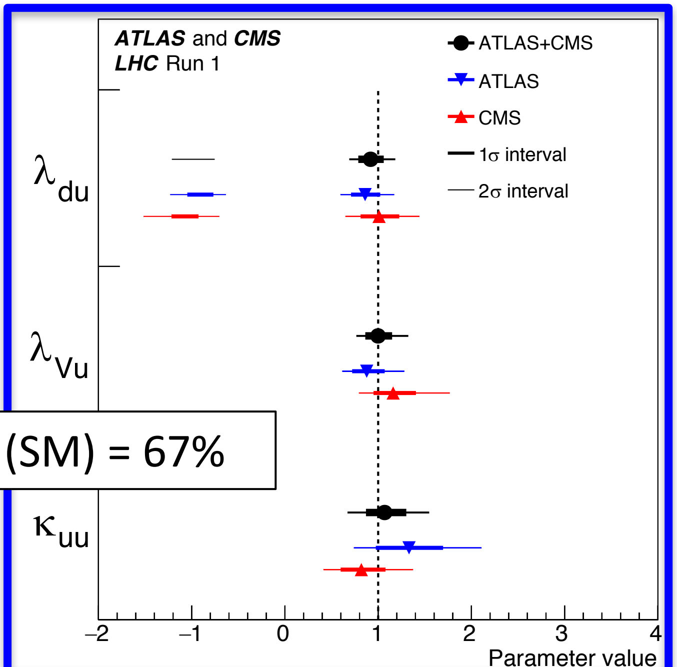
Fermion sector

Extended Higgs sector models allow for asymmetries in couplings between up and down type and between leptons and quarks, eg MSSM, 2HDM type-2(L)

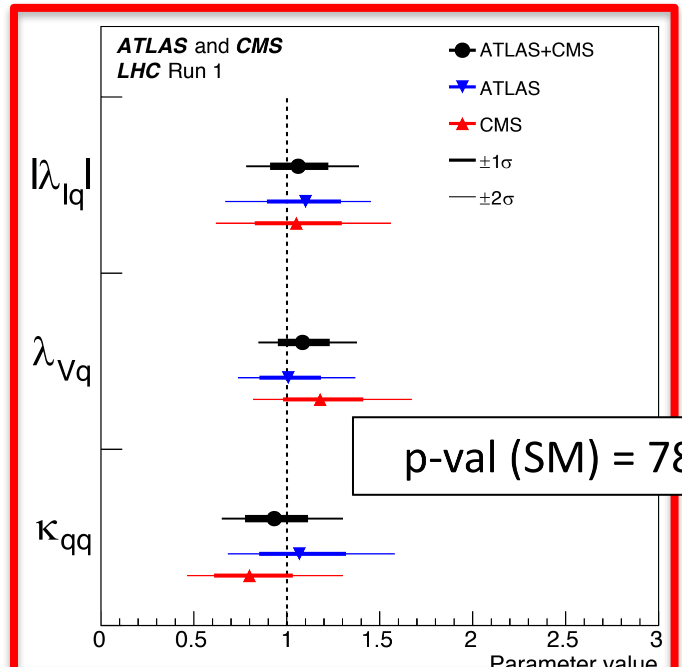
Directly parameterize asymmetries in terms of coupling modifier ratios (**λ**)

$$\lambda_{du} = \kappa_d / \kappa_u$$

$$\lambda_{lq} = \kappa_l / \kappa_q$$



p-val (SM) = 67%



p-val (SM) = 78%

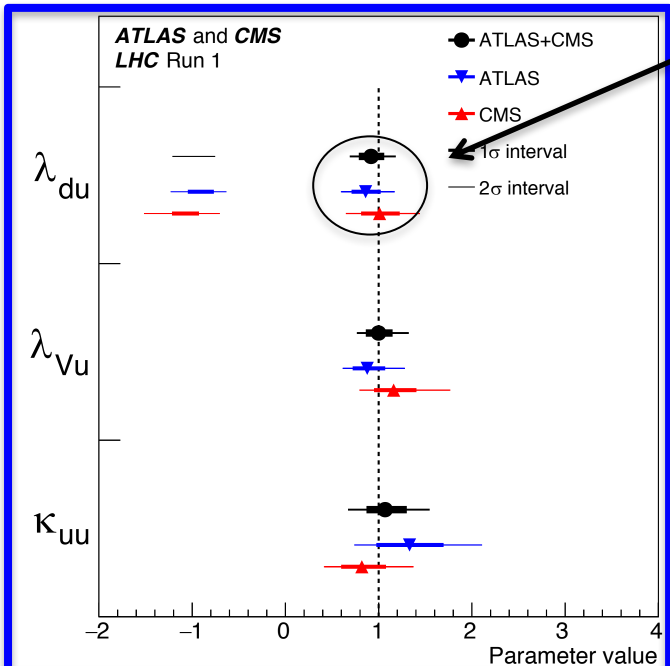
Fermion sector

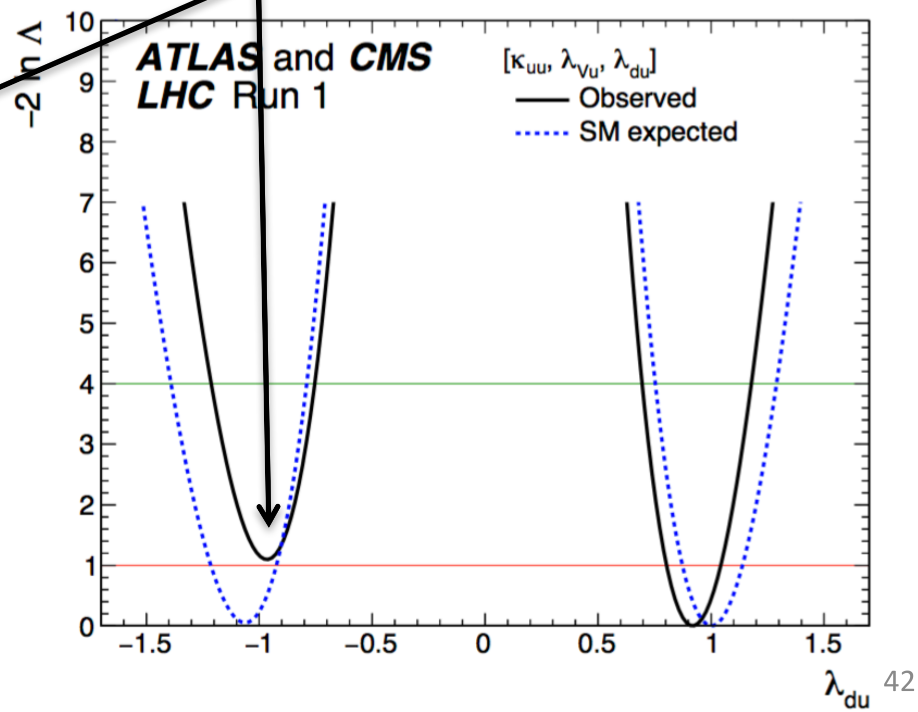
Extended Higgs sector models allow for asymmetries in couplings between up and down type and between leptons and quarks, eg MSSM, 2HDM type-2(L)

Directly parameterize asymmetries in terms of coupling modifier ratios (**λ**)

$$\lambda_{du} = \kappa_d / \kappa_u$$

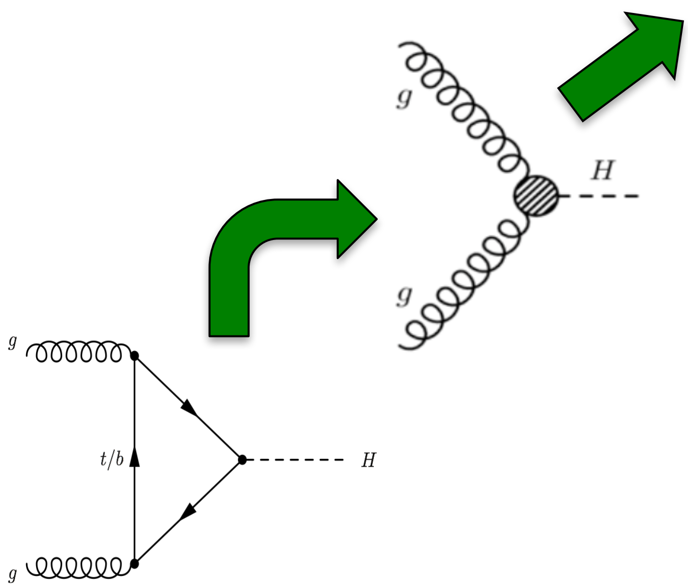
negative solution (just about) excluded due to low H→bb and high ttH and t-b interference in ggH

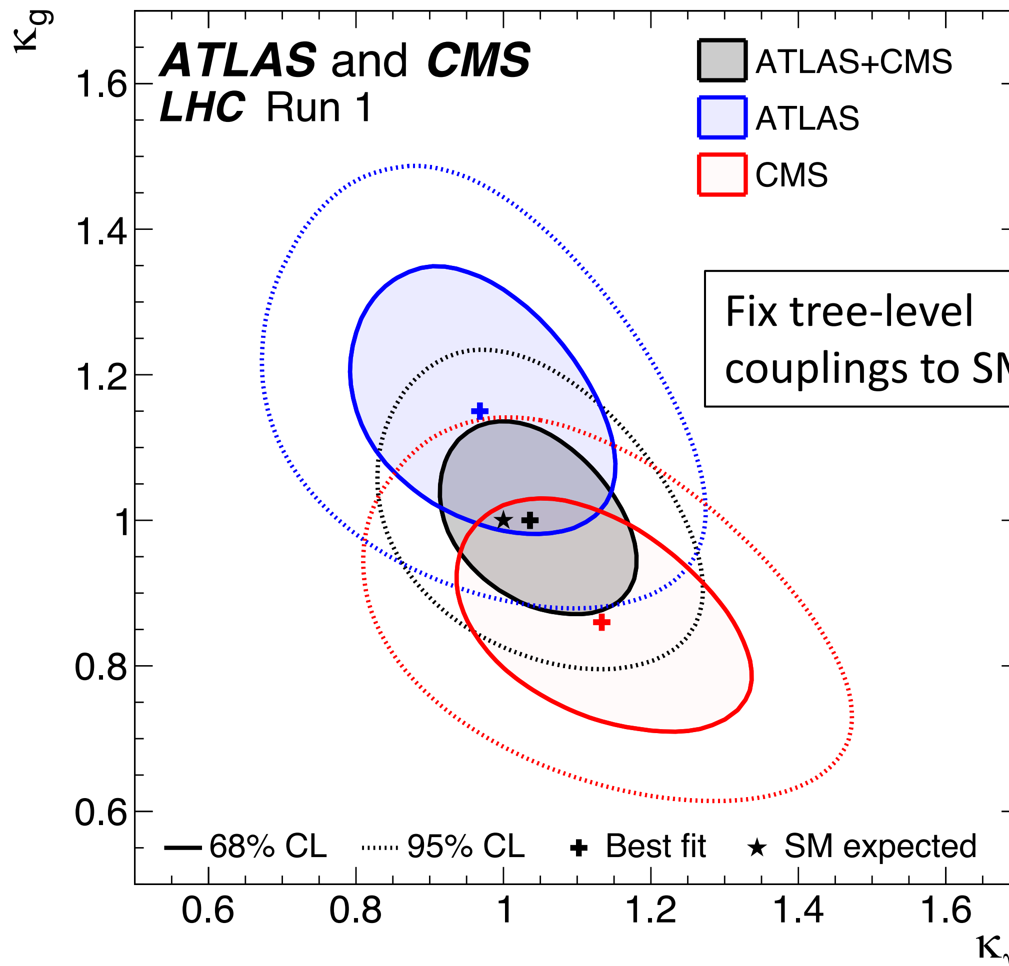




Effective couplings

Relax assumption on loop-induced processes and treat as "**effective couplings**"





Fix tree-level couplings to SM

Model is interesting when BSM physics at Heavy scales

→ Accessible in loops

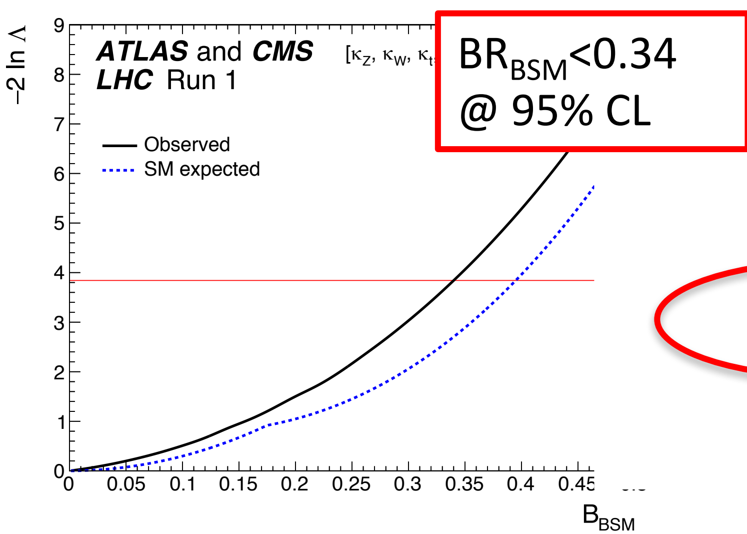
→ Assume **BR_{BSM}=0**

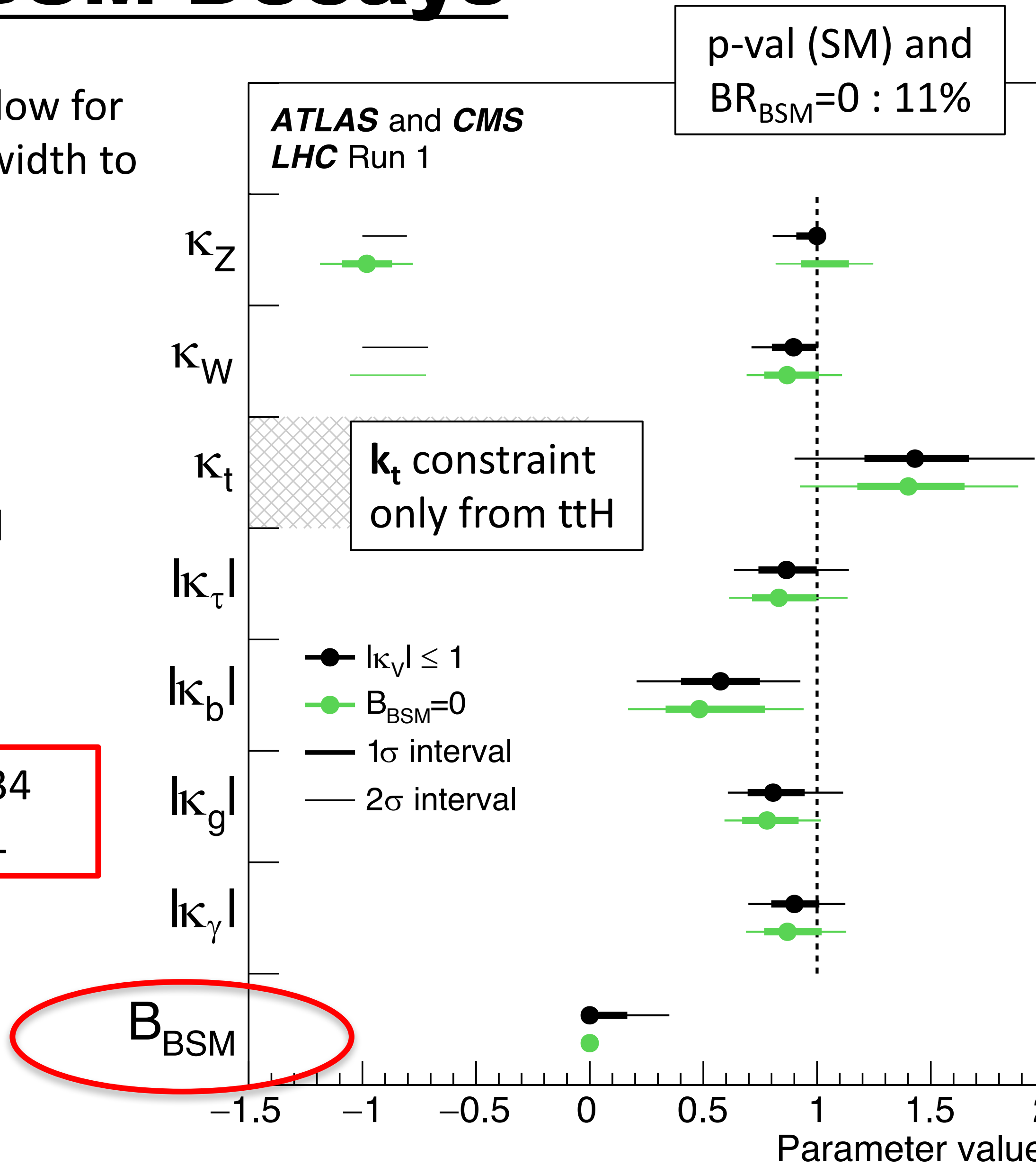
BSM Decays

Relax tree-level couplings and allow for additional contribution to total width to **BSM particles**

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

- Need to impose k_V<1 to avoid degeneracy.
- Many models predict this (2HDM, EWK Singlet…)

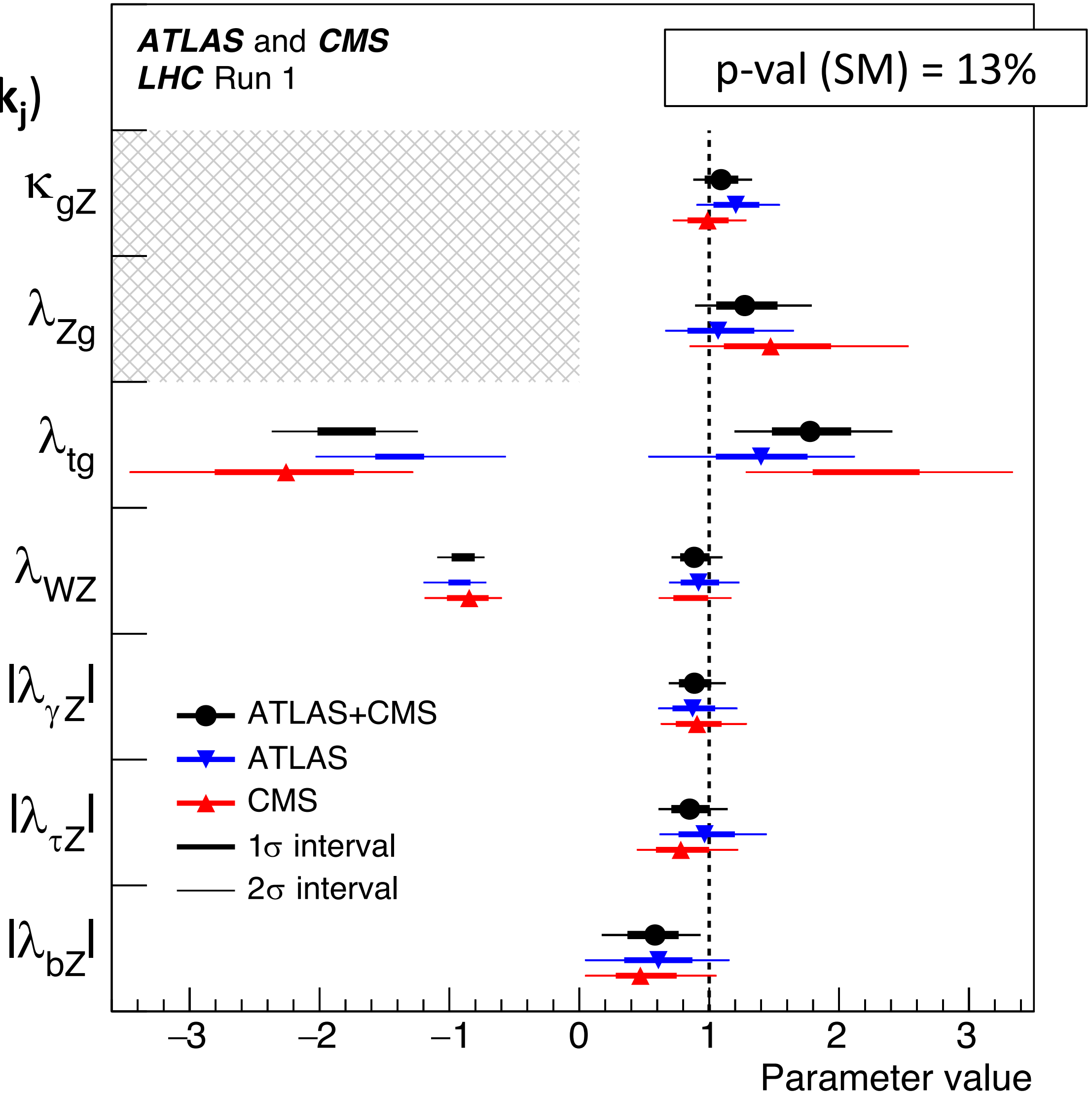




Generic couplings model

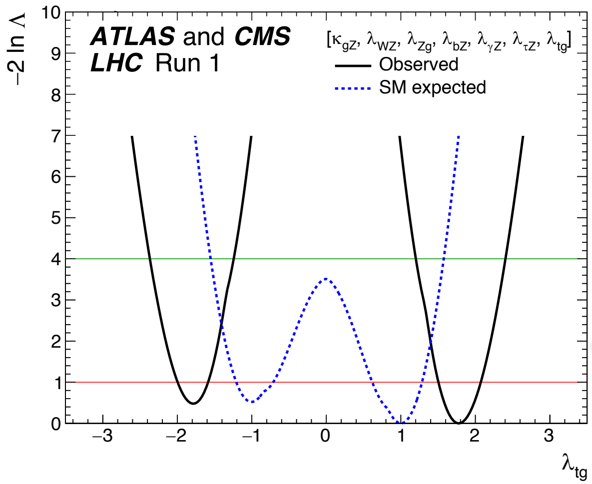
Most generic coupling model using ratios of coupling modifiers (**$\lambda_{ij}=k_i/k_j$**)

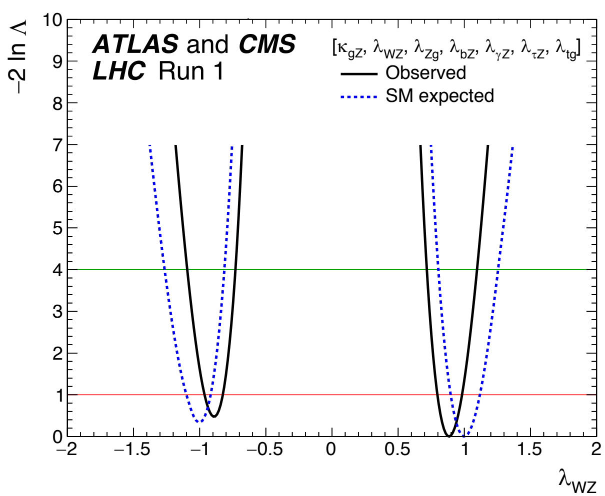
No assumptions necessary on total width since **Γ_H** cancels in the ratios

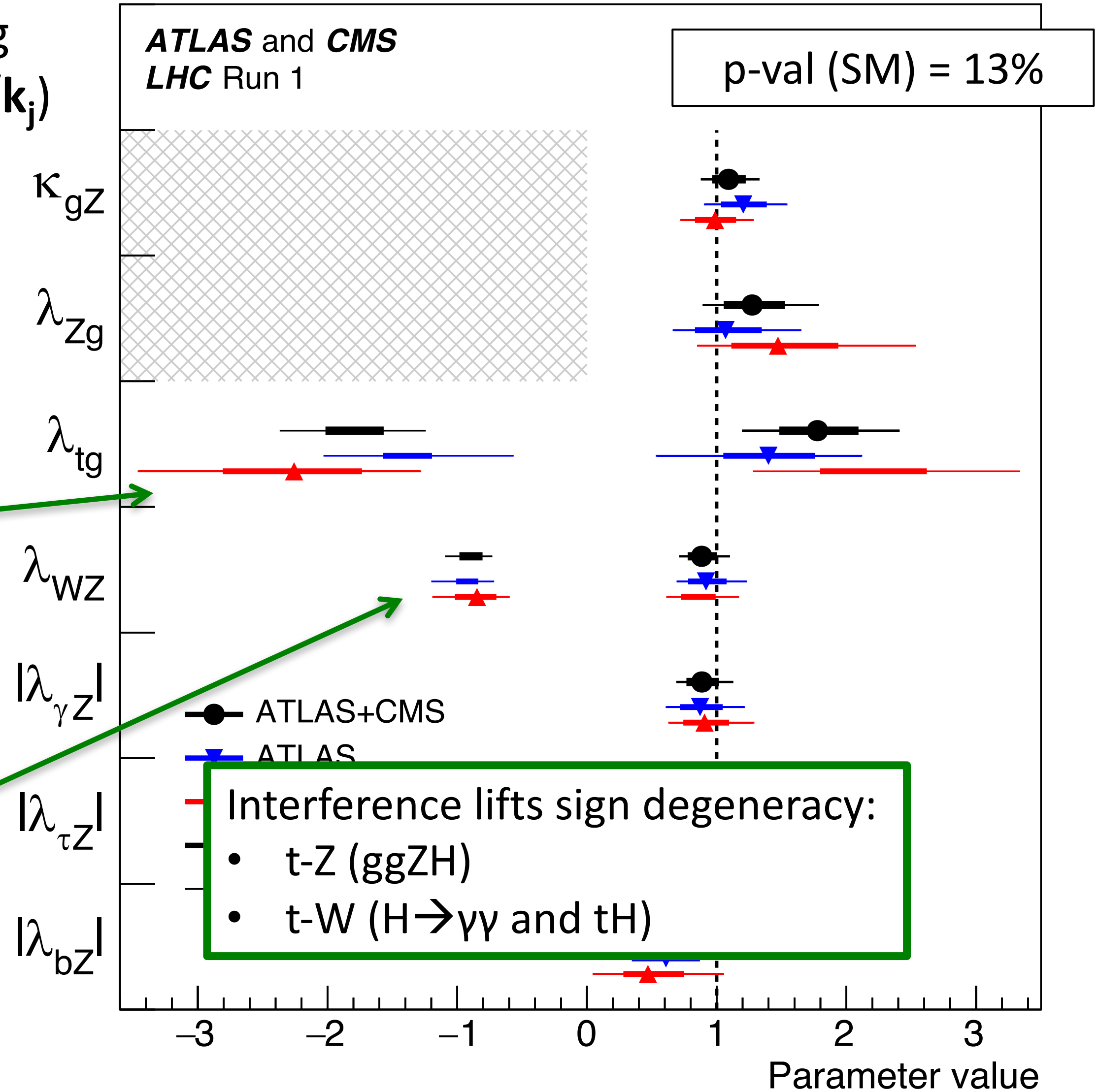


Generic couplings model

Most generic coupling model using ratios of coupling modifiers ($\lambda_{ij}=k_i/k_j$)





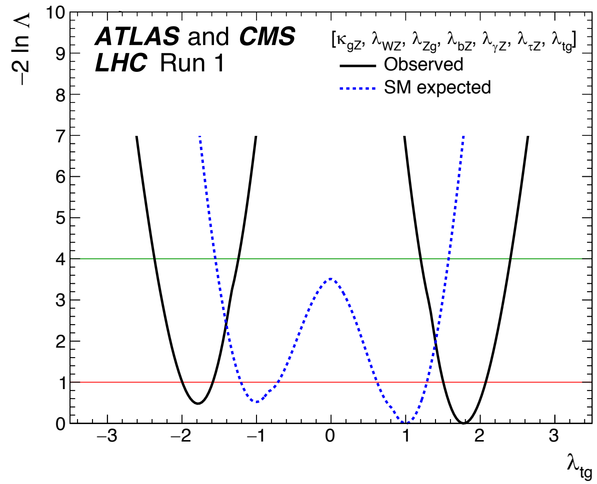


Interference lifts sign degeneracy:

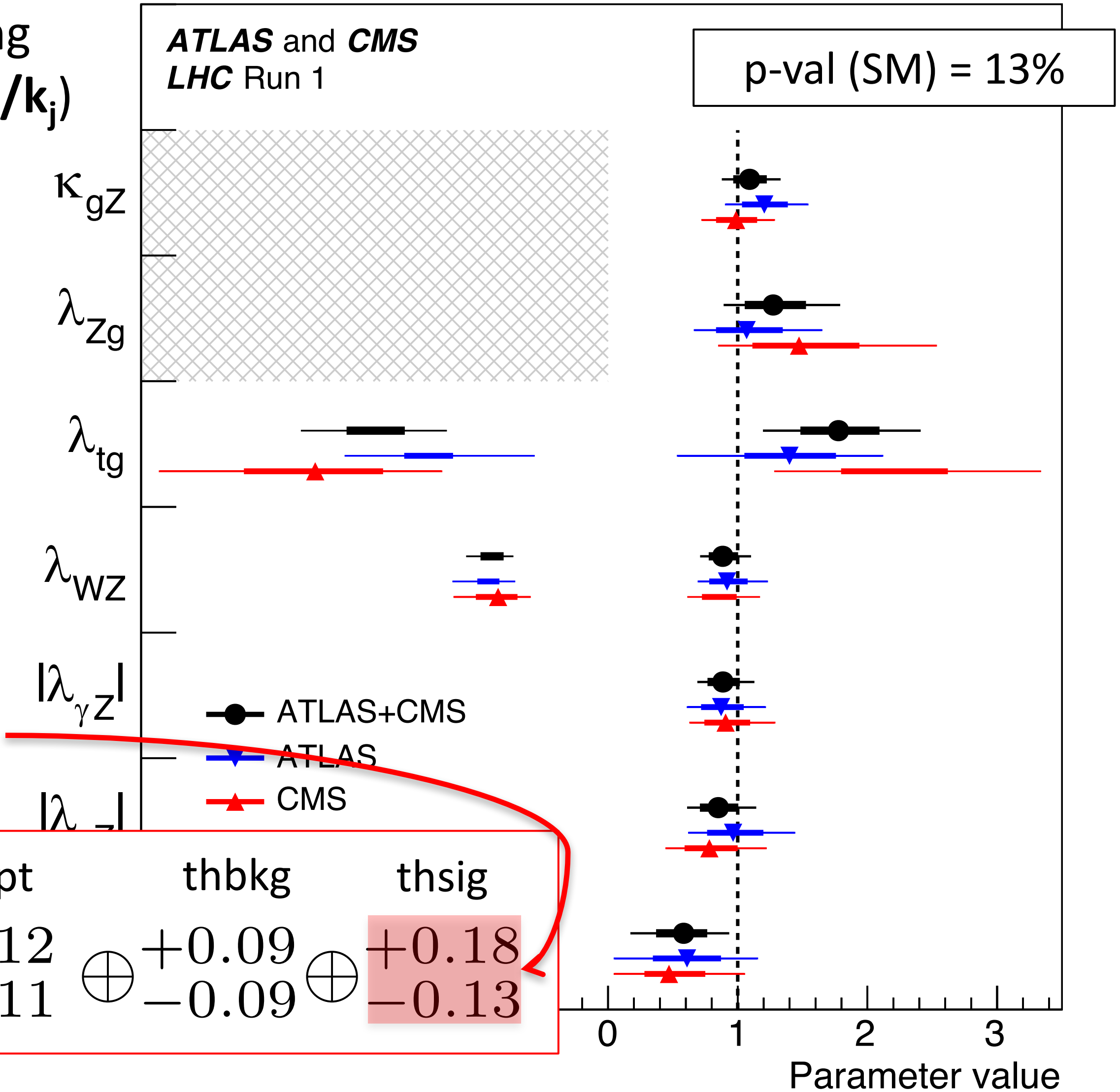
- t-Z (ggZH)
- t-W (H→γγ and tH)

Generic couplings model

Most generic coupling model using ratios of coupling modifiers ($\boldsymbol{\lambda_{ij}=k_i/k_j}$)



Relatively large theory uncertainty* due to anti-correlation of pdf(gg) and pdf(ttH)



stat expt thbkg thsig

$$\lambda_{tg} = 1.76^{+0.21}_{-0.20} \oplus^{+0.12}_{-0.11} \oplus^{+0.09}_{-0.09} \oplus^{+0.18}_{-0.13}$$

** Full breakdown in public document, covariance for paper release*

Re-using coupling modifiers

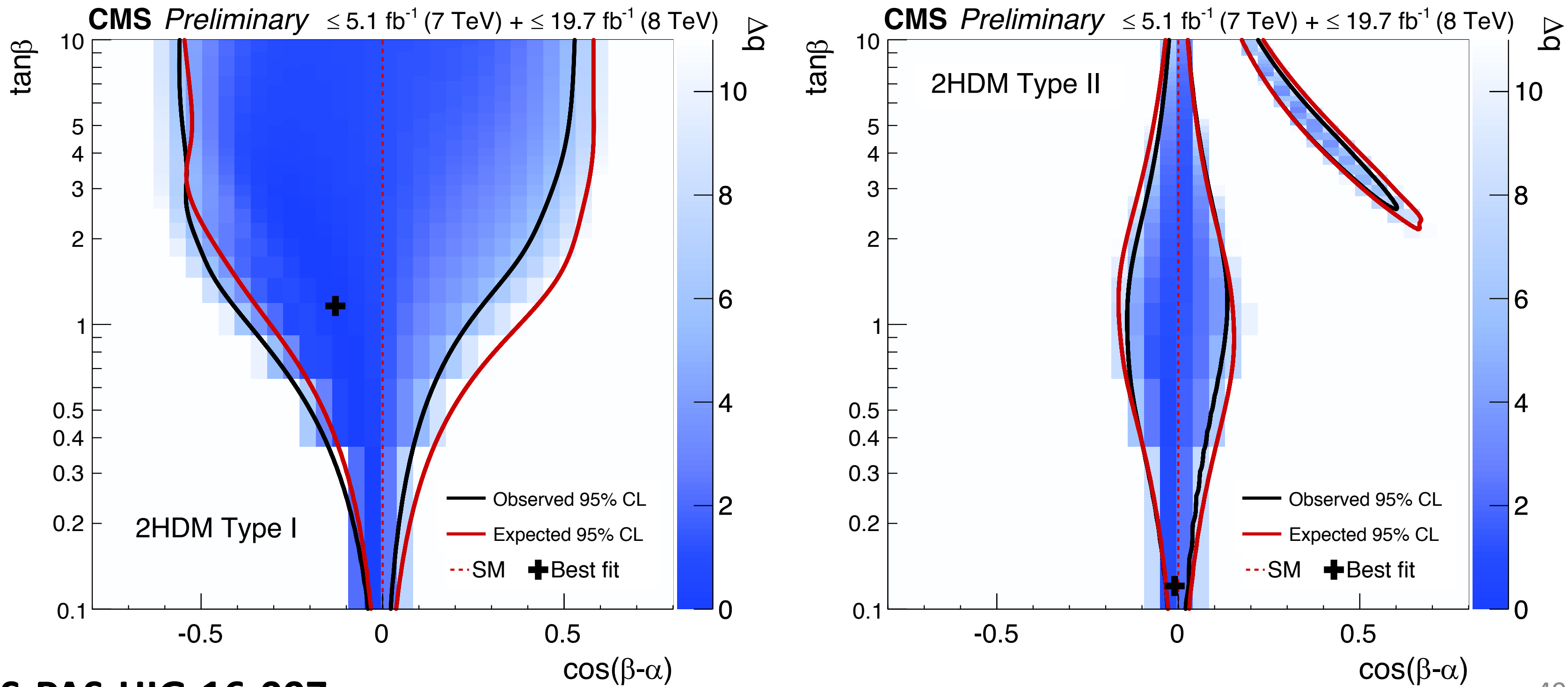
Within the SM, the ONLY free parameter is the Higgs mass so why do we care about these coupling constraints?

Re-using coupling modifiers

In extended Higgs sector models, tree-level coupling modifiers not equal to 1 are predicted

→ **eg. 2HDM**

	2HDM	
	type I	type II/MSSM
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$

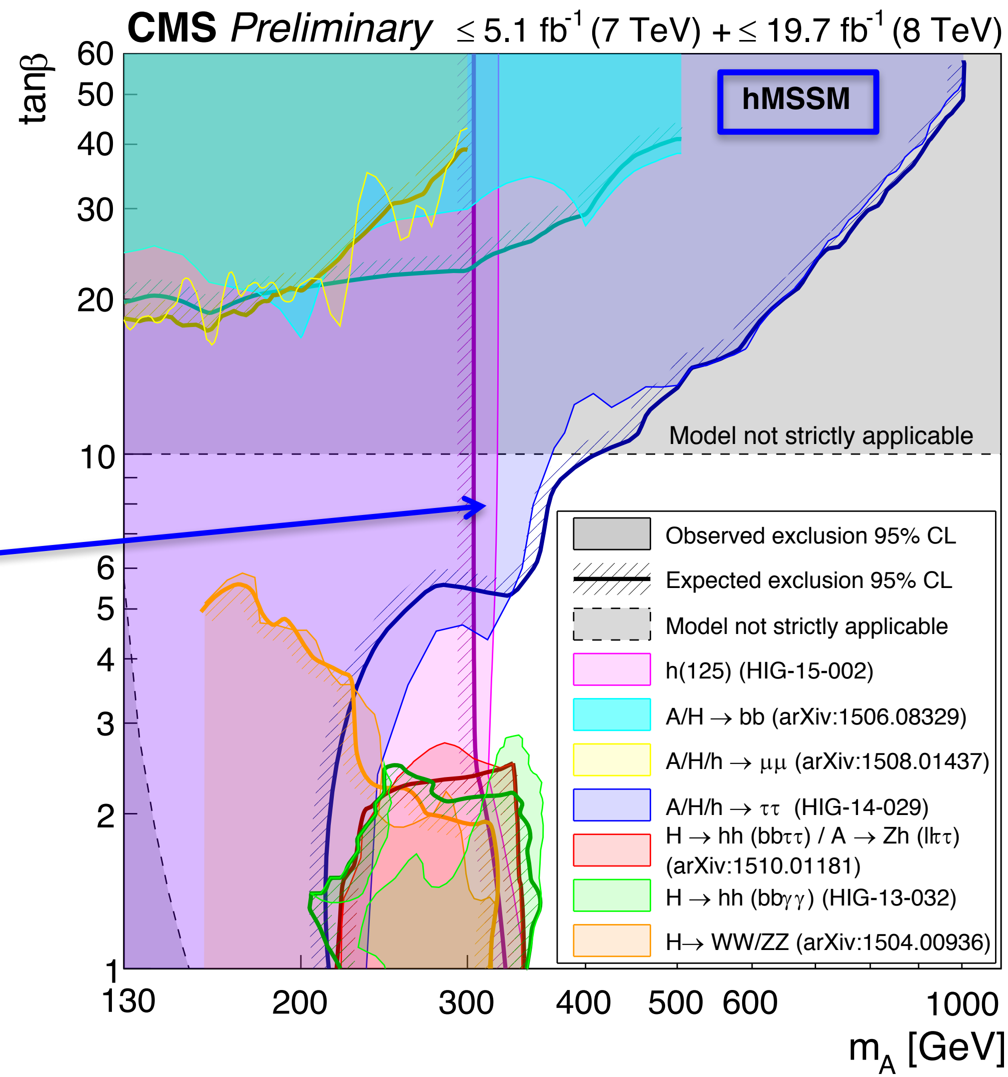


CMS-PAS-HIG-16-007

Re-using coupling modifiers

In extended Higgs sector models, tree-level coupling modifiers not equal to 1 are predicted (2HDM, EWK singlet…)

Provide complementary constraints to direct searches for additional Higgs bosons in MSSM scenario

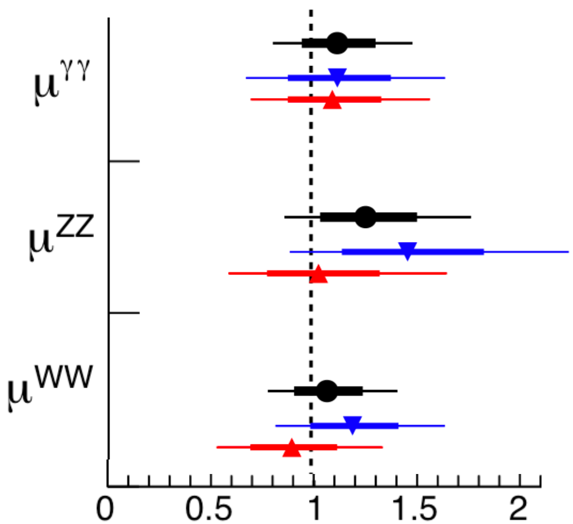


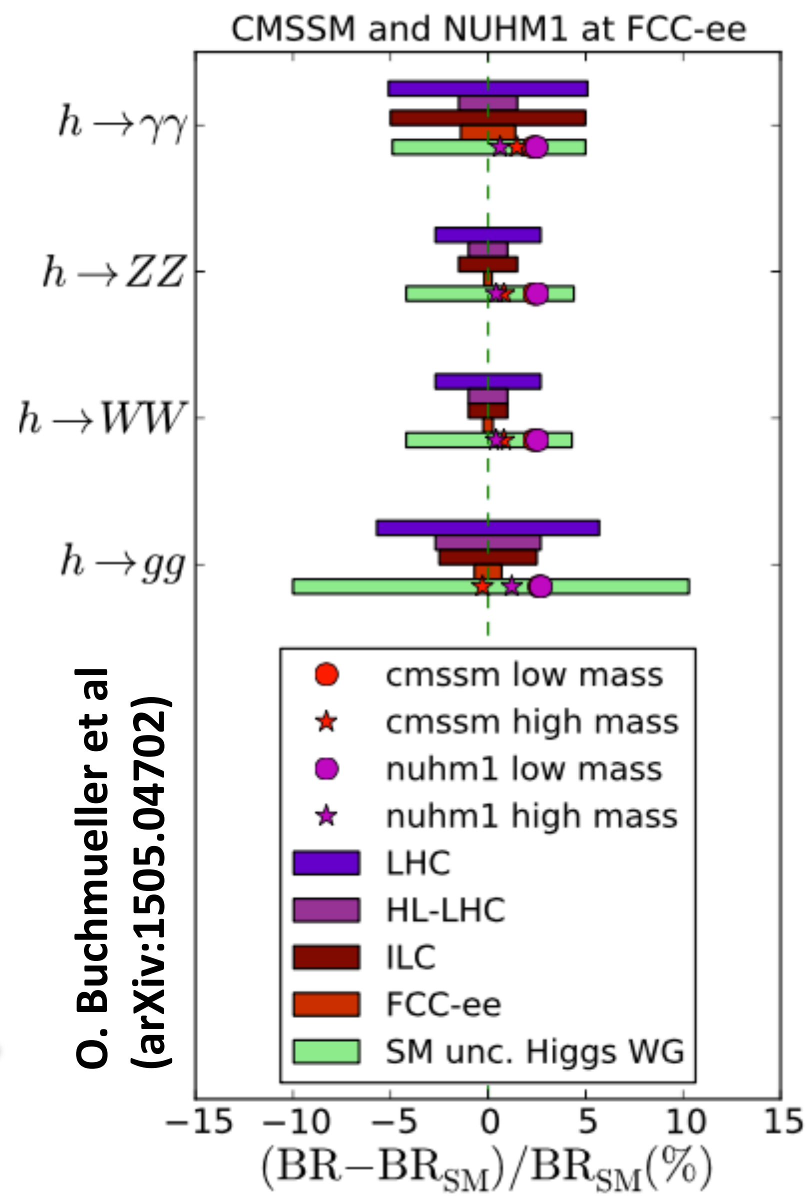
CMS-PAS-HIG-16-007

How accurate is accurate enough?

SUSY models out there can still accommodate the Higgs we've found

Need to measure Higgs decay rates at sub-sub percent level!



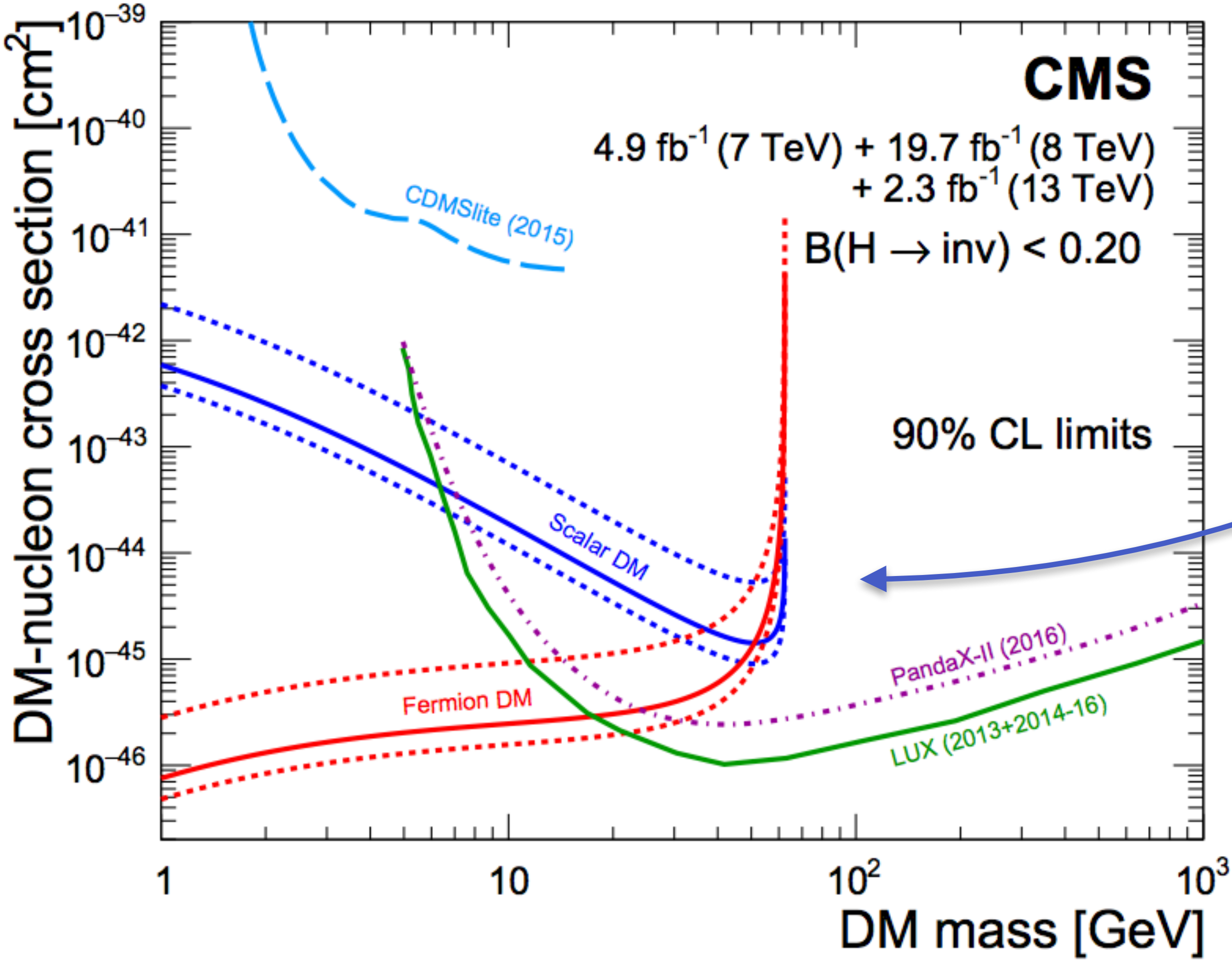


O. Buchmueller et al (arXiv:1505.04702)

Higgs-DM

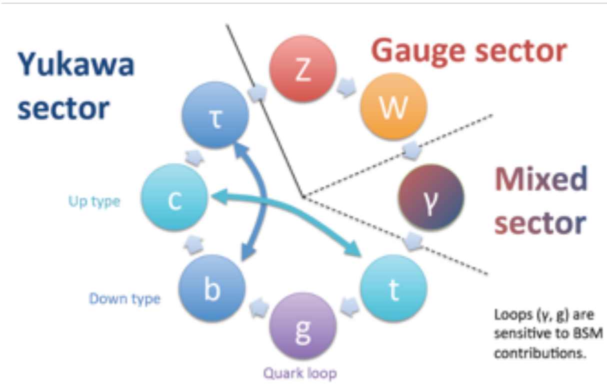
Constraints on total width have implications for dark matter Higgs-portal models…

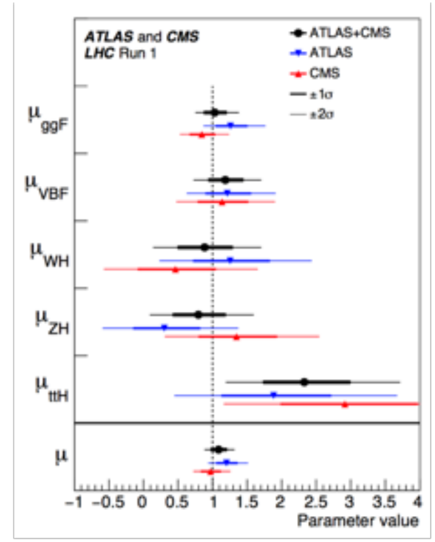
$$\sigma^{SI}_{f-N} = \frac{8\Gamma_{inv} m_\chi^2}{m_H^5 v^2 \beta^3} \frac{m_N^4 f_N^2}{(m_\chi + m_N)^2},$$



Access to low mass DM → complementary constraints compared to direct searches for DM-nucleon interactions

Beyond production and decay





$$L = L_{SM} + \frac{1}{\Lambda}\sum_k \mathcal{O}_k + \ldots$$

On-shell :

$$\delta\mu \approx \left(\frac{v}{\Lambda}\right)^2$$

Inclusive μ high-precision -> precision on new physics scale 1% -> Λ ~ 2.5 TeV

Off-shell/large q² :

$$\delta\mu \approx \left(\frac{q}{\Lambda}\right)^2$$

High momentum production sensitive to new physics without high precision 15% (q=1TeV) -> Λ ~ 2.5 TeV

Beyond production and decay

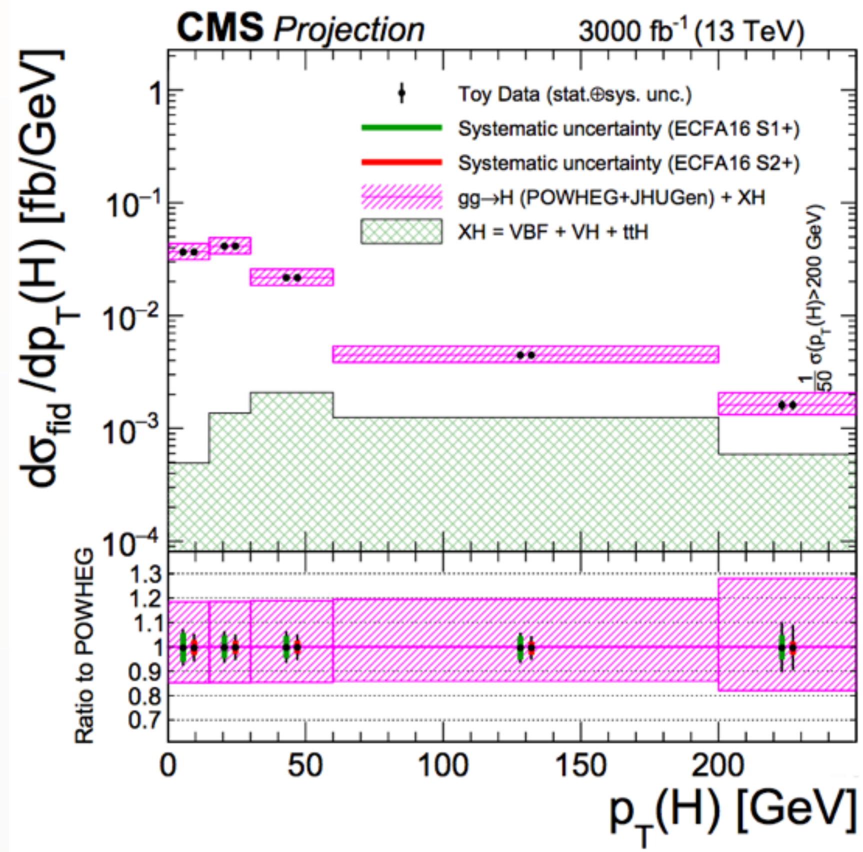
Differential measurements at Run-1 from LHC give a more complete picture of the Higgs boson production.

- BSM likely to effect kinematic distributions not just overall production cross-sections
- Already have some results from ATLAS and CMS but (*much*) more data is needed to make precise statements

→ Relative SM deviation in different regions sensitive to (eg) BSM scale (from ggH loop)

→ Expect dσ ~ 10% for $p_T(H)$>200 GeV @ HL-LHC from single channel (single expt.)

→ Λ > ~ 1 TeV from combination



Summary

ATLAS and CMS combined constraints on Higgs boson production and decay!

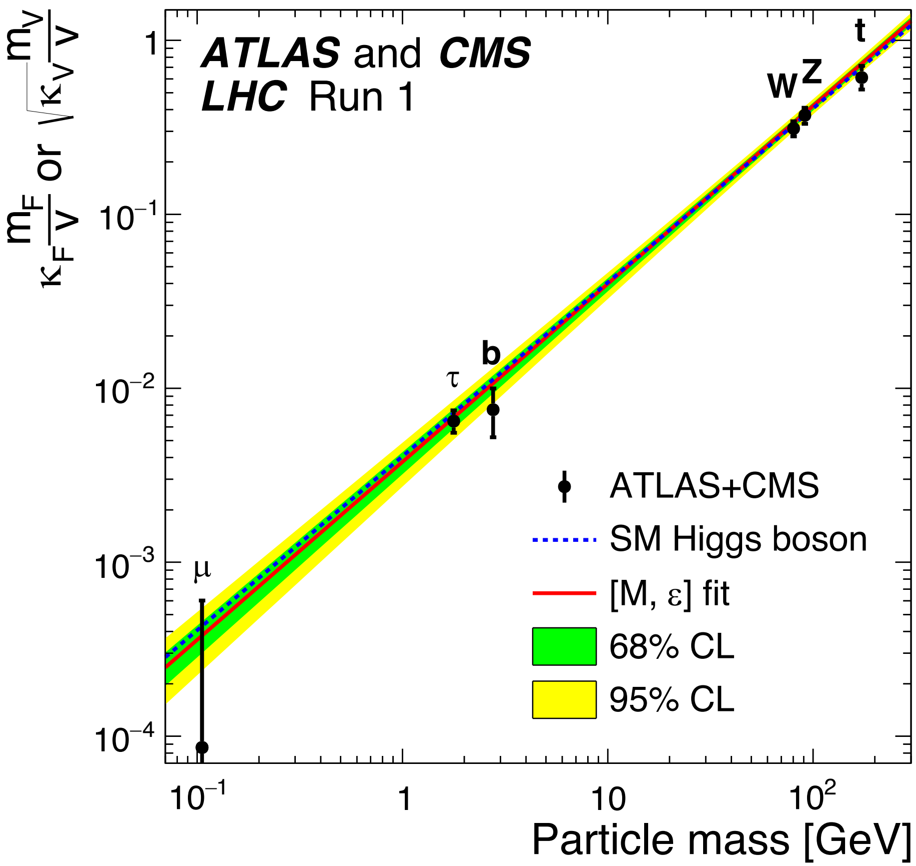
- Use full Run-1 dataset to provide best constraints so far. **Consistency with SM** but uncertainties are large.
- Several places where statistical uncertainties match those from theory!

More data with Run-2 will allow
- Higher precision constraints
- Access to rare modes – 2nd generation
  - H→μμ (H-muon coupling)
  - H→Jψ/ϕ (H-charm coupling)

Access to kinematic tails (high pT) for fuller characterization and BSM searches

Look forward to more combinations during/at the end of Run-2!

Public documentation available: ATLAS-CONF-2015-044/CMS-PAS-HIG-15-002



$\sqrt{s}$=8 → 13 TeV
σ(ggF) x 2.3
σ(VBF) x 2.4
σ(ttH) x 3.9

Thanks !

Inputs to the combination reading list

[51] ATLAS Collaboration, *Measurement of Higgs boson production in the diphoton decay channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector*, Phys. Rev. **D90** (2014) 112015, arXiv:1408.7084 [hep-ex].

[52] CMS Collaboration, *Observation of the diphoton decay of the 125 GeV Higgs boson and measurement of its properties*, Eur. Phys. J. C **74** (2014) 3076, arXiv:1407.0558 [hep-ex].

[53] ATLAS Collaboration, *Measurements of Higgs boson production and couplings in the four-lepton channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector*, Phys. Rev. **D91** (2015) 012006, arXiv:1408.5191 [hep-ex].

[54] CMS Collaboration, *Measurement of the properties of a Higgs boson in the four-lepton final state*, Phys. Rev. D **89** (2014) 092007, arXiv:1312.5353 [hep-ex].

[55] ATLAS Collaboration, *Observation and measurement of Higgs boson decays to WW^* with the ATLAS detector*, Phys. Rev. **D92** (2015) 012006, arXiv:1412.2641 [hep-ex].

[56] ATLAS Collaboration, *Study of the Higgs boson decaying to WW^* produced in association with a weak boson with the ATLAS detector at the LHC*, JHEP **1508** (2015) 137, arXiv:1506.06641 [hep-ph].

[57] CMS Collaboration, *Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states*, JHEP **01** (2014) 096, arXiv:1312.1129 [hep-ex].

[58] ATLAS Collaboration, *Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector*, arXiv:1501.04943 [hep-ex].

[59] CMS Collaboration, *Evidence for the 125 GeV Higgs boson decaying to a pair of τ leptons*, JHEP **05** (2014) 104, arXiv:1401.5041 [hep-ex].

[60] ATLAS Collaboration, *Search for the Standard Model Higgs boson decay to $\mu^+\mu^-$ with the ATLAS detector*, Phys. Lett. **B738** (2014) 68, arXiv:1406.7663 [hep-ex].

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[62] ATLAS Collaboration, *Search for the Standard Model Higgs boson produced in association with top quarks and decaying into $b\bar{b}$ in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, Eur. Phys. J. C **75** (2015) 349, arXiv:1503.05066 [hep-ex].

[63] ATLAS Collaboration, *Search for the associated production of the Higgs boson with a top quark pair in multi-lepton final states with the ATLAS detector*, ATLAS-CONF-2015-007 (2015).

[64] CMS Collaboration, *Search for the standard model Higgs boson produced in association with a top-quark pair in pp collisions at the LHC*, JHEP **1305** (2013) 145, arXiv:1303.0763 [hep-ex].

[65] CMS Collaboration, *Search for the associated production of the Higgs boson with a top-quark pair*, JHEP **09** (2014) 087, arXiv:1408.1682 [hep-ex].

[66] ATLAS Collaboration, *Search for Higgs boson decays to a photon and a Z boson in pp collisions at $\sqrt{s}$=7 and 8 TeV with the ATLAS detector*, Phys. Lett. **B732** (2014) 8, arXiv:1402.3051 [hep-ex].

[67] CMS Collaboration, *Search for a Higgs boson decaying into a Z and a photon in pp collisions at $\sqrt{s} = 7$ and 8 TeV*, Phys. Lett. **B726** (2013) 587–609, arXiv:1307.5515 [hep-ex].

[68] ATLAS Collaboration, *Search for Invisible Decays of a Higgs Boson Produced in Association with a Z Boson in ATLAS*, Phys. Rev. Lett. **112** (2014) 201802, arXiv:1402.3244 [hep-ex].

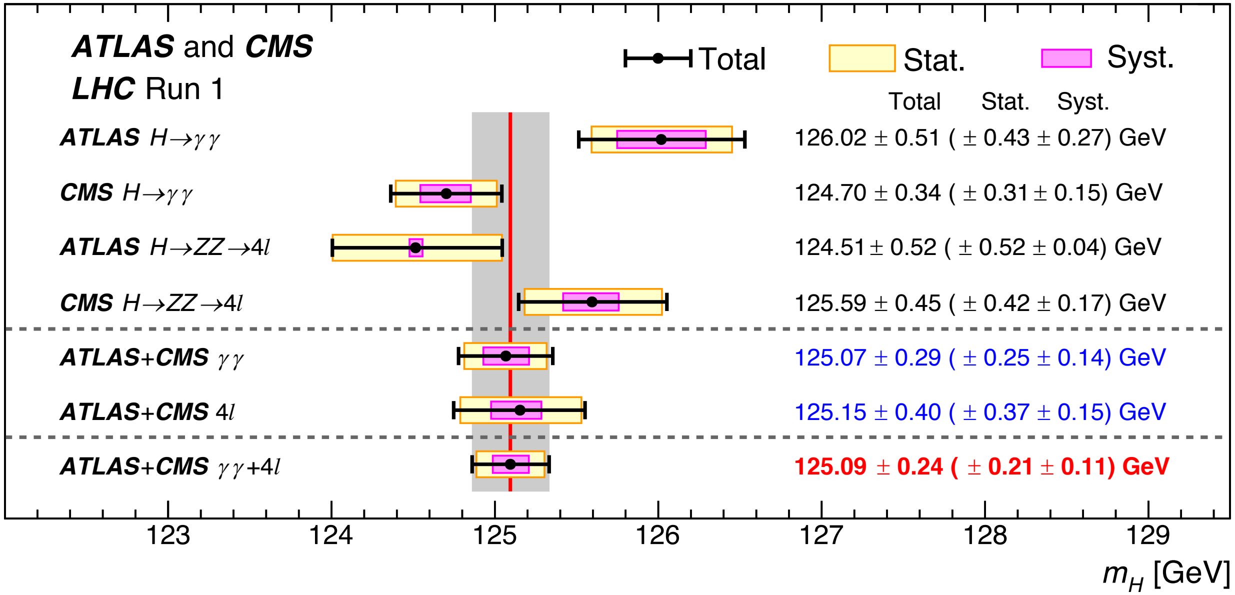
[69] ATLAS Collaboration, *Search for invisible decays of the Higgs boson produced in association with a hadronically decaying vector boson in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, Eur. Phys. J. **C75** no. 7, (2015) 337, arXiv:1504.04324 [hep-ex].

[70] CMS Collaboration, *Search for invisible decays of Higgs bosons in the vector boson fusion and associated ZH production modes*, Eur. Phys. J. **C74** (2014) 2980, arXiv:1404.1344 [hep-ex].

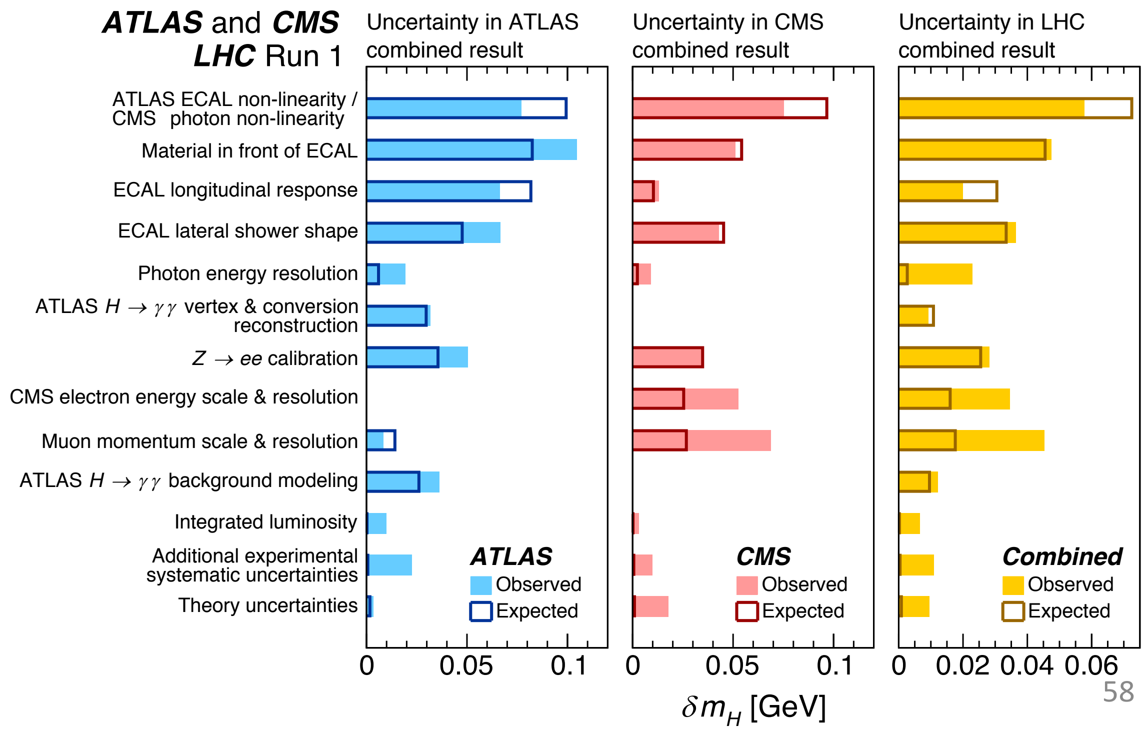
[71] CMS Collaboration, *Search for the standard model Higgs boson produced through vector boson fusion and decaying to $b\bar{b}$*, arXiv:1506.01010 [hep-ex].

[72] ATLAS and CMS Collaborations, *Procedure for the LHC Higgs boson search combination in Summer 2011*, ATL-PHYS-PUB-2011-011, CERN-CMS-NOTE-2011-005 (2011), http://cdsweb.cern.ch/record/1375842.

BACKUP



LHC Mass combination



X-sections inputs

Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ 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)+~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)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

Decay BR

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

BR uncertainties

Channel	M_H [GeV]	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
$H \to bb$	122	2.30	-2.3% $+2.3\%$	$+3.2\%$ -3.2%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+2.0\%$ -2.0%
	126	2.36	-2.3% $+2.3\%$	$+3.3\%$ -3.2%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+2.0\%$ -2.0%
	130	2.42	-2.4% $+2.3\%$	$+3.2\%$ -3.2%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+2.0\%$ -2.0%
$H \to \tau^+\tau^-$	122	$2.51\cdot10^{-1}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.1%	$+2.0\%$ -2.0%
	126	$2.59\cdot10^{-1}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.1\%$ -0.1%	$+2.0\%$ -2.0%
	130	$2.67\cdot10^{-1}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.1\%$ -0.1%	$+2.0\%$ -2.0%
$H \to \mu^+\mu^-$	122	$8.71\cdot10^{-4}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.1\%$ -0.1%	$+2.0\%$ -2.0%
	126	$8.99\cdot10^{-4}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	-0.1% -0.0%	$+0.0\%$ -0.1%	$+2.0\%$ -2.0%
	130	$9.27\cdot10^{-4}$	$+0.1\%$ $+0.0\%$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.1\%$ -0.0%	$+2.0\%$ -2.0%
$H \to c\bar{c}$	122	$1.16\cdot10^{-1}$	-7.1% $+7.0\%$	-0.1% $+0.1\%$	$+6.2\%$ -6.0%	$+0.0\%$ -0.1%	$+2.0\%$ -2.0%
	126	$1.19\cdot10^{-1}$	-7.1% $+7.0\%$	-0.1% $+0.1\%$	$+6.2\%$ -6.1%	$+0.0\%$ -0.1%	$+2.0\%$ -2.0%
	130	$1.22\cdot10^{-1}$	-7.1% $+7.0\%$	-0.1% $+0.1\%$	$+6.3\%$ -6.0%	$+0.1\%$ -0.1%	$+2.0\%$ -2.0%
$H \to gg$	122	$3.25\cdot10^{-1}$	$+4.2\%$ -4.1%	-0.1% $+0.1\%$	$+0.0\%$ -0.0%	-0.2% $+0.2\%$	$+3.0\%$ -3.0%
	126	$3.57\cdot10^{-1}$	$+4.2\%$ -4.1%	-0.1% $+0.1\%$	$+0.0\%$ -0.0%	-0.2% $+0.2\%$	$+3.0\%$ -3.0%
	130	$3.91\cdot10^{-1}$	$+4.2\%$ -4.1%	-0.1% $+0.2\%$	$+0.0\%$ -0.0%	-0.2% $+0.2\%$	$+3.0\%$ -3.0%
$H \to \gamma\gamma$	122	$8.37\cdot10^{-3}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+1.0\%$ -1.0%
	126	$9.59\cdot10^{-3}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+1.0\%$ -1.0%
	130	$1.10\cdot10^{-2}$	$+0.1\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+1.0\%$ -1.0%
$H \to Z\gamma$	122	$4.74\cdot10^{-3}$	$+0.0\%$ -0.1%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.1%	$+5.0\%$ -5.0%
	126	$6.84\cdot10^{-3}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.1%	$+0.0\%$ -0.1%	$+5.0\%$ -5.0%
	130	$9.55\cdot10^{-3}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+5.0\%$ -5.0%
$H \to WW$	122	$6.25\cdot10^{-1}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.5\%$ -0.5%
	126	$9.73\cdot10^{-1}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.5\%$ -0.5%
	130	1.49	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.5\%$ -0.5%
$H \to ZZ$	122	$7.30\cdot10^{-2}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.5\%$ -0.5%
	126	$1.22\cdot10^{-1}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.5\%$ -0.5%
	130	$1.95\cdot10^{-1}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.5\%$ -0.5%

THU uncertainties (on partial widths) uncorrelated

Full correlation model (through $BR = \Gamma/\Gamma_{tot}$) imposed for models for which effects are not expected to be negligible (eg ratios models).

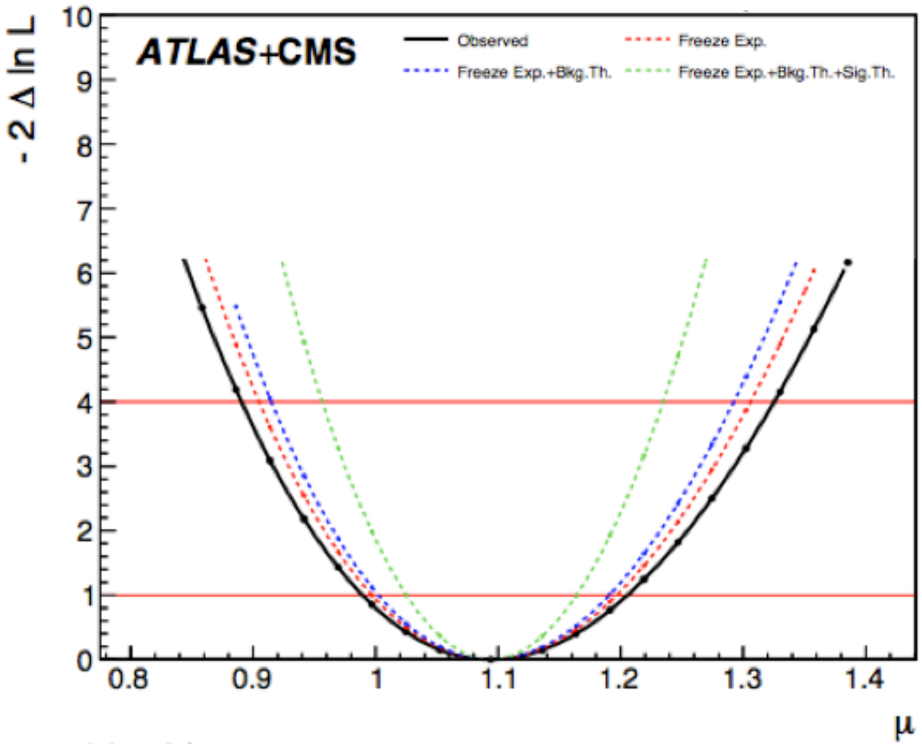
WW, ZZ BR fully correlated in all models

PDF uncertainties

The main theoretical sources of uncertainties on the signal are the following: QCD scales, parton distribution functions (PDF), UEPS, and Higgs boson branching ratios. These uncertainties apply both to the inclusive cross sections and to the acceptance and selection efficiency in the various categories. The PDF uncertainties on the inclusive rates for different Higgs boson production processes are correlated between the two experiments for the same channel but are treated as uncorrelated between different channels, except in two cases:

- the WH and ZH production processes are assumed to be fully correlated;
- the ggF and ttH production processes, which are predicted to be anti-correlated at the level of 60%, are assumed to be fully anti-correlated.

One μ to scale them all



Fixing related nuisance parameters in scans reveals contributions from groups of systematic uncertainties

EG, simplest model (discovery model) Overall scaling parameter,

$$\mu := \mu_i = \mu_f$$

$$\forall i, f \in \{ttH, qqH, H \to ZZ, ...\}$$

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

Theory uncert dominated by ggF incl. x-section

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

Uncertainty in theoretical calculations and statistical uncertainty similar in magnitude!

Generic Model

Parameter	SM prediction	Best-fit	Uncertainty		Best-fit	Uncertainty		Best-fit	Uncertainty	
		value	Stat	Syst	value	Stat	Syst	value	Stat	Syst
		ATLAS+CMS			ATLAS			CMS		
$\sigma(gg \to H \to ZZ)$ (pb)	0.513 ± 0.057	$0.58\,^{+0.11}_{-0.10}$ $\left(^{+0.11}_{-0.10}\right)$	$^{+0.11}_{-0.10}$ $\left(^{+0.11}_{-0.09}\right)$	$^{+0.03}_{-0.02}$ $\left(^{+0.03}_{-0.02}\right)$	$0.76\,^{+0.19}_{-0.17}$ $\left(^{+0.16}_{-0.14}\right)$	$^{+0.19}_{-0.16}$ $\left(^{+0.16}_{-0.13}\right)$	$^{+0.05}_{-0.04}$ $\left(^{+0.04}_{-0.03}\right)$	$0.44\,^{+0.14}_{-0.11}$ $\left(^{+0.15}_{-0.13}\right)$	$^{+0.13}_{-0.11}$ $\left(^{+0.15}_{-0.13}\right)$	$^{+0.05}_{-0.03}$ $\left(^{+0.04}_{-0.03}\right)$
$\sigma_{\mathrm{VBF}}/\sigma_{\mathrm{ggF}}$	0.082 ± 0.009	$0.11\,^{+0.03}_{-0.03}$ $\left(^{+0.03}_{-0.02}\right)$	$^{+0.03}_{-0.02}$ $\left(^{+0.02}_{-0.02}\right)$	$^{+0.02}_{-0.01}$ $\left(^{+0.02}_{-0.01}\right)$	$0.08\,^{+0.03}_{-0.03}$ $\left(^{+0.04}_{-0.03}\right)$	$^{+0.03}_{-0.02}$ $\left(^{+0.04}_{-0.03}\right)$	$^{+0.02}_{-0.01}$ $\left(^{+0.02}_{-0.01}\right)$	$0.14\,^{+0.07}_{-0.05}$ $\left(^{+0.04}_{-0.03}\right)$	$^{+0.06}_{-0.05}$ $\left(^{+0.04}_{-0.03}\right)$	$^{+0.04}_{-0.02}$ $\left(^{+0.02}_{-0.01}\right)$
$\sigma_{WH}/\sigma_{\mathrm{ggF}}$	0.037 ± 0.004	$0.03\,^{+0.03}_{-0.03}$ $\left(^{+0.02}_{-0.02}\right)$	$^{+0.02}_{-0.02}$ $\left(^{+0.02}_{-0.02}\right)$	$^{+0.01}_{-0.01}$ $\left(^{+0.01}_{-0.01}\right)$	$0.05\,^{+0.04}_{-0.03}$ $\left(^{+0.03}_{-0.02}\right)$	$^{+0.03}_{-0.02}$ $\left(^{+0.03}_{-0.02}\right)$	$^{+0.02}_{-0.01}$ $\left(^{+0.02}_{-0.01}\right)$	$0.01\,^{+0.04}_{-0.04}$ $\left(^{+0.03}_{-0.02}\right)$	$^{+0.04}_{-0.03}$ $\left(^{+0.03}_{-0.02}\right)$	$^{+0.02}_{-0.02}$ $\left(^{+0.02}_{-0.01}\right)$
$\sigma_{ZH}/\sigma_{\mathrm{ggF}}$	0.022 ± 0.002	$0.07\,^{+0.04}_{-0.03}$ $\left(^{+0.02}_{-0.01}\right)$	$^{+0.03}_{-0.03}$ $\left(^{+0.01}_{-0.01}\right)$	$^{+0.02}_{-0.02}$ $\left(^{+0.01}_{-0.00}\right)$	$0.01\,^{+0.03}_{-0.01}$ $\left(^{+0.03}_{-0.01}\right)$	$^{+0.02}_{-0.01}$ $\left(^{+0.02}_{-0.01}\right)$	$^{+0.02}_{-0.01}$ $\left(^{+0.01}_{-0.01}\right)$	$0.13\,^{+0.08}_{-0.05}$ $\left(^{+0.02}_{-0.01}\right)$	$^{+0.06}_{-0.05}$ $\left(^{+0.02}_{-0.01}\right)$	$^{+0.04}_{-0.03}$ $\left(^{+0.01}_{-0.01}\right)$
$\sigma_{ttH}/\sigma_{\mathrm{ggF}}$	0.0067 ± 0.0010	$0.022\,^{+0.007}_{-0.006}$ $\left(^{+0.004}_{-0.004}\right)$	$^{+0.005}_{-0.005}$ $\left(^{+0.003}_{-0.003}\right)$	$^{+0.004}_{-0.003}$ $\left(^{+0.003}_{-0.002}\right)$	$0.013\,^{+0.007}_{-0.005}$ $\left(^{+0.006}_{-0.004}\right)$	$^{+0.005}_{-0.004}$ $\left(^{+0.005}_{-0.004}\right)$	$^{+0.004}_{-0.003}$ $\left(^{+0.004}_{-0.003}\right)$	$0.034\,^{+0.016}_{-0.012}$ $\left(^{+0.007}_{-0.005}\right)$	$^{+0.012}_{-0.010}$ $\left(^{+0.005}_{-0.004}\right)$	$^{+0.010}_{-0.006}$ $\left(^{+0.004}_{-0.004}\right)$
$\mathrm{BR}^{WW}/\mathrm{BR}^{ZZ}$	$8.10 \pm < 0.01$	$6.8\,^{+1.7}_{-1.3}$ $\left(^{+2.2}_{-1.7}\right)$	$^{+1.5}_{-1.2}$ $\left(^{+2.0}_{-1.6}\right)$	$^{+0.7}_{-0.5}$ $\left(^{+0.9}_{-0.7}\right)$	$6.5\,^{+2.2}_{-1.6}$ $\left(^{+3.5}_{-2.4}\right)$	$^{+2.0}_{-1.5}$ $\left(^{+3.3}_{-2.2}\right)$	$^{+0.9}_{-0.6}$ $\left(^{+1.3}_{-0.9}\right)$	$7.2\,^{+2.9}_{-2.1}$ $\left(^{+3.2}_{-2.2}\right)$	$^{+2.6}_{-1.8}$ $\left(^{+2.9}_{-2.0}\right)$	$^{+1.3}_{-0.9}$ $\left(^{+1.4}_{-1.0}\right)$
$\mathrm{BR}^{\gamma\gamma}/\mathrm{BR}^{ZZ}$	0.085 ± 0.001	$0.069\,^{+0.018}_{-0.015}$ $\left(^{+0.025}_{-0.019}\right)$	$^{+0.018}_{-0.014}$ $\left(^{+0.024}_{-0.019}\right)$	$^{+0.004}_{-0.003}$ $\left(^{+0.006}_{-0.004}\right)$	$0.063\,^{+0.024}_{-0.018}$ $\left(^{+0.040}_{-0.027}\right)$	$^{+0.023}_{-0.017}$ $\left(^{+0.039}_{-0.027}\right)$	$^{+0.008}_{-0.005}$ $\left(^{+0.011}_{-0.006}\right)$	$0.079\,^{+0.033}_{-0.023}$ $\left(^{+0.035}_{-0.025}\right)$	$^{+0.032}_{-0.023}$ $\left(^{+0.034}_{-0.024}\right)$	$^{+0.010}_{-0.006}$ $\left(^{+0.008}_{-0.005}\right)$
$\mathrm{BR}^{\tau\tau}/\mathrm{BR}^{ZZ}$	2.36 ± 0.05	$1.8\,^{+0.6}_{-0.5}$ $\left(^{+0.9}_{-0.7}\right)$	$^{+0.5}_{-0.4}$ $\left(^{+0.8}_{-0.6}\right)$	$^{+0.3}_{-0.2}$ $\left(^{+0.5}_{-0.3}\right)$	$2.2\,^{+1.1}_{-0.8}$ $\left(^{+1.5}_{-1.0}\right)$	$^{+0.9}_{-0.6}$ $\left(^{+1.3}_{-0.9}\right)$	$^{+0.6}_{-0.4}$ $\left(^{+0.8}_{-0.5}\right)$	$1.6\,^{+0.9}_{-0.6}$ $\left(^{+1.2}_{-0.9}\right)$	$^{+0.8}_{-0.5}$ $\left(^{+1.0}_{-0.7}\right)$	$^{+0.5}_{-0.3}$ $\left(^{+0.7}_{-0.4}\right)$
$\mathrm{BR}^{bb}/\mathrm{BR}^{ZZ}$	21.6 ± 1.0	$4.2\,^{+4.6}_{-2.6}$ $\left(^{+16.9}_{-9.1}\right)$	$^{+2.8}_{-2.0}$ $\left(^{+13.9}_{-7.9}\right)$	$^{+3.6}_{-1.7}$ $\left(^{+9.5}_{-4.4}\right)$	$9.7\,^{+10.2}_{-5.8}$ $\left(^{+29.4}_{-11.8}\right)$	$^{+7.4}_{-4.4}$ $\left(^{+24.3}_{-10.5}\right)$	$^{+7.0}_{-3.8}$ $\left(^{+16.7}_{-5.4}\right)$	$3.7\,^{+4.1}_{-2.4}$ $\left(^{+29.4}_{-11.9}\right)$	$^{+3.1}_{-1.9}$ $\left(^{+23.4}_{-10.4}\right)$	$^{+2.7}_{-1.6}$ $\left(^{+17.7}_{-5.9}\right)$

**Covariance matrix to be provided with paper submission*

Generic model (couplings)

Parameter	Best-fit value	Uncertainty Stat	Expt	Thbgd	Thsig
	ATLAS+CMS				
$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$	$1.10^{+0.11}_{-0.11}$ $\left(^{+0.11}_{-0.11}\right)$	$^{+0.09}_{-0.09}$ $\left(^{+0.09}_{-0.09}\right)$	$^{+0.03}_{-0.02}$ $\left(^{+0.02}_{-0.02}\right)$	$^{+0.01}_{-0.01}$ $\left(^{+0.01}_{-0.01}\right)$	$^{+0.06}_{-0.05}$ $\left(^{+0.06}_{-0.05}\right)$
$\lambda_{Zg} = \kappa_Z / \kappa_g$	$1.26^{+0.23}_{-0.19}$ $\left(^{+0.20}_{-0.17}\right)$	$^{+0.18}_{-0.16}$ $\left(^{+0.15}_{-0.14}\right)$	$^{+0.09}_{-0.07}$ $\left(^{+0.08}_{-0.06}\right)$	$^{+0.06}_{-0.05}$ $\left(^{+0.05}_{-0.04}\right)$	$^{+0.09}_{-0.08}$ $\left(^{+0.08}_{-0.07}\right)$
$\lambda_{tg} = \kappa_t / \kappa_g$	$1.76^{+0.32}_{-0.29}$ $\left(^{+0.29}_{-0.39}\right)$	$^{+0.21}_{-0.20}$ $\left(^{+0.20}_{-0.21}\right)$	$^{+0.12}_{-0.11}$ $\left(^{+0.11}_{-0.12}\right)$	$^{+0.09}_{-0.09}$ $\left(^{+0.14}_{-0.19}\right)$	$^{+0.18}_{-0.13}$ $\left(^{+0.11}_{-0.08}\right)$
$\lambda_{WZ} = \kappa_W / \kappa_Z$	$0.89^{+0.10}_{-0.09}$ $\left(^{+0.12}_{-0.10}\right)$	$^{+0.09}_{-0.08}$ $\left(^{+0.11}_{-0.09}\right)$	$^{+0.03}_{-0.03}$ $\left(^{+0.04}_{-0.03}\right)$	$^{+0.02}_{-0.02}$ $\left(^{+0.03}_{-0.03}\right)$	$^{+0.02}_{-0.01}$ $\left(^{+0.02}_{-0.01}\right)$
$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$	$0.89^{+0.11}_{-0.10}$ $\left(^{+0.13}_{-0.12}\right)$	$^{+0.11}_{-0.09}$ $\left(^{+0.13}_{-0.11}\right)$	$^{+0.03}_{-0.02}$ $\left(^{+0.03}_{-0.02}\right)$	$^{+0.01}_{-0.01}$ $\left(^{+0.02}_{-0.01}\right)$	$^{+0.02}_{-0.02}$ $\left(^{+0.02}_{-0.02}\right)$
$\lambda_{\tau Z} = \kappa_\tau / \kappa_Z$	$0.85^{+0.14}_{-0.12}$ $\left(^{+0.17}_{-0.15}\right)$	$^{+0.12}_{-0.10}$ $\left(^{+0.14}_{-0.13}\right)$	$^{+0.07}_{-0.06}$ $\left(^{+0.09}_{-0.08}\right)$	$^{+0.02}_{-0.02}$ $\left(^{+0.02}_{-0.02}\right)$	$^{+0.02}_{-0.02}$ $\left(^{+0.03}_{-0.02}\right)$
$\lambda_{bZ} = \kappa_b / \kappa_Z$	$0.56^{+0.18}_{-0.18}$ $\left(^{+0.25}_{-0.22}\right)$	$^{+0.12}_{-0.11}$ $\left(^{+0.21}_{-0.18}\right)$	$^{+0.07}_{-0.07}$ $\left(^{+0.09}_{-0.08}\right)$	$^{+0.07}_{-0.08}$ $\left(^{+0.08}_{-0.07}\right)$	$^{+0.03}_{-0.02}$ $\left(^{+0.06}_{-0.04}\right)$

P-Values wrt SM

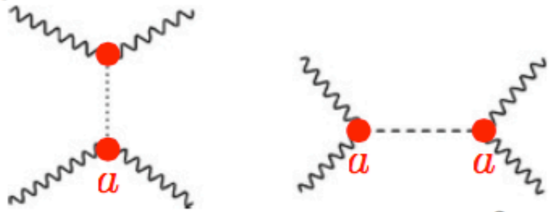
Model	p-value	DoF	Parameters
Global signal strength	34%	1	μ
Production processes	24%	5	$\mu_{\mathrm{ggF}}, \mu_{\mathrm{VBF}}, \mu_{WH}, \mu_{ZH}, \mu_{ttH}$
Decay modes	60%	5	$\mu^{\gamma\gamma}, \mu^{ZZ}, \mu^{WW}, \mu^{\tau\tau}, \mu^{b\bar{b}}$
μ_V and μ_F per decay	88%	10	$\mu_V^{\gamma\gamma}, \mu_V^{ZZ}, \mu_V^{WW}, \mu_V^{\tau\tau}, \mu_V^{b\bar{b}}, \mu_F^{\gamma\gamma}, \mu_F^{ZZ}, \mu_F^{WW}, \mu_F^{\tau\tau}, \mu_F^{b\bar{b}}$
μ_V/μ_F ratio	72%	6	$\mu_V/\mu_F, \mu_F^{\gamma\gamma}, \mu_F^{ZZ}, \mu_F^{WW}, \mu_F^{\tau\tau}, \mu_F^{b\bar{b}}$
Ratios of σ and BR relative to $\sigma(gg \to H \to ZZ)$	16%	9	$\sigma(gg \to H \to ZZ)$, $\sigma_{\mathrm{VBF}}/\sigma_{\mathrm{ggF}}$, $\sigma_{WH}/\sigma_{\mathrm{ggF}}$, $\sigma_{ZH}/\sigma_{\mathrm{ggF}}$, $\sigma_{ttH}/\sigma_{\mathrm{ggF}}$, $\mathrm{BR}^{WW}/\mathrm{BR}^{ZZ}$, $\mathrm{BR}^{\gamma\gamma}/\mathrm{BR}^{ZZ}$, $\mathrm{BR}^{\tau\tau}/\mathrm{BR}^{ZZ}$, $\mathrm{BR}^{b\bar{b}}/\mathrm{BR}^{ZZ}$
Ratios of σ and BR relative to $\sigma(gg \to H \to WW)$	16%	9	$\sigma(gg \to H \to WW)$, $\sigma_{\mathrm{VBF}}/\sigma_{\mathrm{ggF}}$, $\sigma_{WH}/\sigma_{\mathrm{ggF}}$, $\sigma_{ZH}/\sigma_{\mathrm{ggF}}$, $\sigma_{ttH}/\sigma_{\mathrm{ggF}}$, $\mathrm{BR}^{ZZ}/\mathrm{BR}^{WW}$, $\mathrm{BR}^{\gamma\gamma}/\mathrm{BR}^{WW}$, $\mathrm{BR}^{\tau\tau}/\mathrm{BR}^{WW}$, $\mathrm{BR}^{b\bar{b}}/\mathrm{BR}^{WW}$
Coupling ratios	13%	7	$\kappa_{gZ}, \lambda_{Zg}, \lambda_{tg}, \lambda_{WZ}, \lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{bZ}$
Couplings, SM loops	65%	6	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_\mu$
Couplings, BSM loops	11%	7	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_g, \kappa_\gamma$
BSM loops only	82%	2	κ_g, κ_γ
Up vs down couplings	67%	3	$\lambda_{du}, \lambda_{Vu}, \kappa_{uu}$
Lepton vs quark couplings	78%	3	$\lambda_{lq}, \lambda_{Vq}, \kappa_{qq}$
Fermion and vector couplings	59%	2	κ_V, κ_F

kV-kF

M. Trott HC 2015

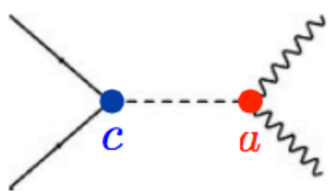
1. SM is of course consistent with the data.

The problem that needed to be solved:



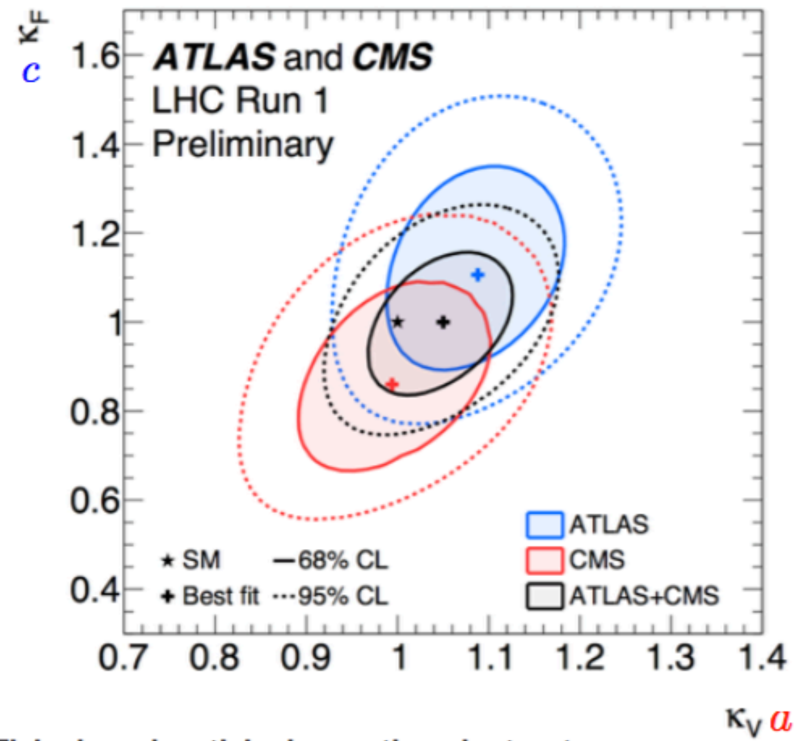
$$W_L^+ W_L^- \to W_L^+ W_L^- \; : \; \mathcal{A} \simeq \frac{g^2}{4\, m_W^2}(s+t)(1-a^2) \to 0$$

$\epsilon_L^\mu \simeq p^\mu / m_W$



Perfect solution to this problem is the SM Higgs.

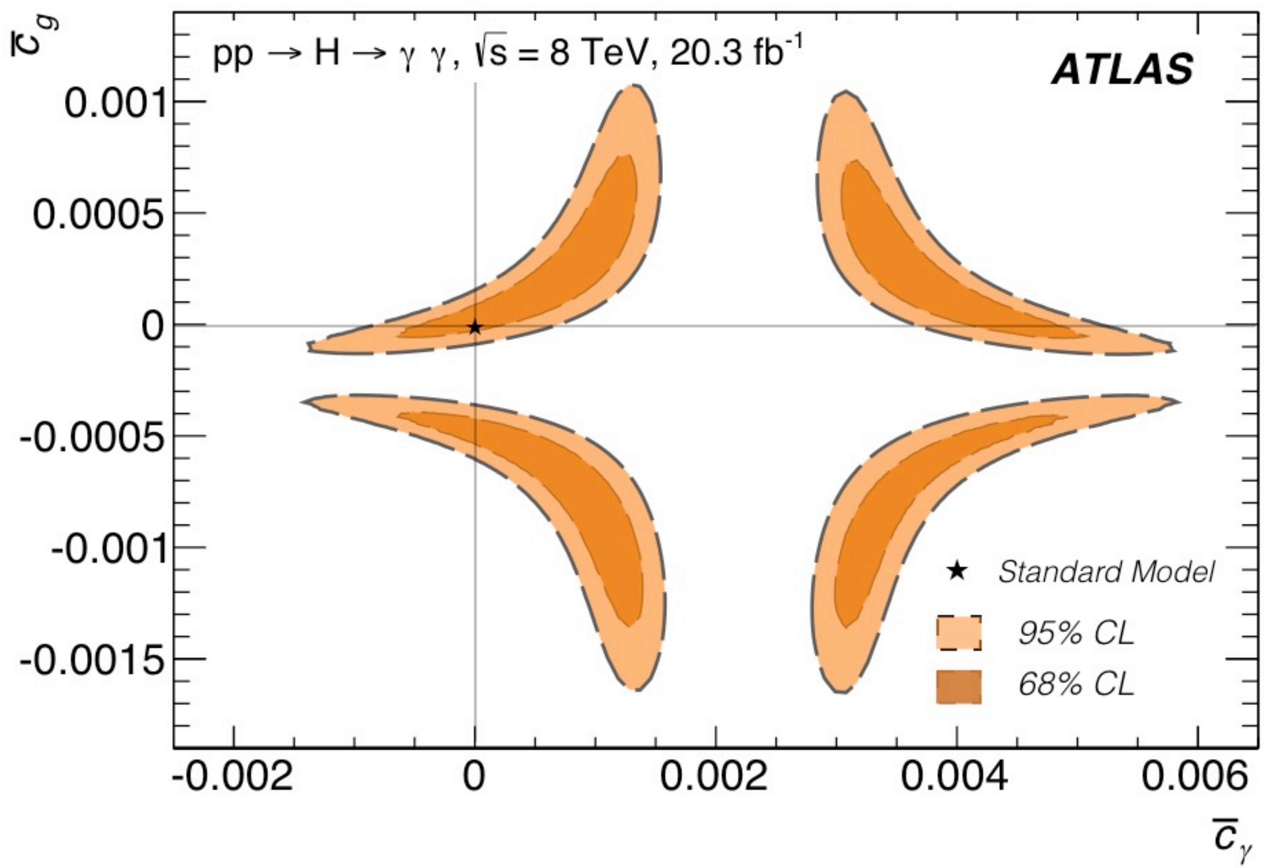
$$\psi\bar{\psi} \to W_L^+ W_L^- \; : \quad \mathcal{A} \simeq \frac{m_\psi \sqrt{s}}{v^2}(1 - a\,c) \to 0$$



This is why this hypothesis test makes sense to do now, and going forward.

ATLAS EFT constraints

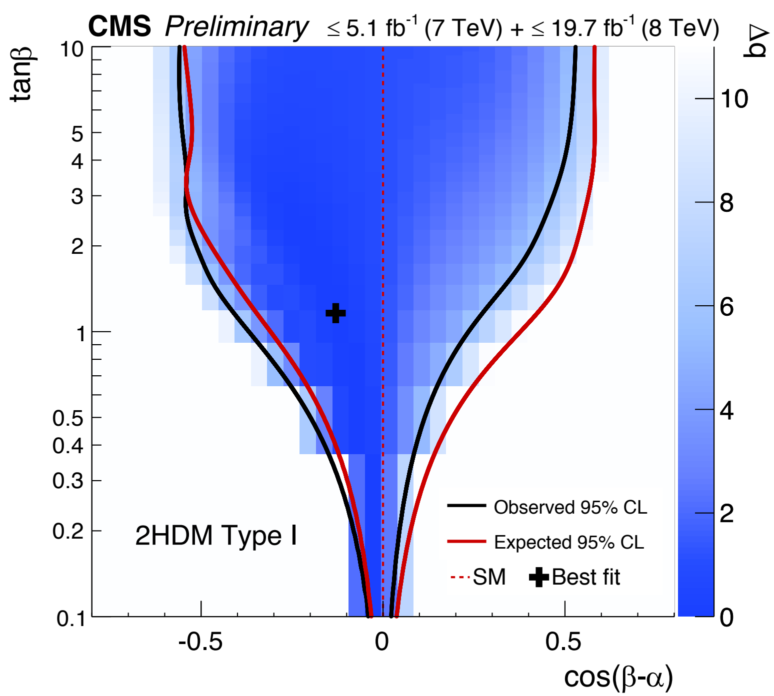
Direct use of differential cross-section measurements (H→γγ) to constrain HO wilson coefficients…



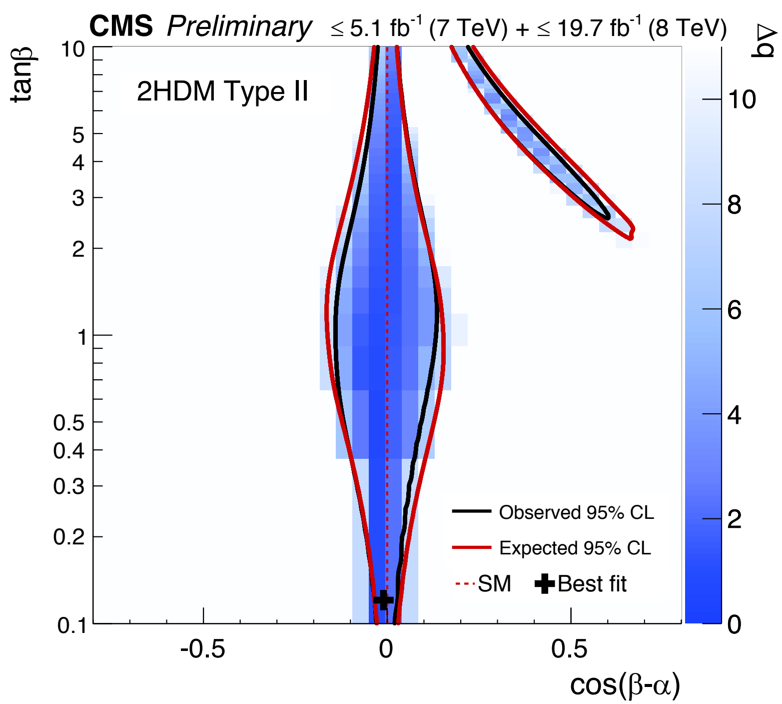
2HDM Simple parameterisation

Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V	$\sin(\beta-\alpha)$			
κ_u	$\cos(\alpha)/\sin(\beta)$			
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

Type-1



Type-2



MSSM H(125) couplings

$$\kappa_V = \frac{s_d(m_A,\tan\beta)+\tan\beta\ s_u(m_A,\tan\beta)}{\sqrt{1+\tan^2\beta}}$$

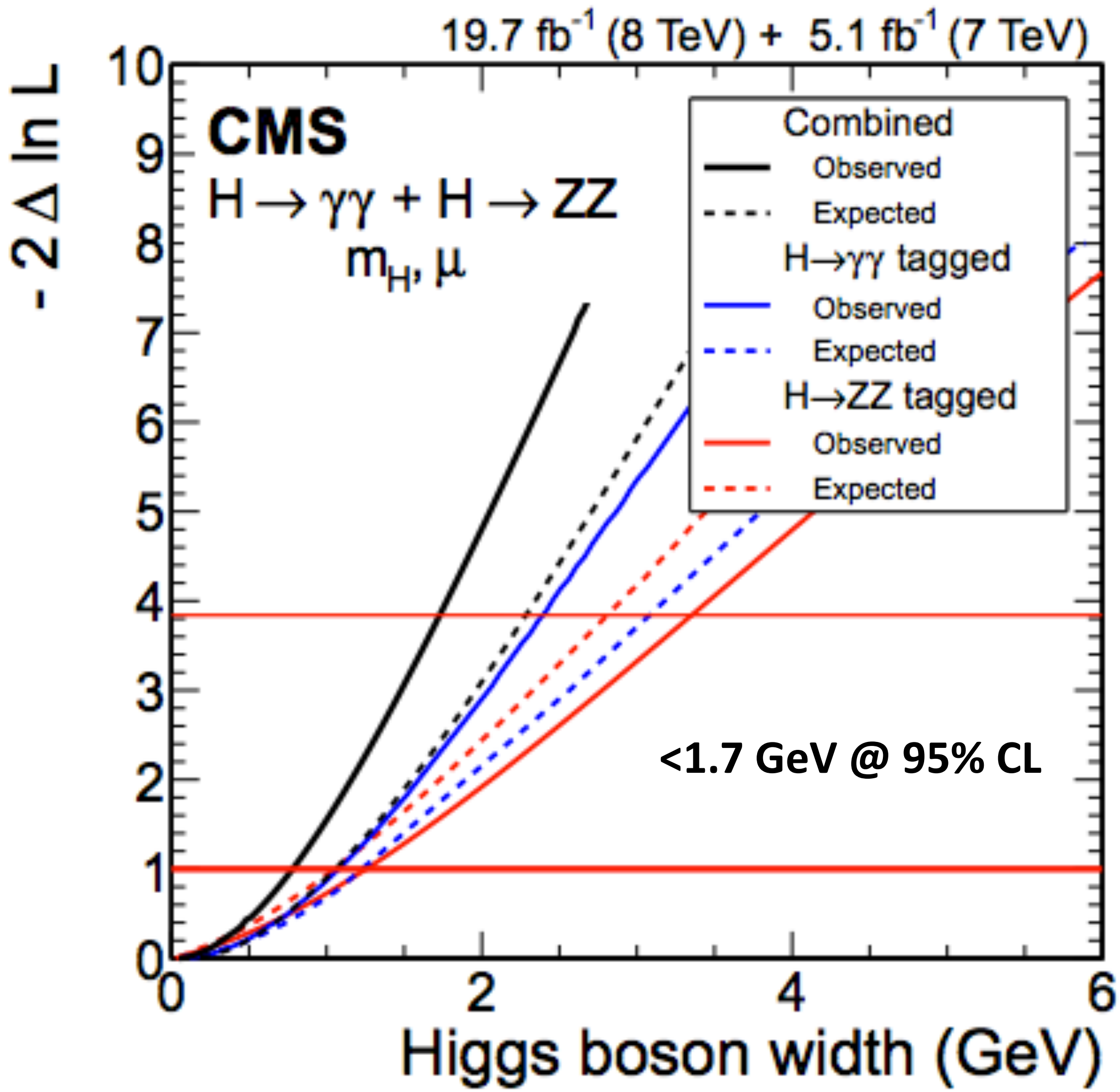
$$\kappa_u = s_u(m_A,\tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

$$\kappa_d = s_d(m_A,\tan\beta)\sqrt{1+\tan^2\beta} \quad ,$$

$$s_u = \frac{1}{\sqrt{1+\frac{\left(m_A^2+m_Z^2\right)^2\tan^2\beta}{\left(m_Z^2+m_A^2\tan^2\beta-m_h^2\left(1+\tan^2\beta\right)\right)^2}}}$$

$$s_d = \frac{\left(m_A^2+m_Z^2\right)\tan\beta}{m_Z^2+m_A^2\tan^2\beta-m_h^2\left(1+\tan^2\beta\right)}\, s_u$$

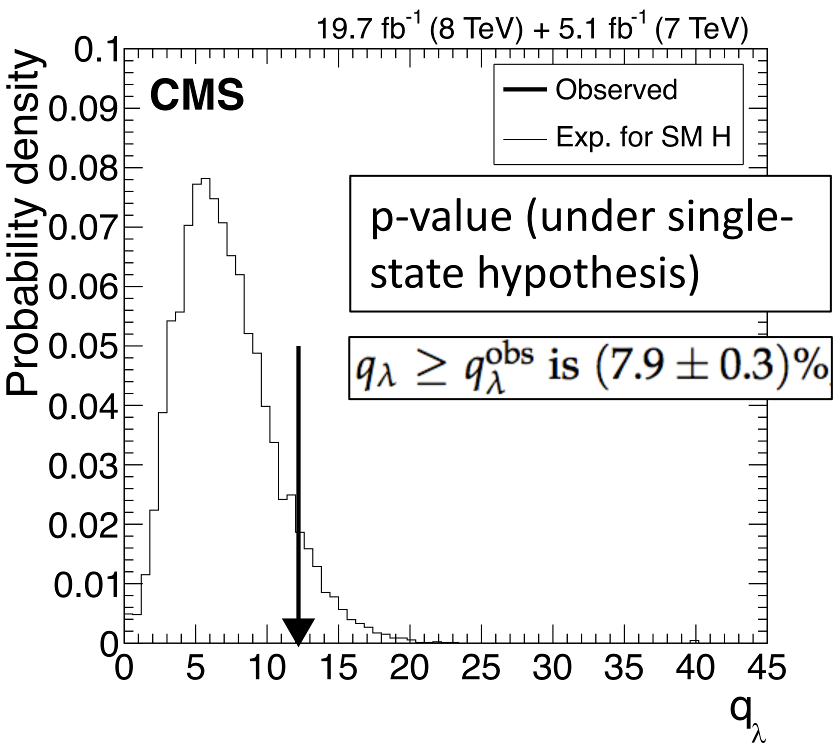
CMS Higgs width measurement



Rank Test

Check compatibility of data with "single-particle state" hypothesis

All parameters constrained to be positive.					
Signal model	$H \to \gamma\gamma$	$H \to ZZ$	$H \to WW$	$H \to \tau\tau$	$H \to bb$
ggH	$\mu_{\gamma\gamma}$	μ_{ZZ}	μ_{WW}	$\mu_{\tau\tau}$	μ_{bb}
VBF	$\lambda^{\gamma\gamma}_{VBF}\,\mu_{\gamma\gamma}$	$\lambda^{ZZ}_{VBF}\,\mu_{ZZ}$	$\lambda^{WW}_{VBF}\,\mu_{WW}$	$\lambda^{\tau\tau}_{VBF}\,\mu_{\tau\tau}$	$\lambda^{bb}_{VBF}\,\mu_{bb}$
VH	$\lambda^{\gamma\gamma}_{VH}\,\mu_{\gamma\gamma}$	$\lambda^{ZZ}_{VH}\,\mu_{ZZ}$	$\lambda^{WW}_{VH}\,\mu_{WW}$	$\lambda^{\tau\tau}_{VH}\,\mu_{\tau\tau}$	$\lambda^{bb}_{VH}\,\mu_{bb}$
ttH	$\lambda^{\gamma\gamma}_{ttH}\,\mu_{\gamma\gamma}$	$\lambda^{ZZ}_{ttH}\,\mu_{ZZ}$	$\lambda^{WW}_{ttH}\,\mu_{WW}$	$\lambda^{\tau\tau}_{ttH}\,\mu_{\tau\tau}$	$\lambda^{bb}_{ttH}\,\mu_{bb}$



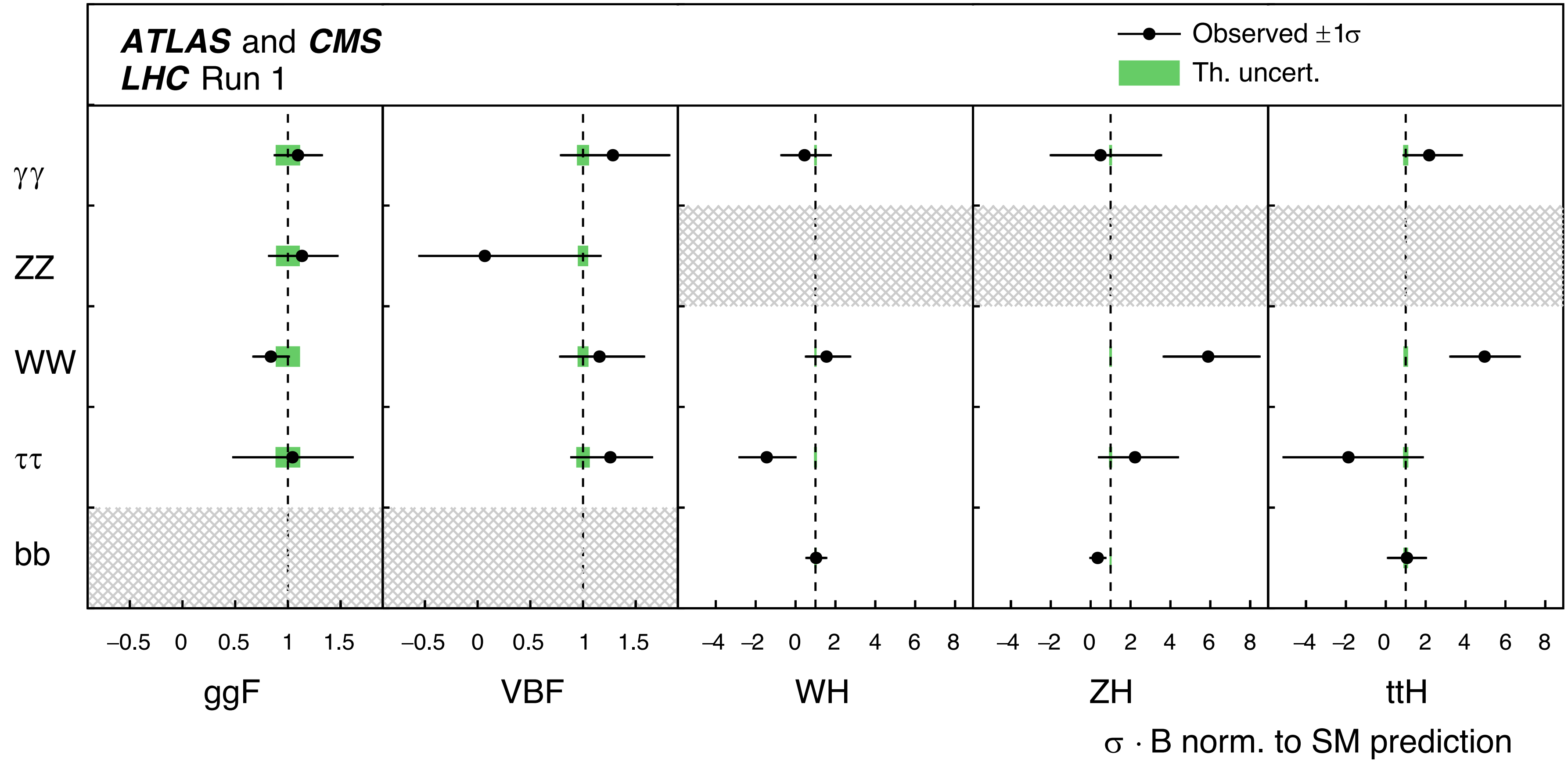
Compare the model for which

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

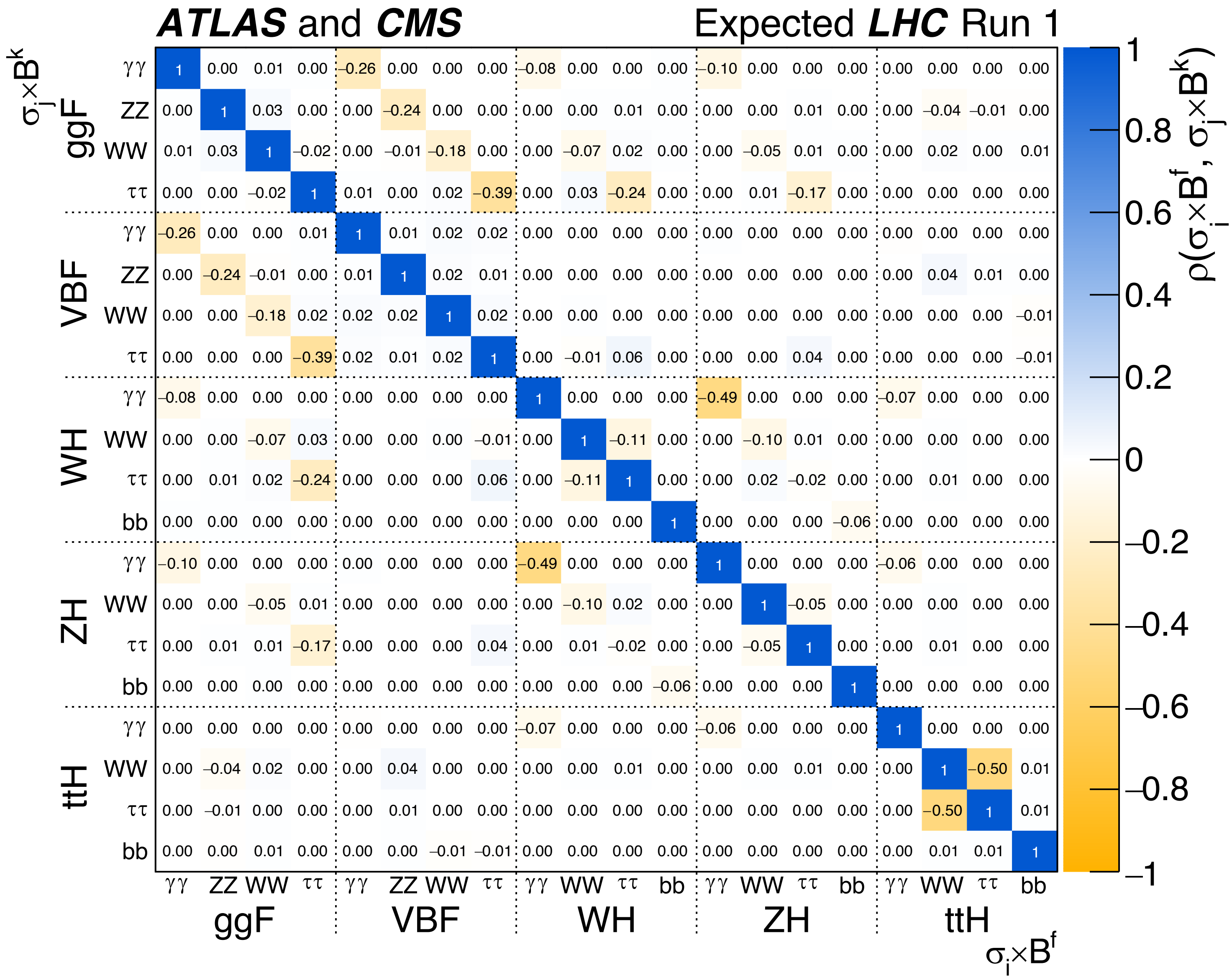
(i.e single narrow state), with "saturated model"

$$q_\lambda = -2 \ln \frac{\mathcal{L}(\text{data} \mid \lambda_i^j = \hat{\lambda}_i, \hat{\mu}_j)}{\mathcal{L}(\text{data} \mid \hat{\lambda}_i^j, \hat{\mu}_j{}')}$$

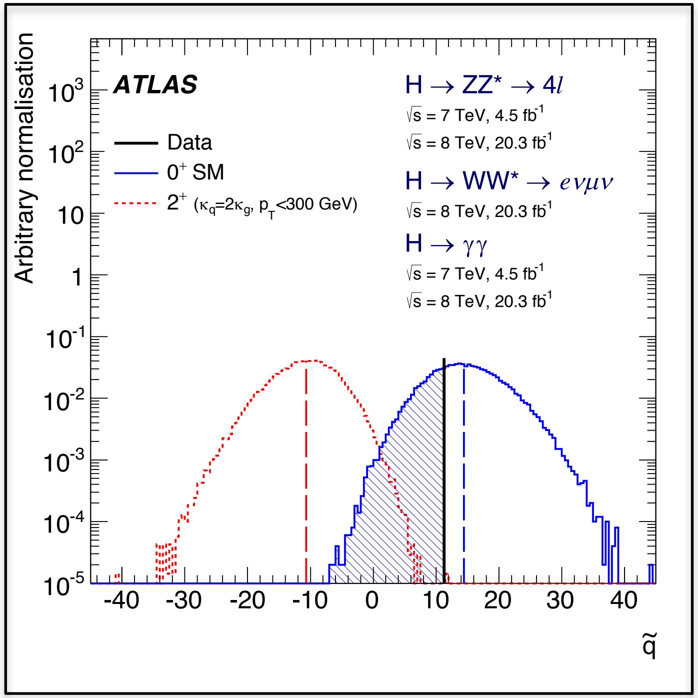
Higgs Prod x Decay



Higgs Prod x Decay



Spin-Parity



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Before you want to know if it looks like, walks like and sounds like a duck, you should first check it isn't an ostrich!

ATLAS and CMS H→WW,ZZ,γγ modes use angular information to distinguish between various J^P hypotheses…

Run-1 data is enough to rule out spin-2 (and many other J^P states) at > 99.9% confidence level

PRD 92 (2015) 012004