Higgs Properties at the LHC

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on behalf of the ATLAS and CMS collaborations

HEFT 2017, Lumley Castle

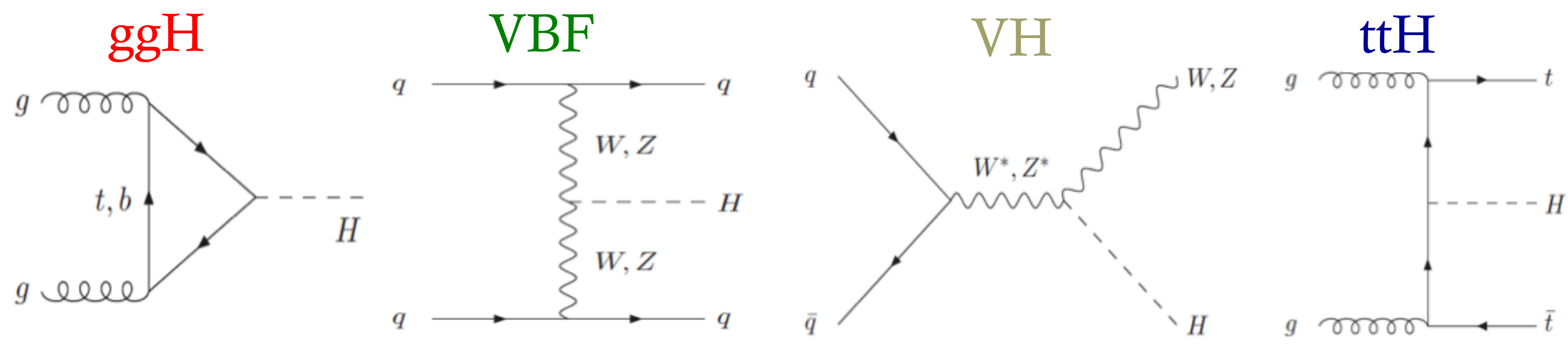
Outline

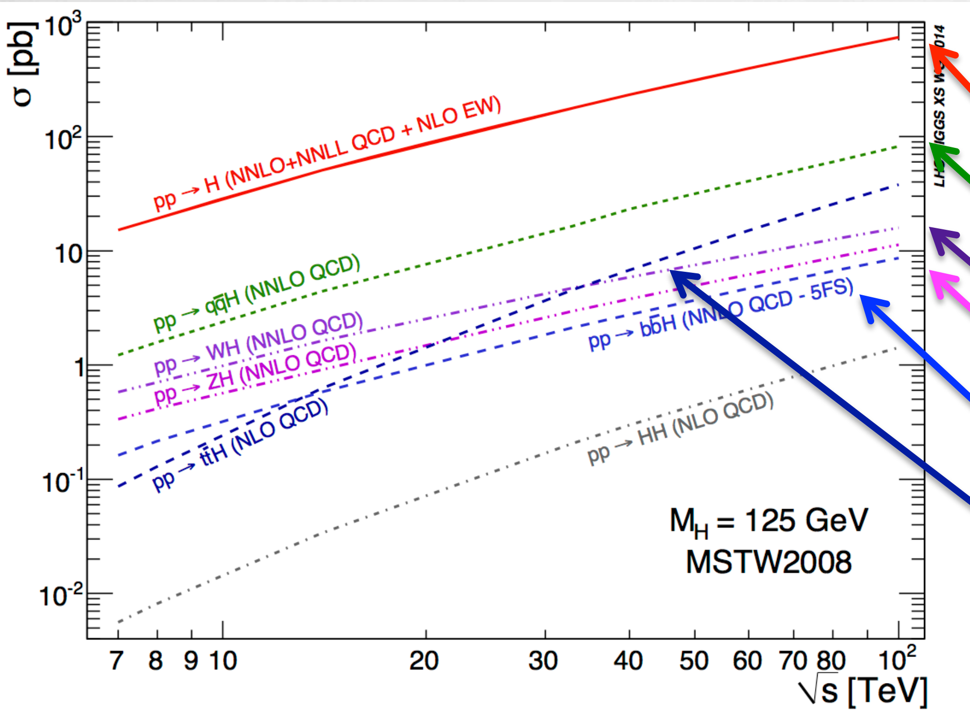
- The newest and best measurements for Higgs couplings, cross sections, and m_H
  - → Spring 2017 results from both ATLAS and CMS in the most sensitive channels, $H \to \gamma\gamma$ and $H \to ZZ \to 4l$
  - Many results now presented using Simplified Template Cross Sections (STXS), PseudoObservables, fiducial cross sections.
- Overview of other couplings and properties measurements: H-Fermion (tau, mu, top),HWW, self-coupling, CP measurements
- Review of the Run 1 ATLAS+CMS Combination
  - The Kappa framework and cross section ratios

Latest Higgs Measurements

Measurement		H→ZZ	H→$\gamma\gamma$	H→WW	H→$\tau\tau$	H→bb
Coupling	CMS	April 2017 35.9 fb-1 CMS-PAS-HIG-16-041	Aug. 2016 CMS-PAS-HIG-16-020	June 2016 2.3 fb-1 CMS-PAS-HIG-15-003	May 2017 CMS-PAS-HIG-16-043	Run 1 VH *Phys. Rev.* **D92** (2015), no. 3, 032008. Run 2 VBF CMS-PAS-HIG-16-003
	ATLAS	June 2016 ATLAS-CONF-2016-079	Aug 2016 13.3 fb-1 ATLAS-CONF-2016-067	Nov 2016 ATLAS-CONF-2016-112 5.8 fb-1	Run 1 JHEP 05 (2014) 1041	Aug 2016 $L = 13.2\ fb^{-1}$ ATLAS-CONF-2016-080 ATLAS-CONF-2016-091
Cross Section	CMS	April 2017 35.9 fb-1 CMS-PAS-HIG-16-041	Mar. 2017 CMS-PAS-HIG-17-015	Nov 2016. 5.8 fb-1 ATLAS-CONF-2016-112		
	ATLAS	May 2017 36.1 fb-1 HIGG-2016-25	Aug. 2016 13.3 fb-1 ATLAS-CONF-2016-067	Nov. 2016 Production XS ATLAS-CONF-2016-112		
Mass	CMS	April 2017 35.9 fb-1 CMS-PAS-HIG-16-041	Run 1 Phys. Rev. Lett. **114**, 191803			
	ATLAS	Run 1 Phys. Rev. Lett. **114**, 191803	Run 1 Phys. Rev. Lett. **114**, 191803			

Higgs Production



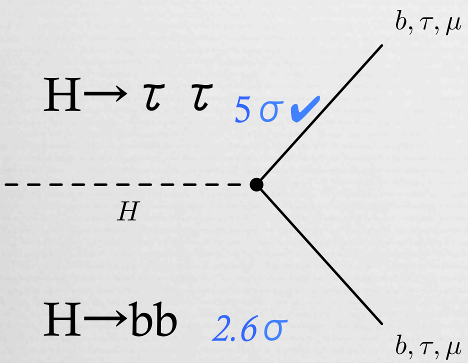


Production process	Observed at $5\,\sigma$
ggF	✔
VBF	✔
WH	
ZH	
bbH	
ttH	

Higgs Decays

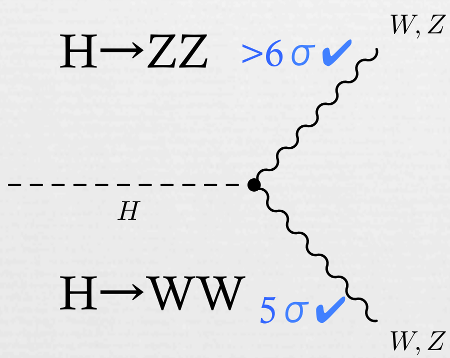
H→ τ τ 5σ✔

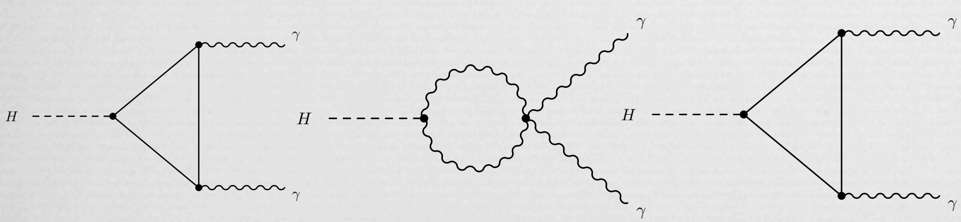
H→bb 2.6σ



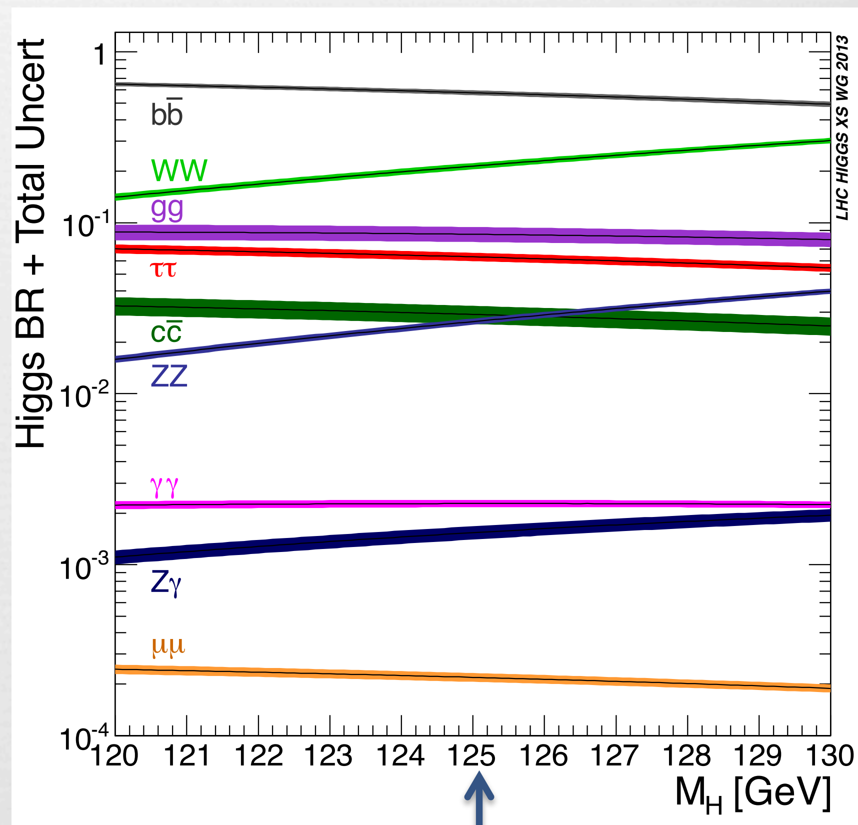
H→ZZ >6σ✔

H→WW 5σ✔





H→ γ γ >5σ✔



m_H= 125.26 ± 0.20 (stat) ± 0.08 (syst) GeV

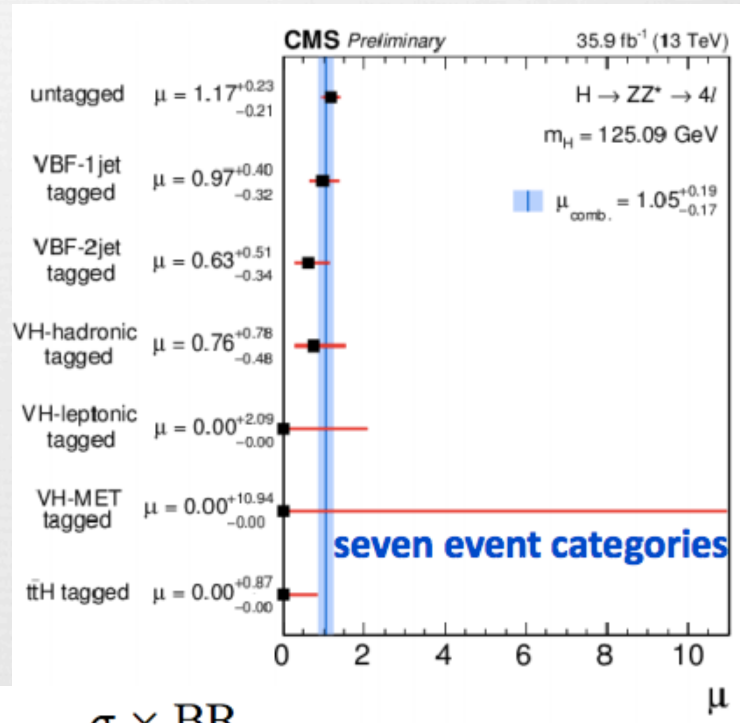
Latest $H \to ZZ \to 4l$ and $H \to \gamma\gamma$ Measurements

H→ZZ→4l

CMS-PAS-HIG-16-041
April 2017; $\mathcal{L}$= 35.9 fb^{-1}

Higgs Signal Strength

- Signal signature:
  - 4 isolated leptons
  - Fully reconstructed mass peak
  - Large S/B ratio
- Events split into 7 categories according to Higgs production modes to increase sensitivity, based on number of leptons, number of bjets, missing energy, kinematic discriminants



$$\mu = \frac{\sigma \times \mathrm{BR}}{(\sigma \times \mathrm{BR})_{\mathrm{SM}}}$$

$$1.05^{+0.15}_{-0.14}(\mathrm{stat.})^{+0.11}_{-0.09}(\mathrm{sys.}) = 1.05^{+0.19}_{-0.17}$$

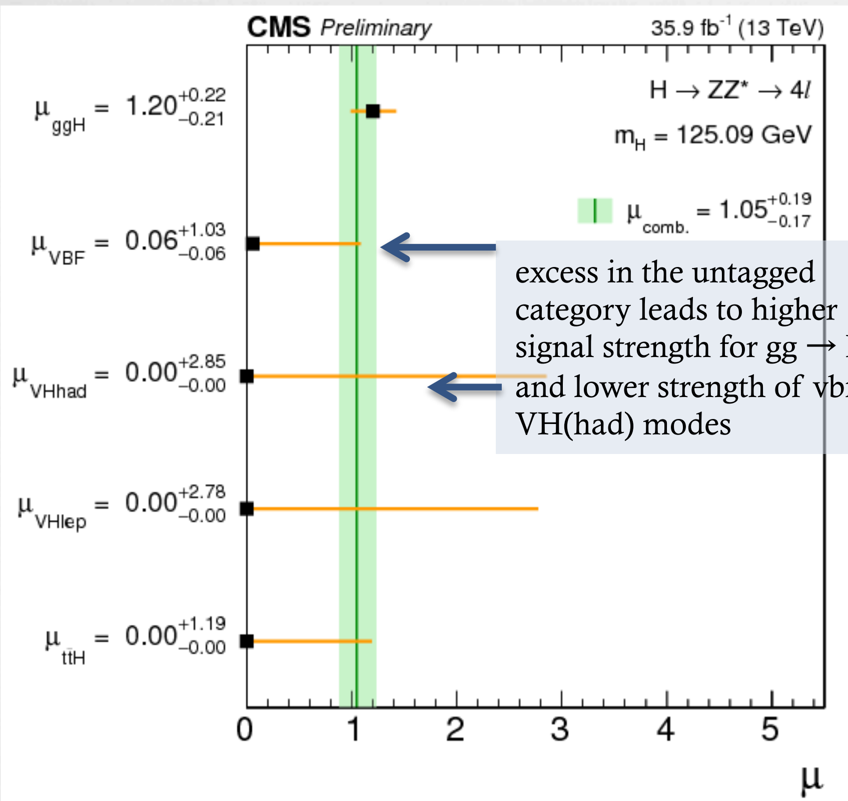
Test against SM Higgs signal with m_H= 125.09GeV
Experimental and Theoretical uncertainties of similar magnitude

CMS-PAS-HIG-16-041

H→ZZ→4l
Higgs Signal Strength

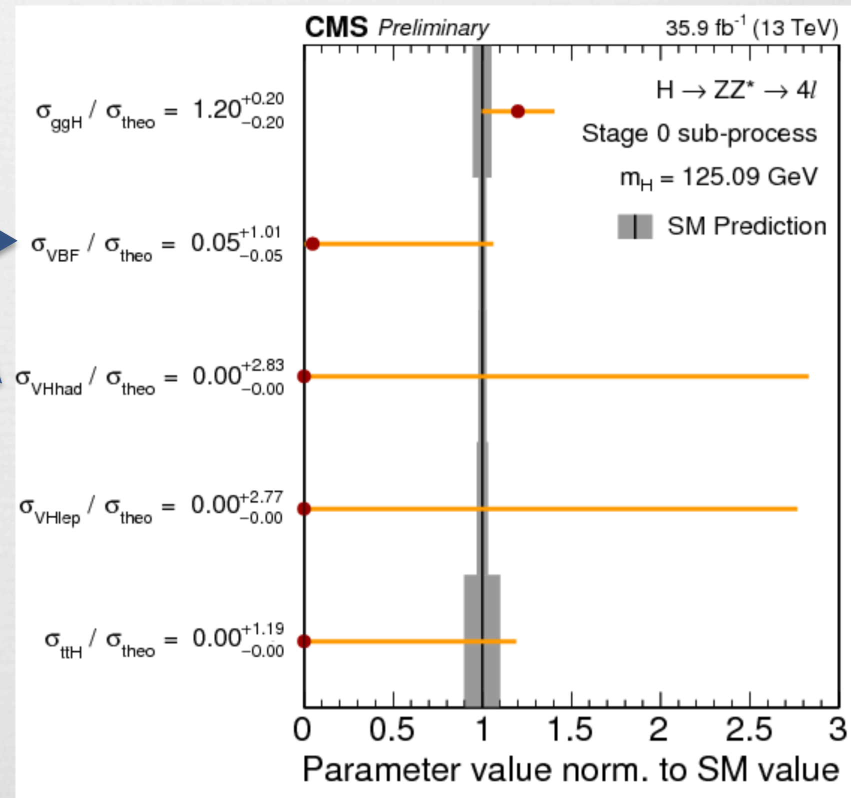
Signal strength by production mode

μ_{ggH} μ_{VBF} μ_{VH} μ_{ttH}



excess in the untagged category leads to higher signal strength for gg → H and lower strength of vbf/VH(had) modes

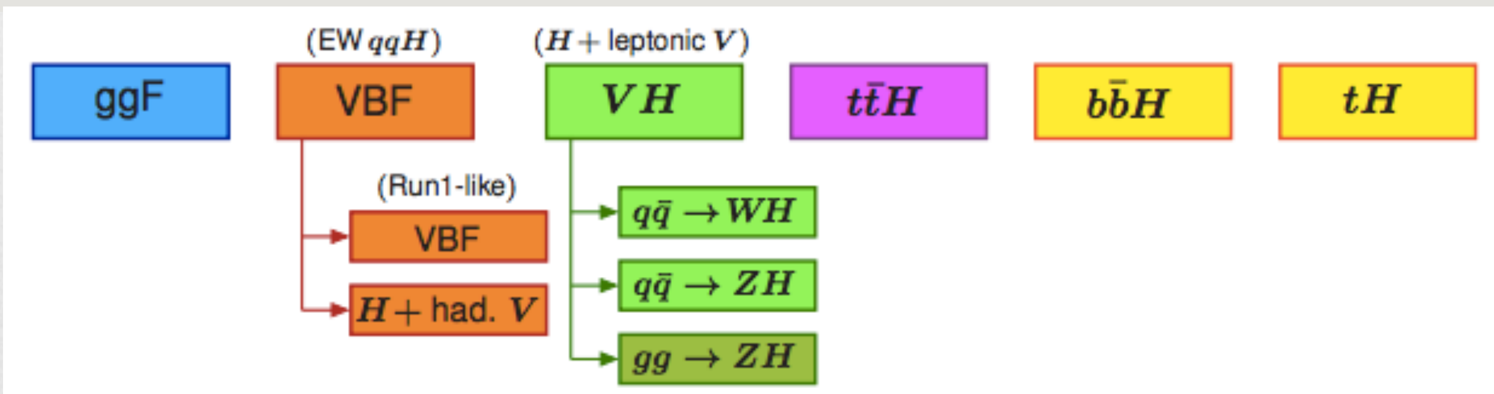
Simplified template cross sections



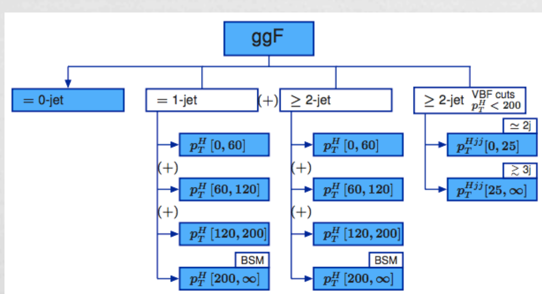
Simplified Template Cross Sections

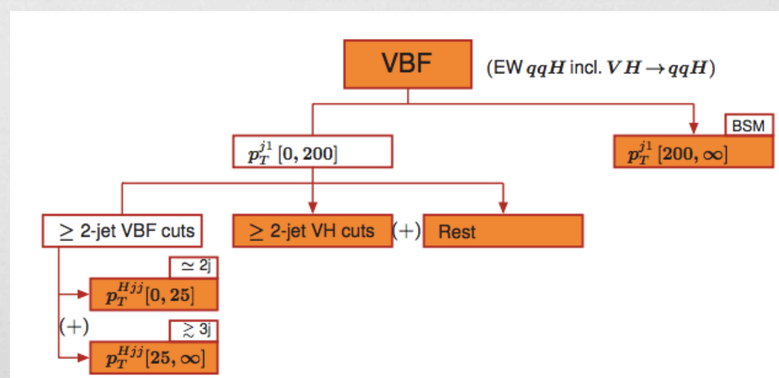
- Defined in the CERN Yellow Report 4
- Define a common binning system for reporting results
  - Separate regions of phases space for which theory uncertainties can evolve
  - Choose phase space regions most sensitive to BSM

Stage 0:



Stage 1:





H→ZZ→4l Higgs Mass Measurement

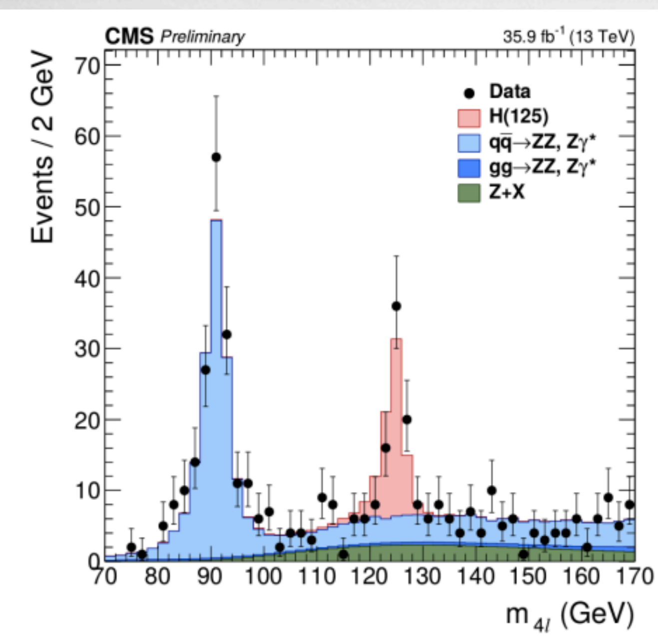
CMS-PAS-HIG-16-041

- Run 1 ATLAS+CMS Combination: (Phys. Rev. Lett. 114, 191803)

$$m_H = 125.09 \pm 0.21 \text{ (stat)} \pm 0.10 \text{ (syst) GeV}$$

- New 4-lepton invariant mass from H→ZZ→llll (CMS-PAS-HIG-16-041)

125.26 ± 0.20 (stat) ± 0.08 (syst) GeV



- 3D fit to L(m_{4l}, D_{mass}, D_{bkg})
- Kinematic fit using a constraint on the intermediate Z mass

$$\mathcal{L}(\hat{p}_T^1, \hat{p}_T^2 | p_T^1, \sigma_{p_T^1}, p_T^2, \sigma_{p_T^2}) =$$

$$\text{Gauss}(p_T^1 | \hat{p}_T^1, \sigma_{p_T^1}) \cdot \text{Gauss}(p_T^2 | \hat{p}_T^2, \sigma_{p_T^2}) \cdot \mathcal{L}(m_{12} | m_Z, m_H),$$

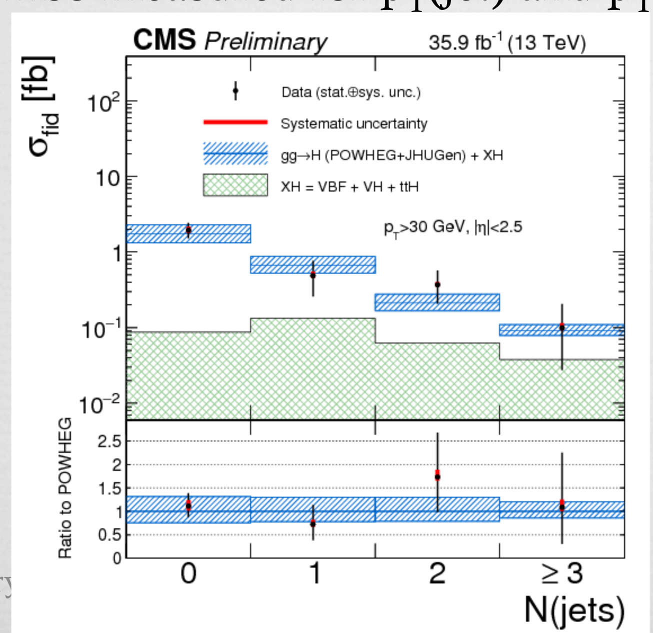
For each event, the likelihood is maximized and the refitted transverse momenta are used to recalculate the four-lepton mass and mass uncertainty. These distributions are then used to build the likelihood used to extract the Higgs boson mass.

H→ZZ→4l
Higgs Cross Section

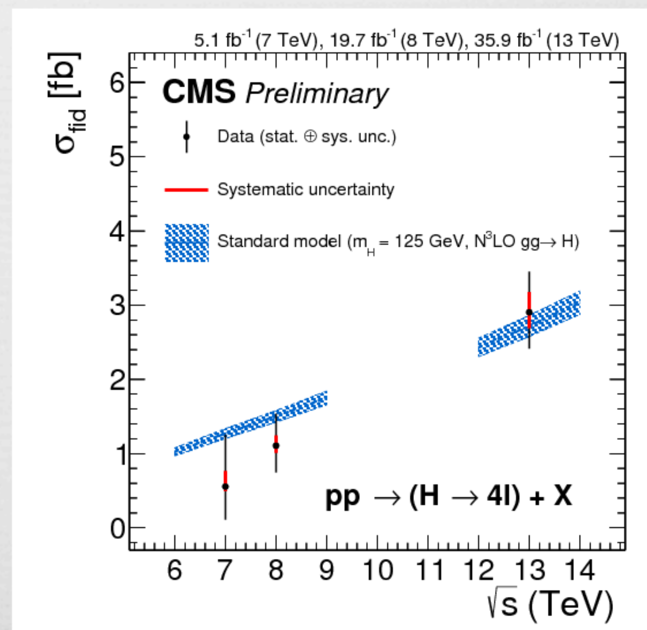
Measured: $\sigma_{fid} = 2.90^{+0.48}_{-0.44}(\text{stat.})^{+0.27}_{-0.22}(\text{sys.})$ fb.
SM expectation: $\sigma_{fid} = 2.72 \pm 0.14$ fb.

Cross sections measured in fiducial phase space to minimize model dependence.

Differential cross section for N(jets),
Also measured for p_T(jet) and p_T(H)



Measured Fiducial σ_{fid} vs $\sqrt{s}$

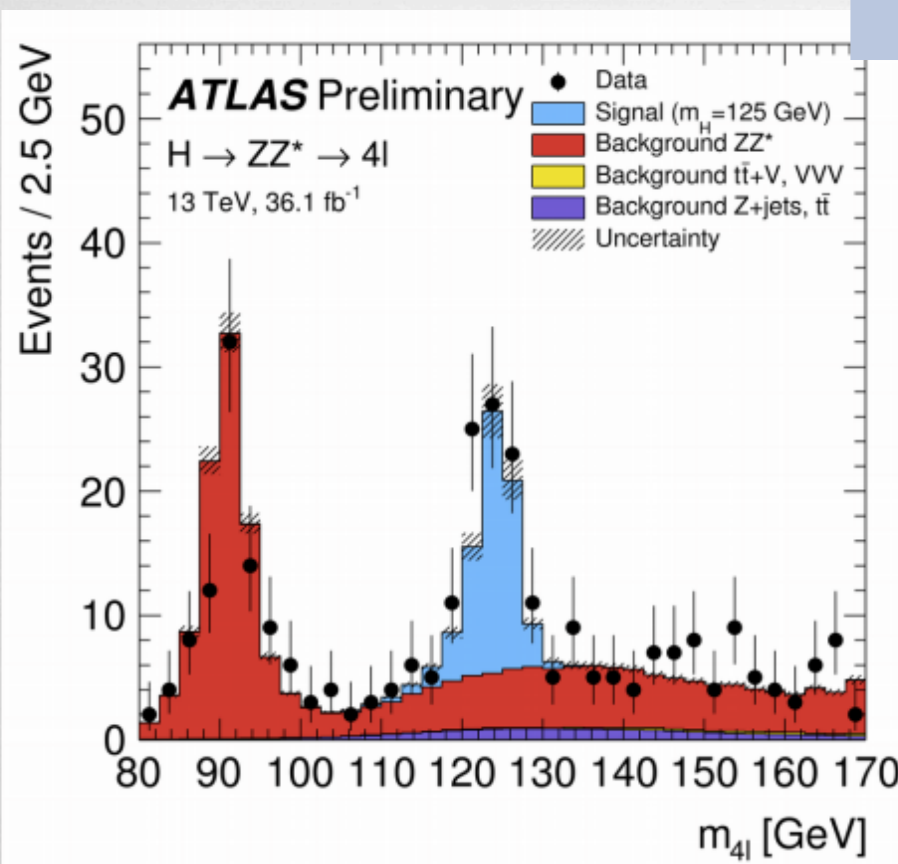


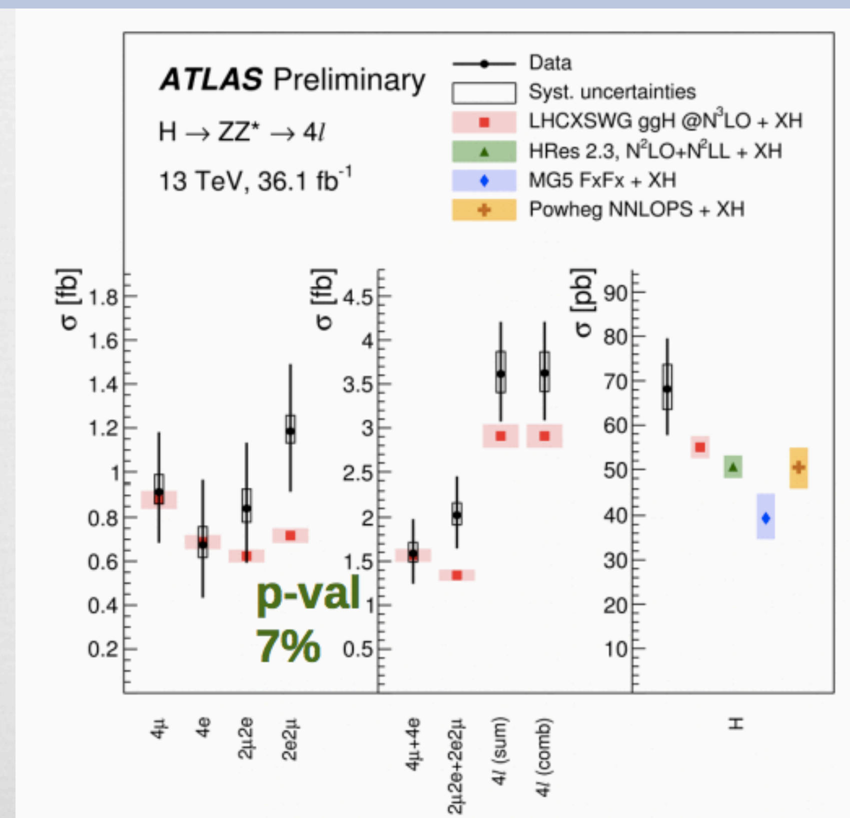
ATLAS-CONF-2017-032
New at LHCP: 36.1 fb^{-1}

$H \rightarrow ZZ \rightarrow 4l$

Measurement of the Higgs fiducial cross sections
Correct for detector efficiency and resolution
Signal extraction: fit the 4l invariant mass

56 Expected Higgs events

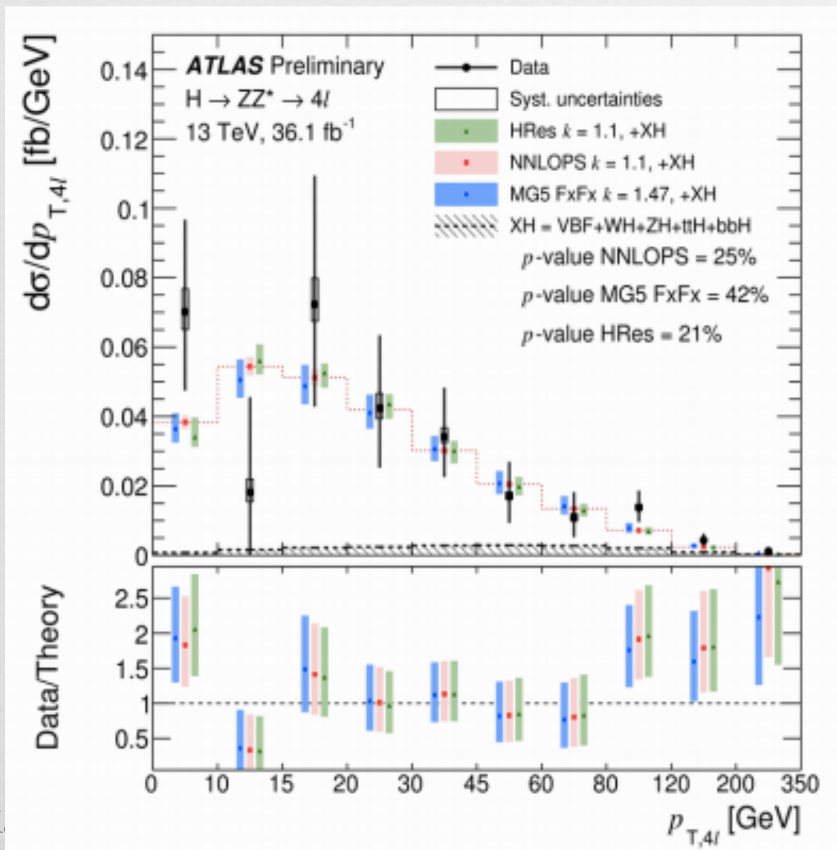


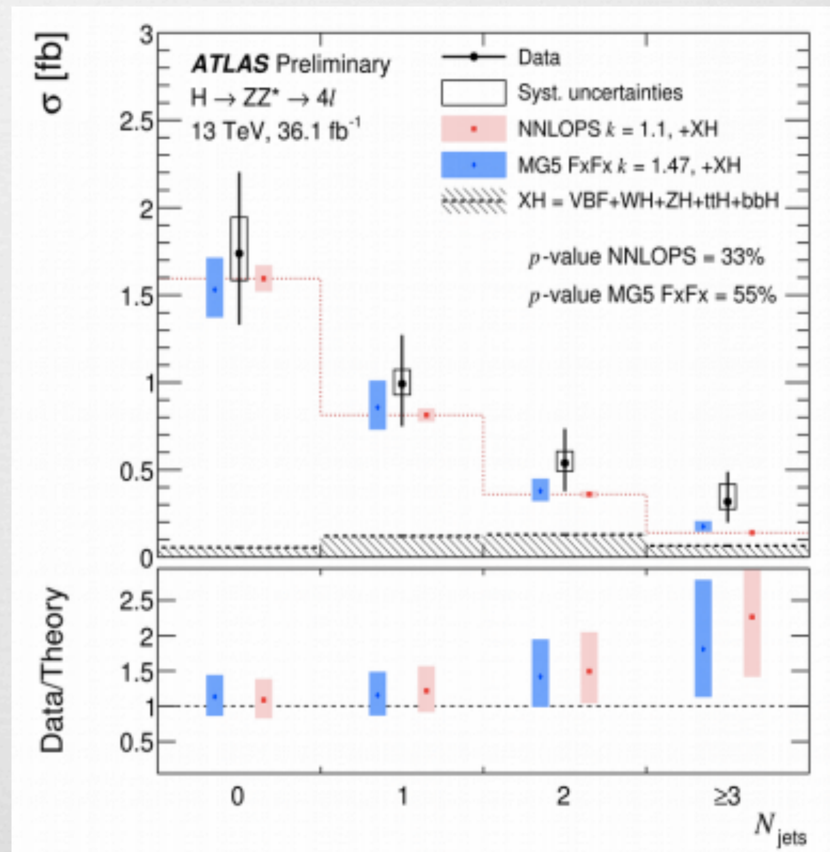


ATLAS-CONF-2017-032
New at LHCP: 36.1 fb^{-1}

H→ZZ→4l

Differential cross section distributions in jet and pT bins



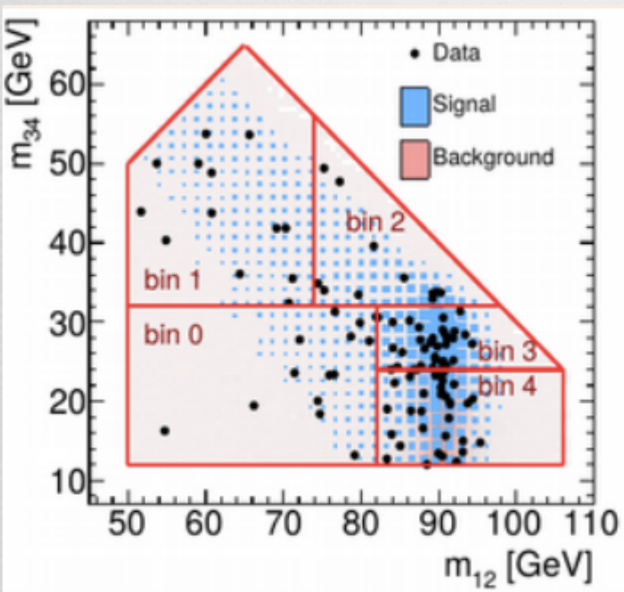


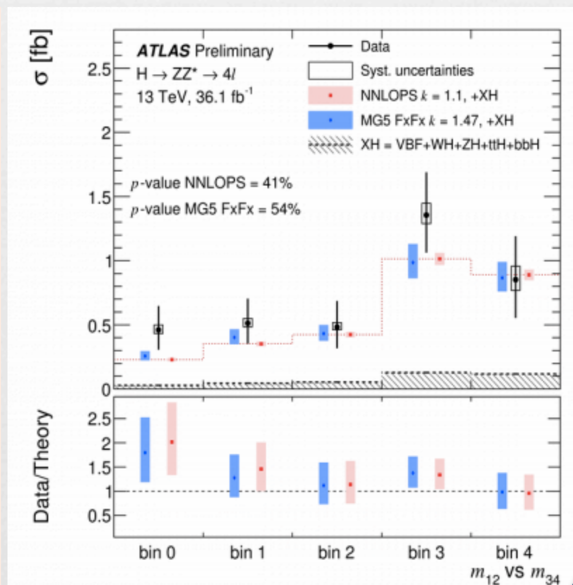
H→ZZ→4l

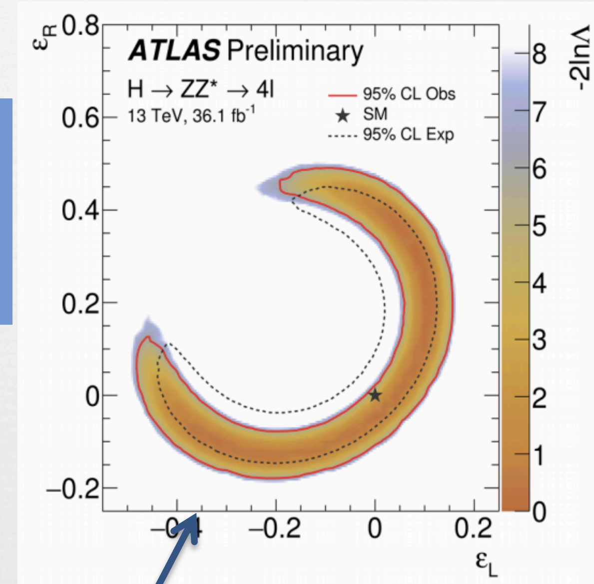
ATLAS-CONF-2017-032
New at LHCP: 36.1 fb^{-1}

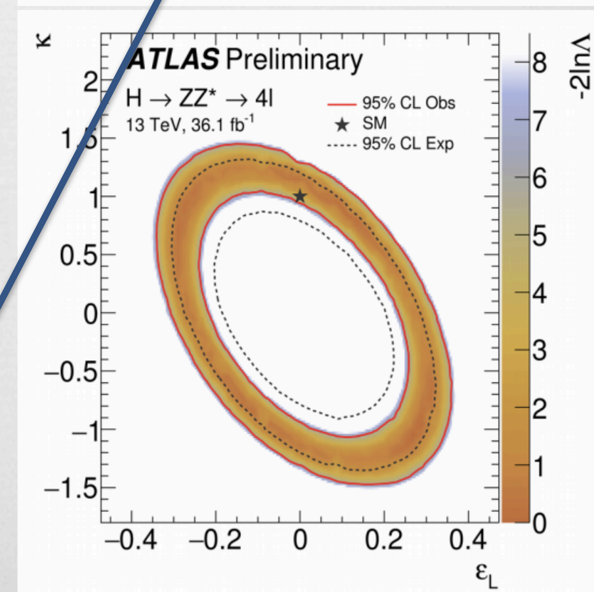
Eleni Mountricha @ LHCP

Use differential fiducial cross sections to look for BSM modified H interactions using pseudo-observables (PO). **PO = form factors parametrizing amplitudes of physical processes.** Calculate the contribution to the double differential decay rate: m12 vs m34









Limits on modified contact terms between H and L/R-handed leptons. (Lepton universality imposed)

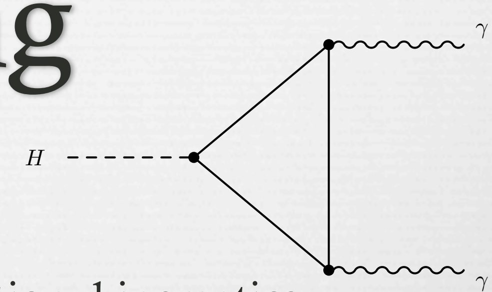
Limits on ε_L and modified coupling to Z-boson

PseudoObservables: Eur. Phys. J. C (2015) 75:128 & YR4

CMS-PAS-HIG-16-40

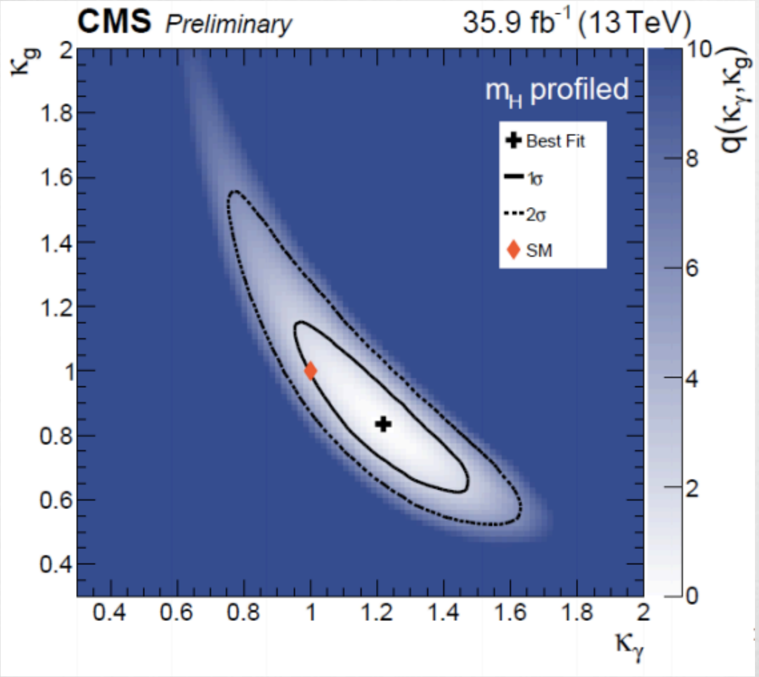
May 2017 35.9 fb-1

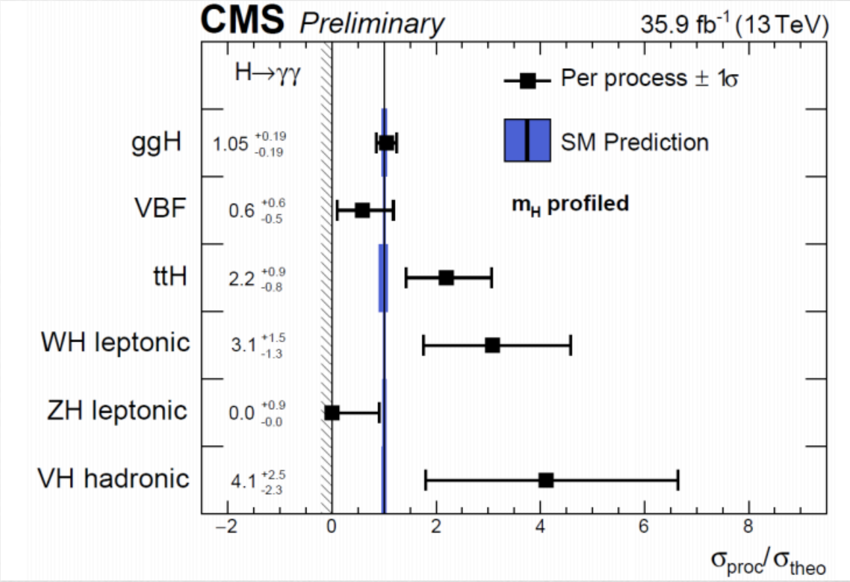
H→γ γ Coupling



- Events separated into 14 categories depending on H production, kinematics
- Cross section ratios measured for each process in the STXS framework
- Coupling modifiers for vector bosons, fermions, photons, gluons

Most likely values of coupling modifiers κ_g and κ_γ





Higgs Cross Section Measurement: $H\to\gamma\gamma$

CMS-PAS-HIG-17-015
CMS March 2017; 34.5 fb^{-1}

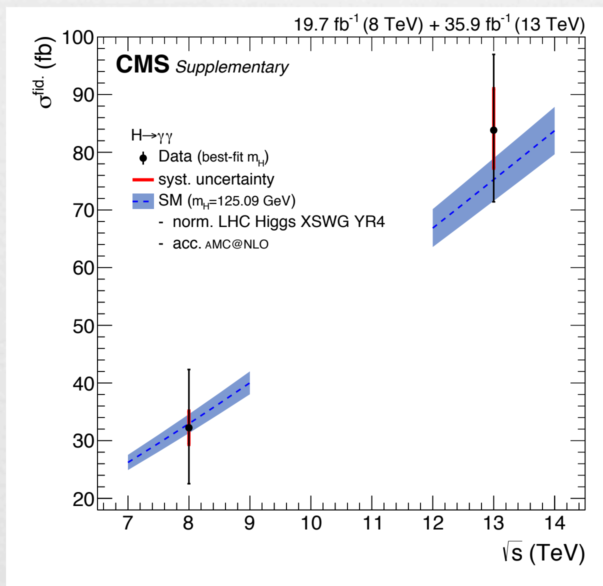
- 3 untagged event categories based on expect mass resolution
- Fiducial cross sections consistent with SM predictions. $\sigma_{fiducial} = 84 \pm 11\ (stat) \pm 7\ (syst)$ fb

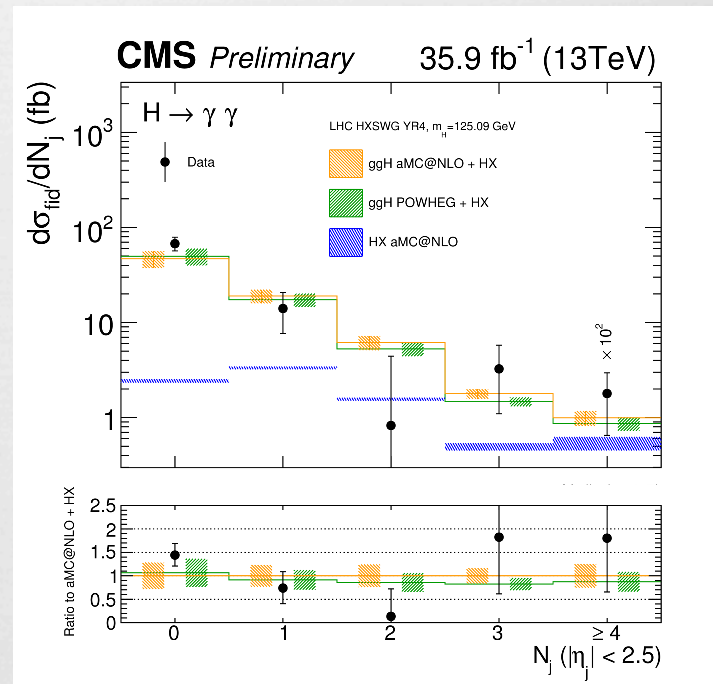
Fiducial volume:

$p_{T1}/m_{\gamma\gamma} < 1/3$, $p_{T2}/m_{\gamma\gamma} < 1/4$

$|\eta_{1,2}| < 2.5$

$Iso_{gen1,2} < 10$ GeV ($\Delta R=0.3$)





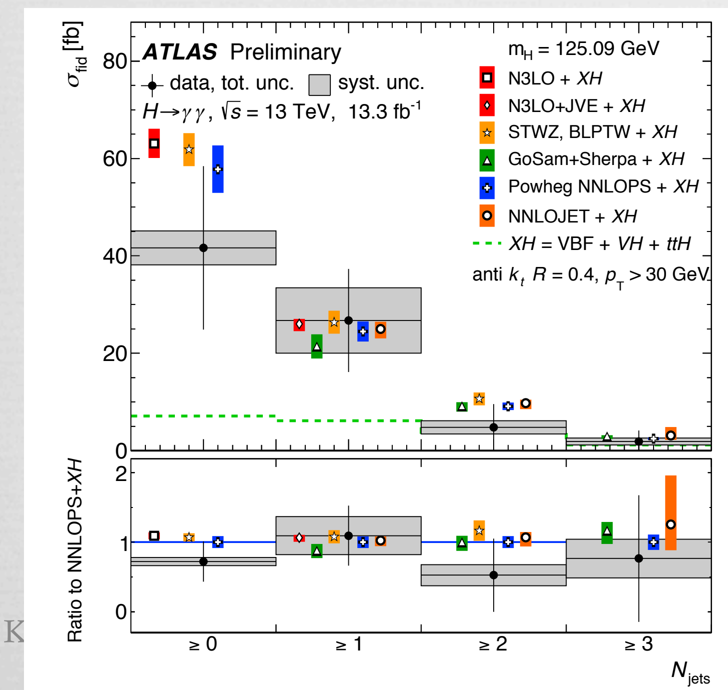
Differential cross sections for N(jets), pT(H)

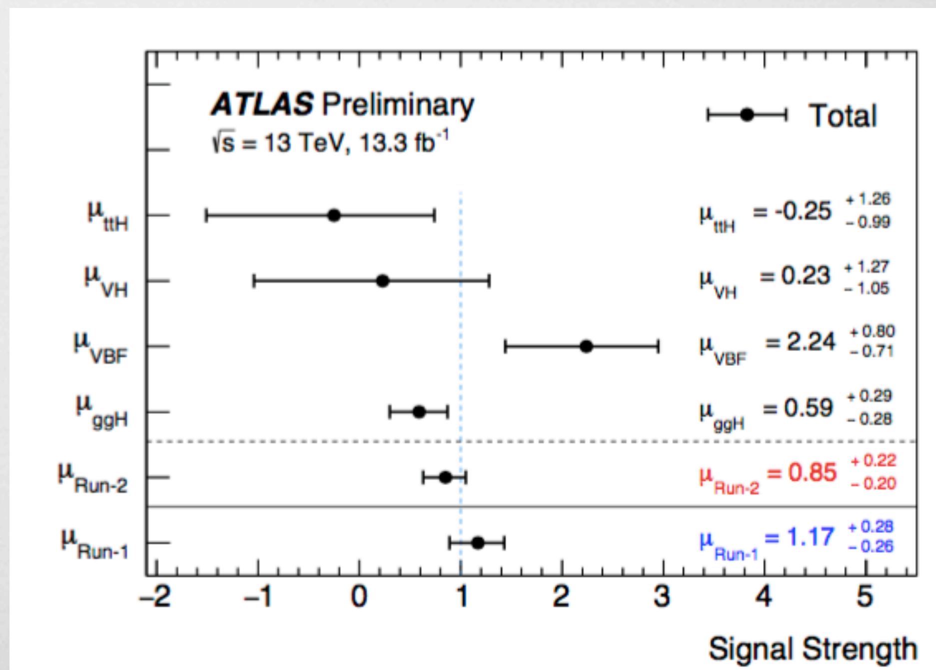
Higgs Cross Section Measurement: H→ $\gamma\gamma$

- Couplings measurement
- Simplified template cross sections
- Fiducial & total-production x-sections
  - Use 3 fiducial phase space regions.

Aug 2016: ATLAS-CONF-2016-067

	diphoton baseline	VBF enhanced	single lepton
Photons	$\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$ $p_T^{\gamma_1} > 0.35\, m_{\gamma\gamma}$ and $p_T^{\gamma_2} > 0.25\, m_{\gamma\gamma}$		
Jets	- - -	$p_T > 30$ GeV, $\lvert y\rvert < 4.4$ $m_{jj} > 400$ GeV, $\lvert\Delta y_{jj}\rvert > 2.8$ $\lvert\Delta\phi_{\gamma\gamma,jj}\rvert > 2.6$	- - -
Leptons	-	-	$p_T > 15$ GeV $\lvert\eta\rvert < 2.47$

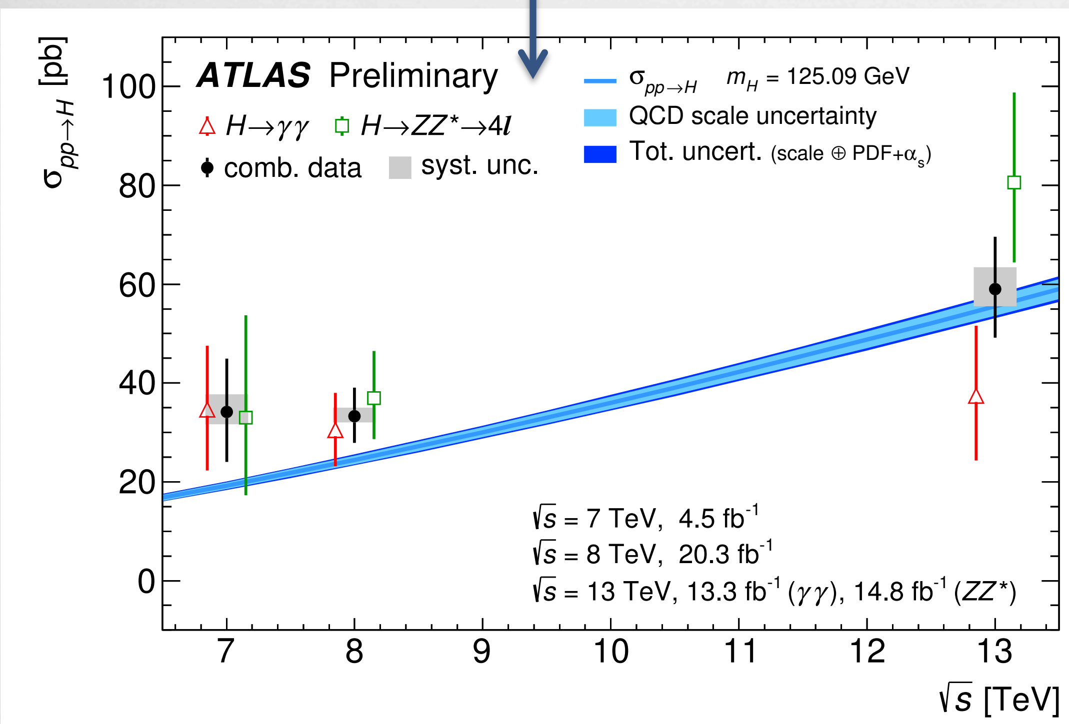


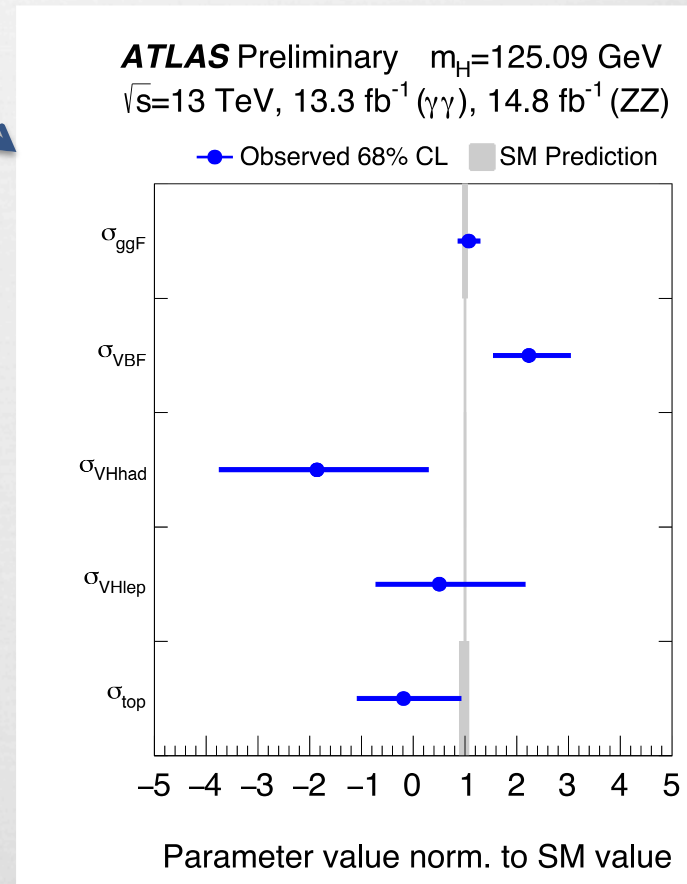


$H\to\gamma\gamma + H\to ZZ$ Combo

ATLAS-CONF-2016-081
Aug 2016

Run 2 Combo:
Stage-0 simplified template cross sections
Fiducial Cross Section



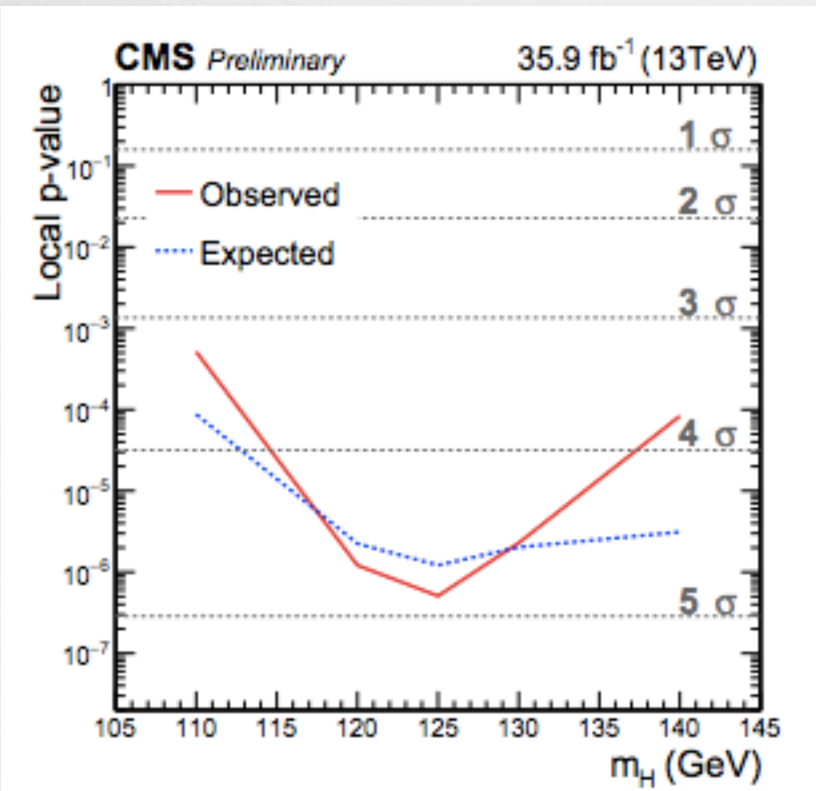


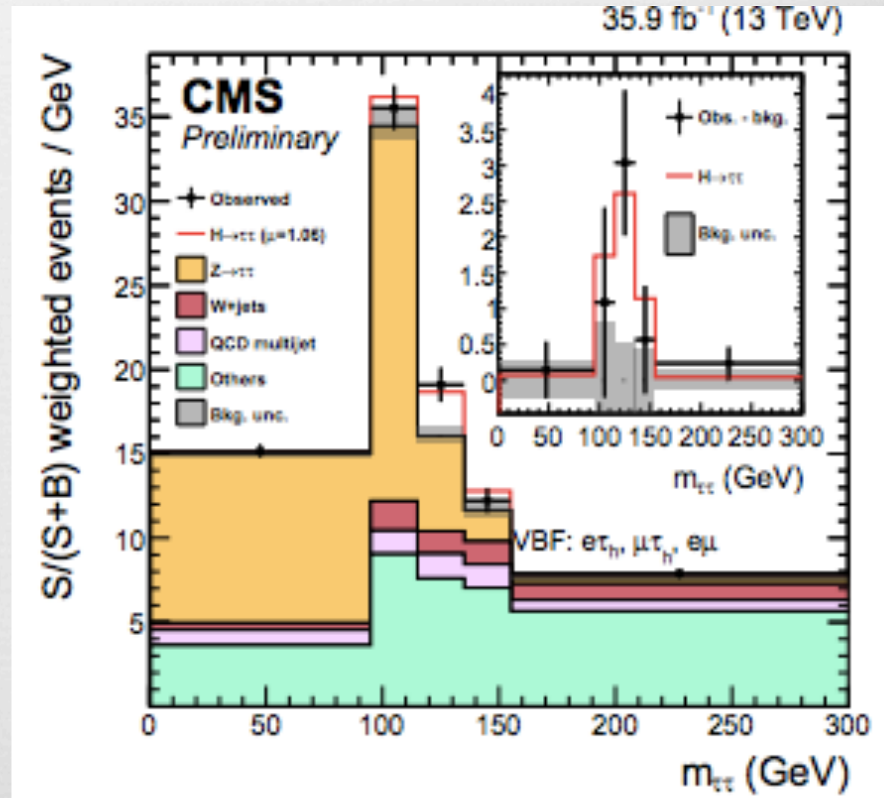
Results from $H \rightarrow \tau\tau$, $H \rightarrow \mu\mu$, $H \rightarrow WW$, ttH, HH

CMS-PAS-HIG-16-043
May 2017 35.9 fb-1

$H \rightarrow \tau\ \tau$

- Signal significance of 4.9 σ (4.7 expected)
- Signal strength: μ = 1.06 ±0.25





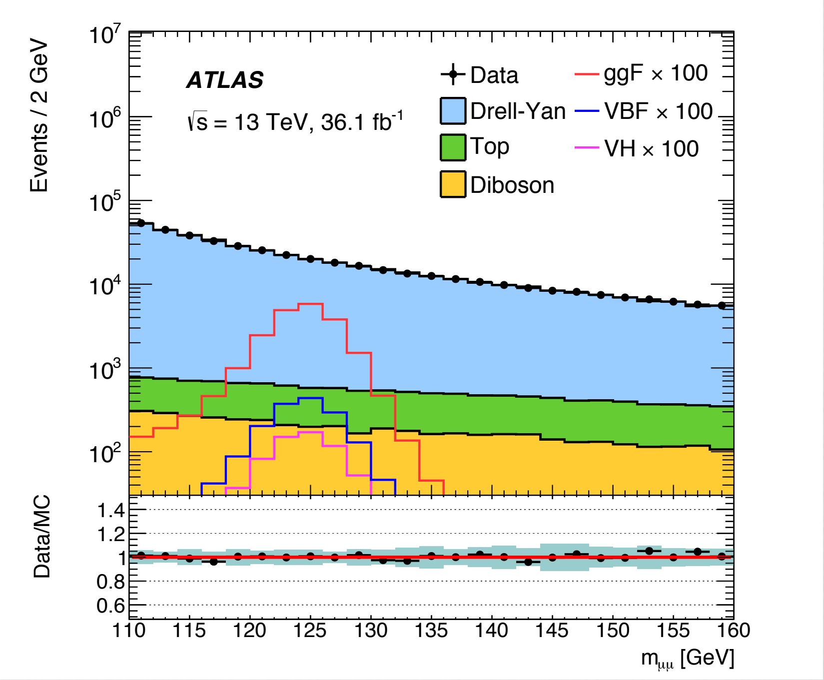
ATLAS-CONF-2017-014
May 2017 36.1 fb-1

H→ μ μ

- Clean analysis with well measured backgrounds
- No significant excess observed. Higgs couplings to fermions are not universal

Observed (expected) upper limit on XS*BR is 3.0 (3.1) times the SM.

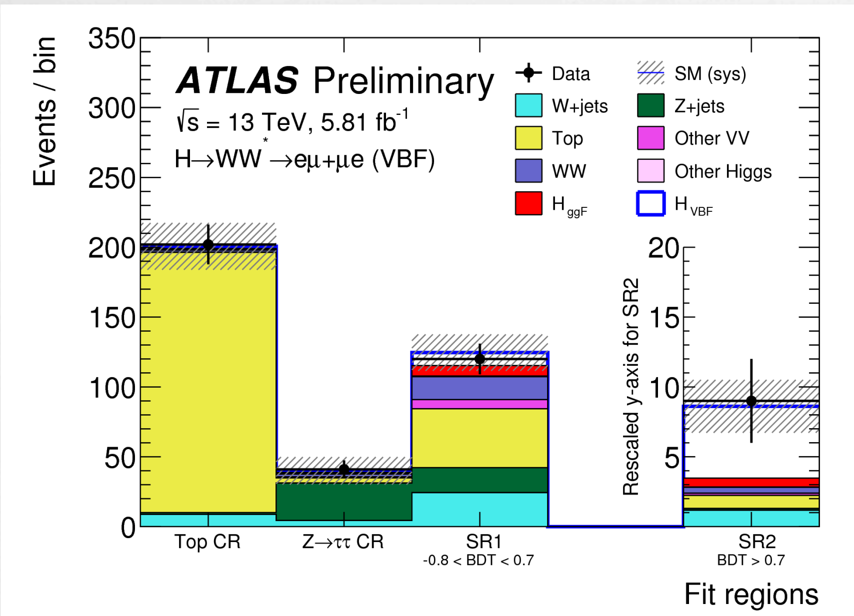
When combined with √s=7 TeV and √s=8 TeV, the observed (expected) upper limit is 2.8 (2.9) times the SM

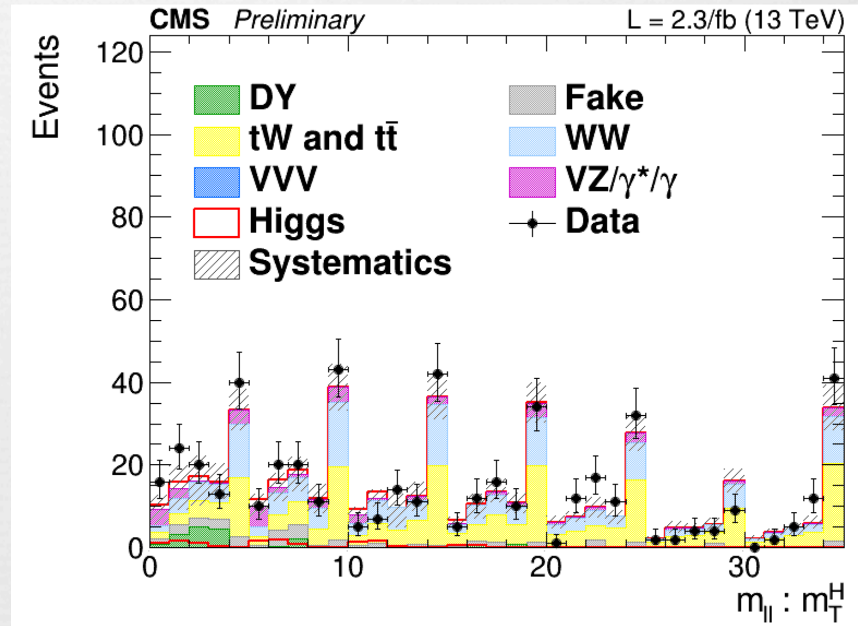


H→WW

ATLAS-CONF-2016-112
Nov 2016. 5.8 fb-1 @13TeV

CMS-PAS-HIG-15-003
June 2016. 2.3 fb-1 @13TeV





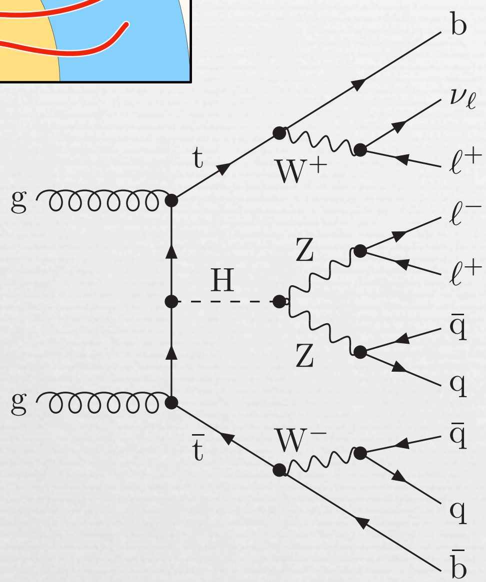
Exp (obs) significance for VBF at 13TeV: 1.9 σ (1.2 σ)
Exp (obs) significance for VH at 13TeV: 0.77 σ (0.24 σ)

Exp (obs) significance at 13TeV: 0.7 σ (2.0 σ)

$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW^*} = 1.4^{+0.8}_{-0.6}(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{sys})\ \mathrm{pb}$$

$$\sigma_{WH} \cdot \mathcal{B}_{H\to WW^*} = 0.9^{+1.1}_{-0.9}(\mathrm{stat})^{+0.7}_{-0.8}(\mathrm{sys})\ \mathrm{pb}$$

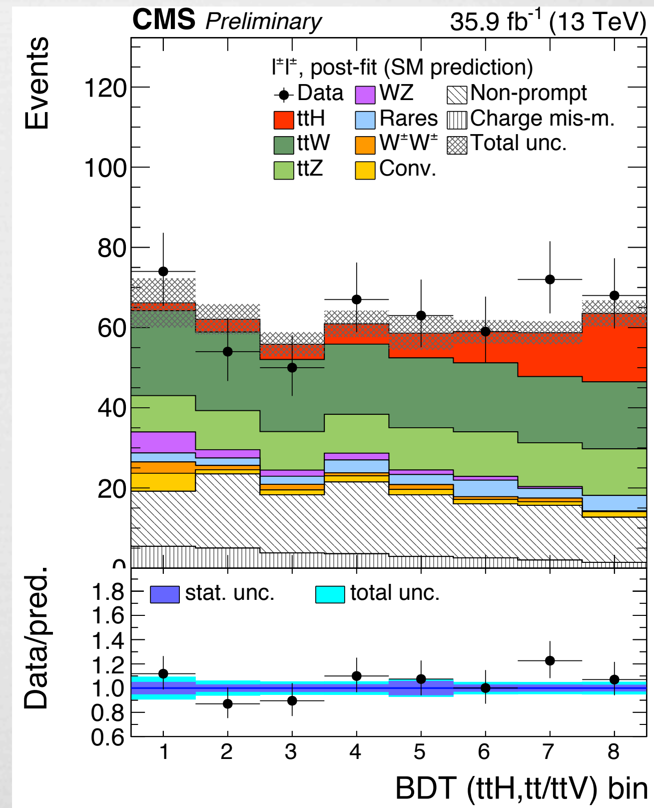
ttH(ZZ,WW, ττ)



Leptonic decay channels

(2, 3, 4+ leptons and a bjet)

March 2017
CMS-PAS-HIG-17-004



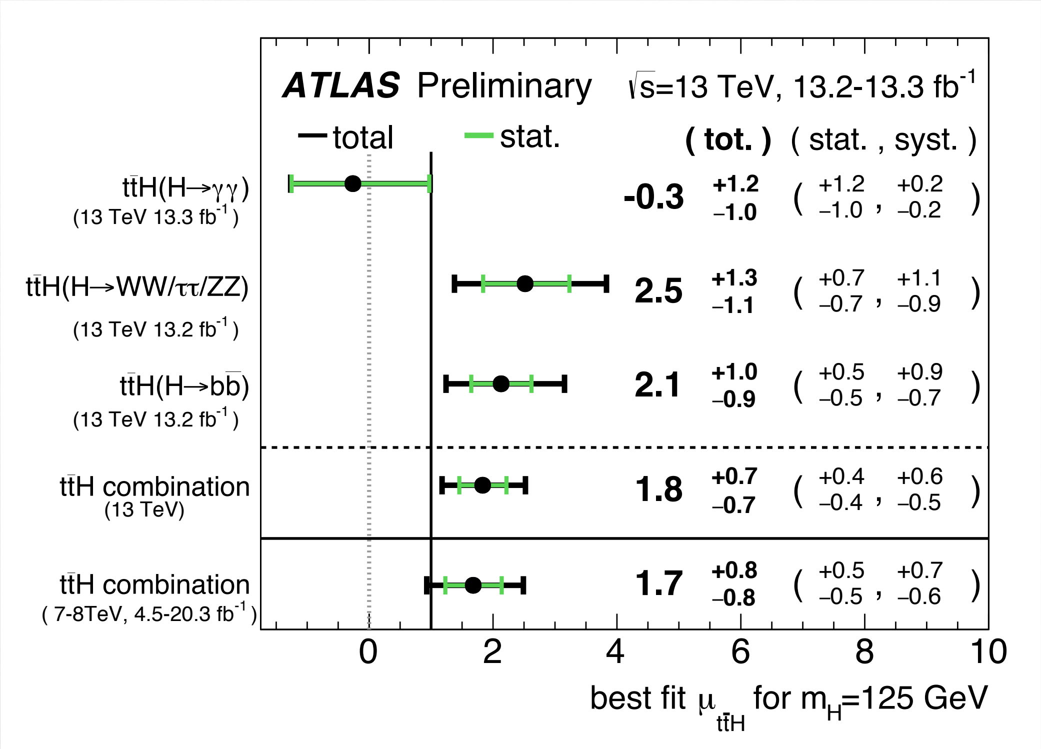
- The observed (expected) best fit ttH yield is 1.5 ± 0.5 ($1.0^{+0.5}_{-0.4}$) times the SM prediction, corresponding to a significance of $3.3\,\sigma$ ($2.5\,\sigma$).

ATLAS-CONF-2016-068
Aug 2016 13.3 fb-1

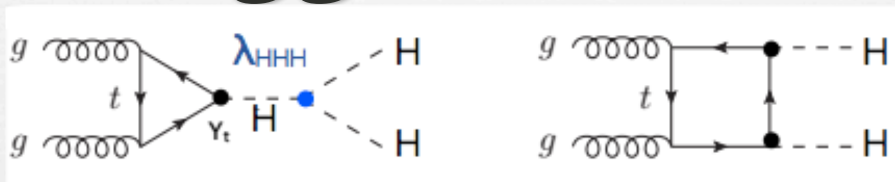
ttH(γγ,multilepton,bb)

- Combination of 3 decay channel analyses

- The ratio of the prod xs to the SM ttH prediction is 1.8±0.7, corresponding to a significance of 2.8 σ (1.8 σ expected).



Di-Higgs Production



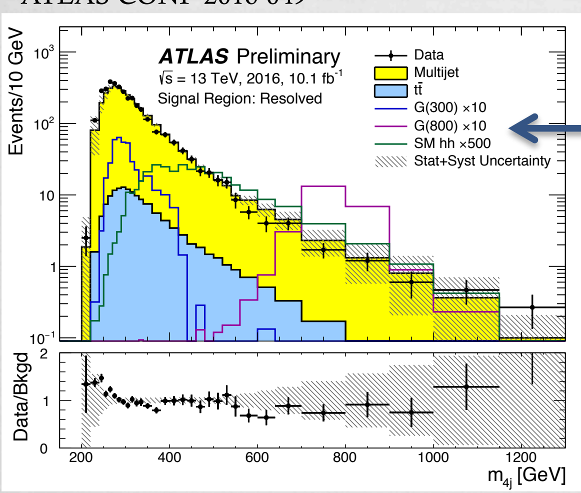
$$V_{SM} = \frac{m_h^2}{2}h^2 + \lambda_{SM} v h^3 + \frac{\kappa_{SM}}{4}h^4$$

- Searches from ATLAS & CMS in final states bbbb, bbττ, bbWW, bbγγ, γγWW
- Effective Lagrangian used to model BSM effects: anomalous λ_{HHH} and y_t couplings and 3/4 new contact interactions
- Projections to High-Luminosity LHC:

$$0.2 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 7.0 \; (-3.5 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 11)$$

no syst (with syst) ATL-PHYS-PUB-2016-024

ATLAS-CONF-2016-049

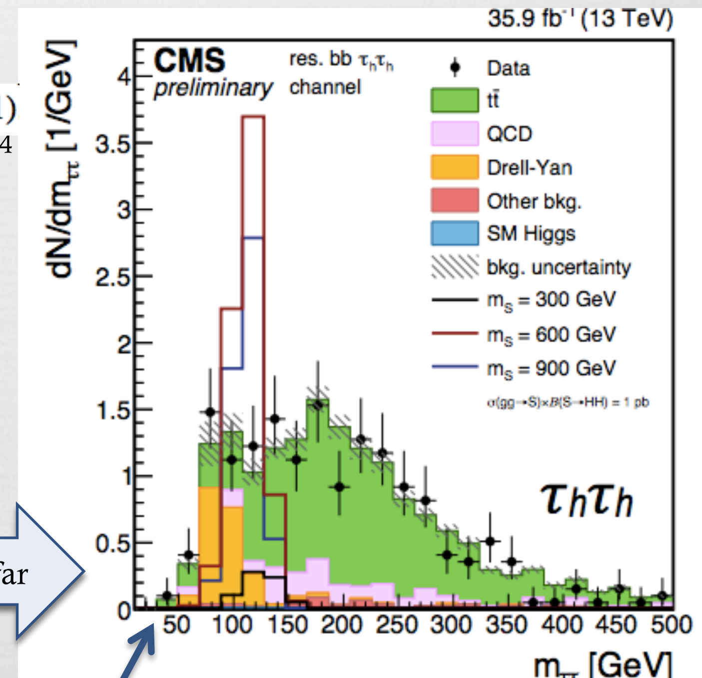


HH -> bbbb

Limit set at 29* SM σ_{HH} (σ_{HH} ×BR < 330fb)

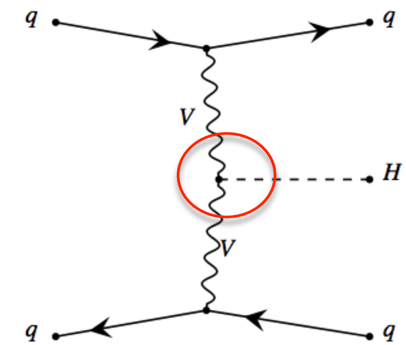
Best HH limit so far

CMS-PAS-HIG-17-002



Limit set at 28* SM σ_{HH}

Higgs CP constraints from VBF H→ τ τ



- Most sensitivity for H→ τ τ comes from the VBF channel; large sensitivity to VBF prod. from H→ τ τ channel
- Constrain CP-odd Bosonic operators in EFT

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{f_{\tilde{B}B}}{\Lambda^2} O_{\tilde{B}B} + \frac{f_{\tilde{W}W}}{\Lambda^2} O_{\tilde{W}W} + \frac{f_{\tilde{B}}}{\Lambda^2} O_{\tilde{B}}$$

$$\tilde{d} = -\frac{m_W^2}{\Lambda^2} f_{\tilde{W}W}$$

$$\tilde{d} = -\hat{\kappa}_W = -\tilde{\kappa}_W / \kappa_{\text{SM}} \tan\alpha.$$

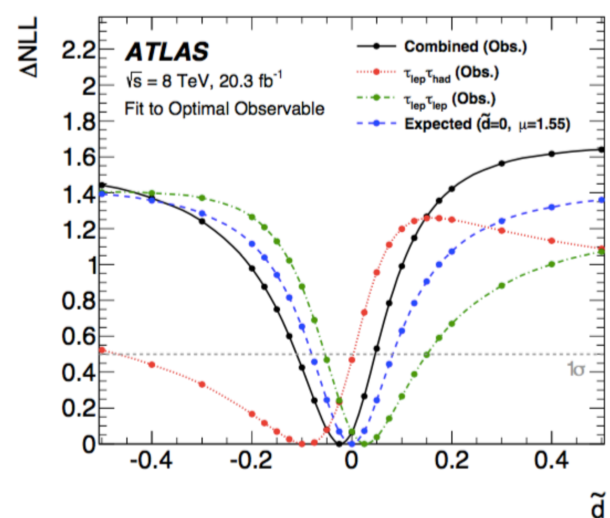
$$\hat{\kappa}_W = \hat{\kappa}_Z$$

- Parametrize CP violation in VBF:

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \tilde{d} \cdot \mathcal{M}_{\text{CP-odd}}.$$

HZZ and HWW terms controlled by d~.

d~ = 0 means no CP-odd term.
At 68% conf level find that d~ is within [-.11,0.05]
EPJC 76 (2016) 658



Additional measurements

- Spin and parity are consistent with the SM Higgs:
  - $H \rightarrow ZZ$: CMS-PAS-HIG-17-011
  - $H \rightarrow ZZ$: ATLAS-CONF-2016-079
  - ATLAS Collaboration, Evidence for the spin-0 nature of the Higgs boson using ATLAS data, Phys. Lett. B 726 (2013) 120, arXiv: 1307.1432 [hep-ex].

- Higgs width measurements:
  - Many assumptions necessary. See talk at Higgs Coupling 2016

- BSM $A/H \rightarrow$ tautau
  - ATLAS-CONF-2016-085; CMS-PAS-HIG-16-006

ATLAS+CMS Run 1 Higgs Combination

The Run 1 ATLAS+CMS Higgs Combination

LHCP, St Petersburg,1 Sept 2015,

Revised and sent to JHEP Sep 2016 https://arxiv.org/abs/1606.02266

Thesis:

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

  Run 1: $M_H = 125.09 \pm 0.24$ *GeV*$= \pm 0.21$ *(stat.)* ± 0.11*(syst.)*

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

- Combing ATLAS and CMS adds a factor of almost $\sqrt{2} = 1.4$ in precision (when signal theory systematics do not dominate)

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

Coupling Combination: Signal Strengths

$i \rightarrow H \rightarrow f$

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

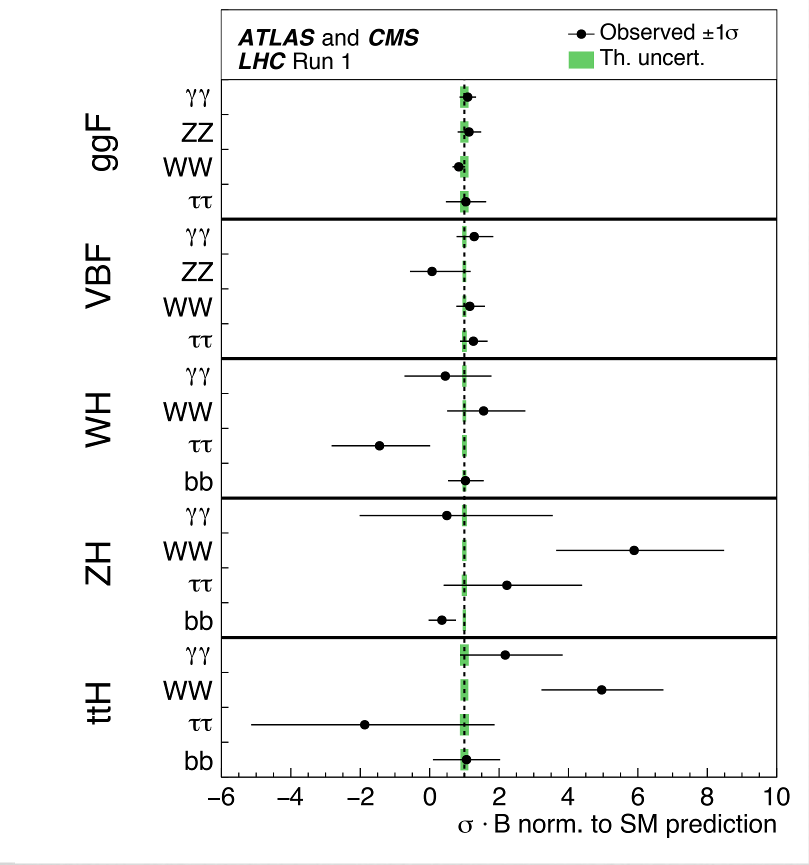
- Most precisely measured H coupling and also most constrained parameterization: Assume all production and decay scale together: the SM predictions of signal yields in all categories are scaled by a global signal strength μ .
- A fit to the combined ATLAS and CMS data at $\sqrt{s}$ = 7 and 8 TeV with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

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

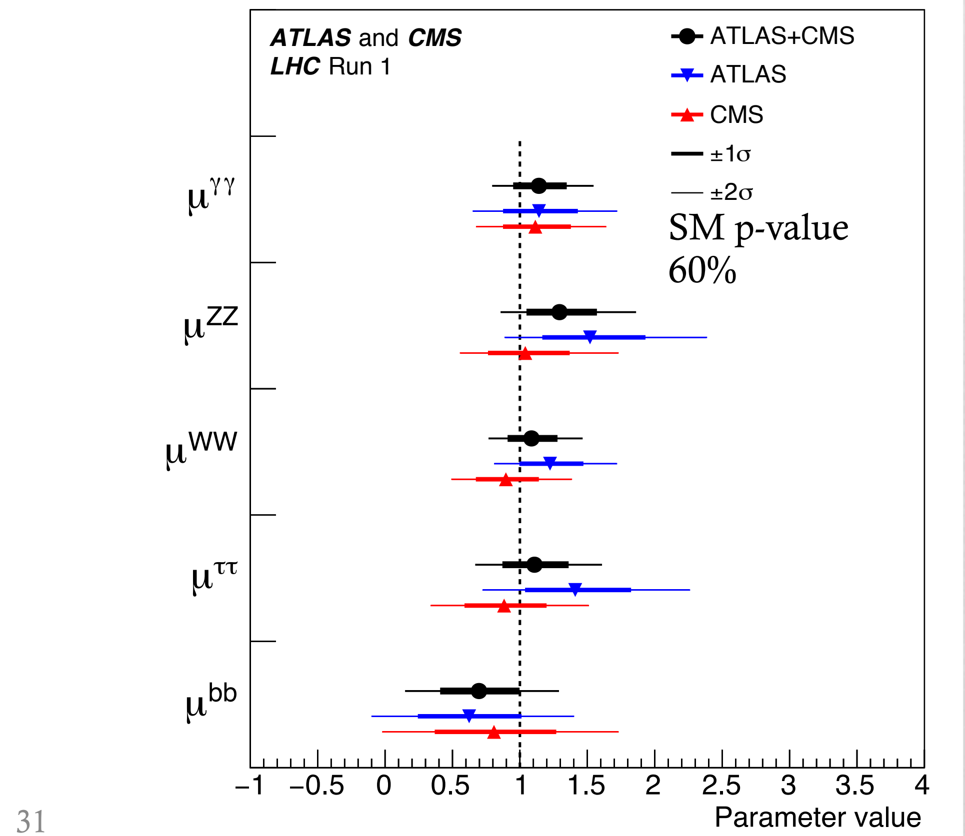
total systematic uncertainty: $^{+0.09}_{-0.08}$

Coupling Combination: Signal Strengths

Production signal strengths
Assume SM BRs



Decay signal strengths
Assume SM Cross Sections



Coupling Combination: Signal Strengths

- Comparing likelihood of the best-fit with no signal: μ_{prod}=0 and μ^{decay}=0 :

Production process	Measured significance (σ)	Expected significance (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		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

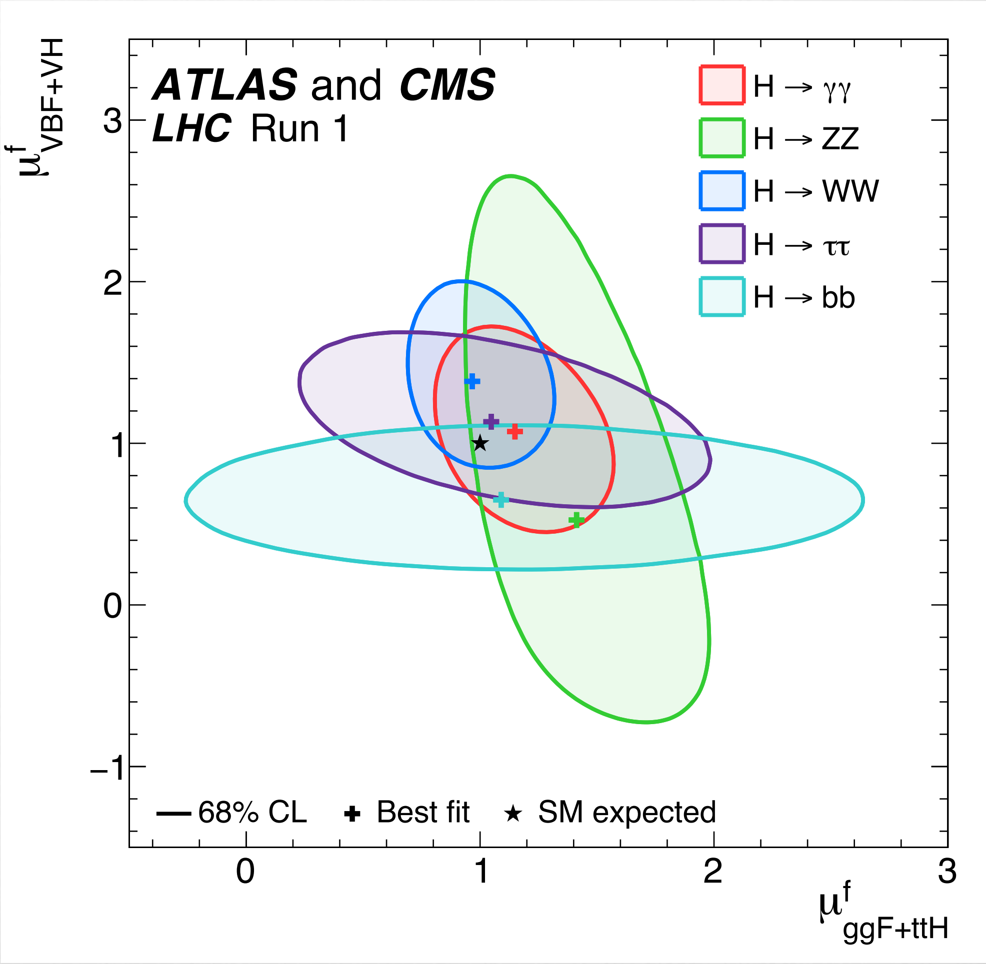
$> 5\ \sigma$ (VBF)

$> 5\ \sigma$ ($H \to \tau\tau$)

First established VBF and H→ $\tau\ \tau$ at 5 σ
ggF, H→ $\gamma\ \gamma$, H→ZZ, H→WW already at 5 σ before the combination

Coupling Combination: Signal Strengths

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



Coupling Combination:
The κ Framework– Coupling modifiers

$$i \rightarrow H \rightarrow f$$

- Scale Higgs boson couplings by modifiers, κ , factorizing production and decay

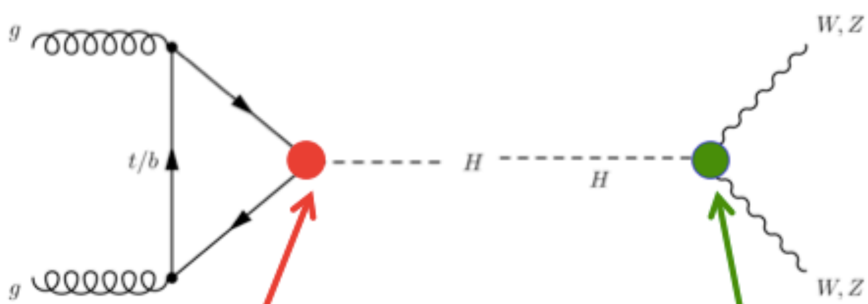
$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} \quad or \quad \kappa_j^2 = \frac{\Gamma^j}{\Gamma_{SM}^j} \qquad \Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$$

- 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: Disentangle Branching Ratios and Cross Sections

- Example for ggF production of H→VV



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

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

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

Wouter Verkerke, NIKHEF

κ -Parameterization

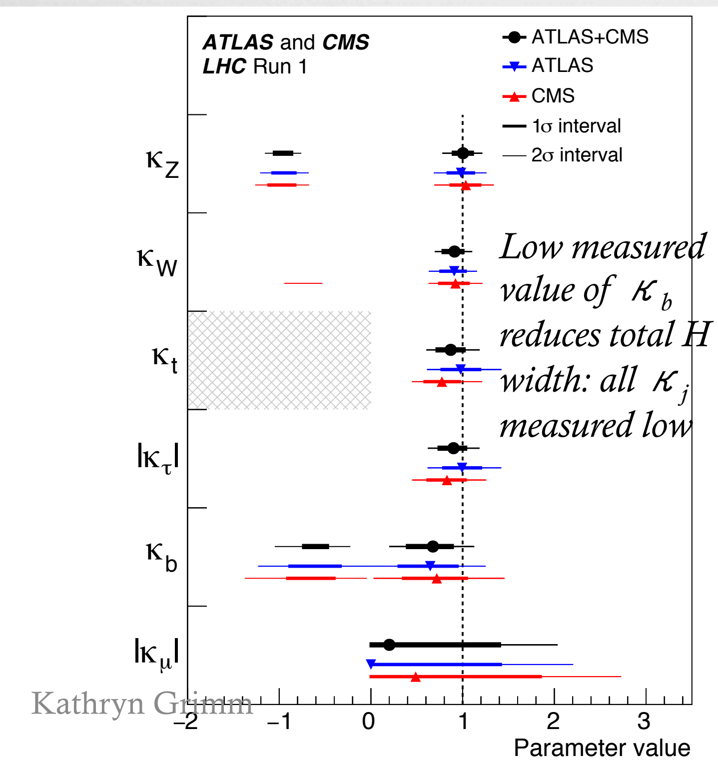
Production	Loops	Interference	Multiplicative factor	
$\sigma(gg\mathrm{F})$	✓	$b-t$	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(V\mathrm{BF})$	–	–	$\sim$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim$	κ_W^2
$\sigma(qq/qg \to ZH)$	–	–	$\sim$	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
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa^2 \sim$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim$	κ_τ^2
Γ^{bb}	–	–	$\sim$	κ_b^2
$\Gamma^{\mu\mu}$	–	–	$\sim$	κ_μ^2
Total width for $\mathrm{BR}_{\mathrm{BSM}} = 0$				
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
Constraints on H couplings

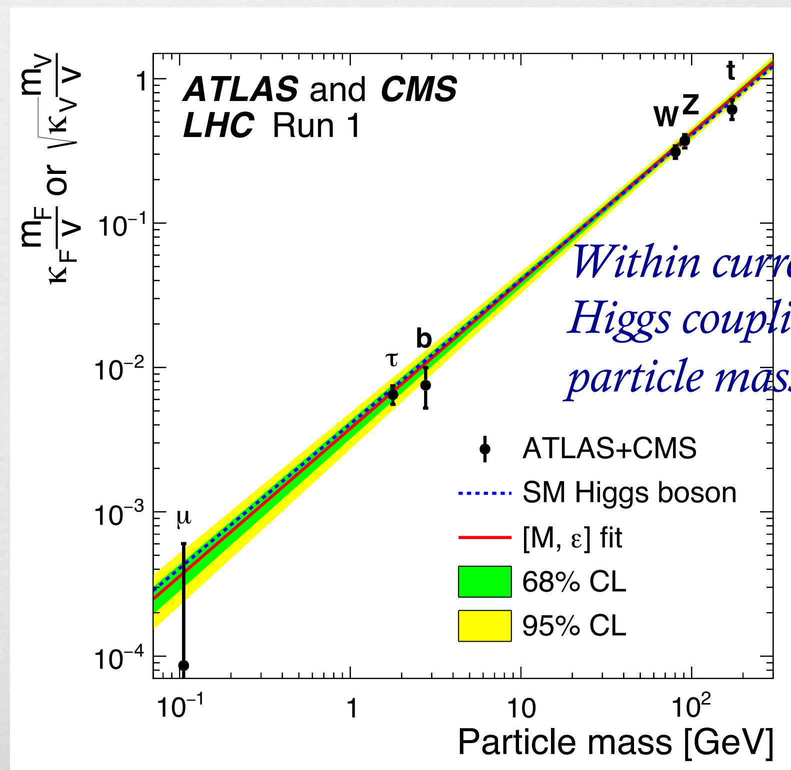
Split coupling modifier by fermion flavor and by W/z

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

What precision is necessary?

- Snowmass report (2013) gives precision necessary for observing NP at 1TeV mass scale

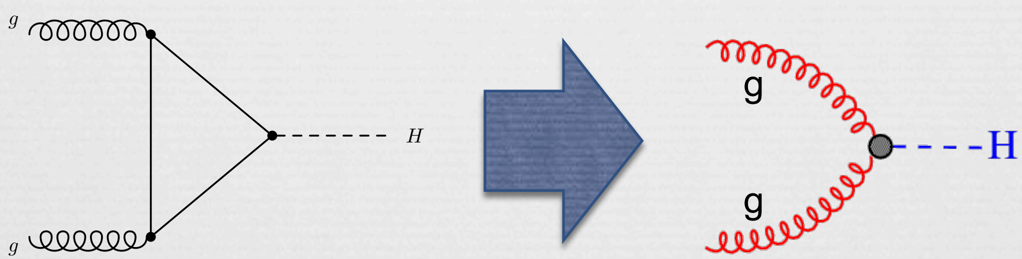
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

arXiv:1310.8361

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_γ)



$1.06\,\kappa_t^2 + 0.01\,\kappa_b^2 - 0.07\,\kappa_t\kappa_b$ $\qquad$ **κ_g^2**

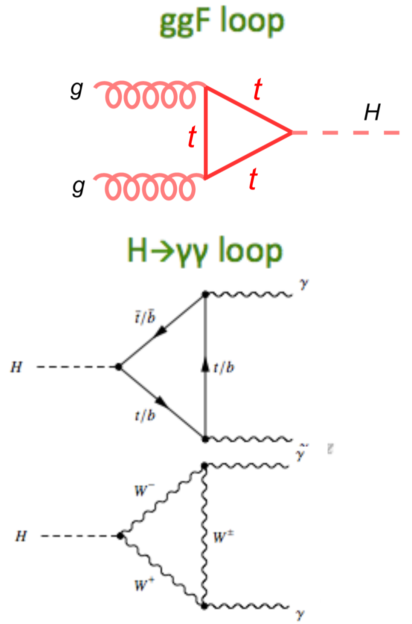
2) Allow for invisible/undetected BSM Higgs decays to increase the Total H width

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

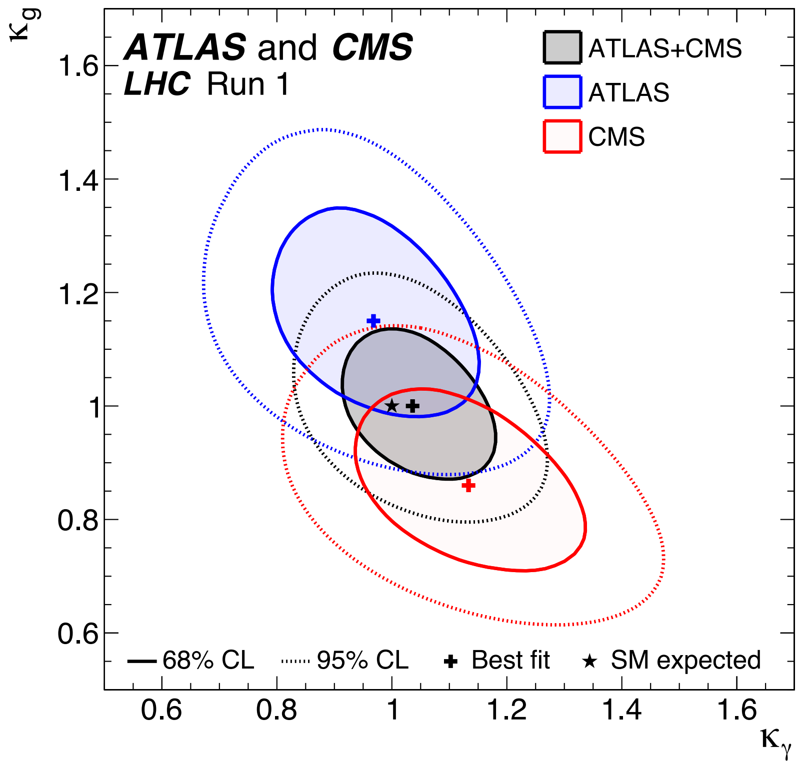
κ -Parameterization
Allowing for BSM contributions

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



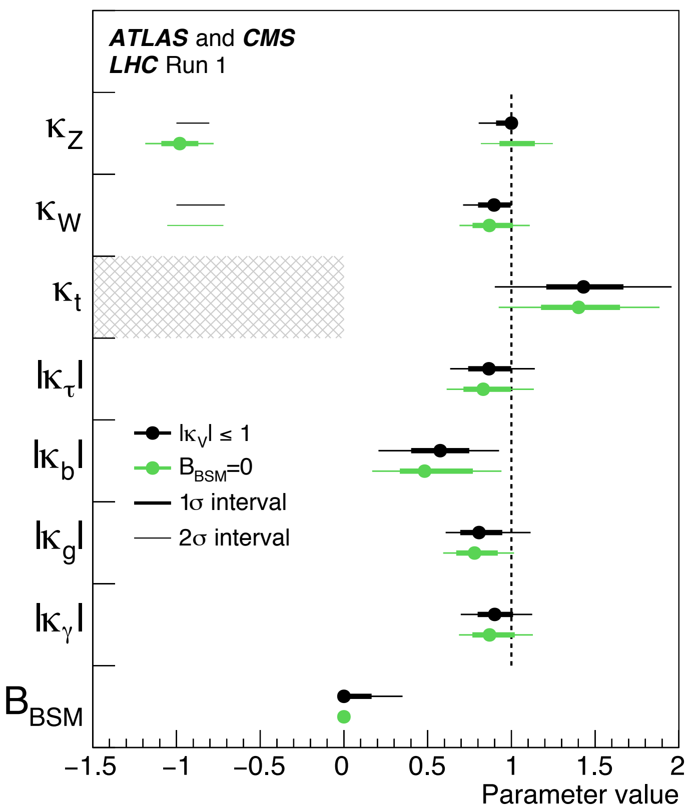
κ -Parameterization
Allowing for BSM contributions

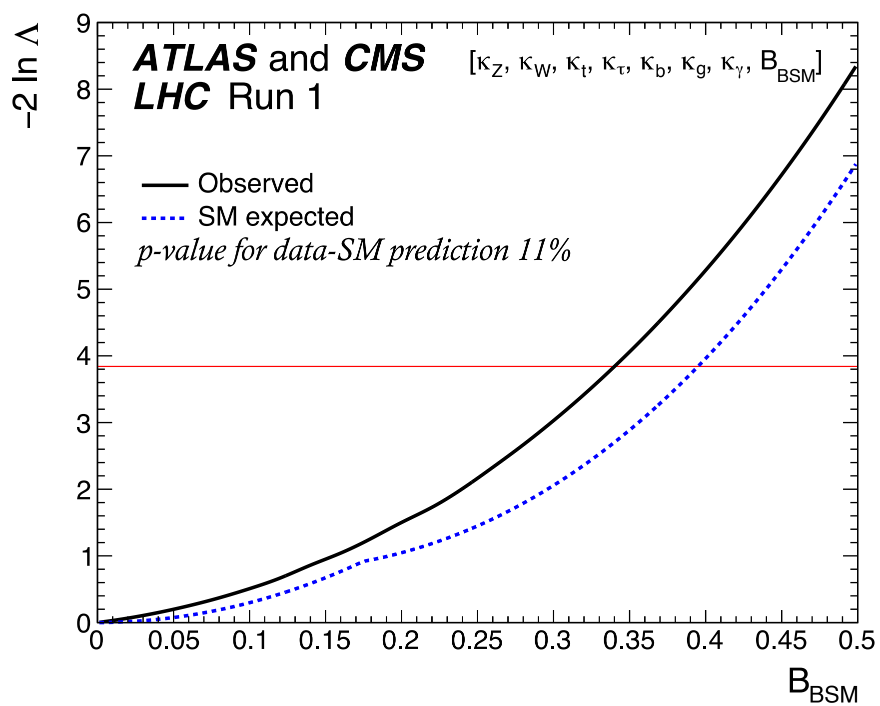
2. Constraints on Higgs couplings allowing BSM physics in loops & decays

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

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

$BR_{BSM} < 0.34$ at 95% C.L. (assuming $\kappa_V \leq 1$)





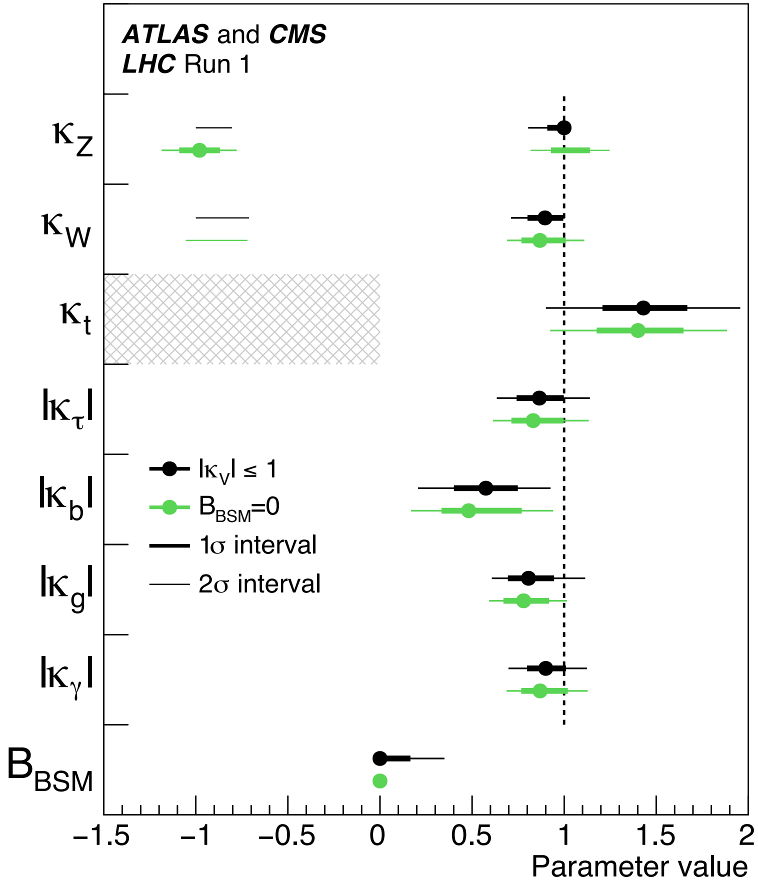
κ -Parameterization
Allowing for BSM contributions

2.

Constraints on Higgs couplings allowir
BSM physics in loops & decays

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

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



Parameterization using ratios of cross sections and branching ratios

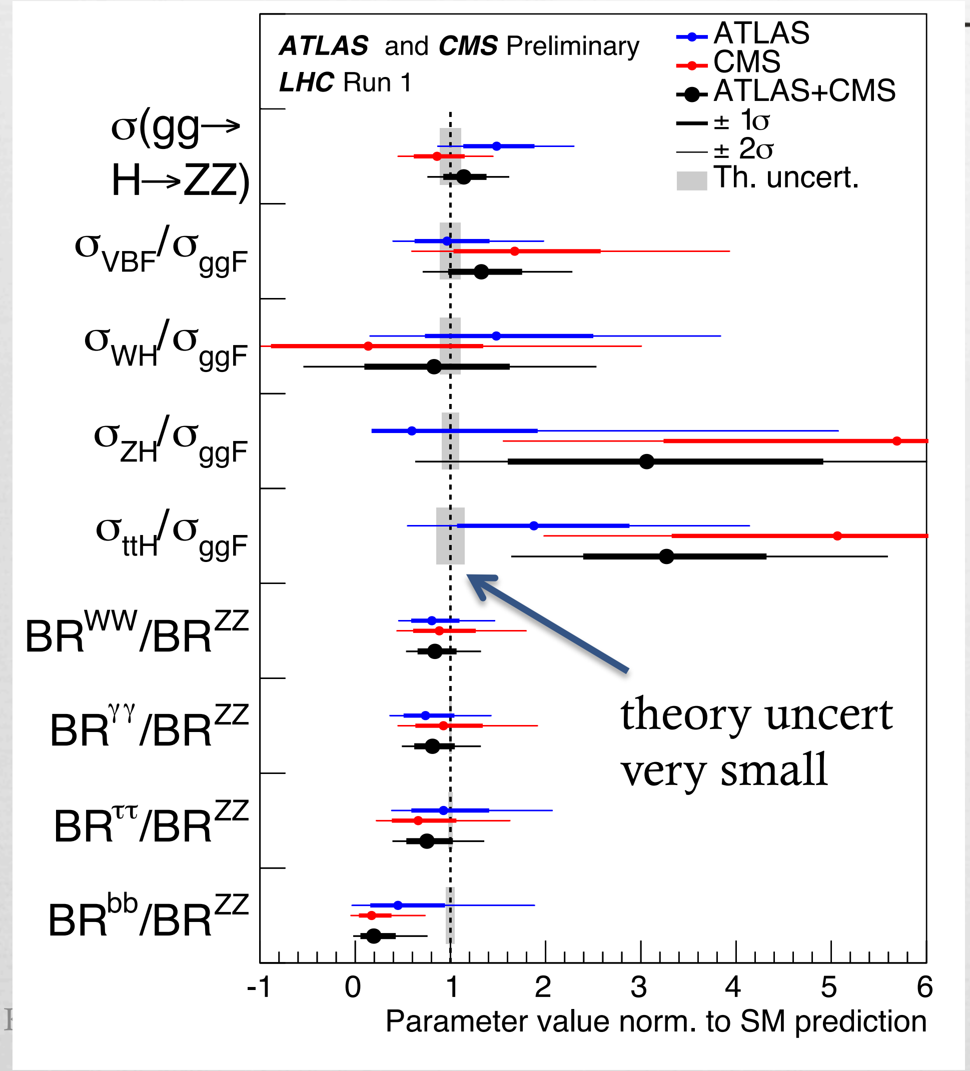
- Take gg→H→ZZ as a reference because of its small systematic uncertainties
- Then use ratios of σ and BR:

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

- 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 $\sigma_i / \sigma_{ggF} \sim 3$) because Hbb does not contribute to the observed excesses.

Overview & Conclusions

- The Run 1 ATLAS+CMS Combination represents a baseline measurement for Higgs properties. Presented in terms of μ's, κ's and cross section ratios.
- More and more precise Higgs measurements are being made in Run 2. The form of those results is evolving, to more EFT friendly Simplified Template Cross Sections, Pseudo observables
- No significant deviations from the SM Higgs seen yet!

Backup

Extracting parameters of interest

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

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

Numerator, $\hat{\hat{\vec{\theta}}}(\vec{\alpha})$: set of nuisance parameter values that maximize the likelihood for a given $\vec{\alpha}$

Denominator, $\hat{\vec{\alpha}}$, $\hat{\vec{\theta}}$: best fit values for nuisance parameters and parameters of interest

Monte Carlo

- ATLAS H->ZZ
  - ggF: N3LO in QCD. NLO EW corrections
    - Alternative: MG5_MC@NLO: NLO accuracy in QCD for 0, 1, 2 extra jets, merged with the FxFx scheme using the NNPDF30_nlo_as_0118 PDF set
  - VBF: NLO QCD and EW corrections + approx NNLO QCD corrections
  - VH: NNLO in QCD, NLO EW
  - ttH: NLO in QCD
- **CMS H->ZZ**
  - Signal samples: ggF, VBF, VH, ttH: generated at NLO in perturbative QCD (pQCD) with POWHEG 2.0.
  - For WH and ZH the MINLO HVJ [23] extension of POWHEG 2.0 is used.
  - The default parton distribution function (PDF) used in all simulations is NNPDF30_nlo_as_0118. The decay of the Higgs boson to four leptons is modeled with JHUGEN.

Monte Carlo

- ATLAS H->WW. ATLAS-CONF-2016-112

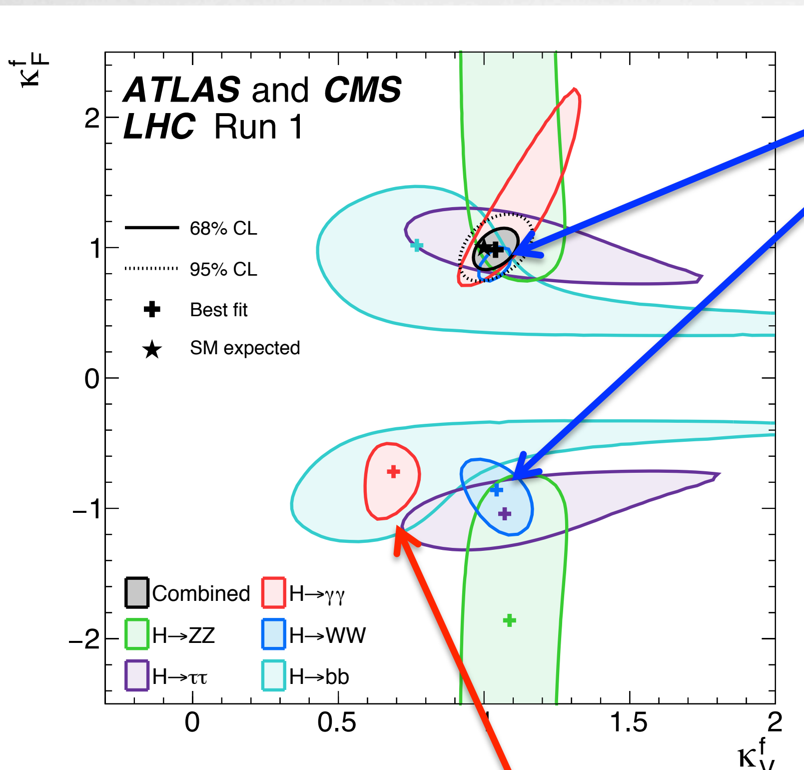
Table 1: Monte Carlo generators used to model the signal and background processes with the corresponding product of the cross section (σ) and branching fraction ($\mathcal{B}$) for the Higgs production modes at $\sqrt{s} = 13$TeV. The uncertainties quoted include the uncertainties from QCD scale, PDF, α_S and branching fraction. The mass of the Higgs boson is set to $m_H = 125$GeV, and the $H \to WW^*$ decay is assumed. Precise MC generator versions are provided in the text.

Mode	MC generator	$\sigma \cdot \mathcal{B}$ (pb)
ggF	Powheg [13–15]+Pythia 8 [19]	$10.38^{+0.58}_{-0.77}$
VBF	Powheg +Pythia 8	0.808 ± 0.021
WH	Powheg +Pythia 8 (MiNLO [25])	0.293 ± 0.007
ZH	Powheg +Pythia 8 (MiNLO)	$0.189^{+0.008}_{-0.007}$

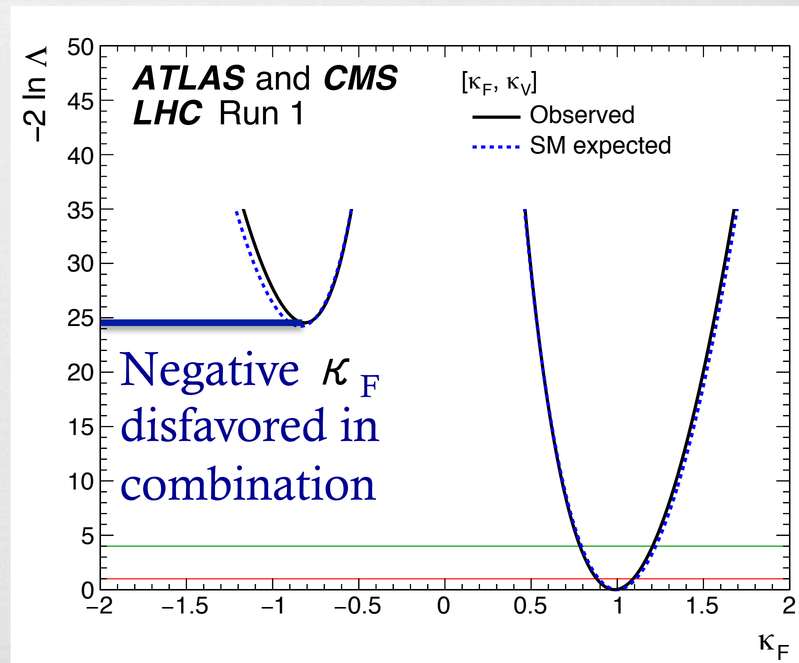
Background	MC generator
$q\bar{q}/g \to \ell\ell\ell\ell, \ell\nu\ell\ell, \ell\nu\ell\nu$	Sherpa [16]
$gg \to \ell\ell\ell\ell, \ell\nu\ell\nu$	Sherpa
EW $\ell\ell\ell\ell, \ell\nu\ell\ell, \ell\nu\ell\nu$	Sherpa
$q\bar{q}/g \to WW, Z^{(*)}Z^{(*)} \to \ell\nu\ell\nu$	Powheg +Pythia 8
$t\bar{t}, tW$	Powheg +Pythia 6 [38]
$t\bar{t}W/Z, tZ$	MadGraph 5 [17]
$W\gamma, Z\gamma$	Sherpa
Z+jets	MadGraph 5
VBF $q\bar{q} \to (Z \to \tau\tau)q\bar{q}$	Sherpa
WWW, WWZ, ZZW, ZZZ	Sherpa

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



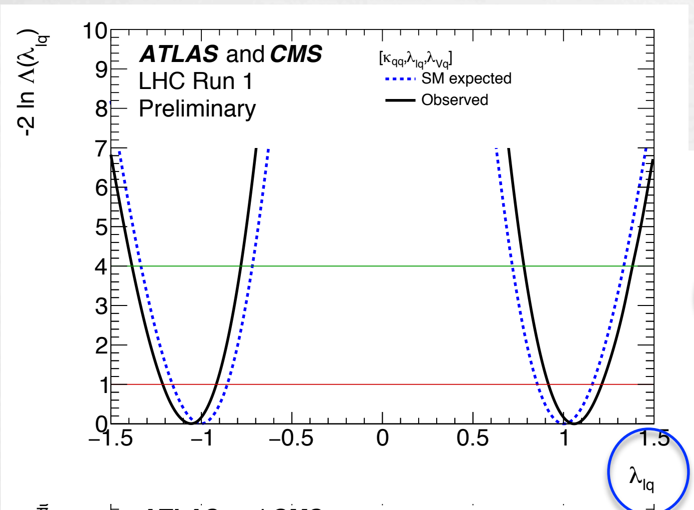
Sensitivity to the (relative) sign of k_V and k_F only comes from the interference of 2 prod or decay modes
The negative YY contour is completely incompatible with the negative WW contour, for example.

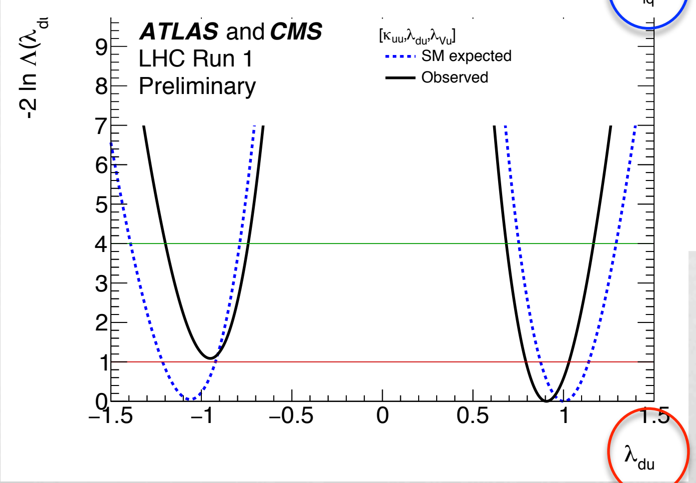
κ -Parameterization

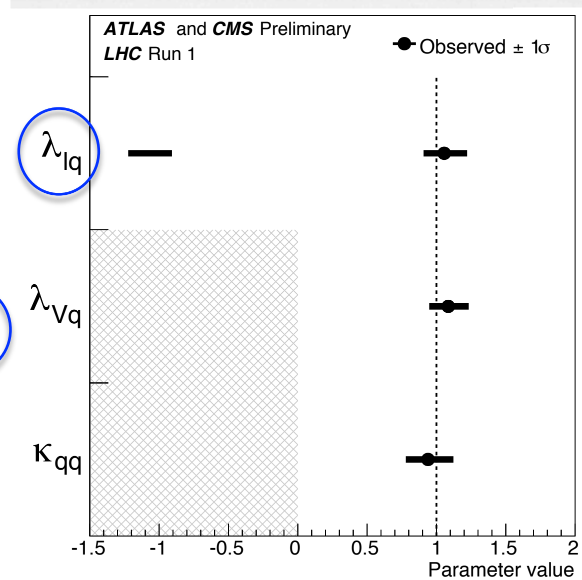
Up/down fermion and lepton/quark symmetries

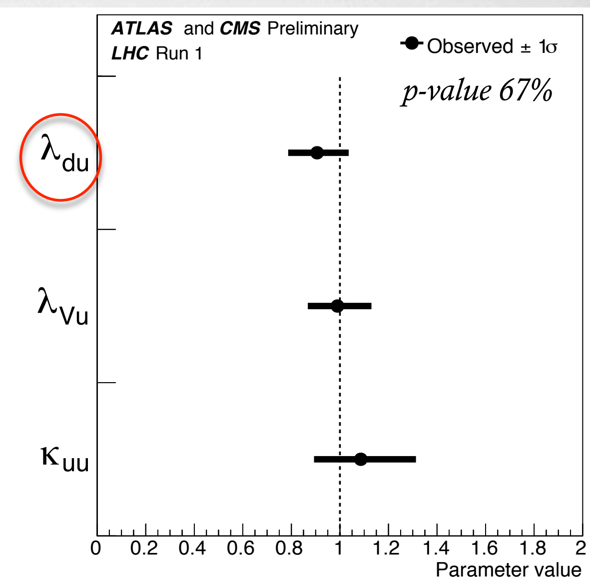
Several BSM physics models (notably 2HDM), predict asymmetries in couplings between up-type and down-type fermion couplings, and between lepton and quark couplings

$$\lambda_{du} = \kappa_d/\kappa_u \qquad \lambda_{\ell q} = \kappa_\ell/\kappa_q$$
$$\lambda_{Vu} = \kappa_V/\kappa_u \qquad \lambda_{Vq} = \kappa_V/\kappa_q$$
$$\kappa_{uu} = \kappa_u \cdot \kappa_u/\kappa_H . \qquad \kappa_{qq} = \kappa_q \cdot \kappa_q/\kappa_H .$$









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

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*

Yellow Report 4

arXiv:1610.07922v2 [hep-ph] 15 May 2017

The LHC Run 2, which started in 2015, now has a qualitatively different goal in what regards the program for measuring the properties of this Higgs boson and the search for deviations from the SM predictions.

The WG2 contributions to this Yellow Report therefore naturally cluster around two main axes, supplemented by a third aspect:

1. How to expand the palette of measurements that can be performed by the experiments.
2. How to interpret existing measurements to set limits on and constrain new physics and characterize discoveries.
3. Tools with which to proceed in practice.

Parameter counting - PO

Higgs (EW) decay amplitudes

Amplitudes	Flavor + CP	Flavor Non Univ.	CPV
$h \to \gamma\gamma, 2e\gamma, 2\mu\gamma$ $4e, 4\mu, 2e2\mu$	6 $\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \varepsilon_{ZZ}$ $\varepsilon_{Ze_L}, \varepsilon_{Ze_R}$	$\varepsilon_{Z\mu_L}, \varepsilon_{Z\mu_R}$	$\varepsilon^{CP}_{ZZ}, \lambda^{CP}_{Z\gamma}, \lambda^{CP}_{\gamma\gamma}$
$h \to 2e2\nu, 2\mu2\nu, e\nu\mu\nu$	4 $\kappa_{WW}, \varepsilon_{WW}$ $\varepsilon_{Z\nu_e}$, Re(ε_{We_L})	$\varepsilon_{Z\nu_\mu}$, Re$(\varepsilon_{W\mu_L})$ Im$(\varepsilon_{W\mu_L})$	ε^{CP}_{WW}, Im(ε_{We_L})

Test UV symmetries!

Higgs (EW) production amplitudes

Amplitudes	Flavor + CP	Flavor Non Univ.	CPV
VBF neutral curr. and Zh	4 $[\kappa_{ZZ}, \kappa_{Z\gamma}, \varepsilon_{ZZ}]$ $\varepsilon_{Zu_L}, \varepsilon_{Zu_R}, \varepsilon_{Zd_L}, \varepsilon_{Zd_R}$	$\varepsilon_{Zc_L}, \varepsilon_{Zc_R}$ $\varepsilon_{Zs_L}, \varepsilon_{Zs_R}$	$[\varepsilon^{CP}_{ZZ}, \lambda^{CP}_{Z\gamma}]$
VBF charged curr. and Wh	1 $[\kappa_{WW}, \varepsilon_{WW}]$ Re(ε_{Wu_L})	Re(ε_{Wc_L}) Im(ε_{Wc_L})	Im(ε_{Wu_L})

12 independent processes & many differential distributions.

1) ***All that can be measured*** *in these processes (if NP is heavy) are* ***these PO****.*

2) *A robust extraction of PO requires a global analysis.*

LHC / HL-LHC Plan