Higgs Boson Production, Decay and Coupling Fits

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For the ATLAS and CMS Collaborations

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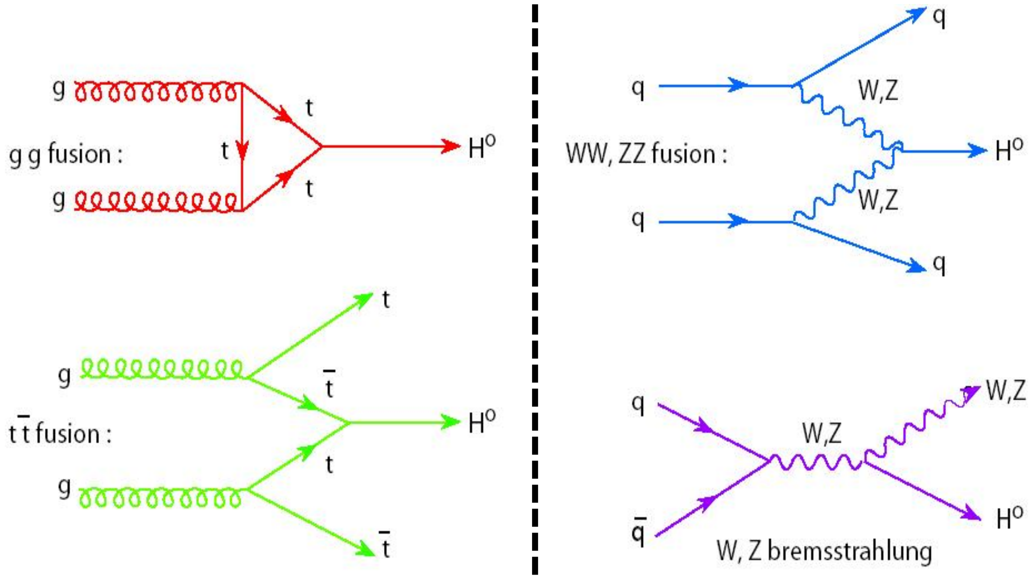
Production Processes

Production processes naturally fall into two groups



Strong Production
Fermion Coupling

Electroweak Production,
Vector Boson Coupling

Higgs candidate events are selected from their decay signatures, independent of production.

Disentangle the production processes using the production signatures (independent of decays) to study couplings.

Cross Sections and Branching Ratios

Not all production processes and decay modes have been established or even studied.

But they need to be included in the global analysis. This is particularly true for decay modes expected with sizable decay branching ratios such as *H→gg, cc* since they affect the BRs of other decays.

Theoretical predictions at $m_H = 125.09$ GeV

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 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

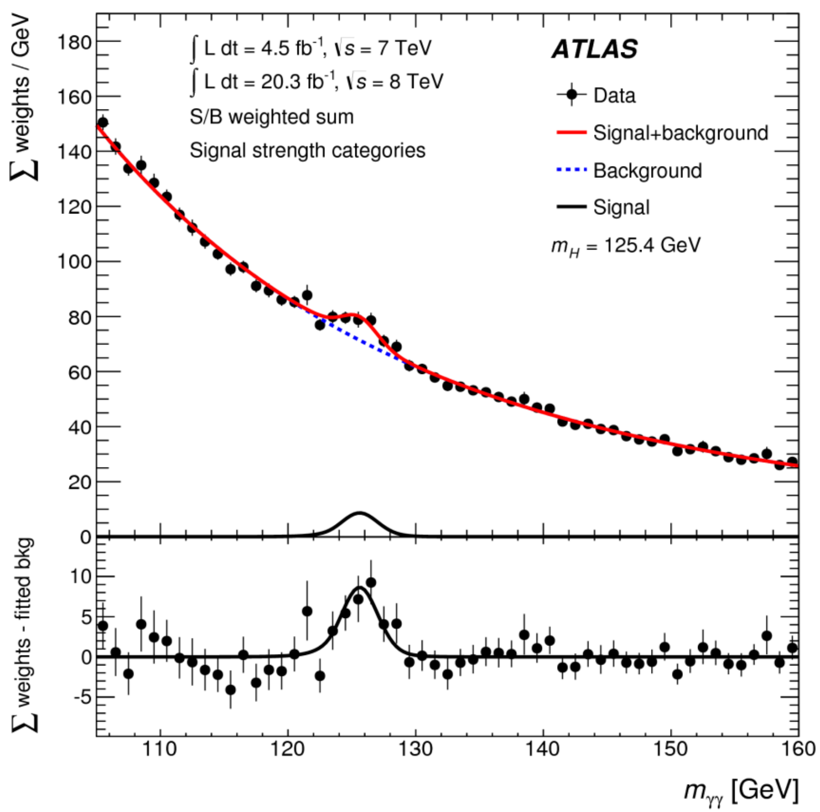
arXiv:1307.1347 (LHC Higgs XS Working Group)

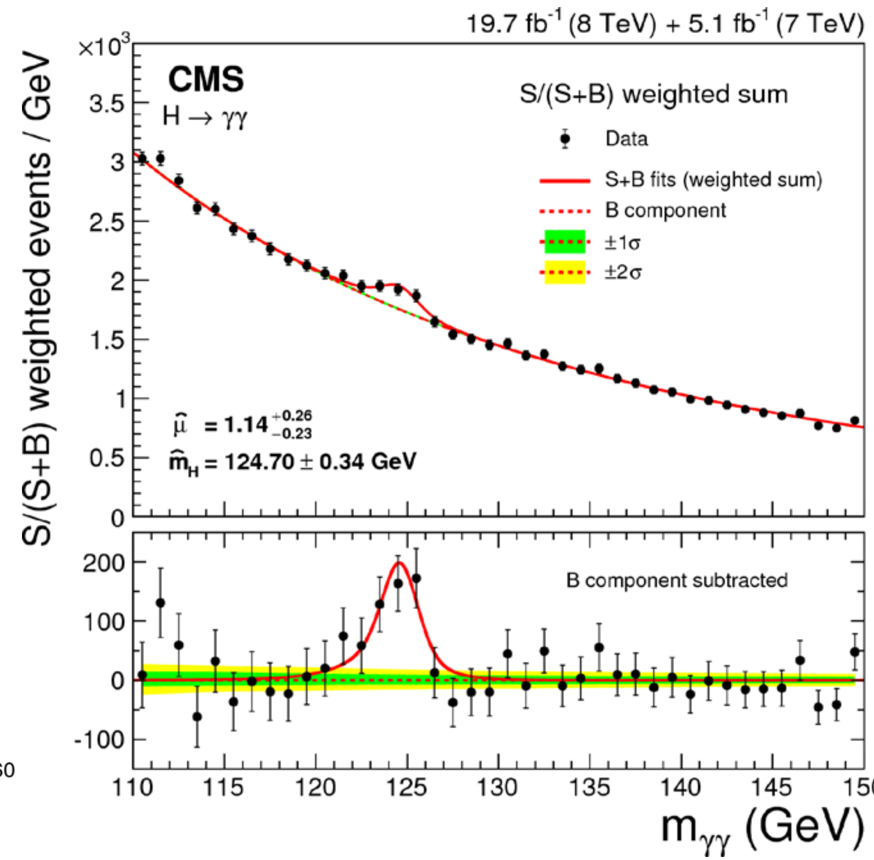
H→γγ Analyses

Simple topology: narrow diphoton resonance over a continuum background

- Determine background from data side-bands;
- Full reconstruction with a typical mass resolution 1-2%;
- Categorization to improve S/B ratios and to disentangle different production processes.

arXiv:1408.7084 (ATLAS)





arXiv:14070558 (CMS)

$H \to ZZ^* \to 4\ell$ Analyses

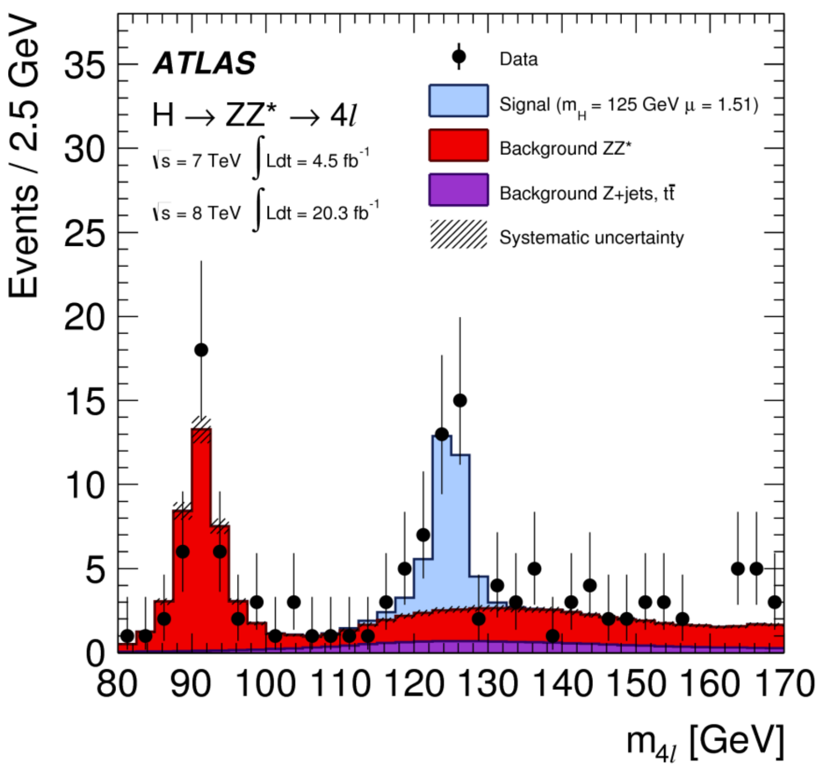
Clean signature: a narrow resonance over small background

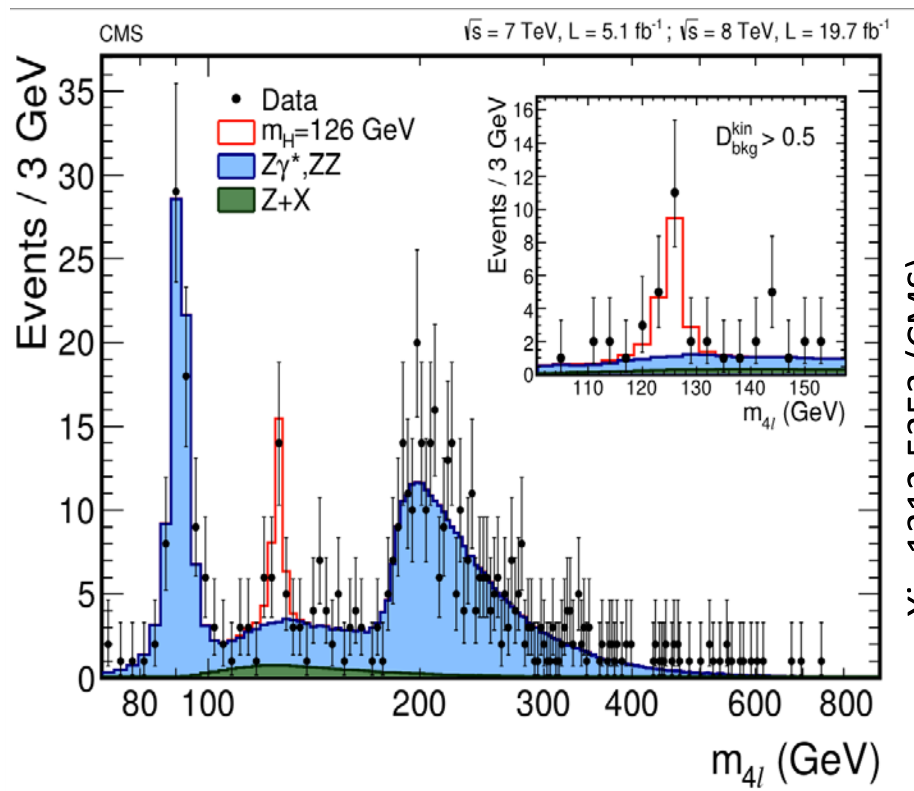
Background: mainly irreducible SM ZZ contribution

Full reconstruction with a good mass resolution: 1-2% similar to $H \to \gamma\gamma$

High signal-background ratio, very small background

arXiv:1408.5191 (ATLAS)



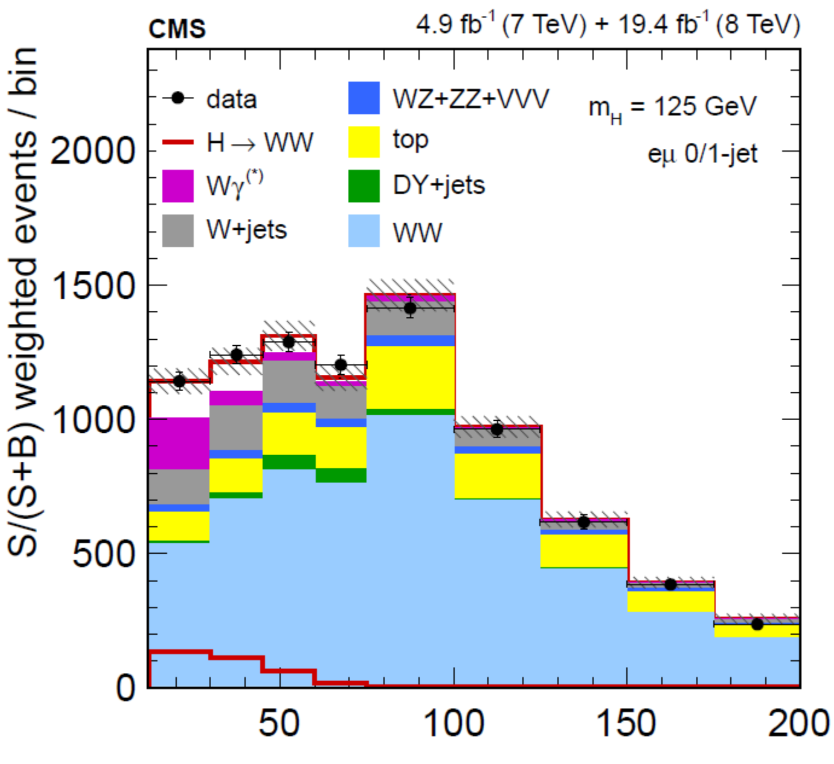


arXiv:1312.5353 (CMS)

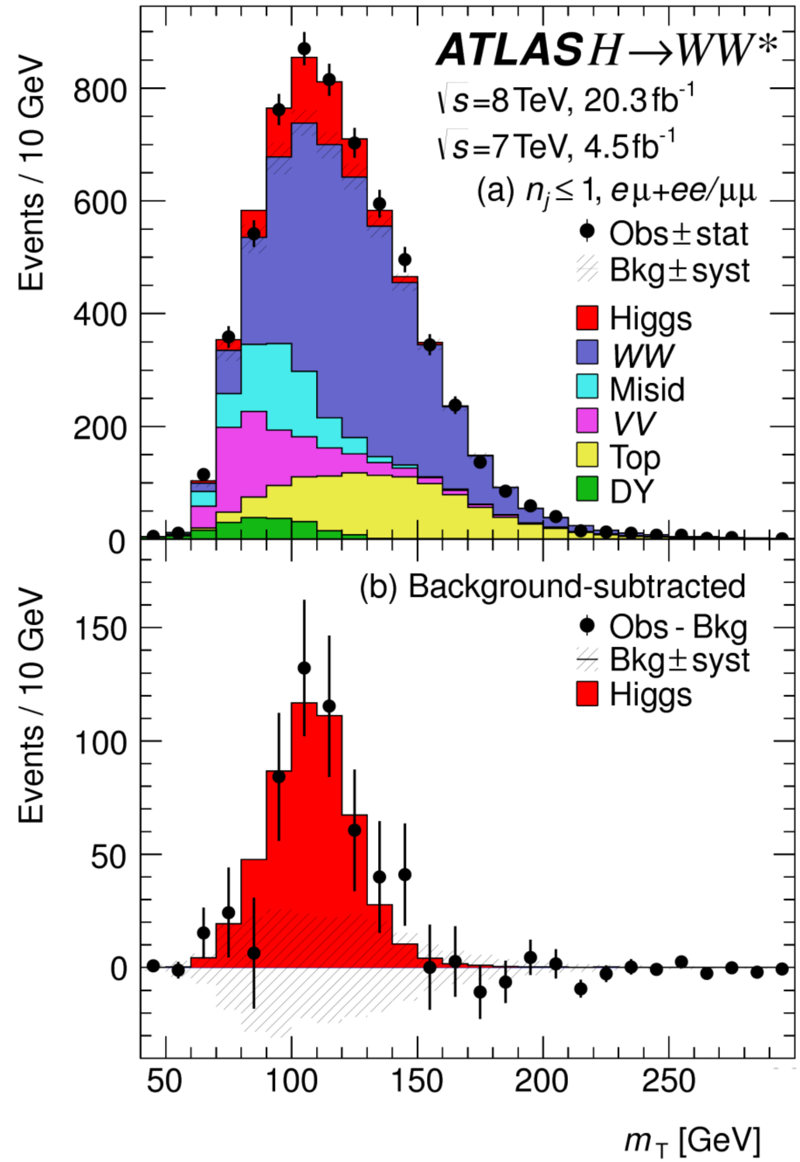
H→WW*→ℓνℓν Analyses

No full Higgs decay reconstruction, dilepton mass, transverse mass et al. as the discriminants

Backgrounds are strongly jet multiplicity dependent => analysis in jet bins
S/B ratio ~ 10-20% in 0/1 jet bin



arXiv:1312.1129 (CMS)



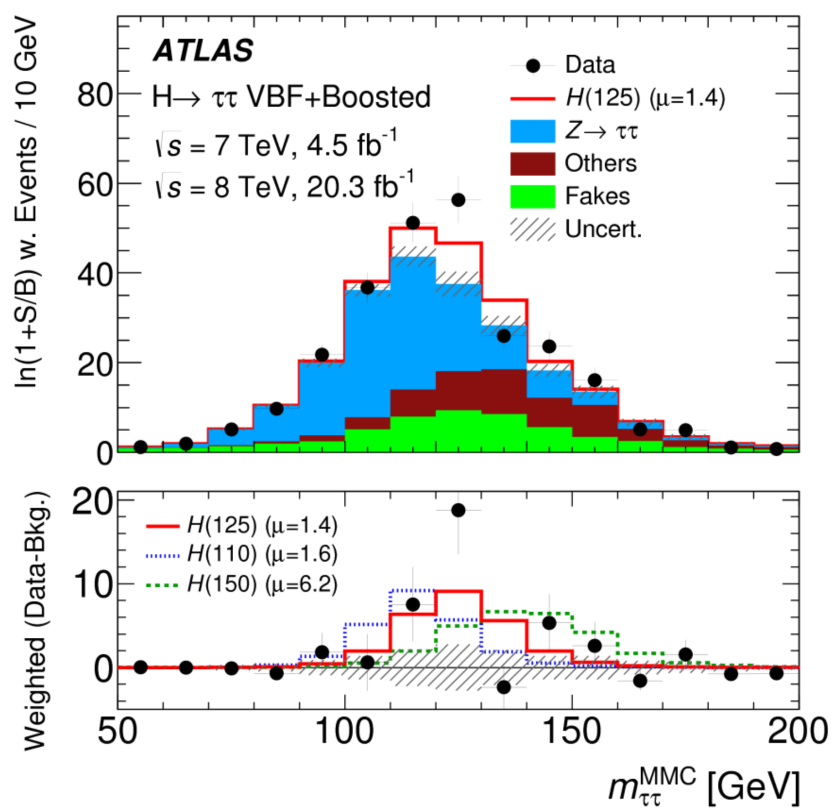
arXiv: 1412.2641 (ATLAS)

H→ττ Analyses

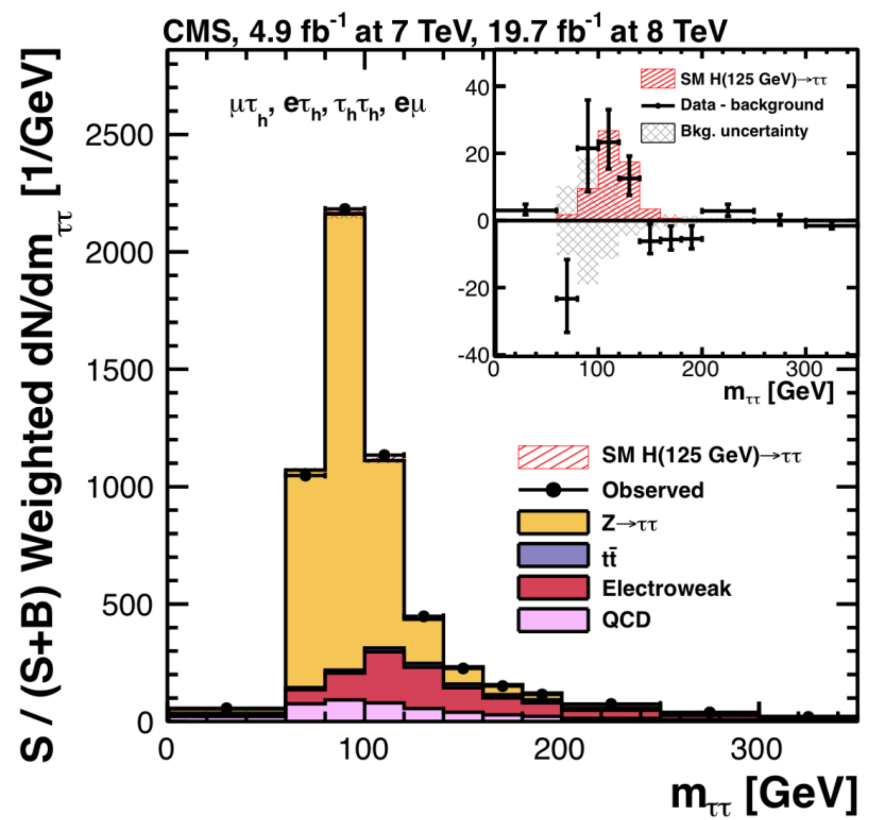
Three final states of the $\tau\tau$ decays:

- lep-lep channel: $H \to \tau\tau \to 2\ell + 4\nu$ (12.4%)
- lep-had channel: $H \to \tau\tau \to \ell + \tau_{had} + 3\nu$ (45.6%)
- had-had channel: $H \to \tau\tau \to 2\tau_{had} + 2\nu$ (42%)

Sensitivity mostly from VBF and boosted ggF production, good ττ mass resolution is the key.



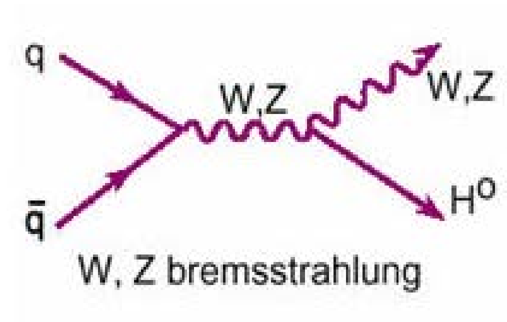
arXiv:1501.04943 (ATLAS)



arXiv:1401.5041 (CMS)

H→bb Analyses

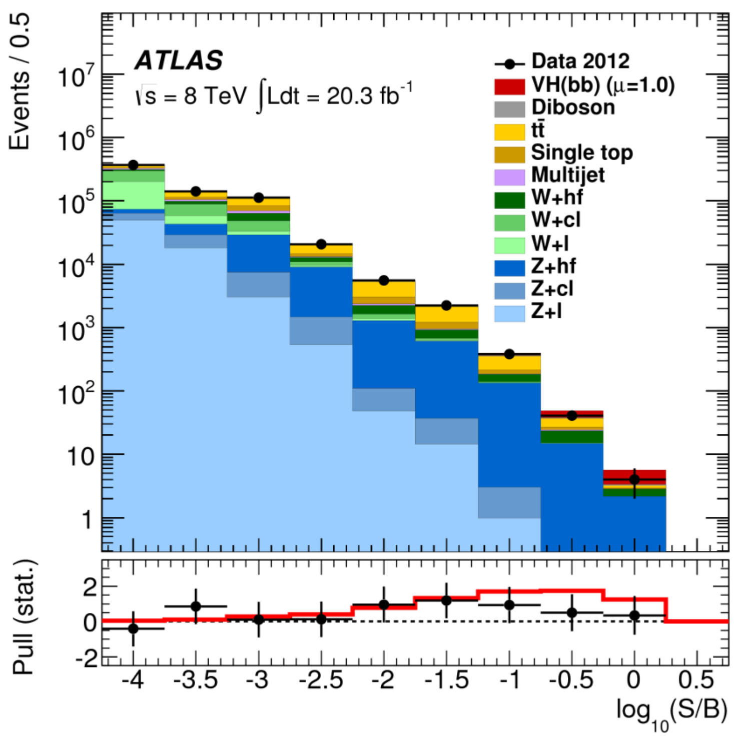
No triggering on leptons or photons from Higgs decays, rely on associated objects such as V $(W \text{ or } Z)$ in the VH production or on unique topology of VBF production.

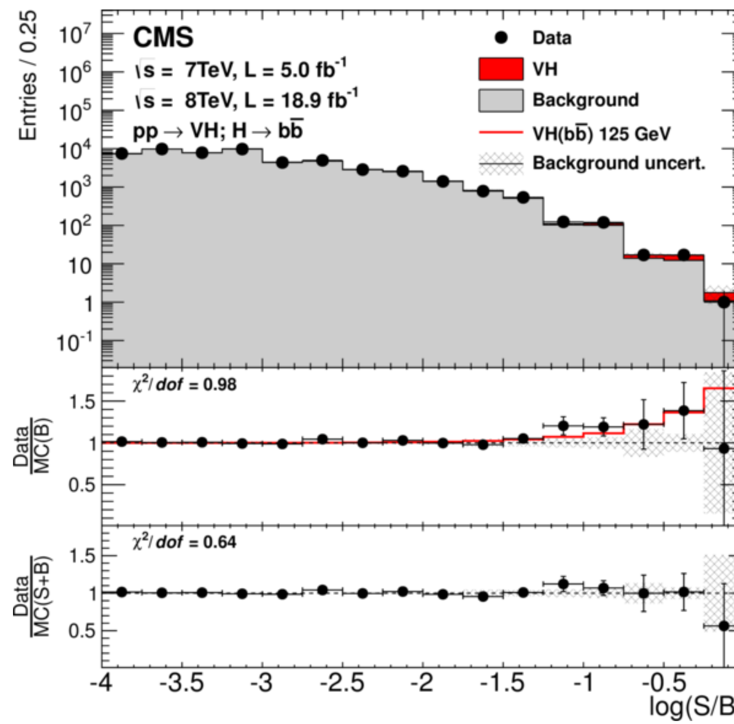


Three distinct VH final states:

- 0-lepton: $\nu\nu b\bar{b}$ (ZH);
- 1-lepton: $\ell\nu b\bar{b}$ (WH);
- 2-leptons: $\ell\ell b\bar{b}$ (ZH)

arXiv:1409.6212 (ATLAS)

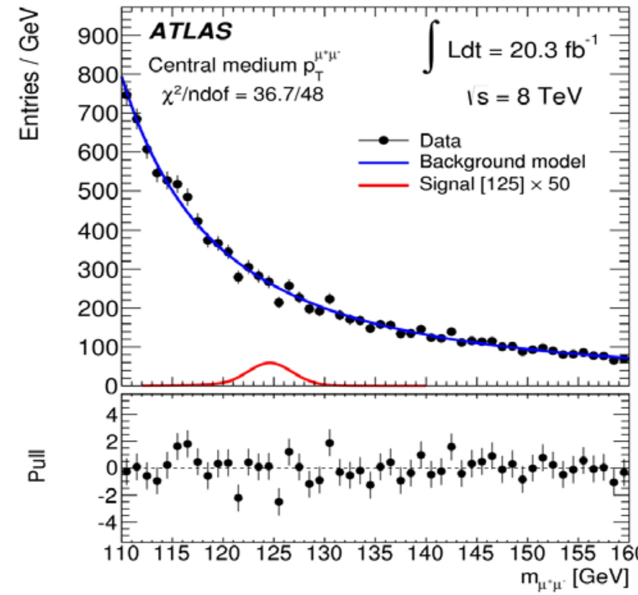




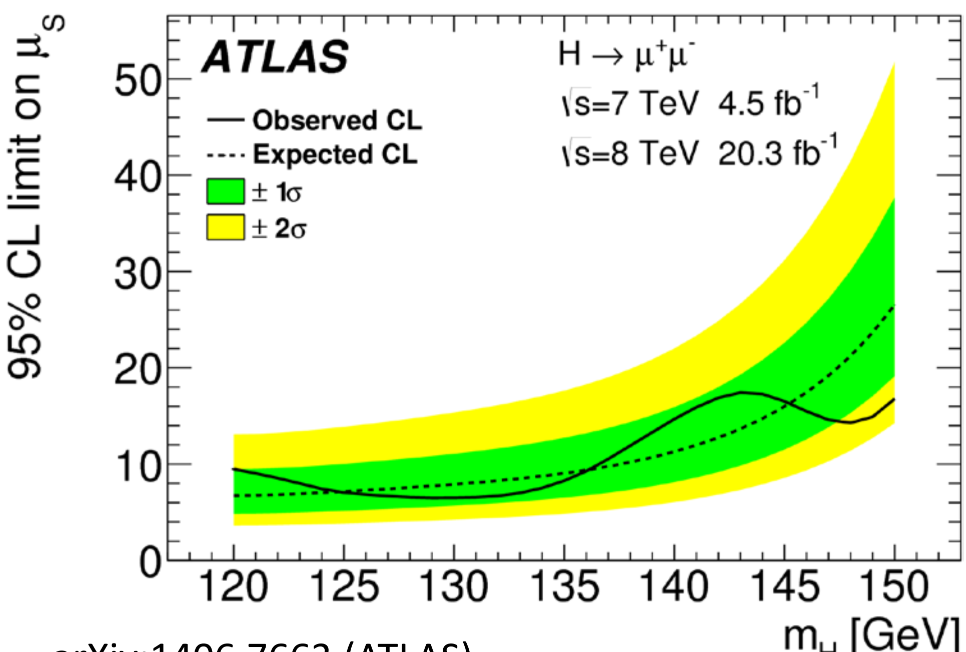
arXiv:1310.3687 (CMS)

$H \to \mu\mu$ Search

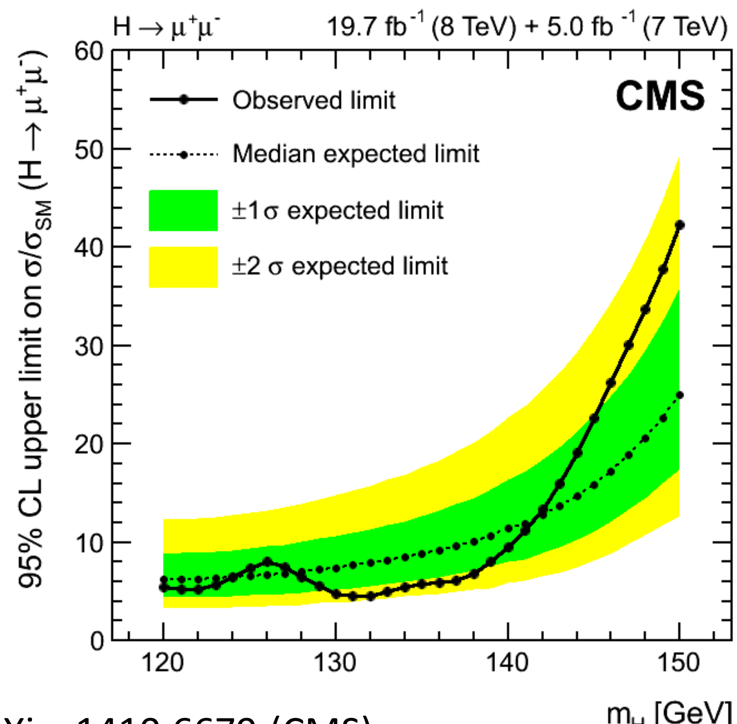
Small $BR(H \to \mu\mu) = 2.2 \times 10^{-4}$ @ 125 GeV, good mass resolution ~ 2 GeV, 10 times smaller than $BR(H \to \gamma\gamma)$ with a much larger background dominated by Drell-Yan production.



Observed limit is about $7\times$ the SM prediction.



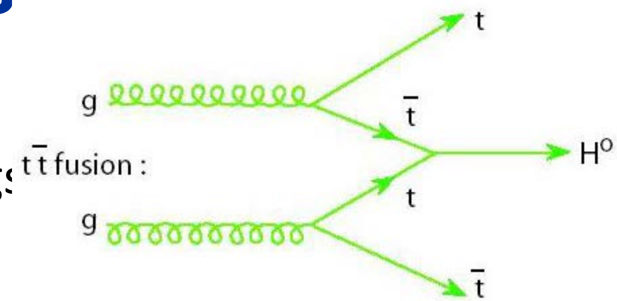
arXiv:1406.7663 (ATLAS)



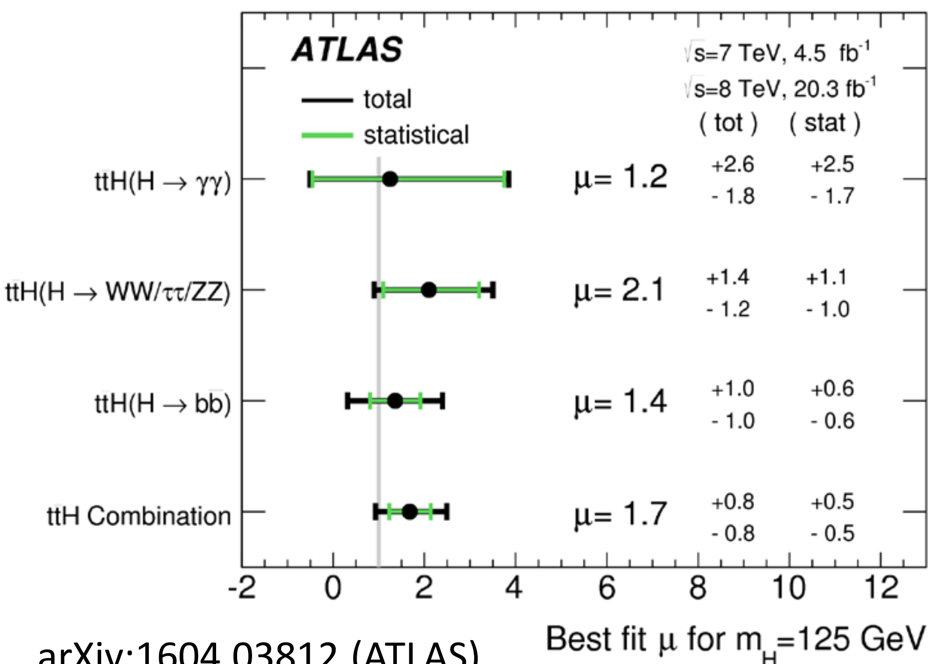
arXiv: 1410.6679 (CMS)

ttH with H→γγ, bb and leptons

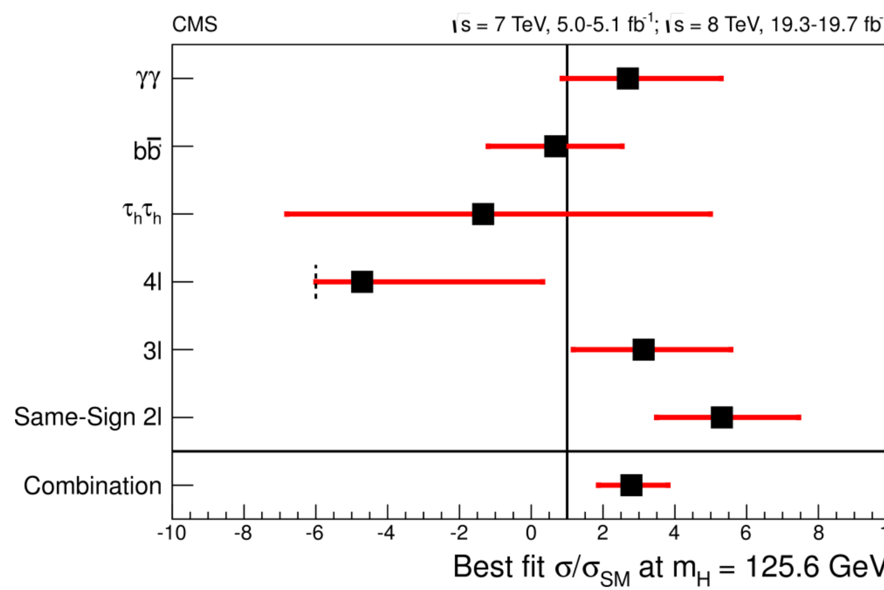
Searches for additional Higgs boson in $t\bar{t}$ events
$\Rightarrow$ allow direct study of top-Higgs Yukawa couplings
but large backgrounds from SM $t\bar{t}$ production.



The $H \to \gamma\gamma$ decay has the cleanest signature, but the smallest rate.
The $H \to$ bb and $H \to (WW^*, ZZ^*, \tau\tau) \to \ell$'s decays have higher rates,
but suffer from large background.

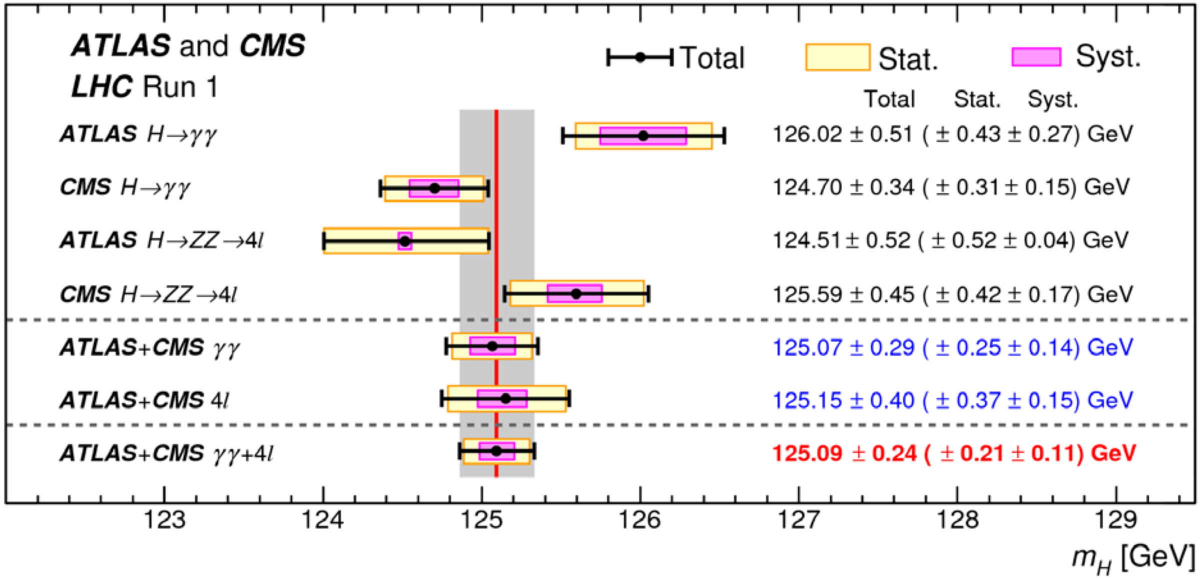


arXiv:1604.03812 (ATLAS)



arXiv:1408.1682 (CMS)

Mass Measurements



$H \rightarrow \gamma\gamma$

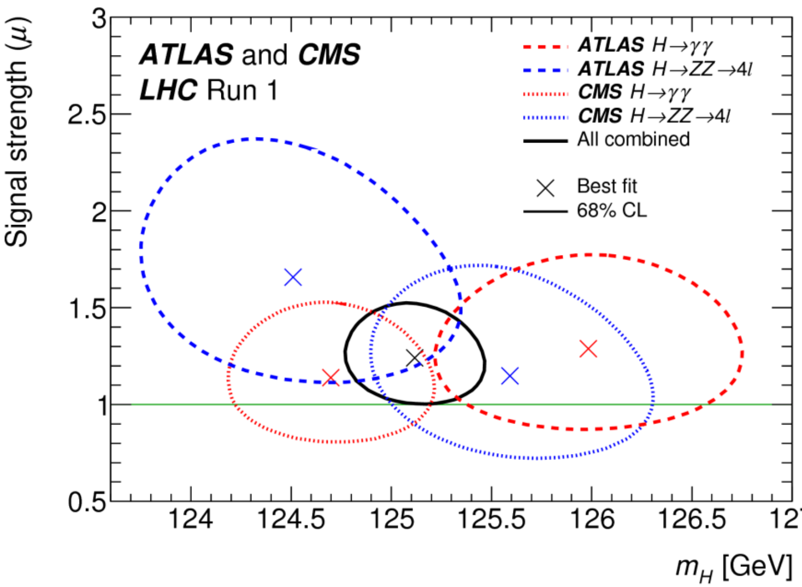
$H \rightarrow ZZ^* \rightarrow 4\ell$

The largest systematic effects are those related to the determinations of the energy/momentum scales of photons and leptons.

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$

Small tensions between individual measurements:

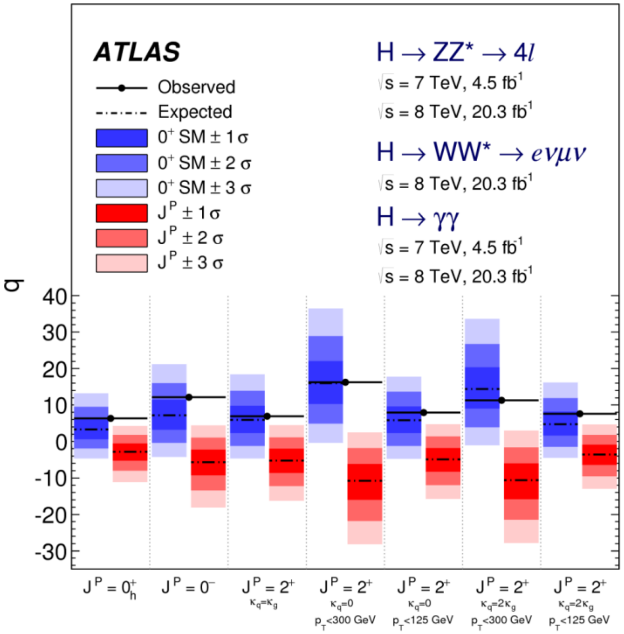
$$m_{\gamma\gamma}^{ATLAS} - m_{\gamma\gamma}^{CMS} = 1.3 \pm 0.6 \text{ GeV } (2.1\sigma)$$
$$m_{4\ell}^{ATLAS} - m_{4\ell}^{CMS} = -0.9 \pm 0.7 \text{ GeV } (1.3\sigma)$$



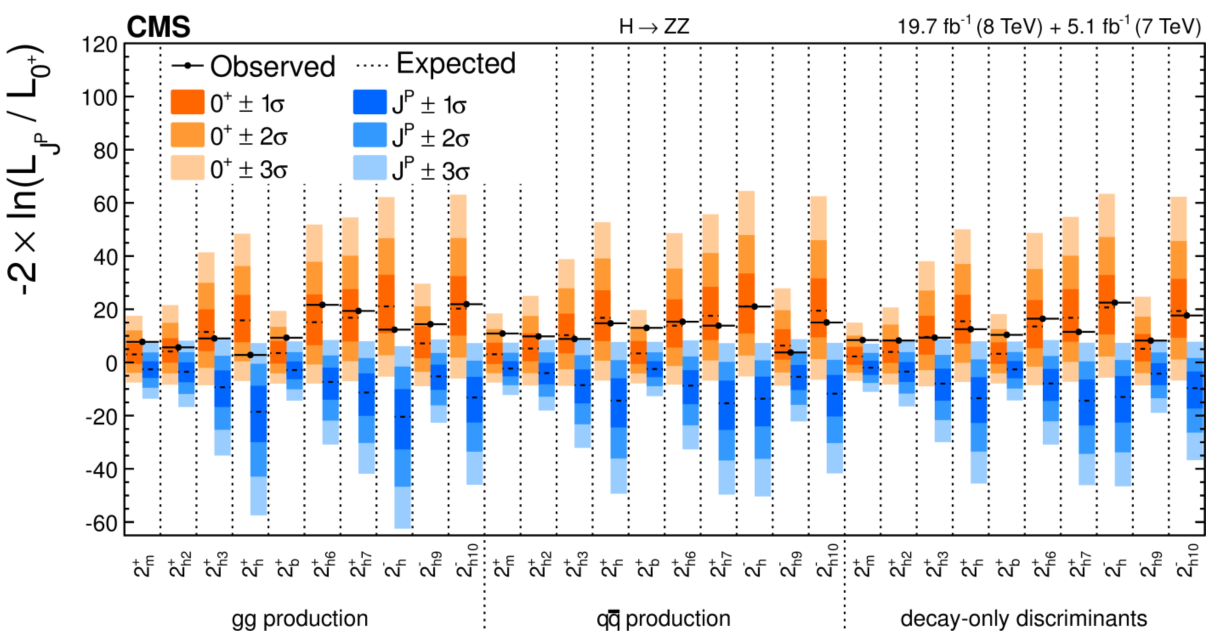
arXiv:1503.07589

Spin/CP Properties

Spin/CP properties have been tested in the $\gamma\gamma, ZZ$ and WW decay modes. The data strongly prefer the SM hypothesis of $J^P = 0^+$. Almost all alternative hypotheses studied have been excluded at 95% CL.



arXiv:1506.05669 (ATLAS)



arXiv:1411.3441 (CMS)

Tensor structure and CP-invariance of the couplings are also studied in $H \rightarrow ZZ^*, WW^*$ and $\tau\tau$ decays, no deviations from the SM expectations have been found.

Signal Rate Characterization

At the LHC, only the products $\sigma \cdot \mathrm{BR}$ are measured, there is no model-independent way to determine the cross section and the branching ratio separately.

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

Signal strengths:

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

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

Only μ_i^f are determined from the Higgs signal rate measurements.

Assumptions and Global Signal Strength

The Higgs boson is assumed to have a narrow width, such that the production and decay factorize.

The signal event kinematics are modeled using the SM Higgs boson

Global signal strength combining
- all production and decay processes
- both 7 and 8 TeV data

Combined	μ	$=$	$1.09^{+0.11}_{-0.10}$	$=$	$1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})\,^{+0.07}_{-0.06}\,(\text{thsig})$
ATLAS	μ	$=$	$1.20^{+0.15}_{-0.14}$	$=$	$1.20^{+0.10}_{-0.10}\,(\text{stat})\,^{+0.06}_{-0.06}\,(\text{expt})\,^{+0.04}_{-0.04}\,(\text{thbgd})\,^{+0.08}_{-0.07}\,(\text{thsig})$
CMS	μ	$=$	$0.98^{+0.14}_{-0.13}$	$=$	$0.98^{+0.10}_{-0.09}\,(\text{stat})\,^{+0.06}_{-0.05}\,(\text{expt})\,^{+0.04}_{-0.04}\,(\text{thbgd})\,^{+0.08}_{-0.07}\,(\text{thsig})$

(ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)

Consistency with SM expectation of $\mu = 1.0$ with a p-value of 34%.

Uncertainties:
- Roughly equal statistical and systematic contributions;
- Theory systematics is already the largest systematic component.

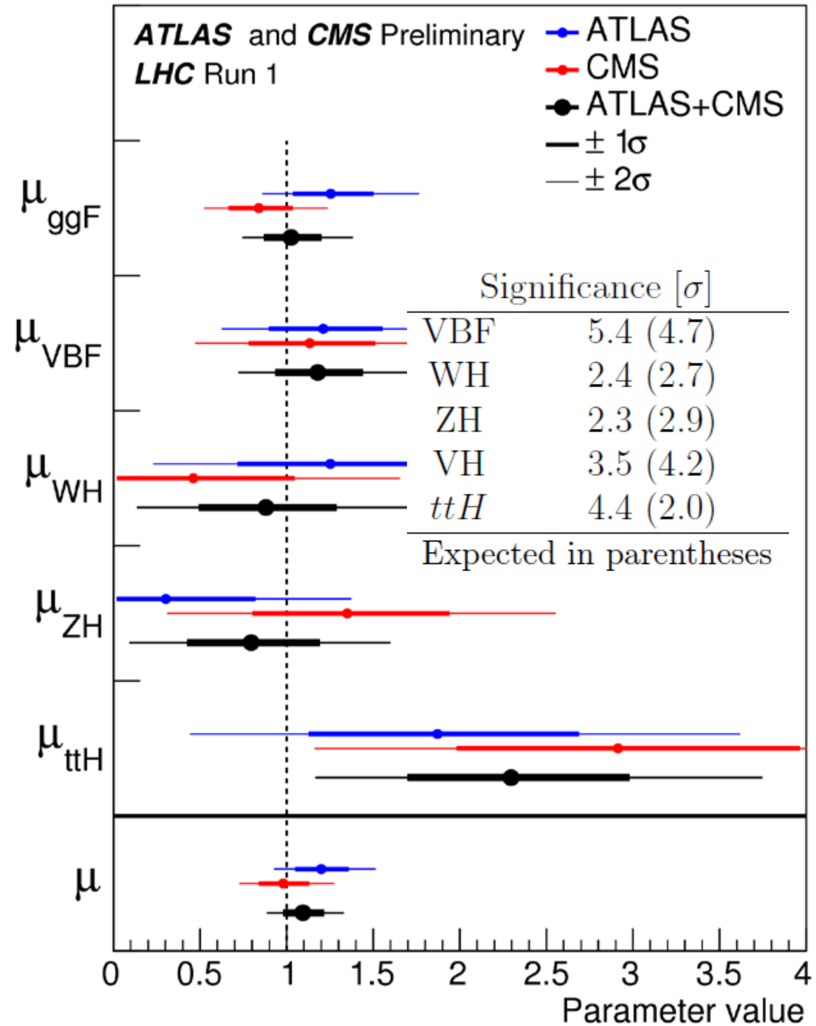
Production Signal Strengths

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}$$

Assuming $\mu^f = 1$, i.e., SM values for branching ratios

$\Rightarrow$ explore potential BSM physics in production.

Production	Combined	ATLAS	CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$	$1.25^{+0.24}_{-0.21}$	$0.84^{+0.19}_{-0.16}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$	$1.21^{+0.33}_{-0.30}$	$1.13^{+0.37}_{-0.34}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$	$1.25^{+0.56}_{-0.52}$	$0.46^{+0.57}_{-0.54}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$	$0.30^{+0.51}_{-0.46}$	$1.35^{+0.58}_{-0.54}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$



(ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)

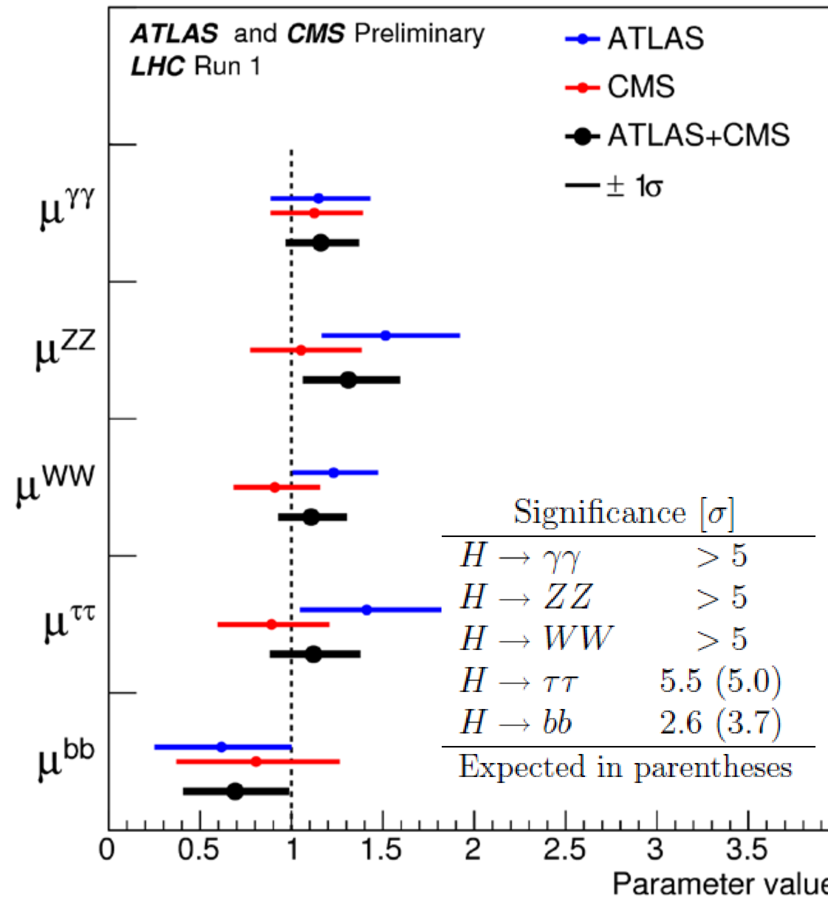
Decay Signal Strengths

$$\mu^f = \frac{BR^f}{\left(BR^f\right)_{SM}}$$

Assuming $\mu_i = 1$, i.e., SM values for production cross sections

$\Rightarrow$ explore potential BSM physics in decays.

Decay	Combined	ATLAS	CMS
$\mu^{\gamma\gamma}$	$1.16^{+0.20}_{-0.18}$	$1.15^{+0.27}_{-0.25}$	$1.12^{+0.25}_{-0.23}$
μ^{ZZ}	$1.31^{+0.27}_{-0.24}$	$1.51^{+0.39}_{-0.34}$	$1.05^{+0.32}_{-0.27}$
μ^{WW}	$1.11^{+0.18}_{-0.17}$	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$
$\mu^{\tau\tau}$	$1.12^{+0.25}_{-0.23}$	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$
μ^{bb}	$0.69^{+0.29}_{-0.27}$	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.52}$

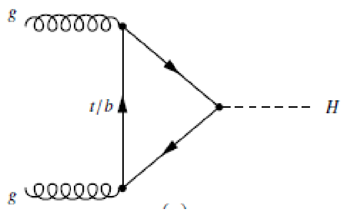


(ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)

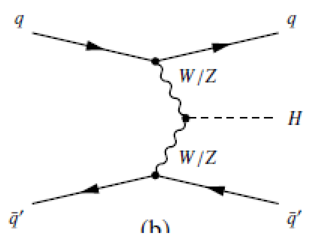
Boson vs Fermion Mediations

The Higgs boson production processes can be associated with Higgs Boson couplings to

- either Fermions



- or vector bosons

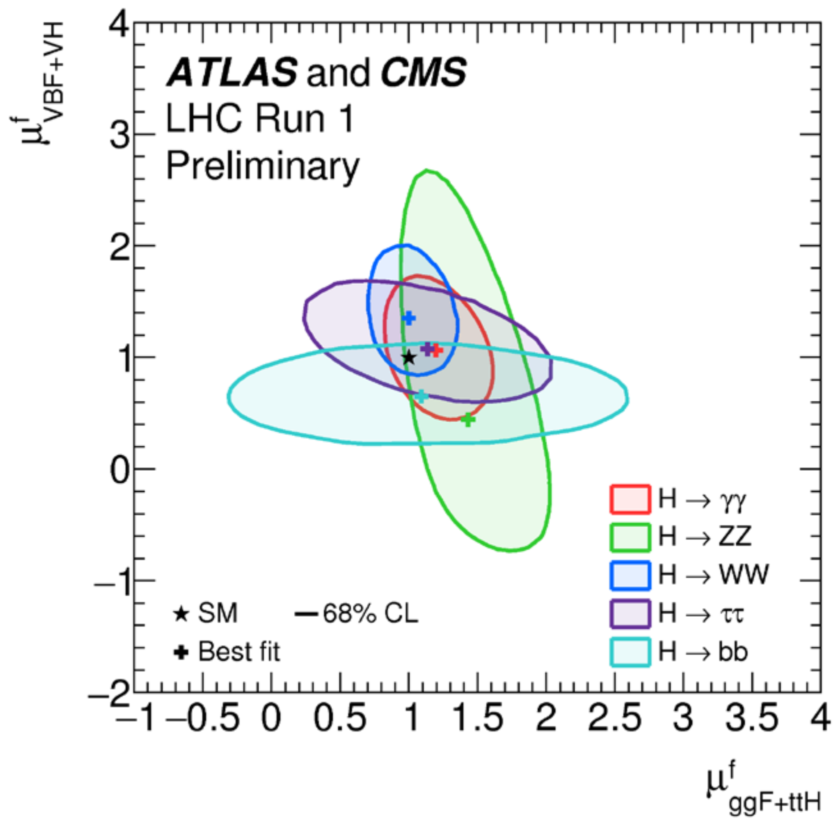


Potential deviations in these couplings can be tested using two production strength parameters:

$\mu_{ggF+ttH}$ and μ_{VBF+VH}

measured for each decay mode separately.

$\mu_{ggF+ttH}$ vs μ_{VBF+VH}



(ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)

Generic σ and BR Parameterization

Because only the products ($\sigma\times$BR) of cross sections and branching ratios are measured at the LHC, the cross sections and decay branching ratios cannot be separately determined in a model independent way.

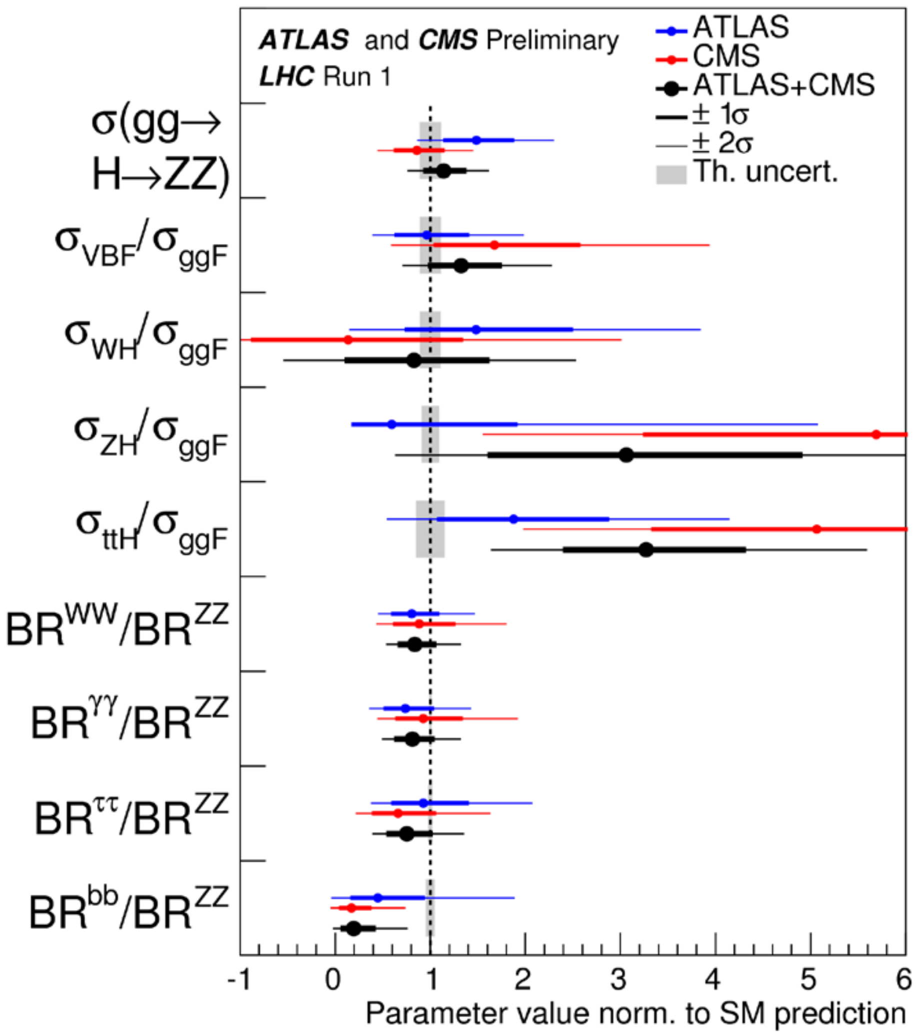
However, the ratios of cross sections and the ratios of decay branching ratios can be extracted with minimum assumptions.

Using $gg \to H \to ZZ$ as a reference, the Higgs boson rate of other production processes and decay modes can be parameterized as

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

Thus the ratios of cross sections and ratios of branching ratios can be extracted in a largely model-independent way.

Generic Parameterization



(ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)

SM compatibility: 16%, but…

$$\frac{\sigma_{ttH}}{\sigma_{ggF}} = \left[3.3^{+1.0}_{-0.9}\right] \times \left(\frac{\sigma_{ttH}}{\sigma_{ggF}}\right)_{SM}$$

$$\frac{\sigma_{ZH}}{\sigma_{ggF}} = \left[3.2^{+1.8}_{-1.4}\right] \times \left(\frac{\sigma_{ZH}}{\sigma_{ggF}}\right)_{SM}$$

$$\frac{BR^{bb}}{BR^{ZZ}} = \left[0.19^{+2.1}_{-1.2}\right] \times \left(\frac{BR^{bb}}{BR^{ZZ}}\right)_{SM}$$

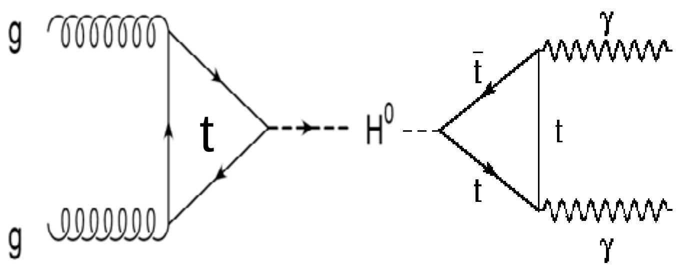
ttH excesses mostly from multi-ℓ's categories (both ATLAS and CMS);

ZH excess mainly from CMS H $\rightarrow$ ZZ two jet category;

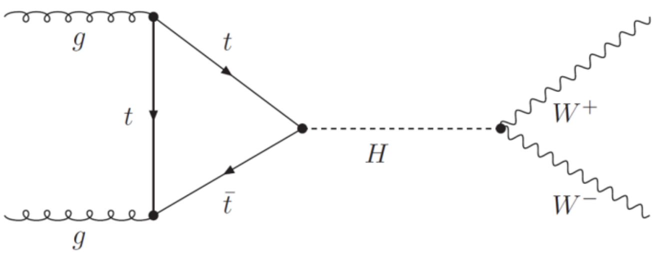
Higher ttH and ZH cross sections coupled with smaller measured VH $\rightarrow$ Vbb rates lead to small BR^{bb}/BR^{ZZ}.

Beyond Signal Strengths

Signal strength mixes different production processes, production and decay, tree- and loop-level Higgs couplings. Consequently it could obscure potential new physics.



same couplings, but a mixture of production and decay



a mixture of fermion and vector boson couplings

Higgs couplings to fermions and vector bosons are at the heart of all these. Potential deviations from SM can be studied from these couplings.

Using scale parameters κ $\left(\text{SM: } \kappa = 1\right)$ to parametrized the deviations:

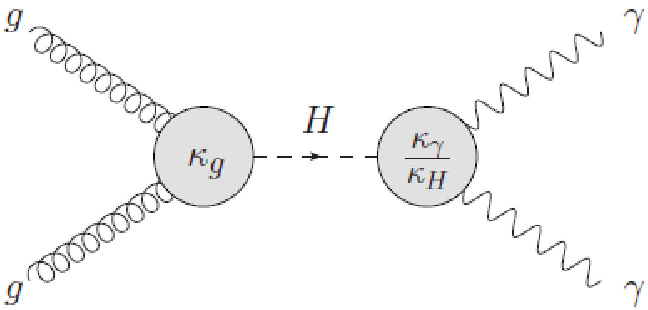
$$g_{Hff} = \frac{\sqrt{2} m_f}{\upsilon}, \qquad g_{HVV} = \frac{2m_V^2}{\upsilon} \quad \Rightarrow \quad g_{Hff} = \kappa_f \cdot \frac{\sqrt{2} m_f}{\upsilon}, \quad g_{HVV} = \kappa_V \cdot \frac{2m_V^2}{\upsilon}$$

Rate Modifications

Example:

$gg \to H \to \gamma\gamma$

Treat loops as effective couplings



$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \left[\sigma(gg \to H) \cdot BR(H \to \gamma\gamma)\right]_{SM} \times \boxed{\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2} \cdot \frac{1}{1 - BR_{BSM}}}$$

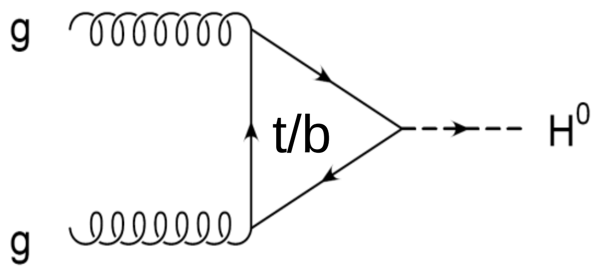
κ_H^2 is the scale factor to the SM Higgs decay width:

$$\kappa_H^2 = \sum_f \kappa_f^2 \cdot BR_{SM}(H \to f)$$

and BR_{BSM} is the total branching ratio to non-SM decays.

κ's can then be extracted from fits to the measured rates. Note $|\kappa|^2$ are usually extracted. Relative signs between different couplings are relevant only if there are sizable interference effects.

Decomposing Loops…



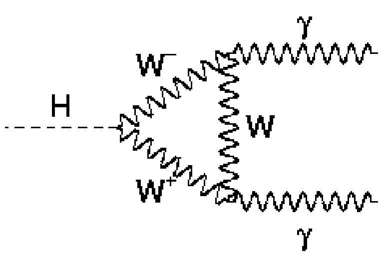
In SM, the $gg \to H$ cross section can be broken into three pieces: $\sigma_{SM} = \sigma_{tt} + \sigma_{bb} + \sigma_{tb}$

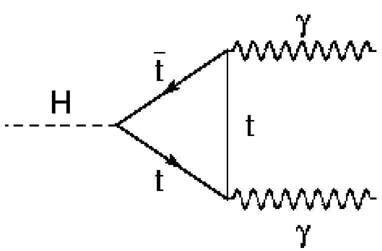
With coupling modifications, the cross section becomes $\Rightarrow \sigma = \kappa_t^2 \sigma_{tt} + \kappa_b^2 \sigma_{bb} + \kappa_t \kappa_b \sigma_{tb}$

The effective *Hgg* coupling scale parameter is

$$\kappa_g^2 = \frac{\sigma}{\sigma_{SM}} = \frac{\kappa_t^2 \sigma_{tt} + \kappa_b^2 \sigma_{bb} + \kappa_t \kappa_b \sigma_{tb}}{\sigma_{tt} + \sigma_{bb} + \sigma_{tb}}$$

$$\approx 1.06 \kappa_t^2 + 0.01 \kappa_b^2 - 0.07 \kappa_t \kappa_b \quad ^*$$





$$\kappa_\gamma^2 = \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \frac{\kappa_t^2 \Gamma_{\gamma\gamma}^{tt} + \kappa_W^2 \Gamma_{\gamma\gamma}^{WW} + \kappa_t \kappa_W \Gamma_{\gamma\gamma}^{tW}}{\Gamma_{\gamma\gamma}^{tt} + \Gamma_{\gamma\gamma}^{WW} + \Gamma_{\gamma\gamma}^{tW}}$$

$$\approx 0.07 \kappa_t^2 + 1.59 \kappa_W^2 - 0.66 \kappa_t \kappa_W \quad ^*$$

* $m_H = 125.09$ GeV

Cross Section and Width Decompositions

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

(ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)

Fermions and Bosons

$\kappa_F\,,\ \kappa_V$

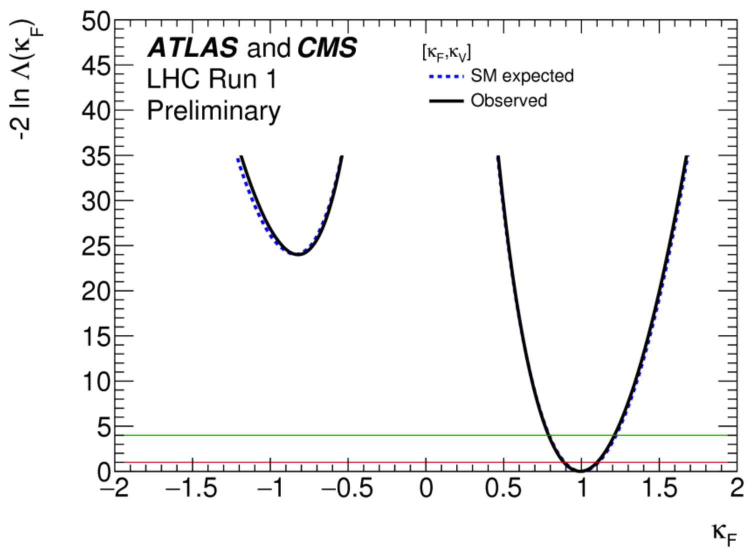
κ_F : for all fermions $(\kappa_F \equiv \kappa_t = \kappa_b = \kappa_\tau = \ldots)$

κ_V : for all vector bosons $(\kappa_V \equiv \kappa_W = \kappa_Z)$

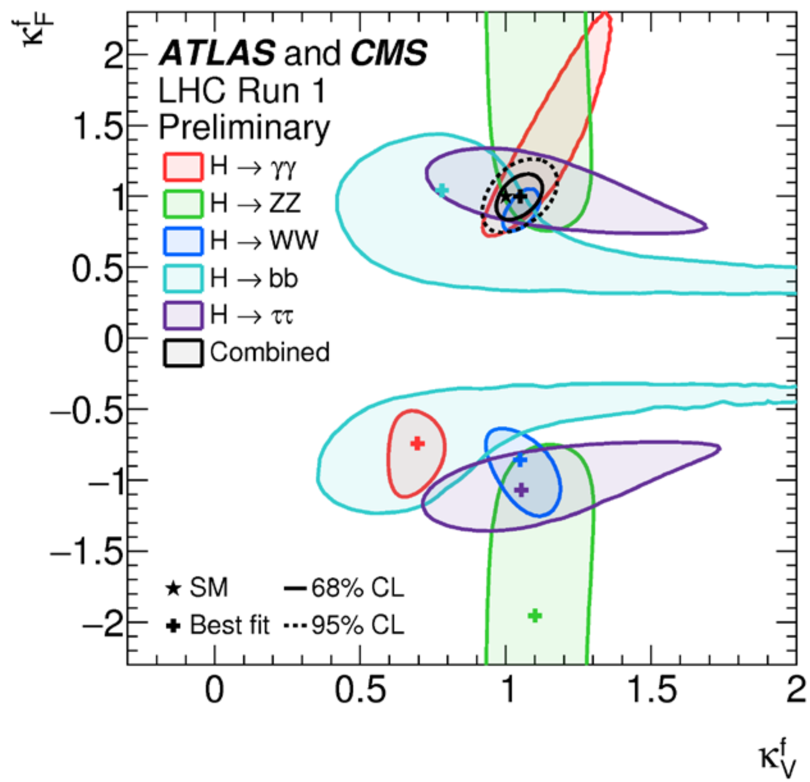
κ_g and κ_γ are decomposed to their tree-level couplings

$$\Rightarrow \kappa_H^2 \approx 0.75\kappa_F^2 + 0.25\kappa_V^2$$

Insufficient to resolve the relative sign between κ_F and κ_V from individual analyses, but the combination excludes the relative negative sign.



(ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)

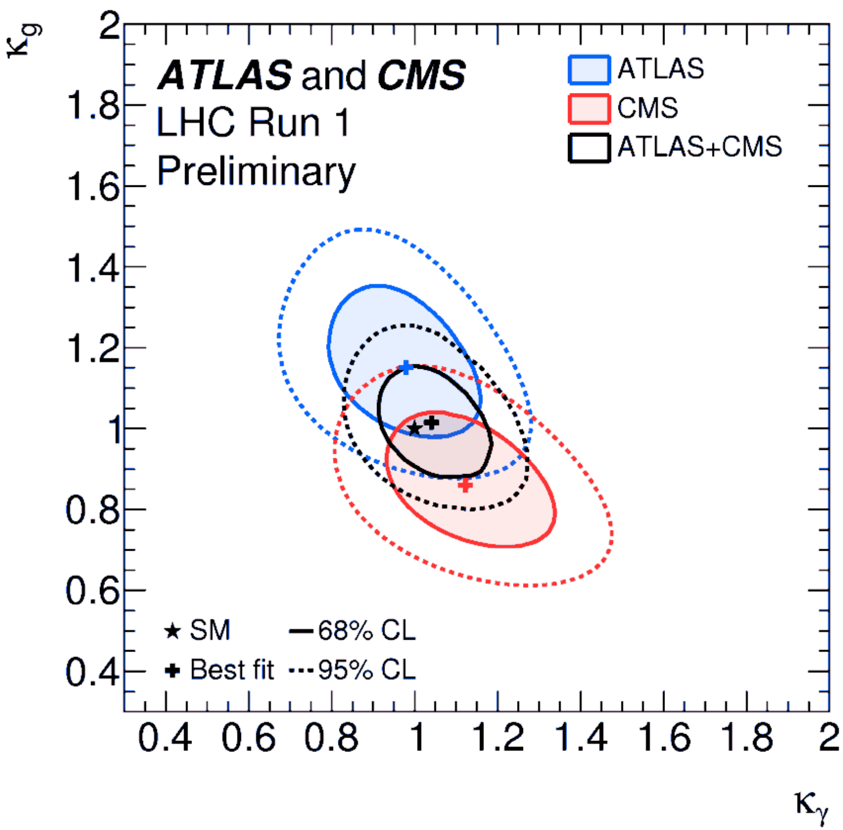


Vertex Loops

κ_g , κ_γ

- κ_g and κ_γ for $gg \to$ H and H $\to \gamma\gamma$ couplings;
- All other tree-level scale parameters $\kappa_i = 1$;
- No Beyond-Standard-Model decays.

$$\Rightarrow \kappa_H^2 \approx 0.91 + 0.09\kappa_g^2 + 0.0023\kappa_\gamma^2$$



Probe $gg \to H$ production and $H \to \gamma\gamma$ decay loops, sensitive to potential new physics in these loops.

Consistency with the SM expectations $(\kappa_g = 1, \kappa_\gamma = 1)$ at 82%.

(ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)

Up- and Down-type Fermions

$$\lambda_{du},\ \lambda_{Vu},\ \kappa_{uu}$$

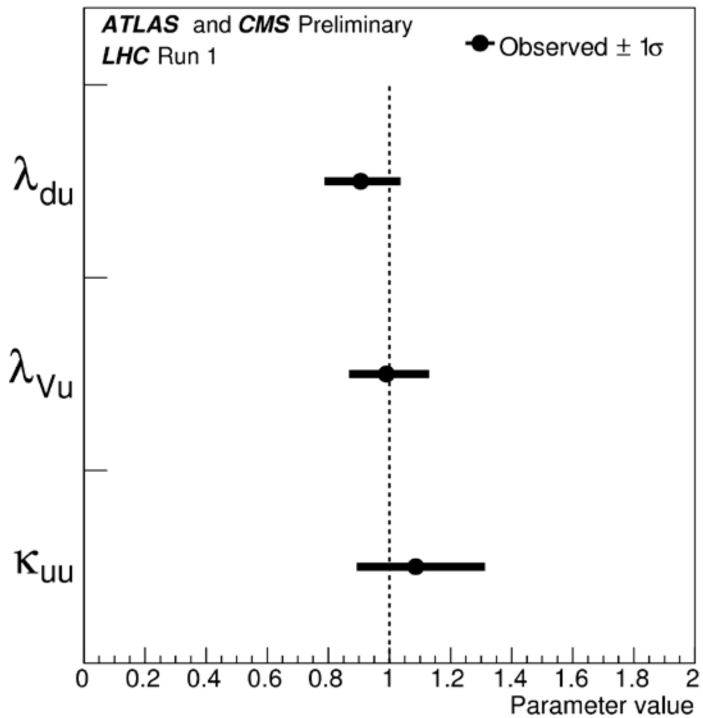
- all up-type fermions have equal couplings;
- all down-type fermions have equal couplings;
- No Beyond-Standard-Model decays.

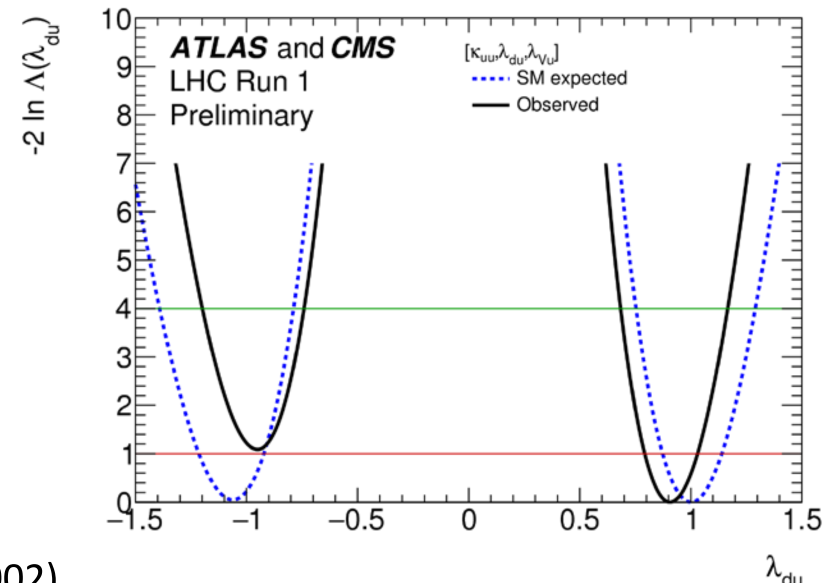
$$\lambda_{du} = \frac{\kappa_d}{\kappa_u},\ \lambda_{Vu} = \frac{\kappa_V}{\kappa_u},\ \kappa_{uu} = \frac{\kappa_u^2}{\kappa_H}$$

Up-type couplings: $gg \to H,\ H \to \gamma\gamma,$

Down-type couplings: $H \to bb,\ H \to \tau\tau$

Small sensitivity to the sign from the interference between the top- and bottom-loop in $gg \to H$





(ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)

Leptons and Quarks

$$\lambda_{\ell q},\ \lambda_{Vq},\ \kappa_{qq}$$

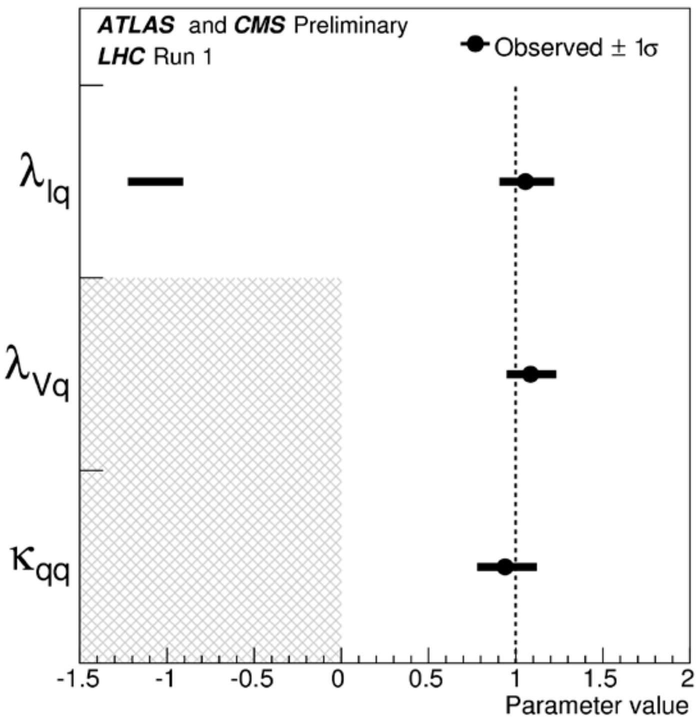
- all leptons have coupling κ_ℓ;
- all quarks have coupling κ_q;
- No Beyond-Standard-Model decays.

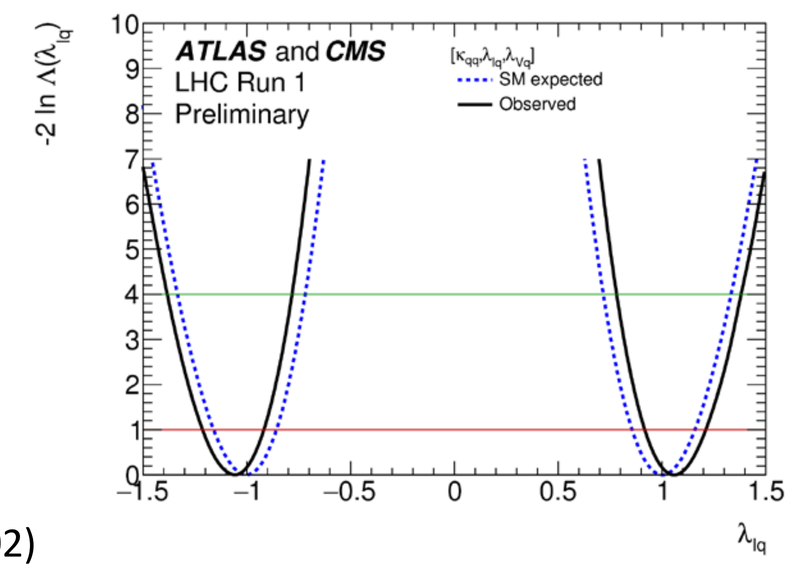
$$\lambda_{\ell q} = \frac{\kappa_\ell}{\kappa_q},\ \lambda_{Vq} = \frac{\kappa_V}{\kappa_q},\ \kappa_{qq} = \frac{\kappa_q^2}{\kappa_H}$$

Quark couplings: $gg \to H,\ H \to \gamma\gamma,\ H \to bb$

Lepton couplings: $H \to \tau\tau$

No information to the relative sign between the two couplings as there is no sizable lepton-quark interference effect.





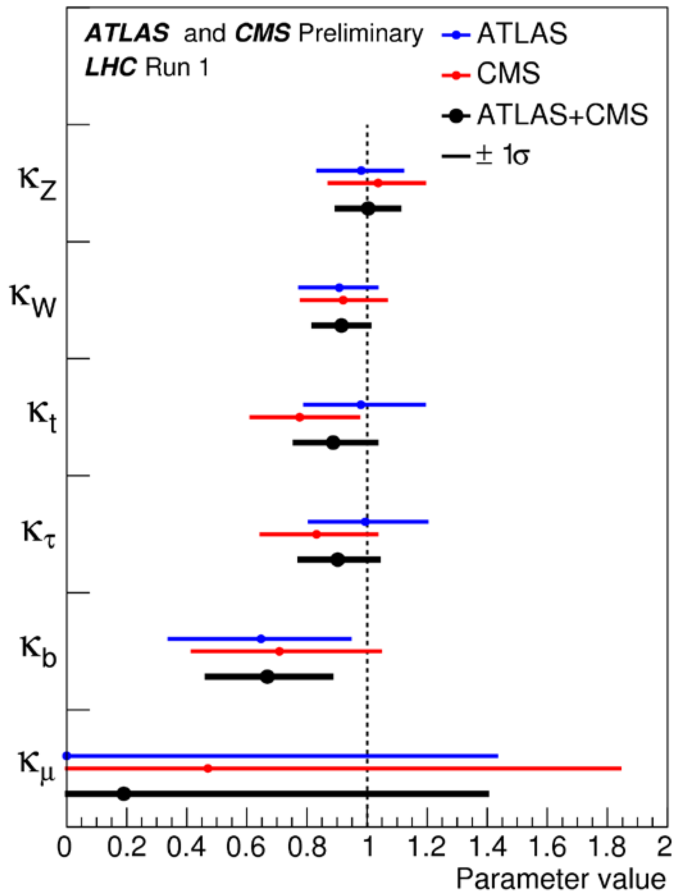
(ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)

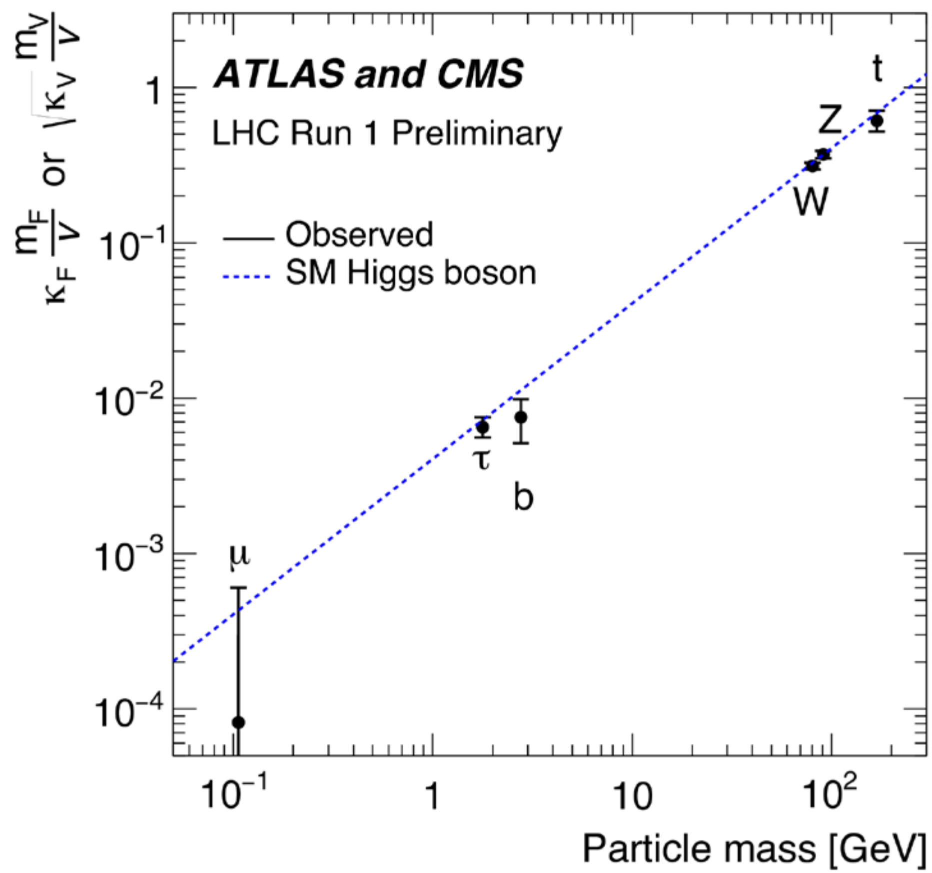
Standard Model Fit

$\kappa_Z, \kappa_W, \kappa_t,$
$\kappa_b, \kappa_\tau, \kappa_\mu$

- resolve all loops;
- one coupling parameter per SM particle;
- no Beyond-Standard-Model decays

(ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)





Beyond Standard Model Fit

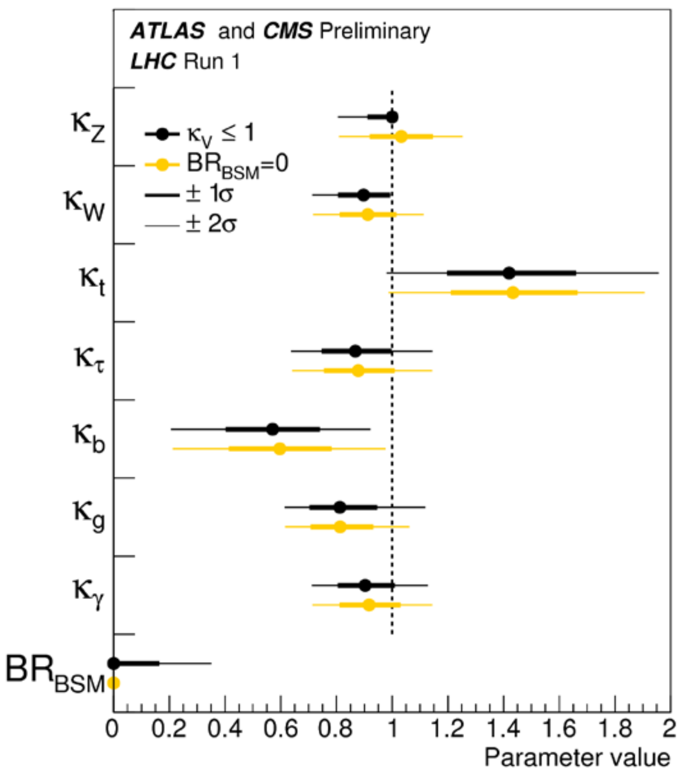
$\kappa_Z,\ \kappa_W,\ \kappa_t,\ \kappa_b,\ \kappa_\tau,\ \kappa_g,\ \kappa_\gamma,\ BR_{BSM}$

8 parameter fits:

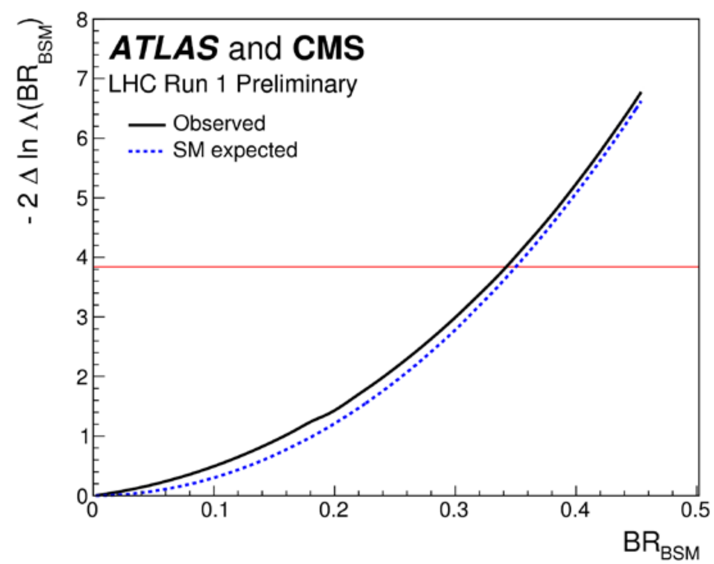
- allow deviations in all tree-level couplings;
- allow independent deviations in loop-couplings;
- allow Beyond-Standard-Model decays;
- with weak constraints $\kappa_V \leq 1$

$$\Gamma_H = \Gamma_H^{SM} \times \frac{\kappa_H^2}{1-BR_{BSM}},\quad BR(H\to xx) = BR_{SM}(H\to xx)\times(1-BR_{BSM})\cdot\frac{\kappa_x^2}{\kappa_H^2}$$

(ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)



$BR_{BSM} < 0.34\ (0.35)$ at 95% CL observed (expected)



Parameterization using Coupling Ratios

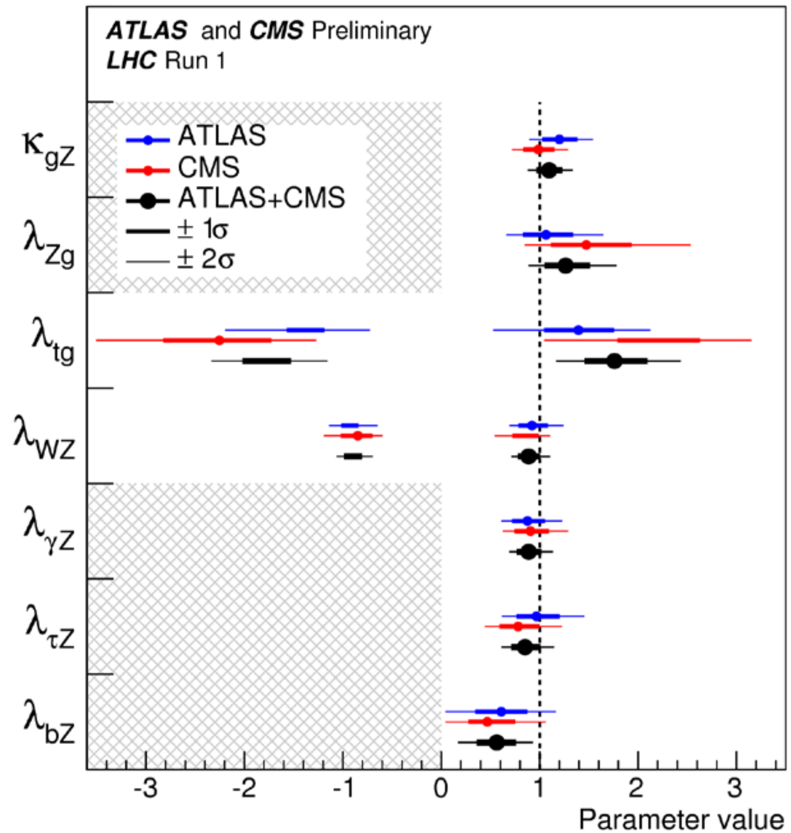
Since the cross sections and decay BRs are not independently measured at the LHC, the most model-independent parameterization using couplings is through their ratios.

The parameterization of cross sections and BRs using $gg \to H \to ZZ$ as the reference can be reparameterized using coupling ratios.

$$\kappa_{gZ} = \frac{\kappa_g \cdot \kappa_Z}{\kappa_H}$$ parameterize the $gg \to H \to ZZ$ rate

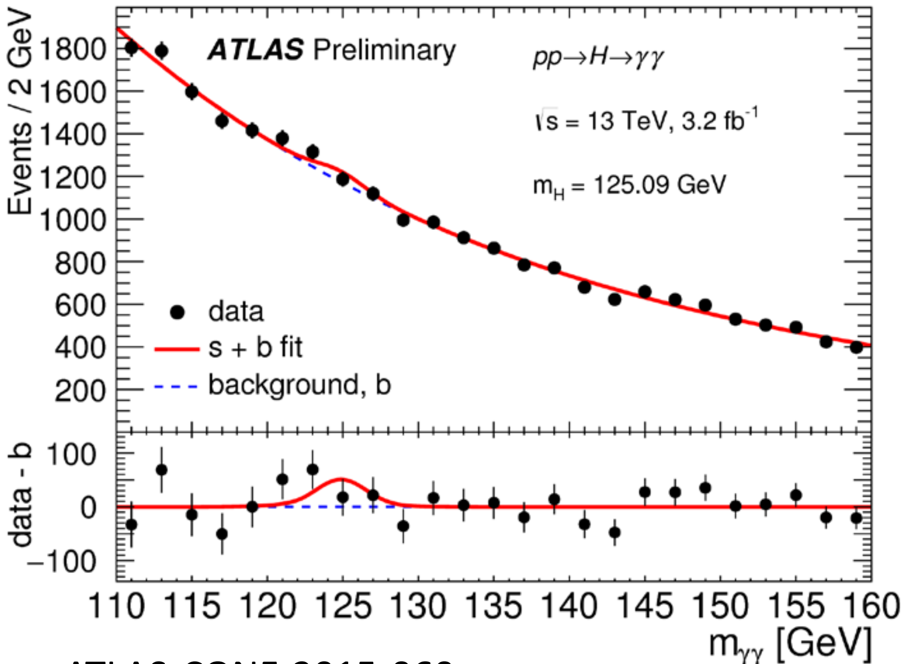
6 coupling ratios:

$$\lambda_{Zg} = \kappa_Z / \kappa_g\ ,$$
$$\lambda_{WZ} = \kappa_W / \kappa_Z\ ,$$
$$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z\ ,$$
$$\lambda_{\tau Z} = \kappa_\tau / \kappa_Z\ ,$$
$$\lambda_{bZ} = \kappa_b / \kappa_Z\ ,$$
$$\lambda_{tg} = \kappa_t / \kappa_g \ \left(\lambda_{tZ} \cdot \lambda_{Zg} \right)$$

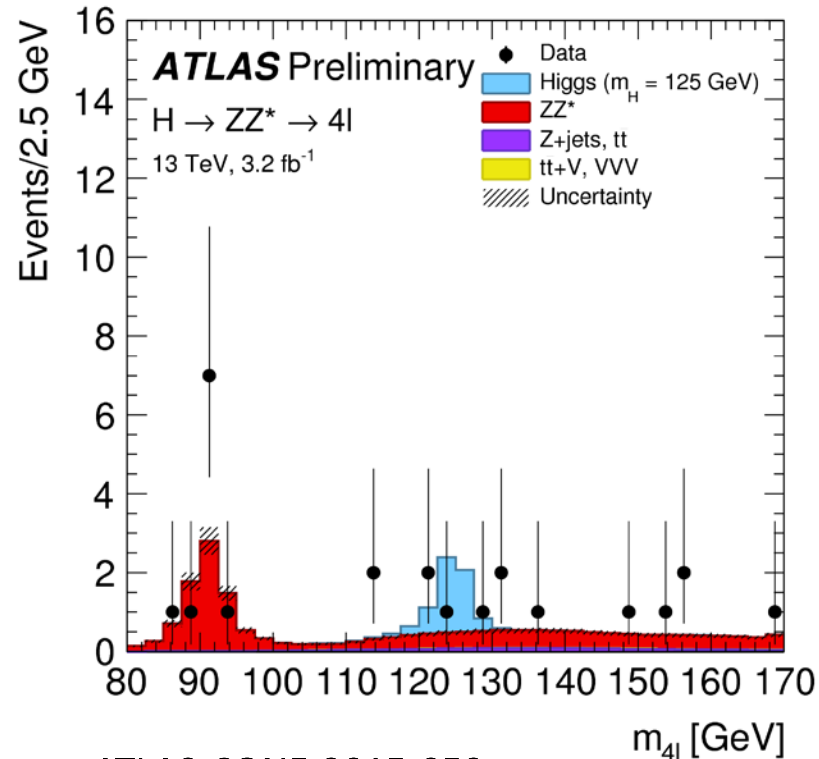


(ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)

First 13 TeV Results (2015)



ATLAS-CONF-2015-060



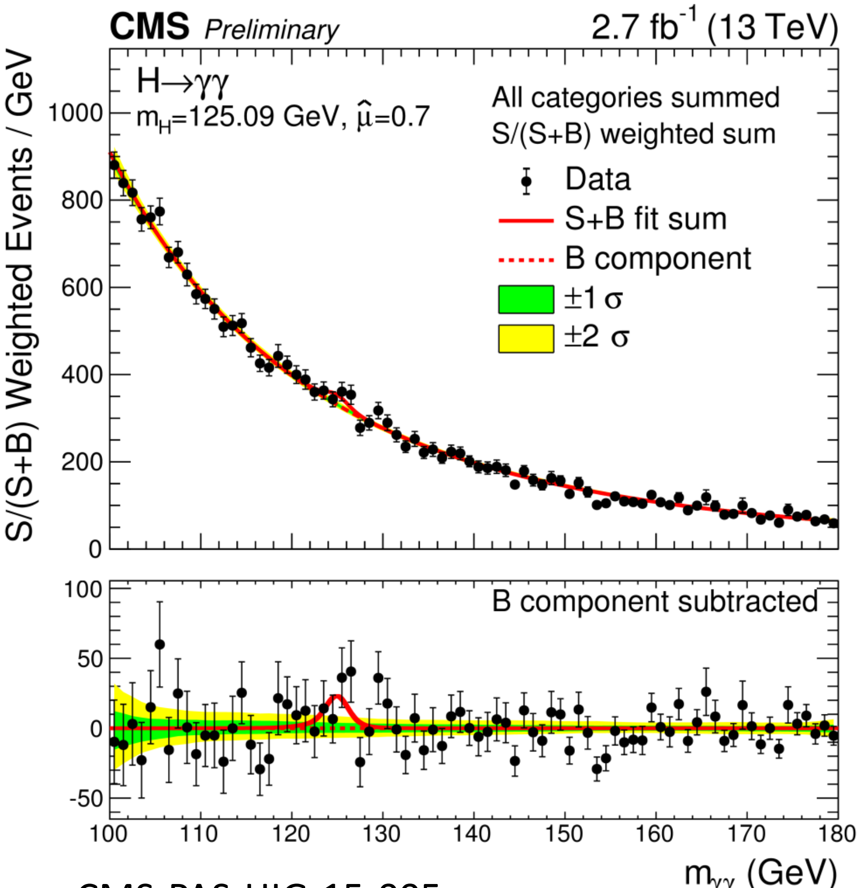
ATLAS-CONF-2015-059

$$\sigma = 40 \pm 26(\text{stat.})^{+16}_{-10}(\text{syst.}) \pm 2(\text{lumi.})\ \text{pb} \qquad \sigma = 12^{+25}_{-16}\ \text{pb}$$

$$\left[\text{SM prediction:}\quad \sigma = 50.9^{+4.5}_{-4.4}\ \text{pb @ 125.09 GeV}\right]$$

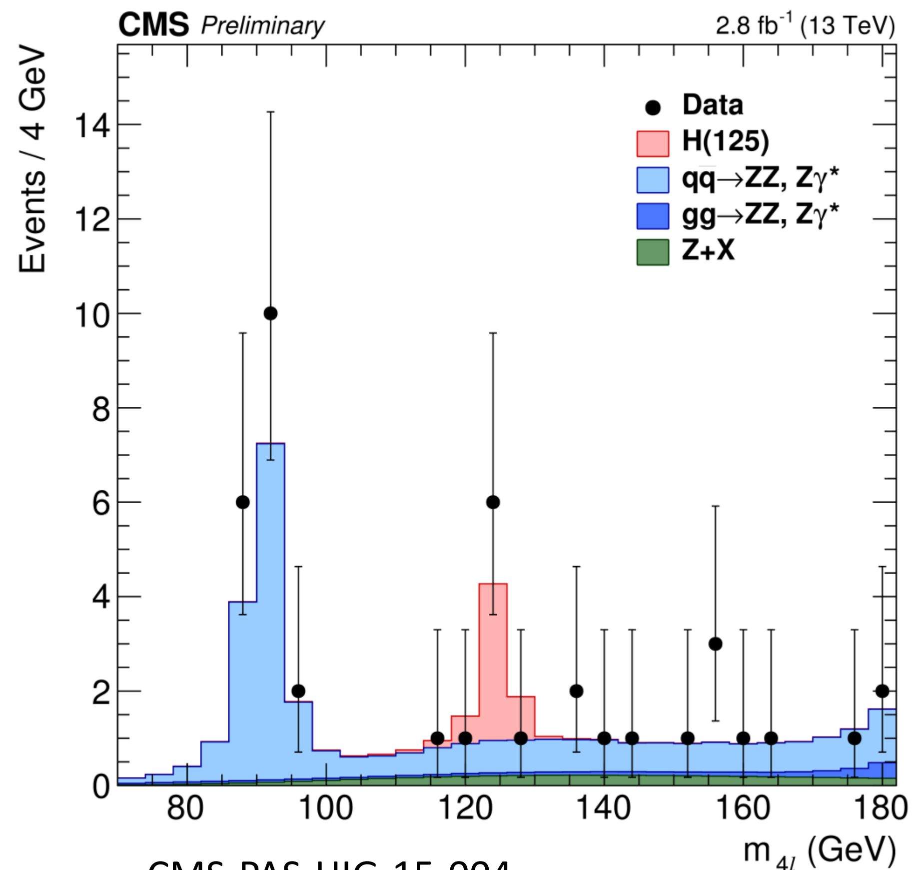
The Higgs signal is yet to be established…

First 13 TeV Results (2015)



CMS-PAS-HIG-15-005

$$\mu = 0.69^{+0.47}_{-0.42}$$

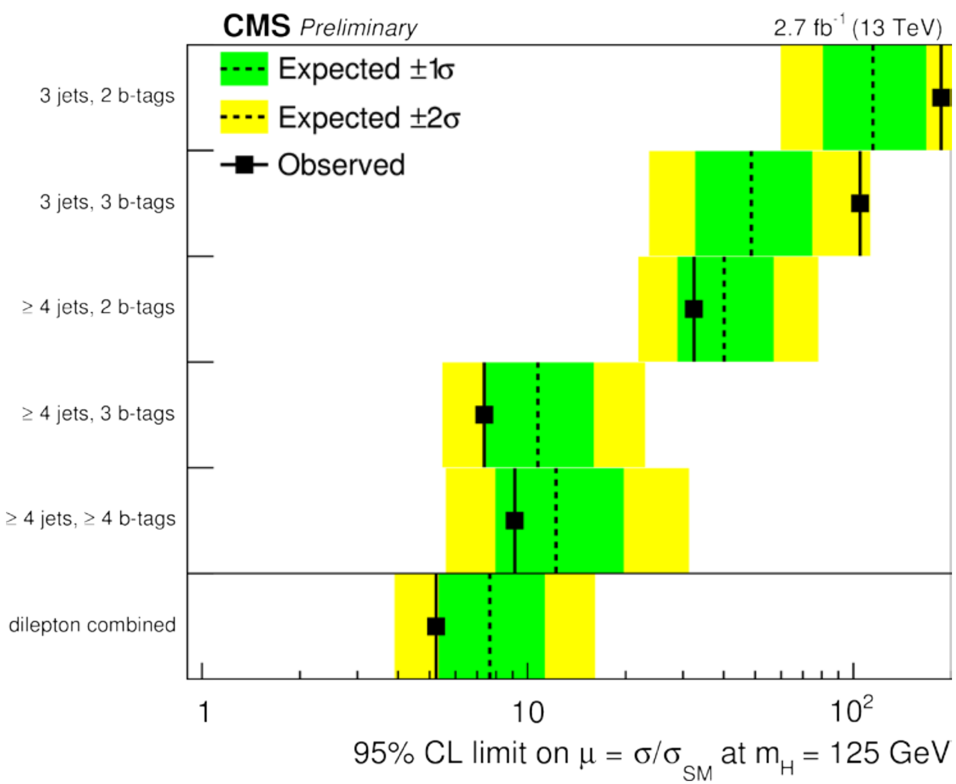


CMS-PAS-HIG-15-004

$$\mu = 0.82^{+0.57}_{-0.43}$$

First 13 TeV Results (2015)

ttH with $H \rightarrow bb$

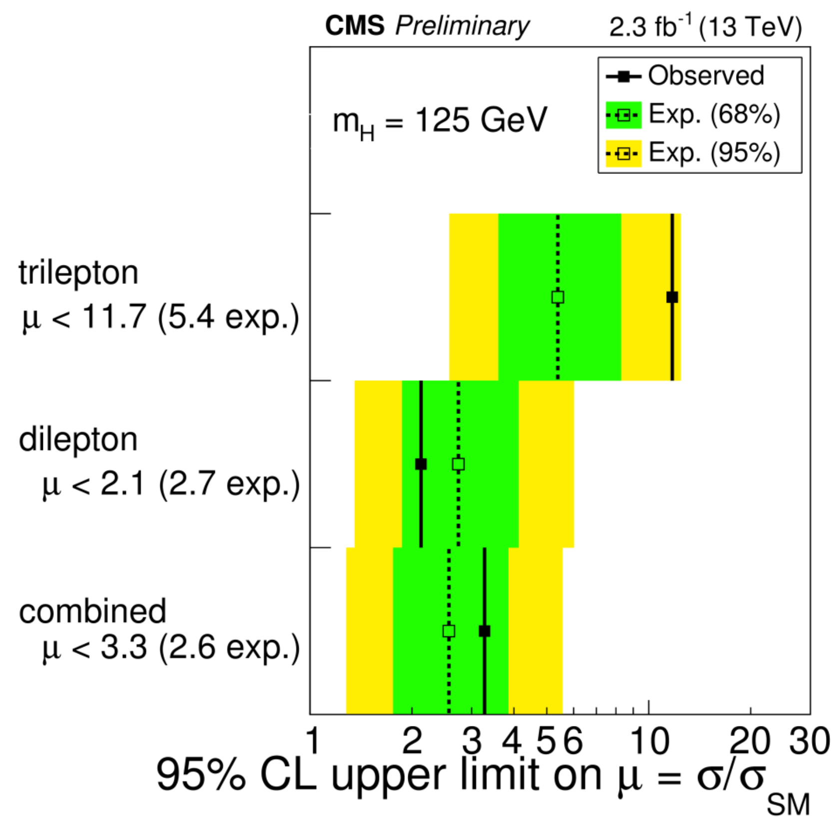


$$\mu = -2.0 \pm 1.8$$

$$\left[\mu < 2.6(3.6) \text{ @ } 95\% \text{ CL}\right]$$

CMS-PAS-HIG-16-004

ttH with $H \rightarrow multi\text{-}\ell\text{'s}$



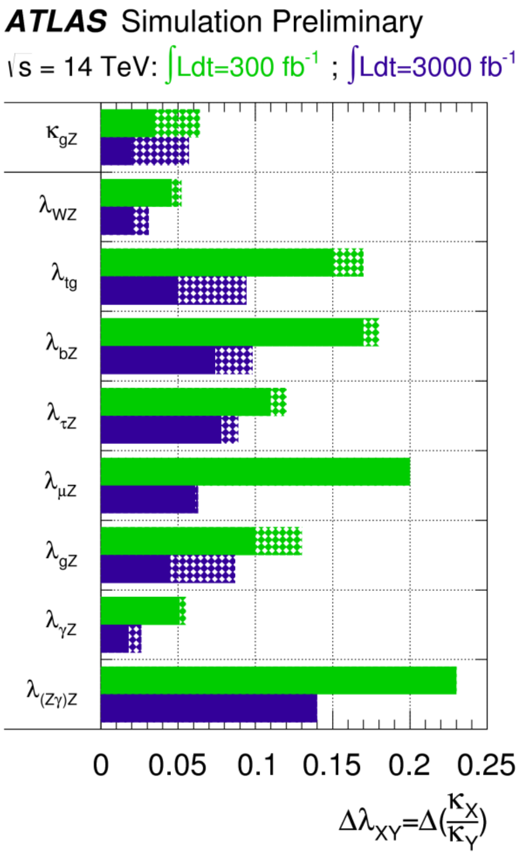
$$\mu = 0.6^{+1.4}_{-1.1}$$

$$\left[\mu < 3.3(2.6) \text{ @ } 95\% \text{ CL}\right]$$

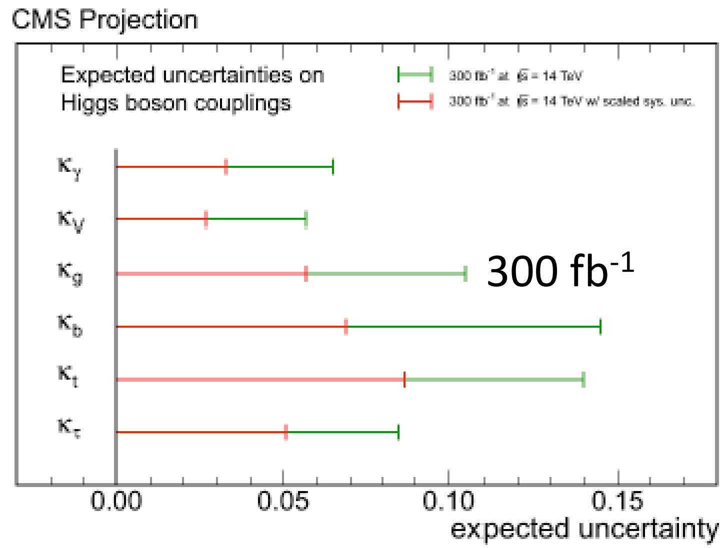
CMS-PAS-HIG-15-008

Coupling Projections

Many studies done for US Snowmass process, Europe ECFA studies, and for the detector upgrades



ATL-PHYS-PUB-2014-016



arXiv:1307.7135 (CMS)

(Extrapolated from 2011/2012 results)

Two assumptions on systematics:

1. no change
2. $\Delta(\text{theory})/2$, rest $\propto 1/\sqrt{Lumi}$

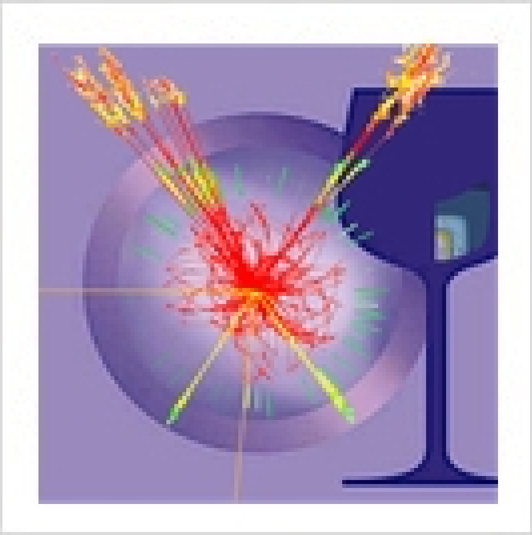
At HL-LHC, a precision of ~ 5% is expected for some coupling modifiers, ratios between some of them can be measured with better precisions.

Summary

All measurements at 7 and 8 TeV suggest that the 125 GeV particle is a SM-like Higgs boson. It's major couplings to SM particles have been measured with precisions of ~15%.

There are, however, a few "anomalies" in the measurements that only more data can ascertain their origins. The Higgs boson has opened a new window for testing SM and for searching for BSM physics.

If it smells like wine, tastes like wine, it probably is wine. But it remains to be seen whether it is French or Spanish wine…



ATLAS and CMS Individual Measurements

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