Higgs Boson coupling measurements at the LHC

First release of ATLAS + CMS Higgs coupling combination

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LHCP 2015

St. Petersburg, Russia Aug 30th – Sep 5th 2015

Outline

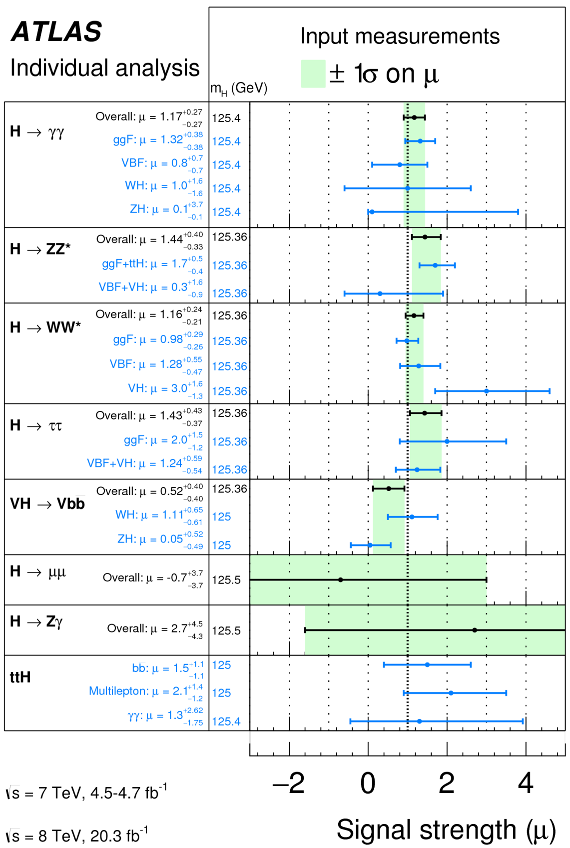
- Introduction
- Mass measurement
- Production, decay and couplings
  - Signal strengths
  - Coupling modifiers and κ-framework
  - Generic parameterizations
- Conclusions

ATLAS and CMS individual combinations

ATLAS

Mass: *Phys. Rev. Lett. 114, 191803*

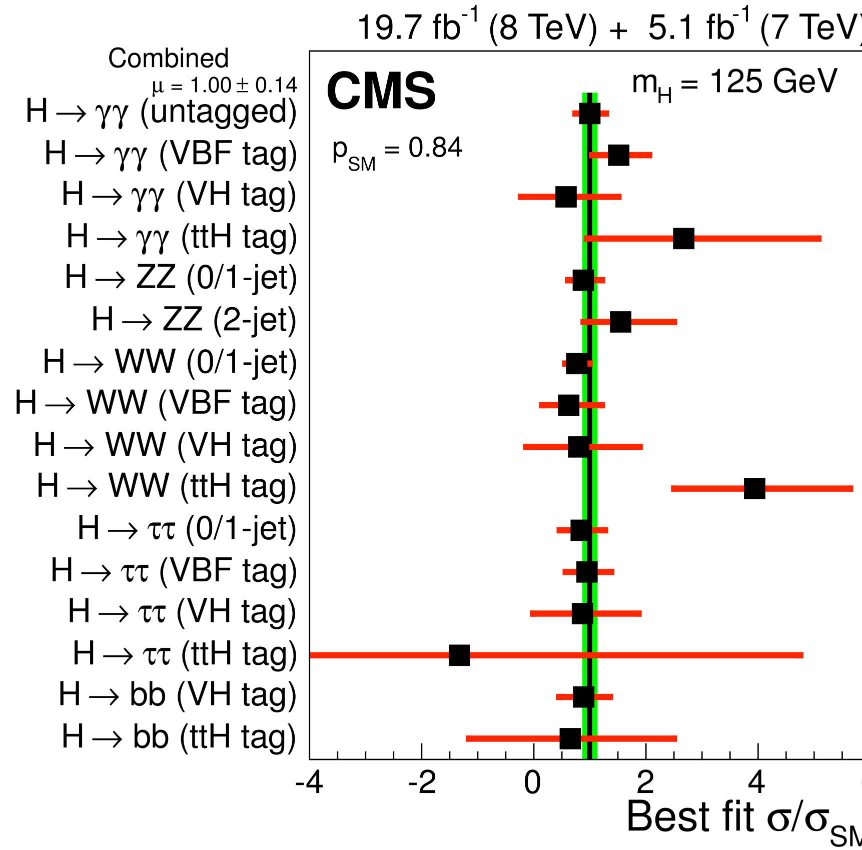
Couplings: **arXiv:1507.04548**



CMS

Mass and couplings:

Eur. Phys. J. C 75 (2015) 212

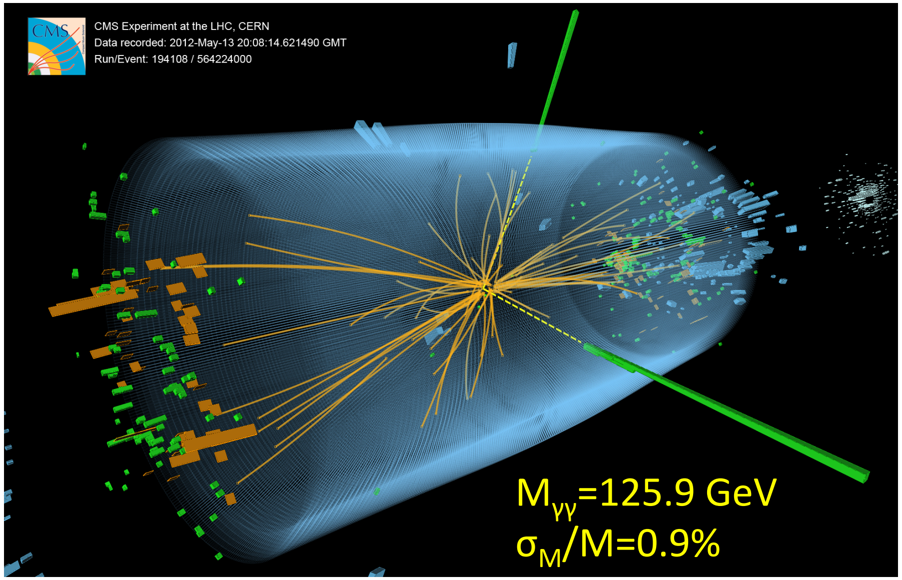


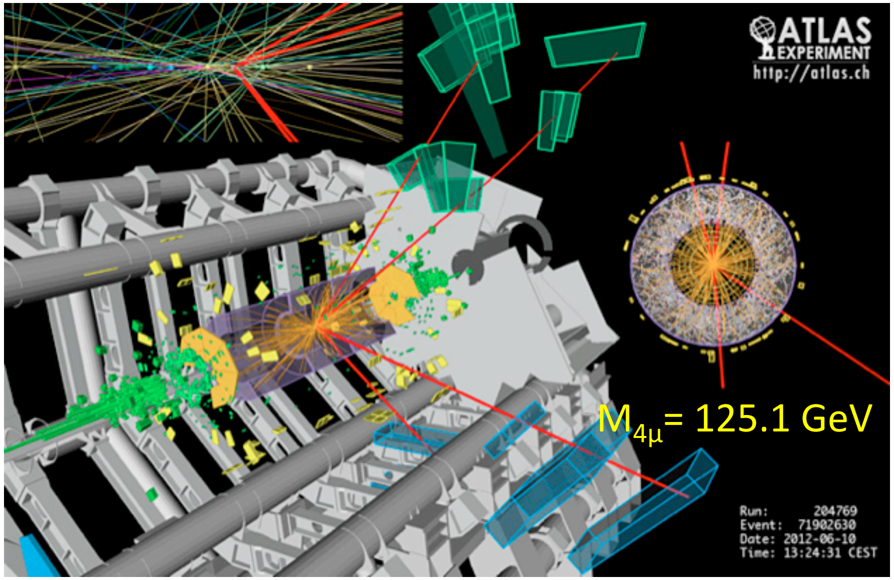
All results are based on the LHC pp collision Run 1 data:
~5 fb^{-1} at 7 TeV (2011) + ~20 fb^{-1} at 8 TeV (2012) per experiment

Higgs boson mass measurement

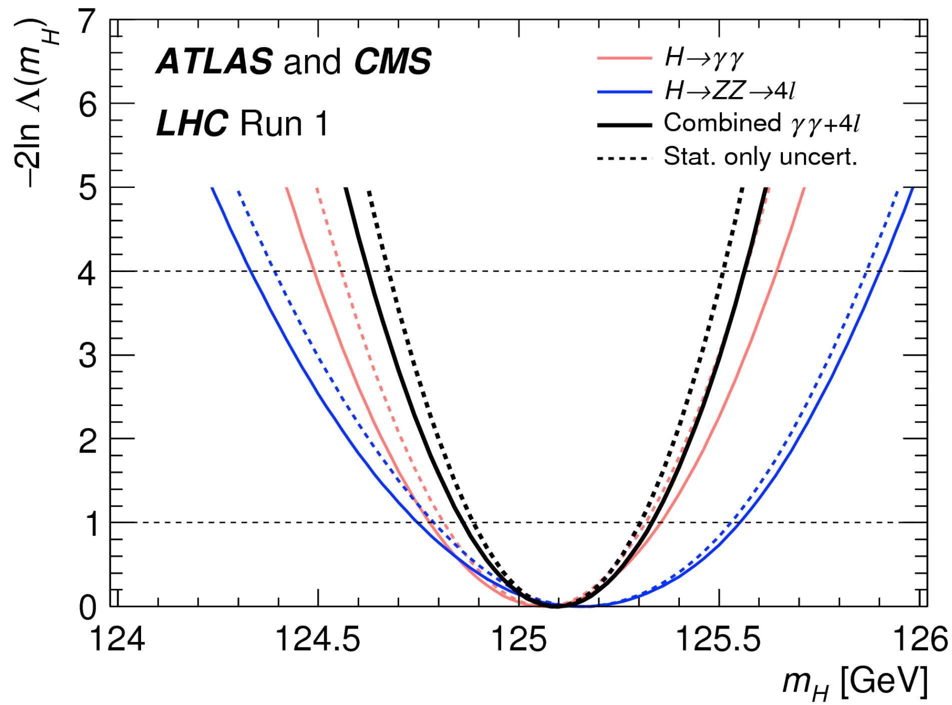
- First step is the measurement of the Higgs boson mass
- SM cross sections and decay BRs depend on the mass
- The mass is measured using high resolution $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$

See talk of Manuela Venturi (Monday)





1D scan

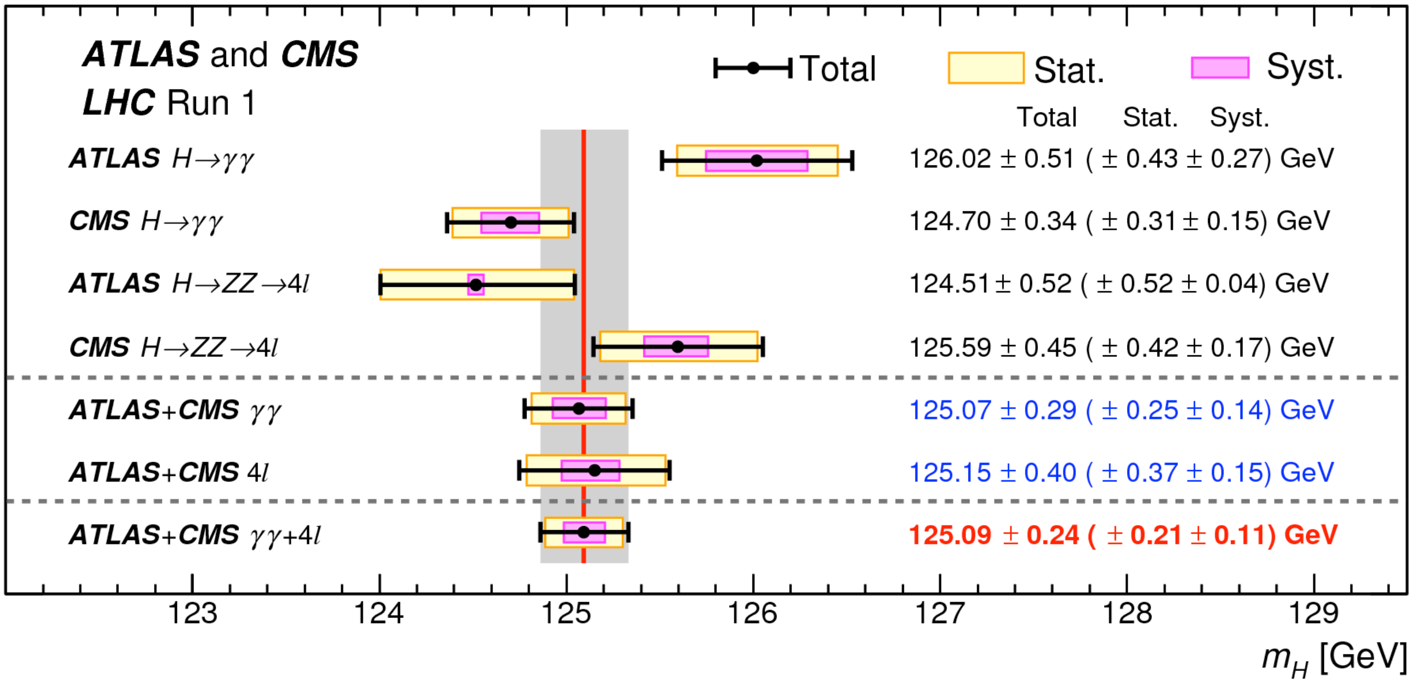


$M_H = 125.09 \pm 0.24$ GeV

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

Measurement in the individual channels

Mass is measured with high precision channels γγ and ZZ→4l



Some tension between the four measurements (p-value ~10%) and opposite in ATLAS and CMS - very good agreement in the central values

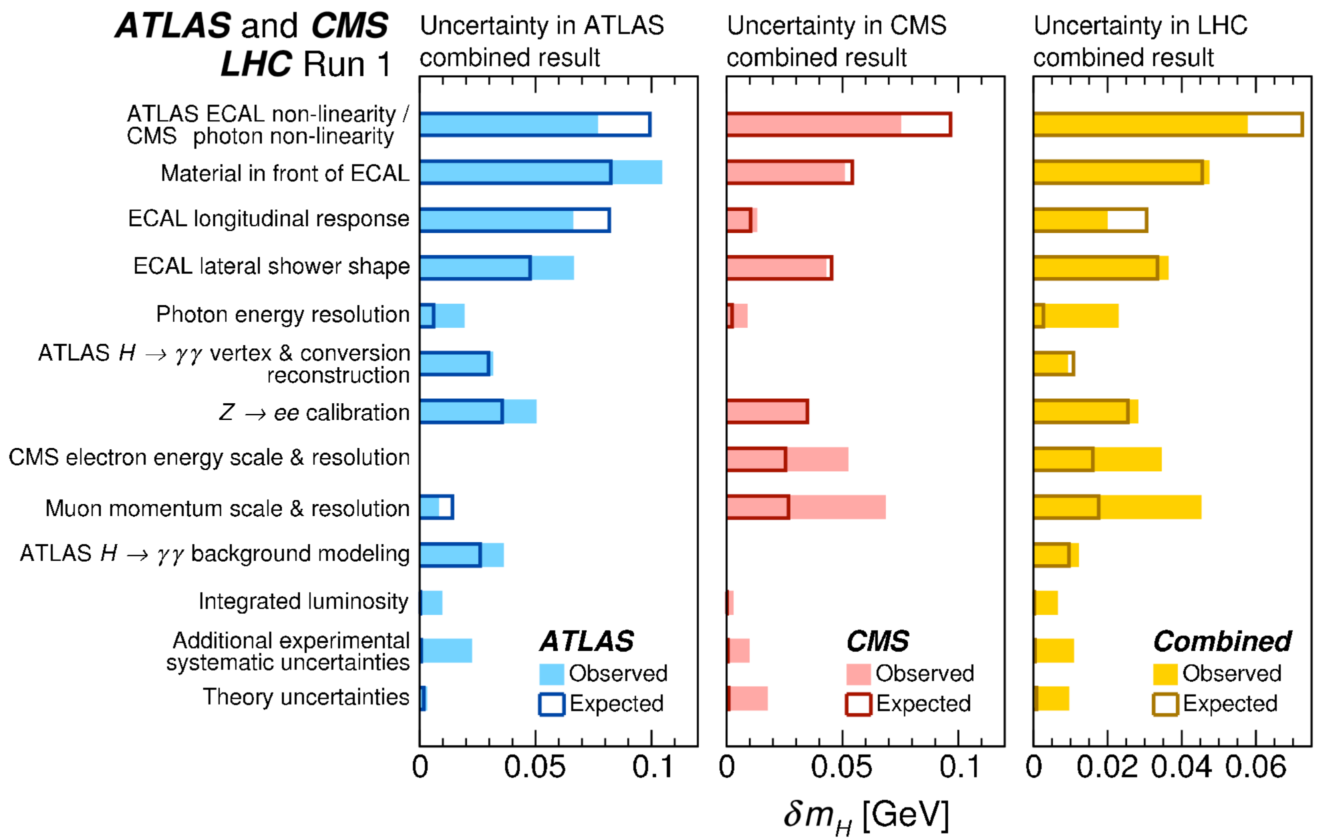
$$m_H^{\gamma\gamma} = 125.07 \pm 0.29 \text{ GeV}$$
$$= 125.07 \pm 0.25 \,(\text{stat.}) \pm 0.14 \,(\text{syst.}) \text{ GeV}$$

$$m_H^{4\ell} = 125.15 \pm 0.40 \text{ GeV}$$
$$= 125.15 \pm 0.37 \,(\text{stat.}) \pm 0.15 \,(\text{syst.}) \text{ GeV}$$

Systematic uncertainties

- Mass combination set the basis for coupling combination
- Systematic uncertainties were studied carefully in preparation for couplings even if currently much smaller than statistical uncertainties for mass

Energy scale uncertainties are the most important in the combination



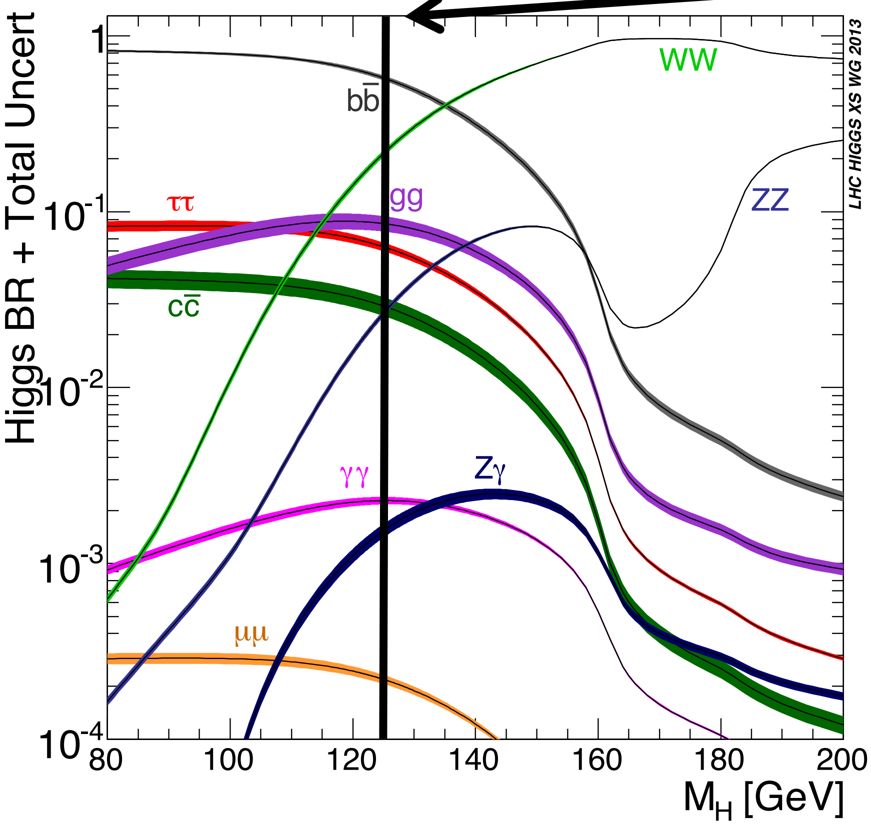
Coupling combination

- ATLAS and CMS results are combined for the measurement of the Higgs boson production and decay rates and tests of its couplings
- Gain a factor √2=1.4 in precision (still statistics limited, also for many syst. uncertainties)
- All results are compared to the Standard Model (SM) predictions

CONF Note/PAS:
- ATLAS-CONF-2015-044
- CMS-PAS-HIG-15-002

SM Higgs boson decays

m_H=125.09 GeV



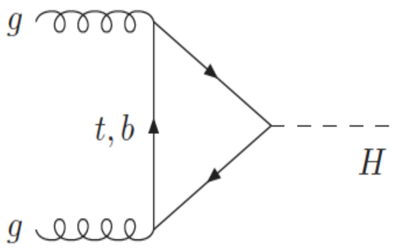
Decay channel	Branching ratio [%]
$H \rightarrow b\bar{b}$	57.5 ± 1.9
$H \rightarrow WW$	21.6 ± 0.9
$H \rightarrow gg$	8.56 ± 0.86
$H \rightarrow \tau\tau$	6.30 ± 0.36
$H \rightarrow c\bar{c}$	2.90 ± 0.35
$H \rightarrow ZZ$	2.67 ± 0.11
$H \rightarrow \gamma\gamma$	0.228 ± 0.011
$H \rightarrow Z\gamma$	0.155 ± 0.014
$H \rightarrow \mu\mu$	0.022 ± 0.001

SM BR theory uncertainties 2-5% for most important ones

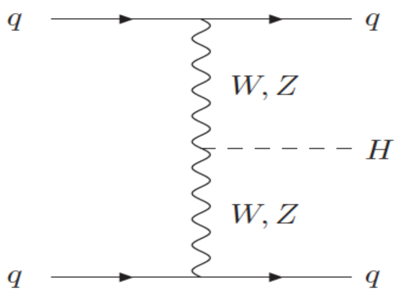
The natural width of the Higgs boson is expected to be very small, 4.1 MeV (<< resolution)

Main production processes

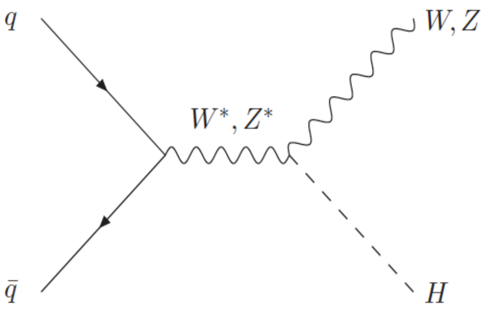
ggH



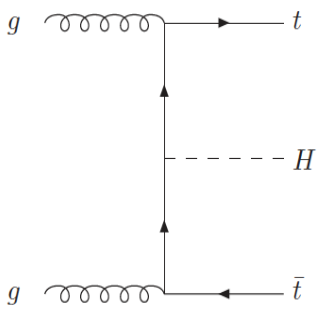
VBF

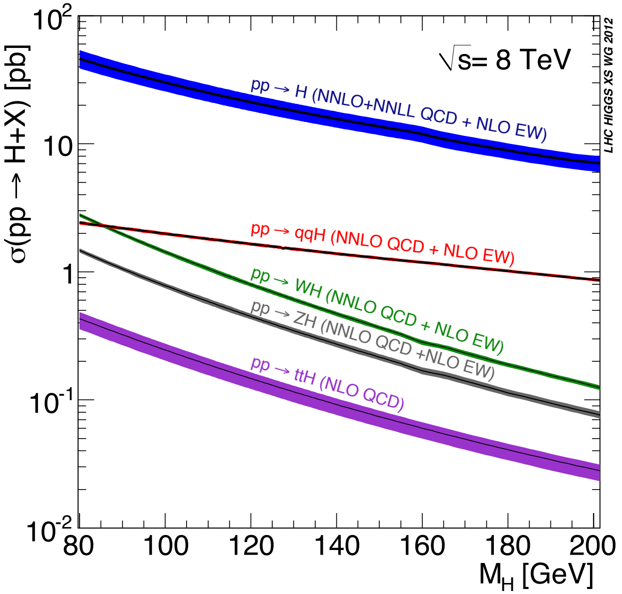


VH



ttH



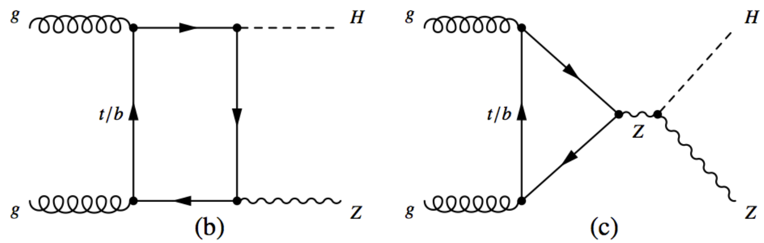


Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+APP.NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.357 ± 0.015	0.446 ± 0.019	NNLO(QCD)+NLO(EW)
ZH: $gg \to ZH$			LO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NLO(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	

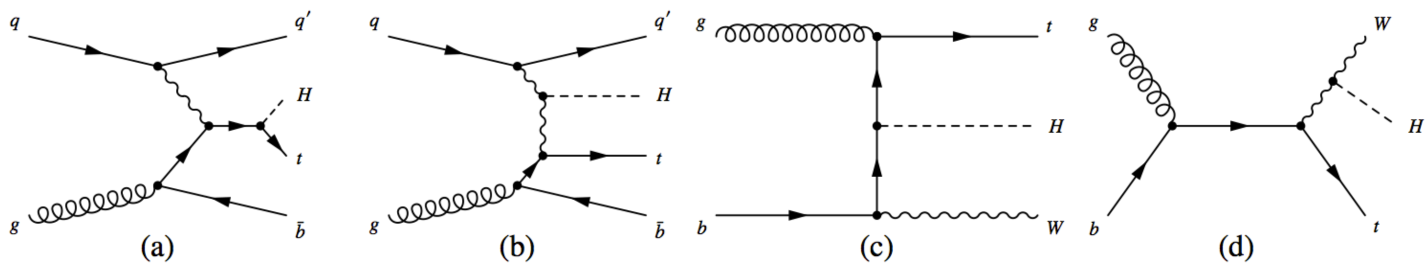
SM ggF, ttH, bbH theory uncertainty: ~10%
VBF, VH, ZH: 2-3%

Other production processes

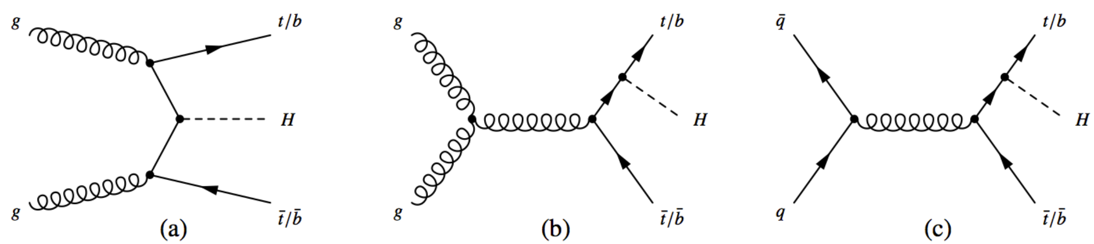
- ggZH:
  - O(10%) effect on VHbb in SM, higher p_T than qqZH



- tHq + tHW
  - Not really sensitive but has larger effects for negative couplings



- bbH
  - Similar to ttH but not really distinguishable from ggF



Input channels for the combination

Mainly ggF

Decay / Production	**Untagged**	**VBF**	**VH**	**ttH**
H→γγ	■	■	■	■
H→ZZ→4l	■	■	■	■
H→WW→2l2ν	■	■	■	■
H→ττ	■	■	■	■
H→bb			■	■
H→μμ	■	■		

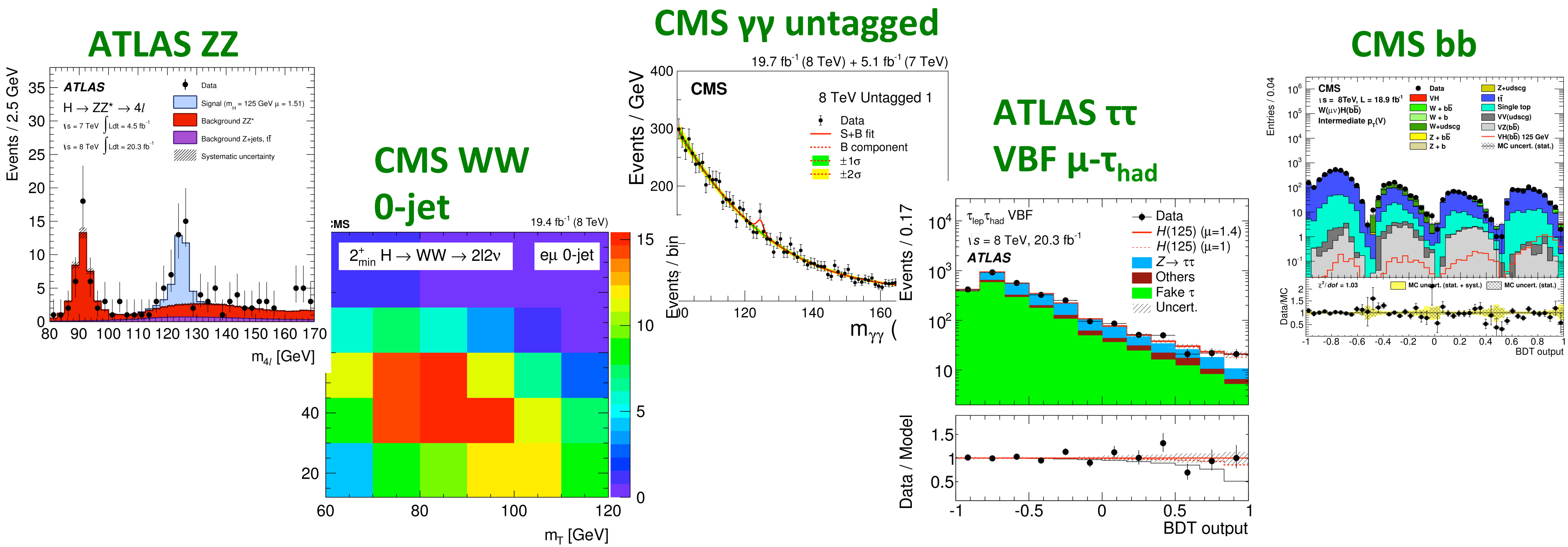
■ Combined

- Other production modes included in the fit and selected by other channels but not specifically tagged
  For example tHq and tHW are selected by the ttH analyses

- All these channels are directly sensitive to the couplings of the Higgs boson to W, Z and γ bosons and to τ, b and t fermions
  + indirectly to gluons and t-quarks

Categories addressing production and decays

- Many different final discriminant distributions combined



- Purity varies between categories (especially for production modes)
- A total of O(100) categories for each experiment are combined

Signal yield

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

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

L: integrated luminosity,
A: acceptance,
E: efficiency

Statistical treatment

- Profile likelihood ratio test statistics:

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

  - for each likelihood evaluation, all systematic uncertainties (**nuisances**) are varied to maximize the profile likelihood (**profiled**)
- ~4200 nuisances in the combined fits
  - A large part related to the finite MC statistics
  - Signal theory normalization uncertainties
  - BG theory uncertainties (for BGs not using the data)
  - Other experimental uncertainties
- Most experimental uncertainties are assumed uncorrelated between the two experiments and many tests have been carried out to check the possible impact that was found negligible
- Main correlated systematic uncertainties are the cross sections and BRs between ATLAS and CMS: QCD scale uncertainties and PDF
  - Theory cross sections and BR, Higgs p_T, … state-of-the art calculations in common between the two experiments for this analysis

Measurements, compatibility tests

- Different measurement and compatibility tests are carried out (described here):
  - Fits of signal strengths μ – σ, BR relative to SM
  - Fits in the κ-framework – coupling modifiers
  - Generic fits (based on XS and BR, and on coupling modifier ratios)
- All of them assume a SM-like Higgs boson Spin Parity 0^+ and with a narrow width such that production and decay are decoupled

See talk of Kerstin Tackmann today

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

- Results are rigorously valid on for small deviations from this hypothesis but larger differences would be detected
- At the LHC we can only measure σxBR need further assumptions to extract σ or BR independently

Signal strengths μ

- μ is the so called signal strength (μ=1 in the SM)
- $\mu_i = \frac{\sigma_i}{\sigma_i^{SM}}$ and $\mu^f = \frac{BR^f}{BR^f_{SM}}.$ $\mu_i^f \equiv \frac{\sigma_i \cdot BR^f}{(\sigma_i \cdot BR^f)_{SM}} = \mu_i \times \mu^f$
- Most constrained parameterization: one single signal strength μ (and assuming the same at 7 and 8 TeV)

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

- Expected uncertainties very similar to observed
- Signal theory uncertainty due to QCD scale and PDF as large as statistical uncertainty. Being reduced from the theory side

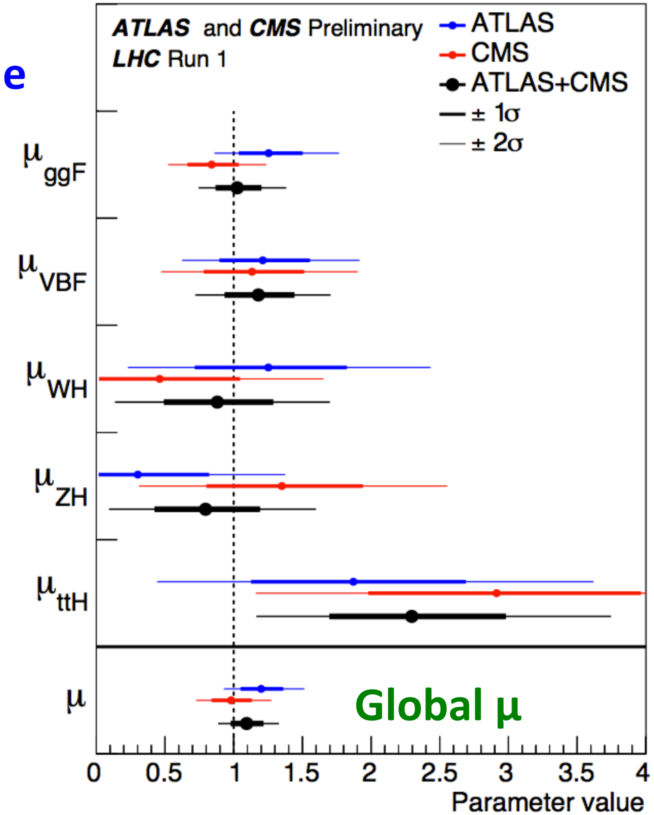
See talk of Alessandro Vicini (Monday)

All other measurement still dominated by statistical uncertainties

Signal strength μ: production, decay

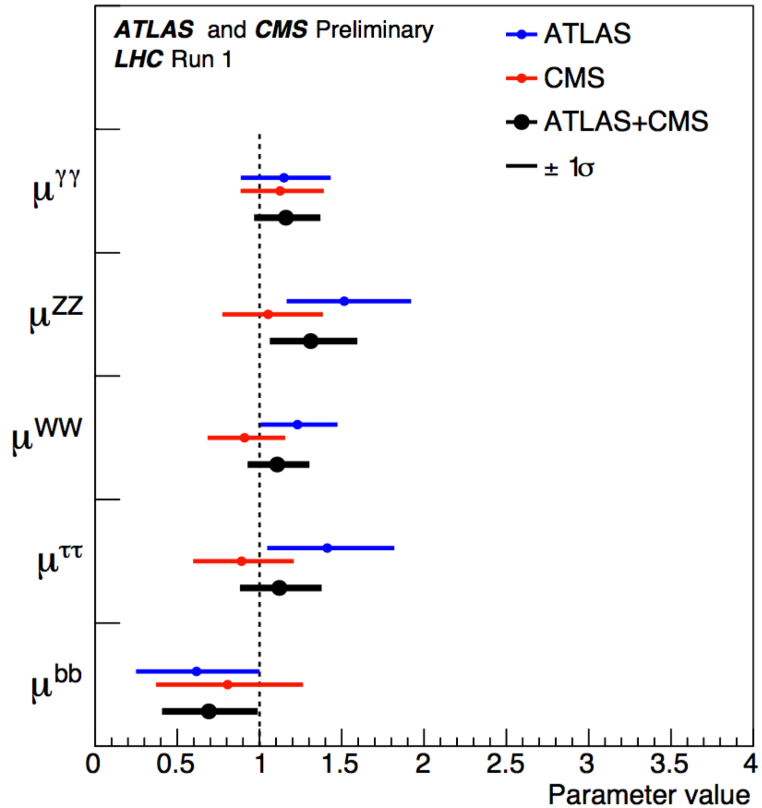
SM p-value 25%

SM BRs assumed



Global μ

SM production σ assumed



SM p-value 60%

- Signal strengths in different channels are consistent with 1 (SM)
- Largest difference in ttH: 2.3σ excess with respect to SM

Significance in the different channels

- Comparing likelihood of the best-fit with μ_{prod}=0 and μ^{decay}=0 we obtain:

Production process	Observed 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→ττ	**5.5**	**5.0**
H→bb	2.6	3.7

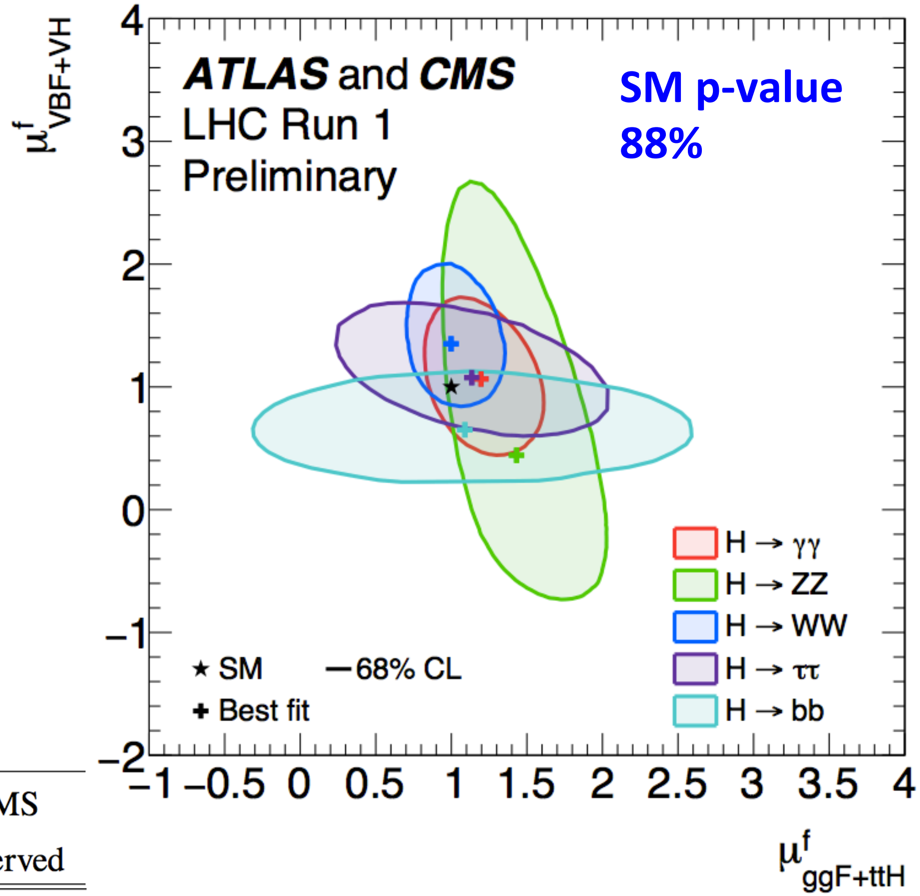
- Combination largely increases the sensitivity

VBF and H→ττ now established at over 5 σ. Same as ggF and H→ZZ, γγ, WW from single experiments

μ_V vs μ_F

- Can also fit μ_V^f vs μ_F^f per decay:
  - $\mu_V^f = \mu^f_{VBF+VH}$
  - $\mu_F^f = \mu^f_{ggF+ttH}$
- μ_{V}/μ_f can be measured in the different decay channels and combined:

$$\mu_{V}/\mu_f = 1.06^{+0.35}_{-0.27}$$



Parameter	ATLAS+CMS observed	ATLAS+CMS expected unc.	ATLAS observed	CMS observed
μ_V/μ_F	$1.06^{+0.35}_{-0.27}$	$^{+0.34}_{-0.26}$	$0.91^{+0.41}_{-0.30}$	$1.29^{+0.67}_{-0.46}$
$\mu_F^{\gamma\gamma}$	$1.13^{+0.24}_{-0.21}$	$^{+0.21}_{-0.19}$	$1.18^{+0.33}_{-0.29}$	$1.03^{+0.30}_{-0.26}$
μ_F^{ZZ}	$1.29^{+0.29}_{-0.25}$	$^{+0.24}_{-0.20}$	$1.54^{+0.44}_{-0.36}$	$1.00^{+0.33}_{-0.27}$
μ_F^{WW}	$1.08^{+0.22}_{-0.19}$	$^{+0.19}_{-0.17}$	$1.26^{+0.29}_{-0.25}$	$0.85^{+0.25}_{-0.22}$
$\mu_F^{\tau\tau}$	$1.07^{+0.35}_{-0.28}$	$^{+0.32}_{-0.27}$	$1.50^{+0.66}_{-0.49}$	$0.75^{+0.39}_{-0.29}$
$\mu_F^{b\bar{b}}$	$0.65^{+0.37}_{-0.28}$	$^{+0.45}_{-0.34}$	$0.67^{+0.58}_{-0.42}$	$0.64^{+0.54}_{-0.36}$

SM p-value 62%

κ-framework

- The k-framework has been developed within the LHC Higgs Cross Section WG
- Higgs boson couplings are scaled by coupling modifiers κ
- The definition is such that:

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

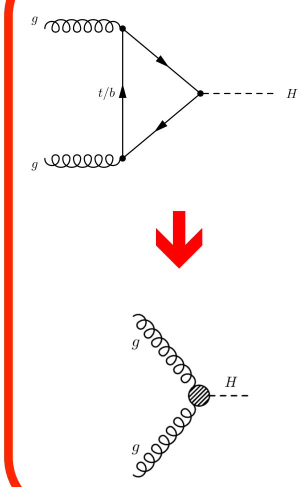
$$\kappa_H^2 = \sum_j \mathrm{BR}^j_{\mathrm{SM}} \kappa_j^2 \qquad \Gamma_{\mathrm{H}} = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

- With $\mathrm{BR}_{\mathrm{BSM}}$ the BR of invisible + undetected decays
  - Undetected decays can be either non SM decays or come from different BRs of known but not measured decays: cc, gg, …

If New Physics lower than $m_H/2$, $\mathrm{BR}_{\mathrm{BSM}}$ could be affected
If above $m_H/2$, effective couplings of the loops would be modified

Scaling of σ's and BR's with κ's

- Loops can be resolved or parameterized with **an effective κ**
  - No effective couplings for ggZH and tH because of the limited sensitivity

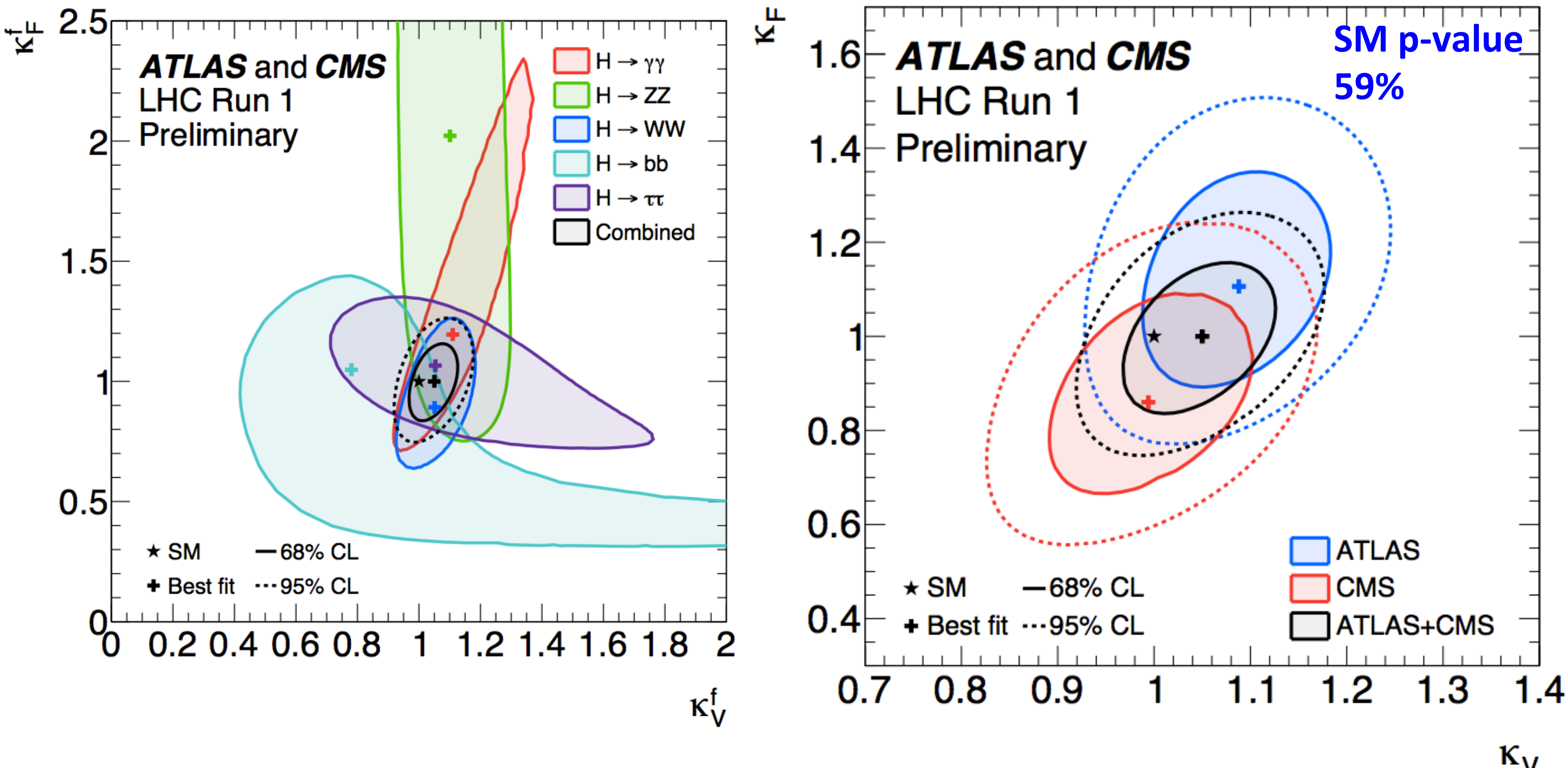


Production	Loops	Interference	Multiplicative factor
$\sigma(\text{ggF})$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\text{VBF})$	–	–	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim \kappa_W^2$
$\sigma(q\bar{q} \to ZH)$	–	–	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
$\sigma(ttH)$	–	–	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	–	$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq')$	–	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
Partial decay width			
$\Gamma_{b\bar{b}}$	–	–	$\sim \kappa_b^2$
Γ_{WW}	–	–	$\sim \kappa_W^2$
Γ_{ZZ}	–	–	$\sim \kappa_Z^2$
$\Gamma_{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
$\Gamma_{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
$\Gamma_{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
Total width for $\text{BR}_{\text{BSM}} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

- not measured κ's are scaled as similar ones: $\kappa_c=\kappa_t$, $\kappa_\mu=\kappa_\tau$, $\kappa_s=\kappa_b$

κ_V, κ_F contours

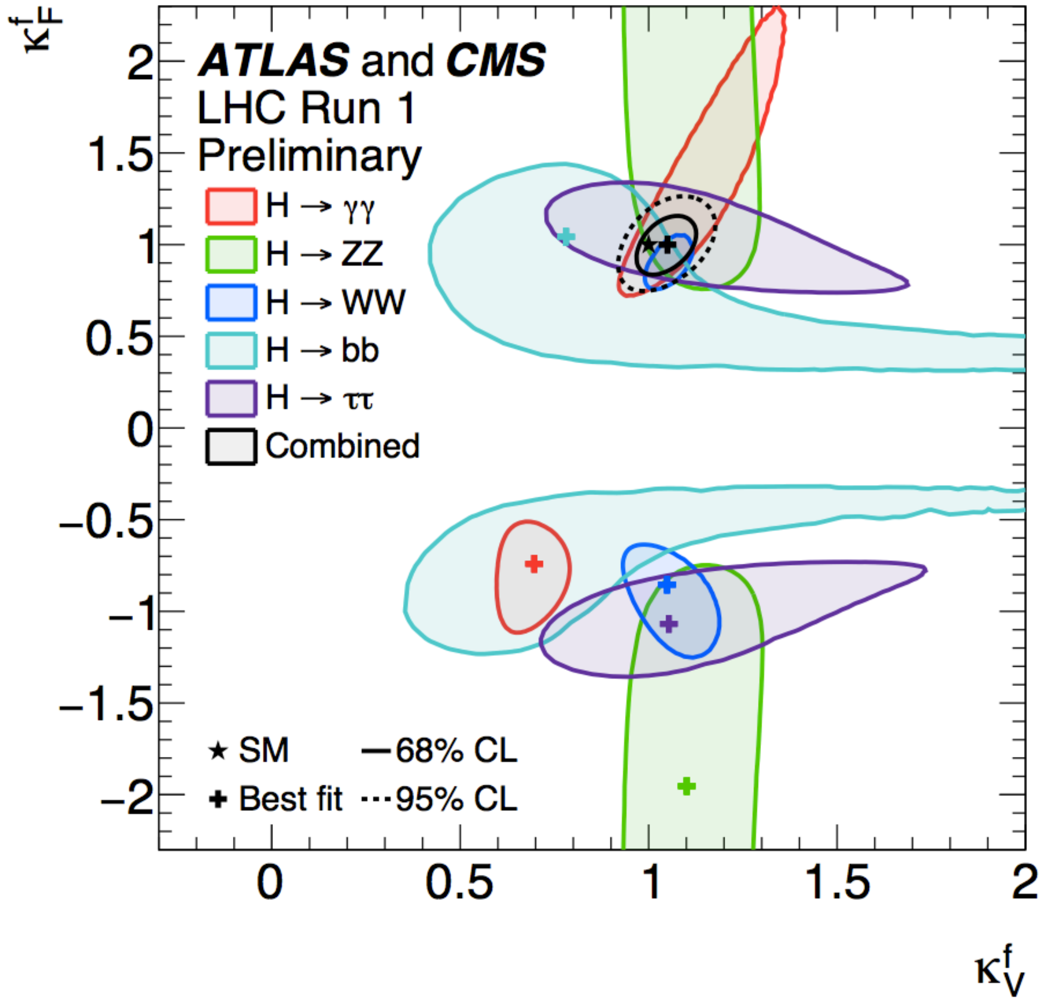
- All vector and fermion couplings are scaled by κ_V and κ_F



All results in agreement with SM ($\kappa_V = \kappa_f = 1$) within 1σ

κ_V, κ_F contours

- Negative couplings would change sign of interference

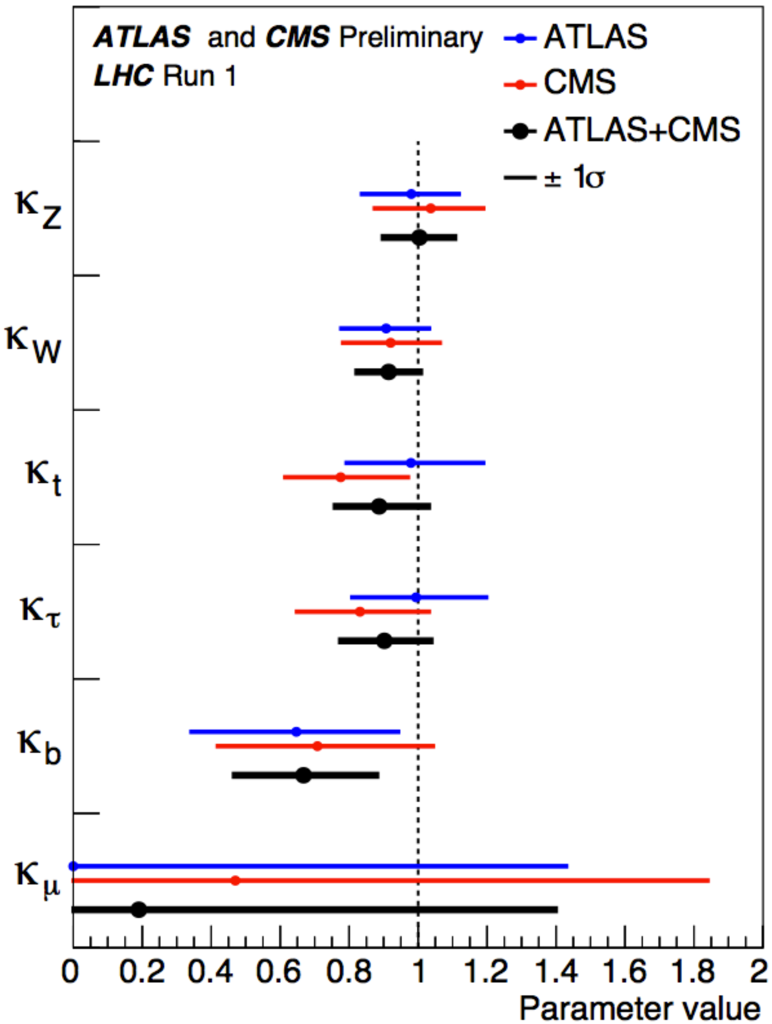


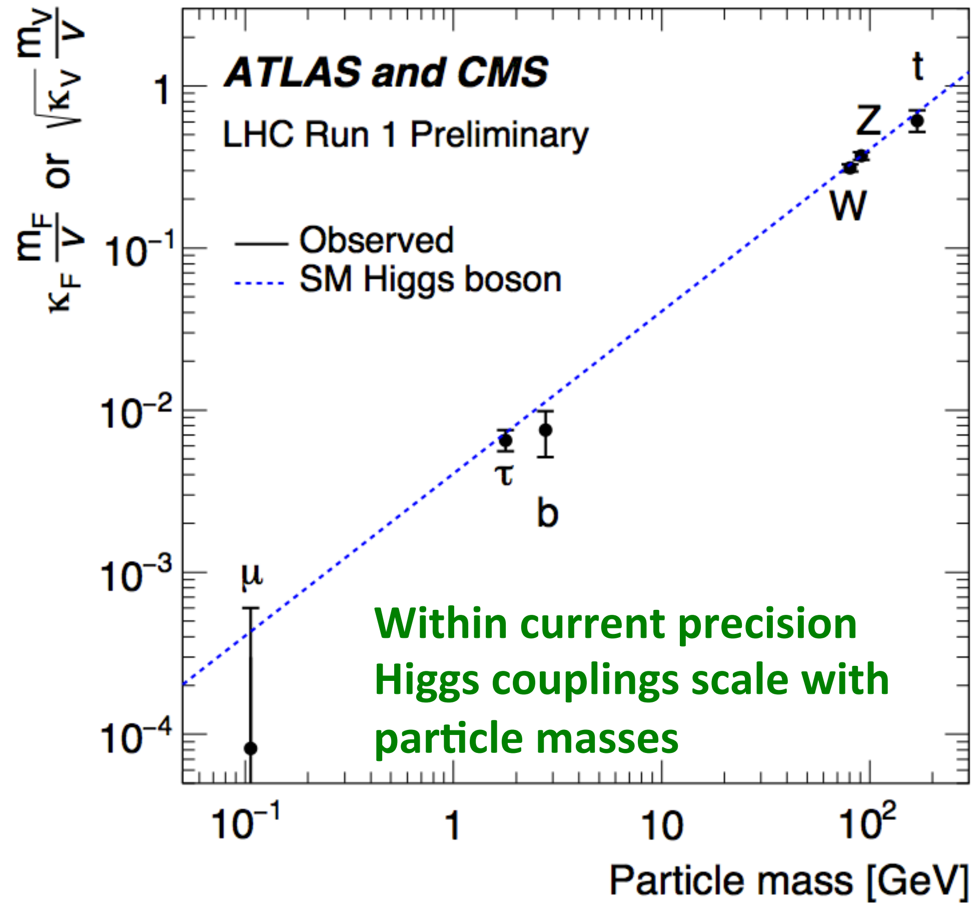
Almost 5σ exclusion of $\kappa_F<0$

- The other two quadrants are symmetric with respect to (0,0), all physical quantities only depend on a product of two κ's

No BSM in the loops

- Fitting the 5 main tree level coupling modifiers + κ_μ and resolving all the loops.



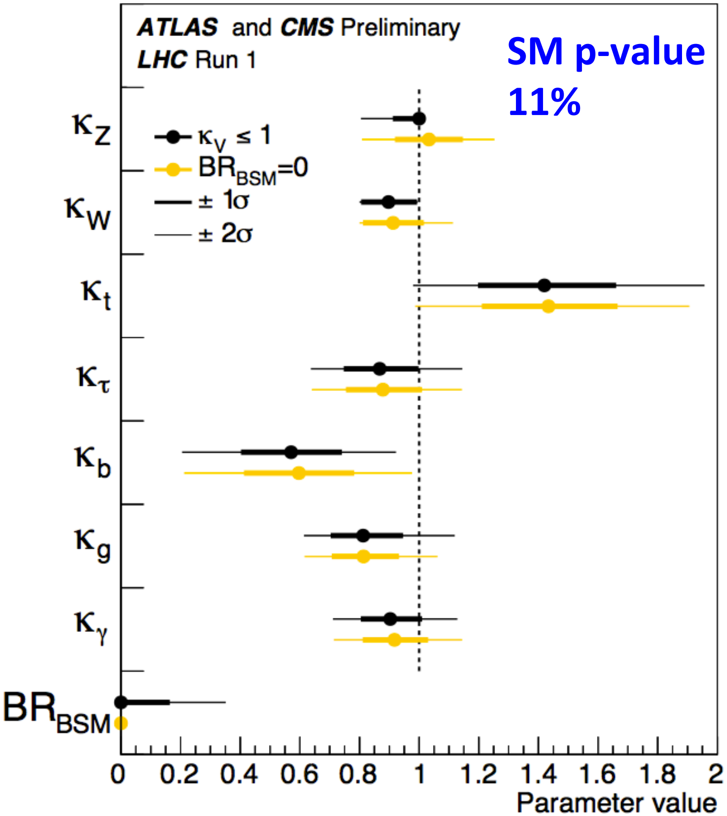


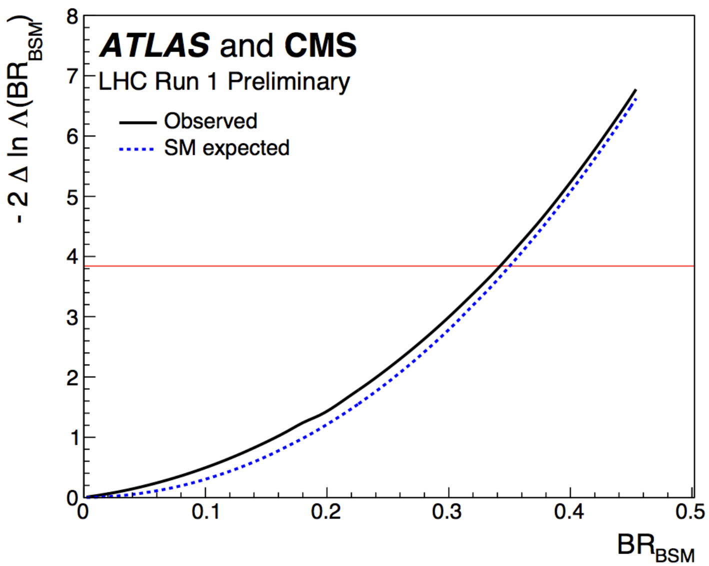
BSM physics in the loops

- We can also allow effective couplings κ_g and κ_γ
- Only σ x BRs can be measured, without further assumptions the width of the Higgs boson cannot be measured. Options are:
  - $BR_{BSM}=0$
  - kV≤1 (as in 2HDM) - BR_{BSM} can be measured

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

Constraints on the width:
Roberto di Nardo (yesterday)





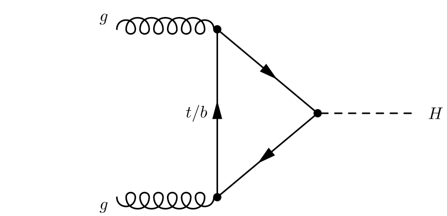
For constraints on BSM see:
Wouter Verkerke (Friday)

$BR_{BSM} < 0.34$ at 95% C.L. (assuming $\kappa_V \leq 1$)
BR_{BSM} includes all possible non standard decays, visible or invisible

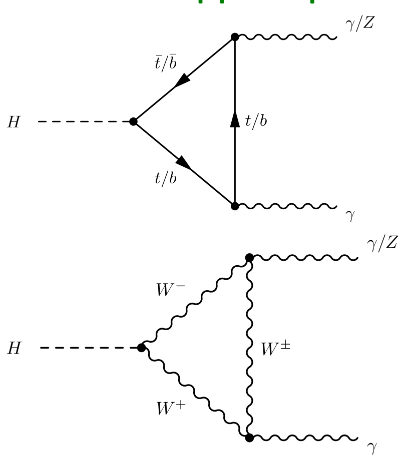
κ_g and κ_γ

- Assuming tree level couplings as in the SM and only modifications to the two main loops of ggF and H→γγ

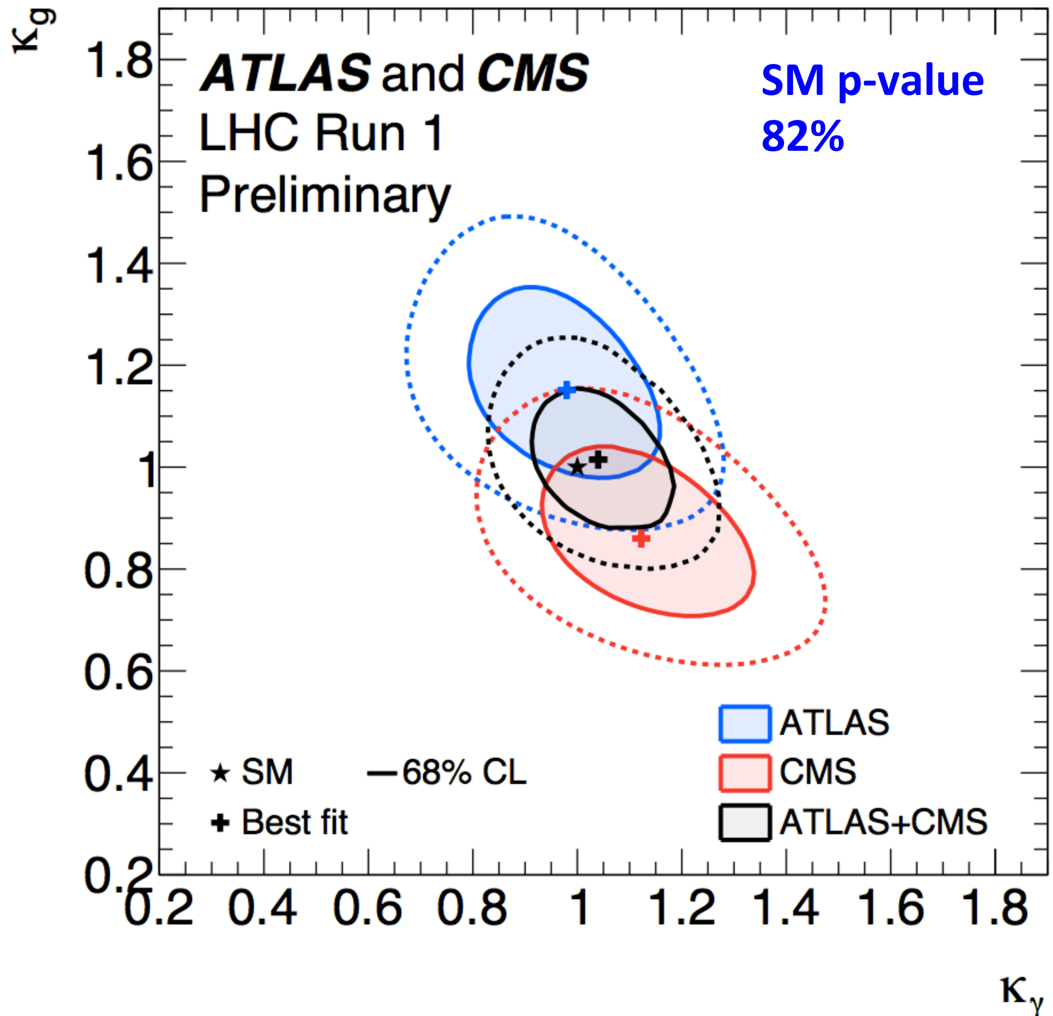
ggF loop



H→γγ loop



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



Up-down fermion and lepton-quark symmetries

No surprises, all found to be consistent with with 1

Parameter	ATLAS+CMS	
	observed	expected unc.
λ_{du}	$0.91^{+0.12}_{-0.11}$	$[-1.21, -0.92] \cup [0.87, 1.14]$
λ_{Vu}	$0.99^{+0.13}_{-0.12}$	$^{+0.20}_{-0.12}$
κ_{uu}	$1.09^{+0.22}_{-0.19}$	$^{+0.20}_{-0.27}$
λ_{lq}	$[-1.21, -0.92] \cup [0.92, 1.21]$	$[-1.16, -0.86] \cup [0.86, 1.16]$
λ_{Vq}	$1.09^{+0.14}_{-0.13}$	$^{+0.13}_{-0.11}$
κ_{qq}	$0.94^{+0.17}_{-0.15}$	$^{+0.18}_{-0.16}$

SM p-value 67%

SM p-value 78%

Most generic parameterizations used

- Not possible to disentangle production cross section from decay BR in a model-independent way
- It is instead possible to measure ratios of cross sections and BR or ratios of κ's ($\lambda_{ij} = \kappa_i/\kappa_j$)
- The two most generic parameterizations considered here refer to ggF, H→ZZ→4l that is the cleanest channel and less affected by systematic uncertainties

σ and BR ratio model	Coupling-strength ratio model
$\sigma(gg \to H \to ZZ)$	$\kappa_{gZ} = \kappa_g \cdot \kappa_Z/\kappa_H$
$\sigma_{VBF}/\sigma_{ggF}$	
σ_{WH}/σ_{ggF}	
σ_{ZH}/σ_{ggF}	$\lambda_{Zg} = \kappa_Z/\kappa_g$
$\sigma_{ttH}/\sigma_{ggF}$	$\lambda_{tg} = \kappa_t/\kappa_g$
BR^{WW}/BR^{ZZ}	$\lambda_{WZ} = \kappa_W/\kappa_Z$
$BR^{\gamma\gamma}/BR^{ZZ}$	$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$
$BR^{\tau\tau}/BR^{ZZ}$	$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$
BR^{bb}/BR^{ZZ}	$\lambda_{bZ} = \kappa_b/\kappa_Z$

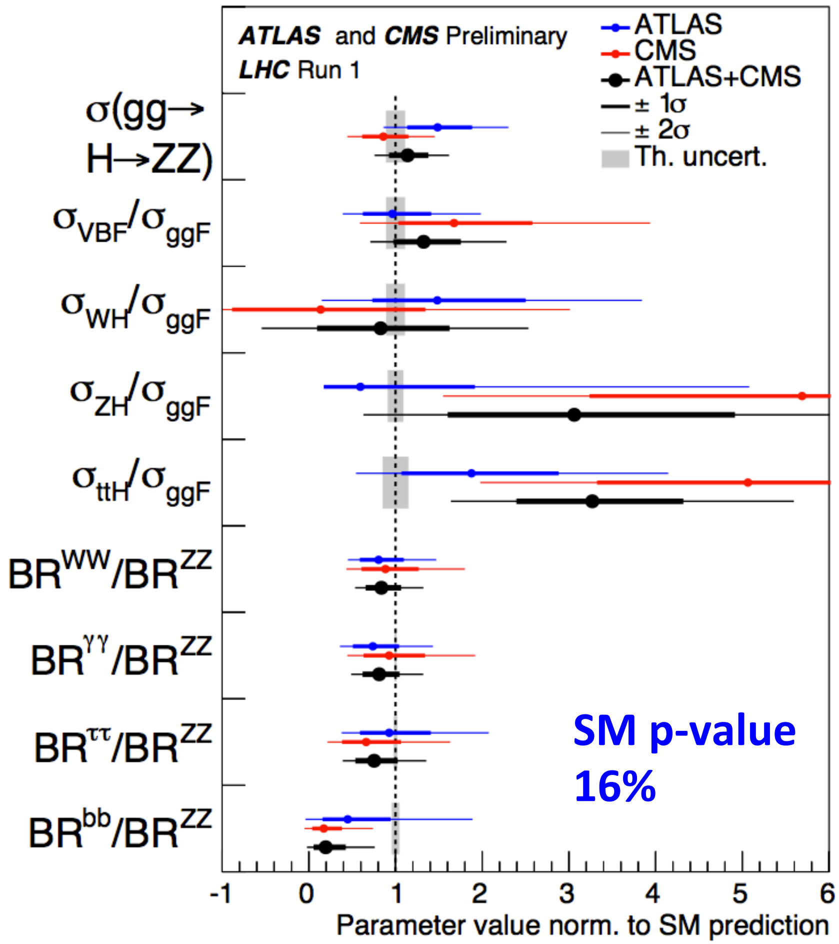
In this parameterization BR^{ZZ}, BR^{WW}, σ_{WH}, σ_{WH} and σ_{VBF} are function of κ_Z and κ_W

e.g. for example

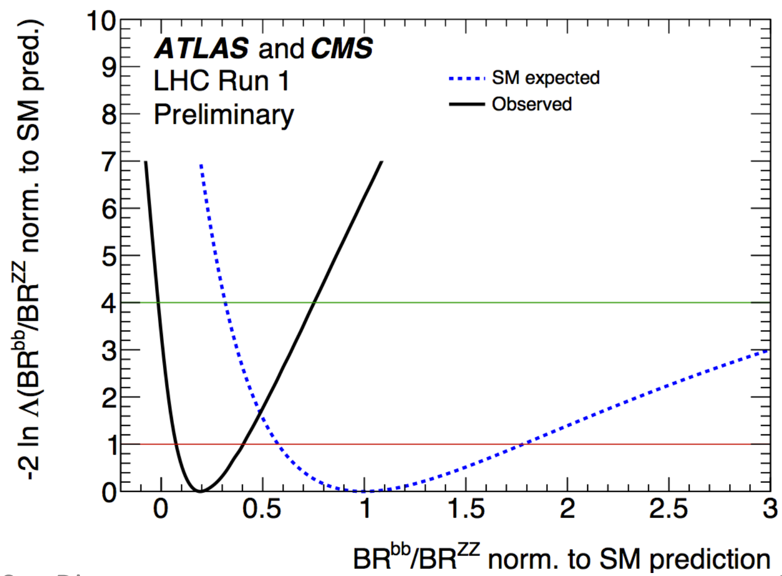
$\sigma_{WH}/\sigma_{ggF} \sim (\lambda_{WZ}/\lambda_{zg})^2$

σ and BR ratio parametrization

- Parameterization of ratio of observables with minimal dependence on theory predictions
- Results remain valid when theory predictions are updated



- Results are in general agreement with the SM
- Largest difference is seen in BR^{bb}/BR^{ZZ}, at the level of 2.4 σ
  - Effect mainly coming from large ZH and ttH (both ratios σ_i/σ_{ggF} ~ 3)

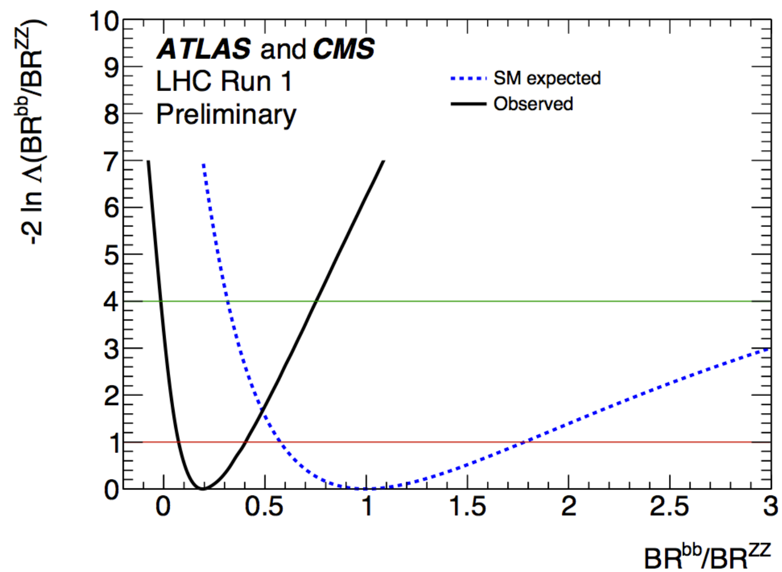


σ and BR ratio parametrization

- Parameterization of ratio of observables with minimal dependence on theory predictions
- Results remain valid when theory predictions are updated

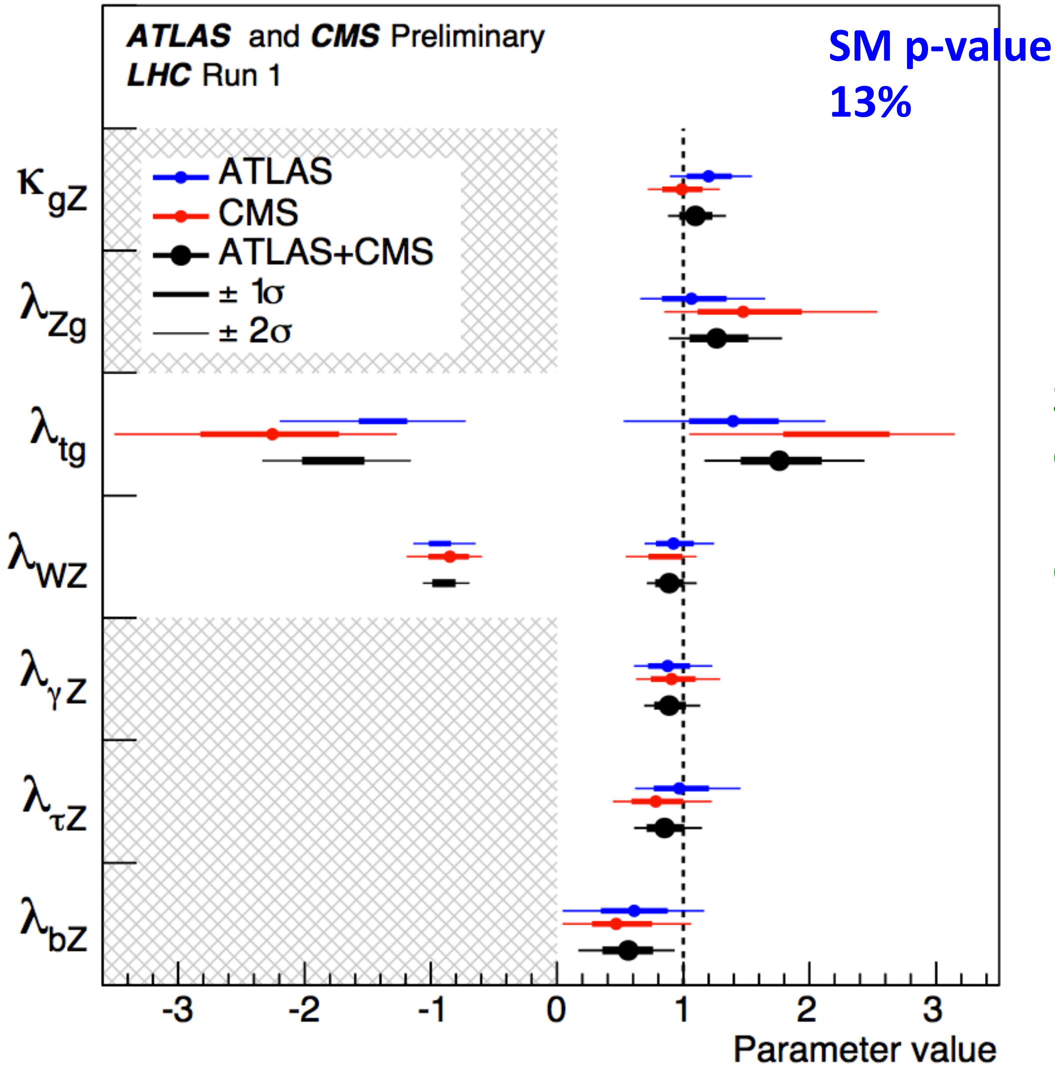
Parameter	SM prediction	Best-fit value	Uncertainty Stat	Uncertainty Syst
		ATLAS+CMS		
$\sigma(gg \to H \to ZZ)$ (pb)	0.513 ± 0.057	$0.58\ ^{+0.11}_{-0.10}$ $\left(^{+0.11}_{-0.10}\right)$	$^{+0.11}_{-0.10}$ $\left(^{+0.11}_{-0.09}\right)$	$^{+0.03}_{-0.02}$ $\left(^{+0.03}_{-0.02}\right)$
$\sigma_{\rm VBF}/\sigma_{\rm ggF}$	0.082 ± 0.009	$0.11\ ^{+0.03}_{-0.03}$ $\left(^{+0.03}_{-0.02}\right)$	$^{+0.03}_{-0.02}$ $\left(^{+0.02}_{-0.02}\right)$	$^{+0.02}_{-0.01}$ $\left(^{+0.02}_{-0.01}\right)$
$\sigma_{WH}/\sigma_{\rm ggF}$	0.037 ± 0.004	$0.03\ ^{+0.03}_{-0.03}$ $\left(^{+0.02}_{-0.02}\right)$	$^{+0.02}_{-0.02}$ $\left(^{+0.02}_{-0.02}\right)$	$^{+0.01}_{-0.01}$ $\left(^{+0.01}_{-0.01}\right)$
$\sigma_{ZH}/\sigma_{\rm ggF}$	0.022 ± 0.002	$0.07\ ^{+0.04}_{-0.03}$ $\left(^{+0.02}_{-0.01}\right)$	$^{+0.03}_{-0.03}$ $\left(^{+0.01}_{-0.01}\right)$	$^{+0.02}_{-0.02}$ $\left(^{+0.01}_{-0.00}\right)$
$\sigma_{ttH}/\sigma_{\rm ggF}$	0.0067 ± 0.0010	$0.022\ ^{+0.007}_{-0.006}$ $\left(^{+0.004}_{-0.004}\right)$	$^{+0.005}_{-0.005}$ $\left(^{+0.003}_{-0.003}\right)$	$^{+0.004}_{-0.003}$ $\left(^{+0.003}_{-0.002}\right)$
${\rm BR}^{WW}/{\rm BR}^{ZZ}$	$8.10 \pm < 0.01$	$6.8\ ^{+1.7}_{-1.3}$ $\left(^{+2.2}_{-1.7}\right)$	$^{+1.5}_{-1.2}$ $\left(^{+2.0}_{-1.6}\right)$	$^{+0.7}_{-0.5}$ $\left(^{+0.9}_{-0.7}\right)$
${\rm BR}^{\gamma\gamma}/{\rm BR}^{ZZ}$	0.085 ± 0.001	$0.069\ ^{+0.018}_{-0.015}$ $\left(^{+0.025}_{-0.019}\right)$	$^{+0.018}_{-0.014}$ $\left(^{+0.024}_{-0.019}\right)$	$^{+0.004}_{-0.003}$ $\left(^{+0.006}_{-0.004}\right)$
${\rm BR}^{\tau\tau}/{\rm BR}^{ZZ}$	2.36 ± 0.05	$1.8\ ^{+0.6}_{-0.5}$ $\left(^{+0.9}_{-0.7}\right)$	$^{+0.5}_{-0.4}$ $\left(^{+0.8}_{-0.6}\right)$	$^{+0.3}_{-0.2}$ $\left(^{+0.5}_{-0.3}\right)$
${\rm BR}^{b\bar{b}}/{\rm BR}^{ZZ}$	21.6 ± 1.0	$4.2\ ^{+4.6}_{-2.6}$ $\left(^{+16.9}_{-9.1}\right)$	$^{+2.8}_{-2.0}$ $\left(^{+13.9}_{-7.9}\right)$	$^{+3.6}_{-1.7}$ $\left(^{+9.5}_{-4.4}\right)$

- Results are in general agreement with the SM
- Largest difference is seen in BR^{bb}/BR^{ZZ}, at the level of 2.4 σ
  - Effect mainly coming from large ZH and ttH (both ratios σ_i/σ_{ggF} ~ 3)



Ratios of κ's

- Again, results in agreement with SM



Similar features as in σ and BR ratio parameterization observed here

Conclusions

- **ATLAS and CMS Higgs boson results on the mass and the couplings have been combined - sensitivity improved by almost √2**
- The mass of the Higgs boson has been measured at 0.2%:

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

- **Higgs to ττ and VBF production established at more that 5σ level**
- The most precise results on Higgs production and decay and constraints on its couplings have been obtained (O(10%) precision)

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

- Different parameterizations have been studied and all results all consistent with the SM predictions within uncertainties: min. SM p-value of all combined fits >10%
- LHC Run-2 at 13 TeV, precision will be improved during the coming years thanks to higher energy, larger integrated luminosity and progress in the theory predictions

Backup

Backup

Tevatron results

- Most sensitive Higgs boson production/decay channel is VH, H→bb
- CDF and D0 combined have a sensitivity for at the level of 2σ with approximately 10 fb^{-1} per experiment at 1.96 TeV proton-antiproton CM energy
- Excess of >3σ at m_H=120-125 GeV

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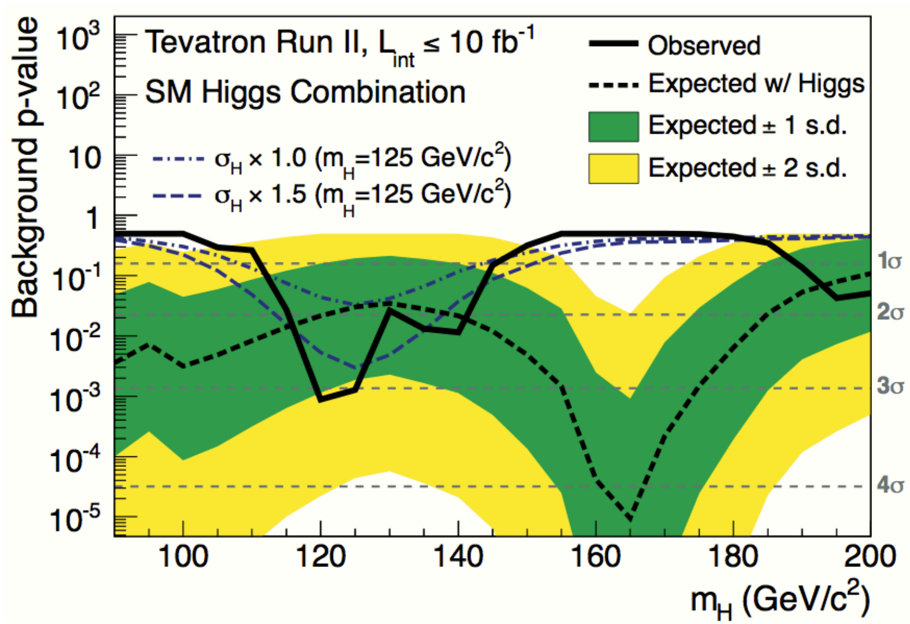
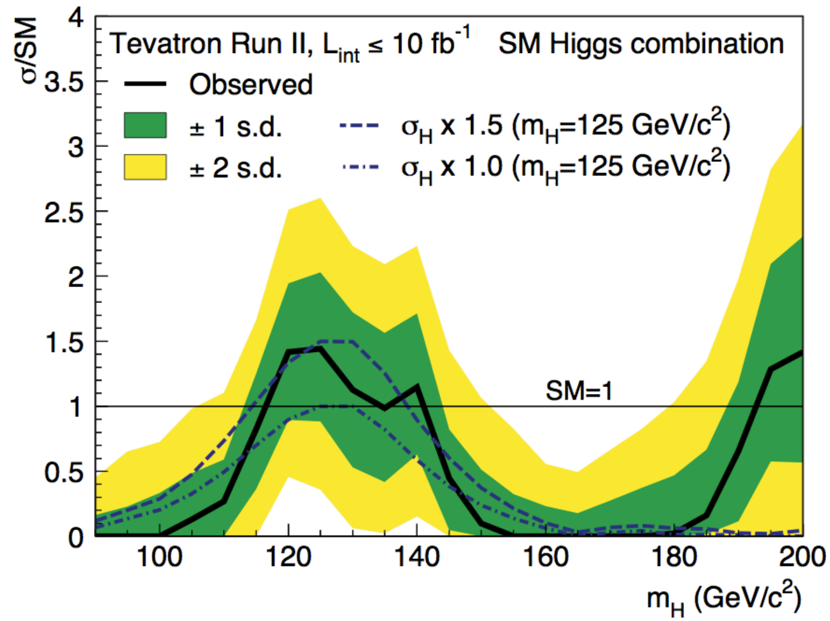
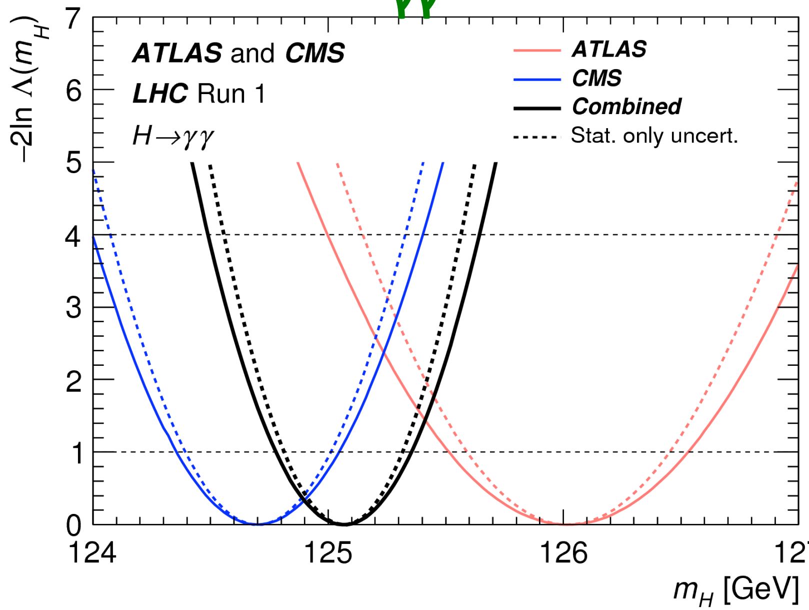




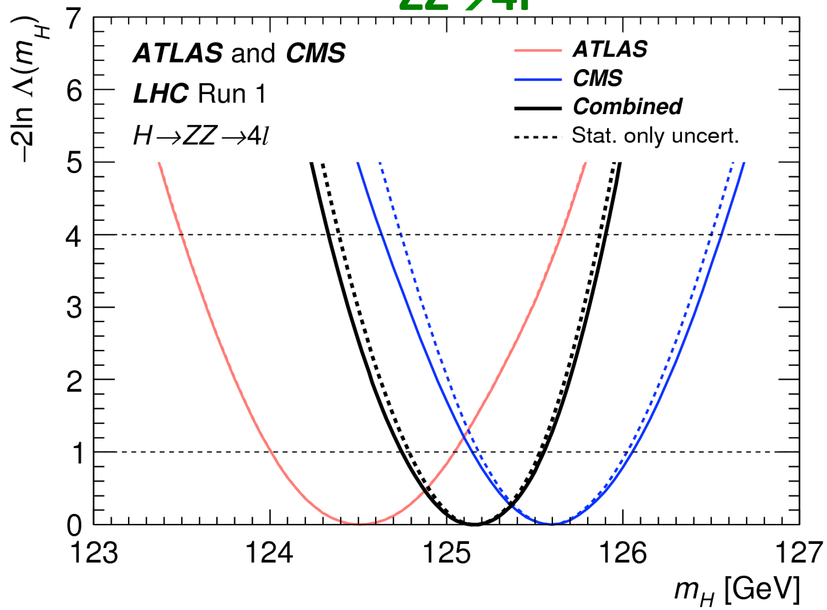
Measurement in the individual channels

- Mass is measured with high precision channels γγ and ZZ→4l

γγ



ZZ→4l

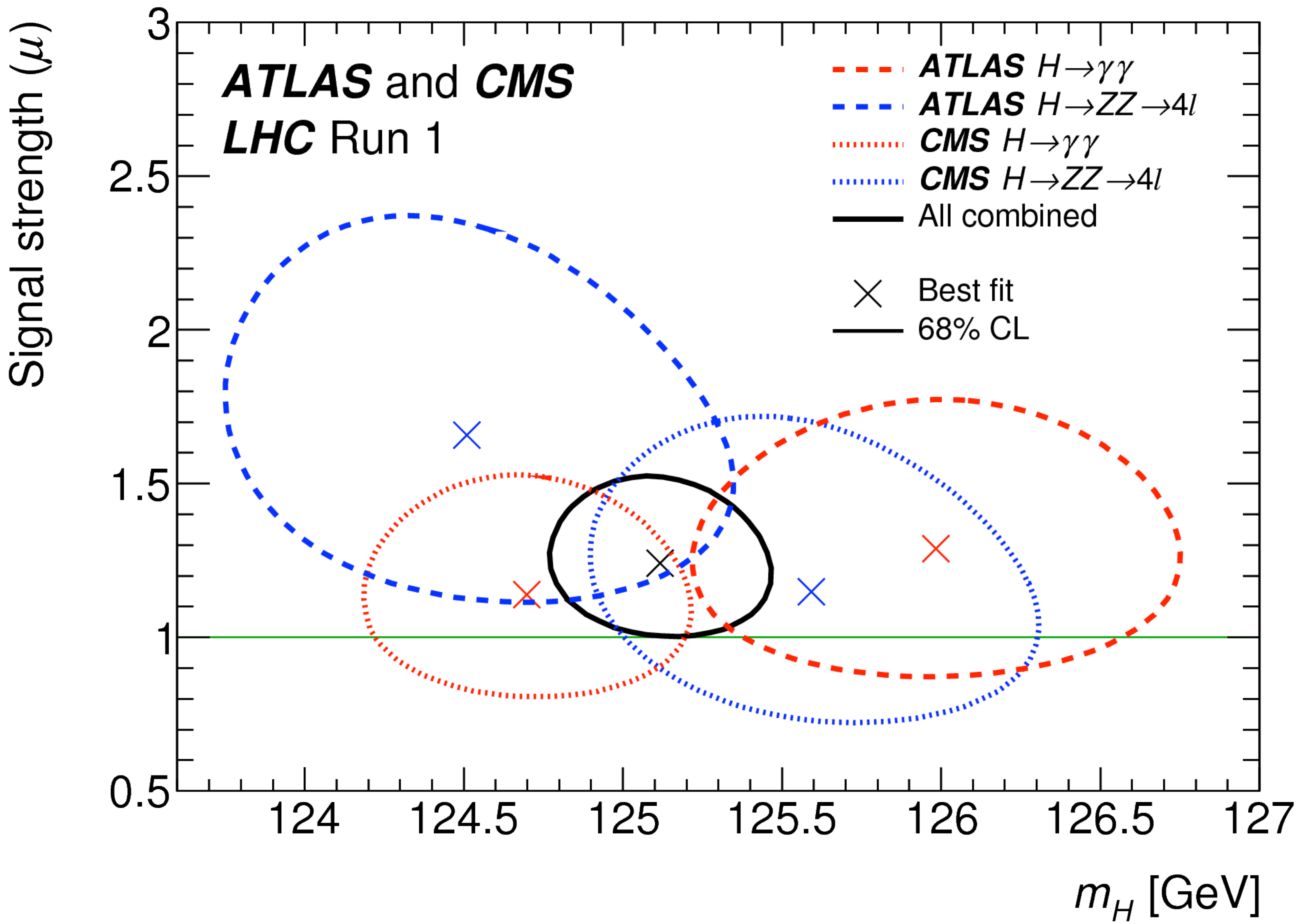


Some (opposite) tension between the two channels but very good agreement in the central values

$$m_H^{\gamma\gamma} = 125.07 \pm 0.29 \text{ GeV}$$
$$= 125.07 \pm 0.25\,(\text{stat.}) \pm 0.14\,(\text{syst.}) \text{ GeV}$$

$$m_H^{4\ell} = 125.15 \pm 0.40 \text{ GeV}$$
$$= 125.15 \pm 0.37\,(\text{stat.}) \pm 0.15\,(\text{syst.}) \text{ GeV}$$

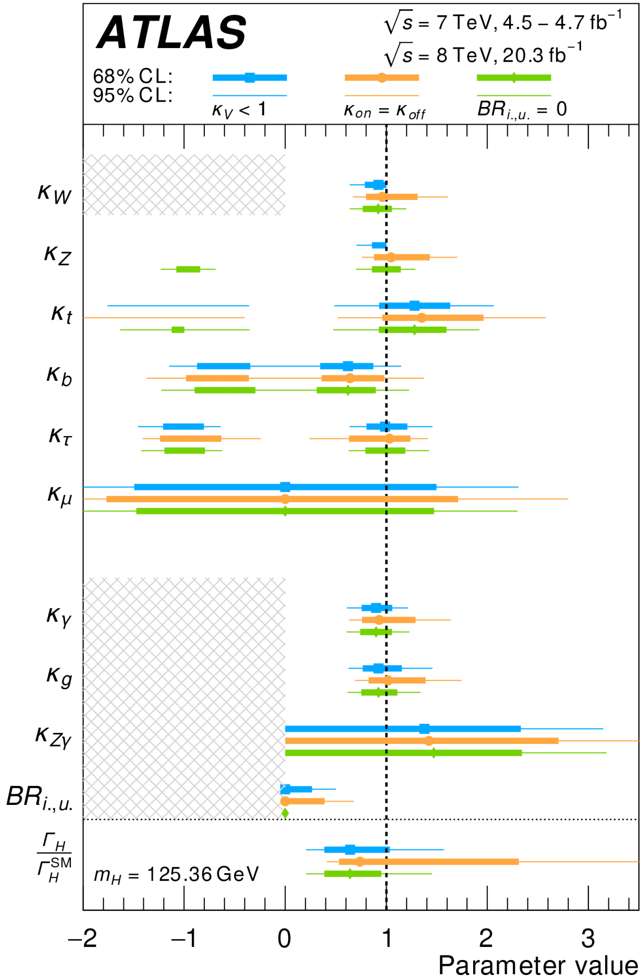
μ vs mass



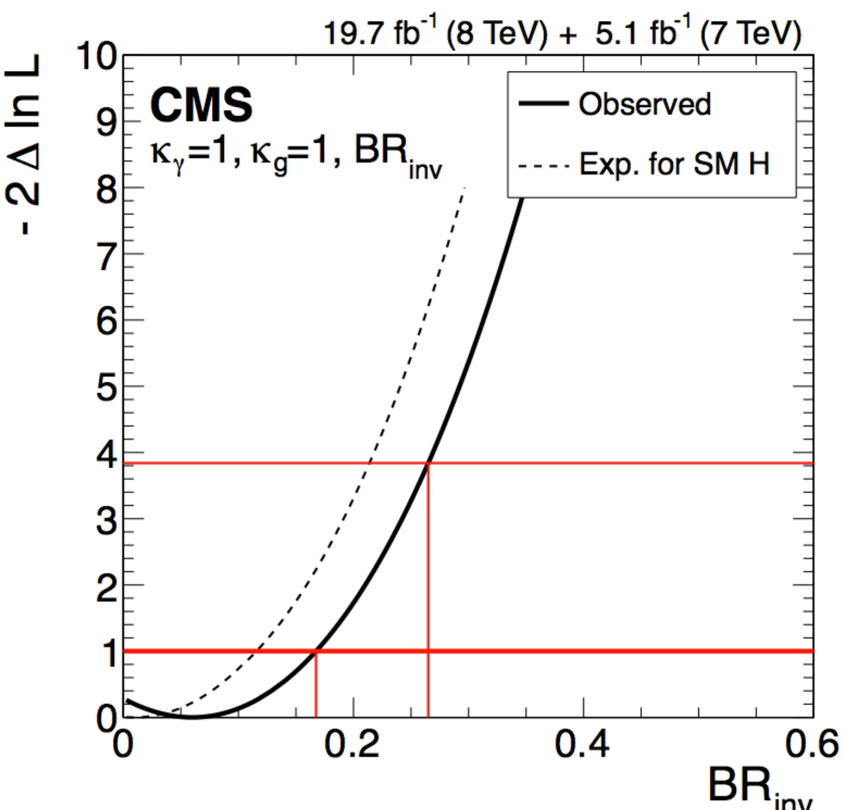
Signal strength (μ)
ATLAS and CMS
LHC Run 1
ATLAS $H\rightarrow\gamma\gamma$
ATLAS $H\rightarrow ZZ\rightarrow 4l$
CMS $H\rightarrow\gamma\gamma$
CMS $H\rightarrow ZZ\rightarrow 4l$
All combined
Best fit
68% CL
3
2.5
2
1.5
1
0.5
124
124.5
125
125.5
126
126.5
127
m_H [GeV]

ATLAS and CMS individual combinations

ATLAS also combines H→Zγ and off-shell couplings (orange results)



CMS, assuming BR_{BSM} only into invisible decays and combining direct searches for H→ invisible decays obtains:
BR_{BSM}<0.49 (0.32 expected) at 95% CL



Signal strengths μ

- μ is the so called signal strength (μ=1 in the SM)

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \quad \text{and} \quad \mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}}. \qquad \mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

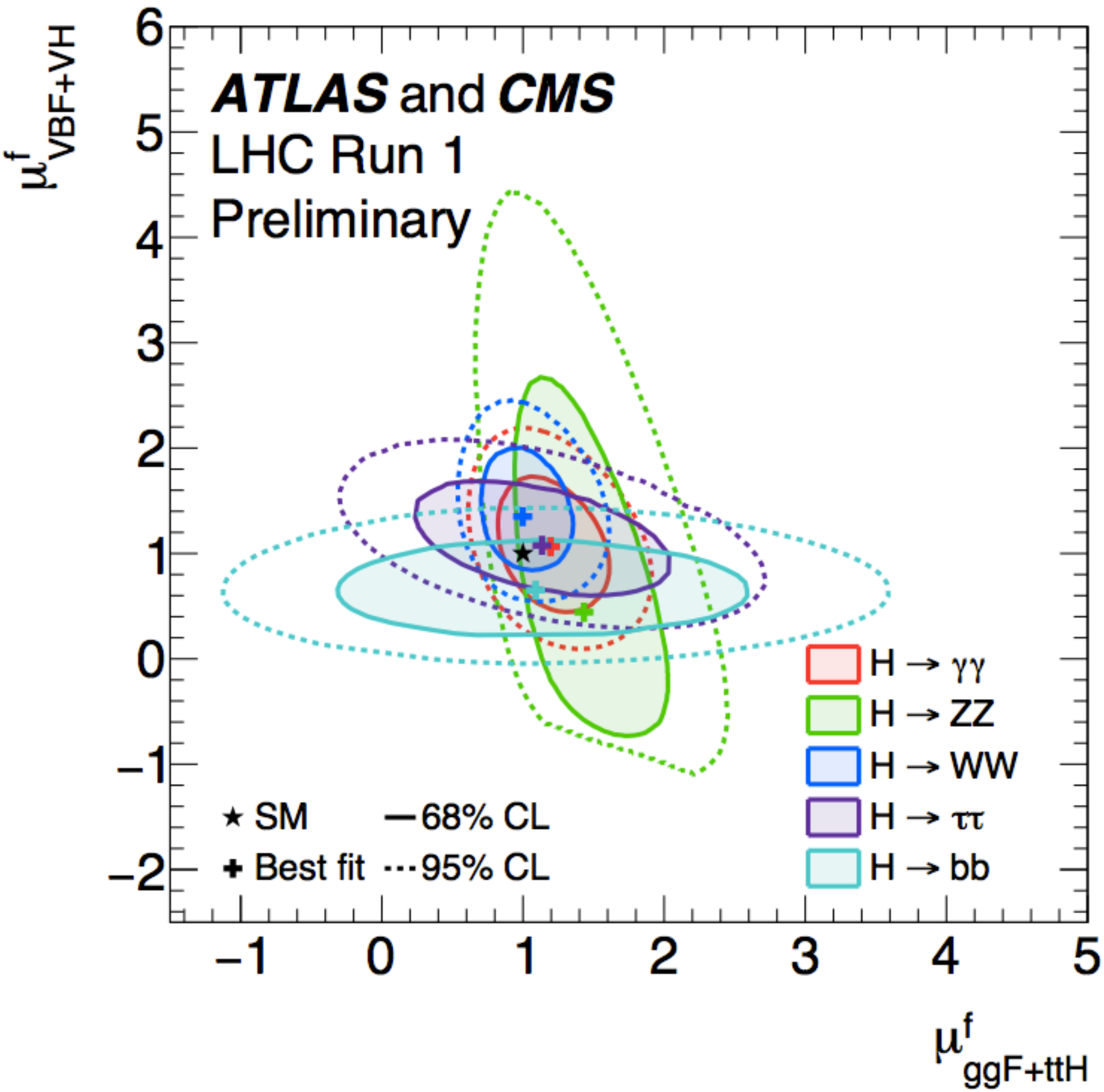
- Most constrained parameterization: one single signal strength μ (and assuming the same at 7 and 8 TeV)

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

	Best-fit μ	Uncertainty				
		Total	Stat	Expt	Thbgd	Thsig
ATLAS and CMS (meas.)	1.09	$^{+0.11}_{-0.10}$	$^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	$^{+0.07}_{-0.06}$
ATLAS and CMS (exp.)	–	$^{+0.11}_{-0.10}$	$^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	$^{+0.06}_{-0.06}$
ATLAS (meas.)	1.20	$^{+0.15}_{-0.14}$	$^{+0.10}_{-0.10}$	$^{+0.06}_{-0.06}$	$^{+0.04}_{-0.04}$	$^{+0.08}_{-0.07}$
CMS (meas.)	0.98	$^{+0.14}_{-0.13}$	$^{+0.10}_{-0.09}$	$^{+0.06}_{-0.05}$	$^{+0.04}_{-0.04}$	$^{+0.08}_{-0.07}$

- Signal theory uncert. due to QCD scale and PDF as large as stat. unc. as the statistical measurement on the combined mu only. Will be reduced with latest theory calculations and PDF as discussed in the theory talks yesterday

μ_V vs μ_F

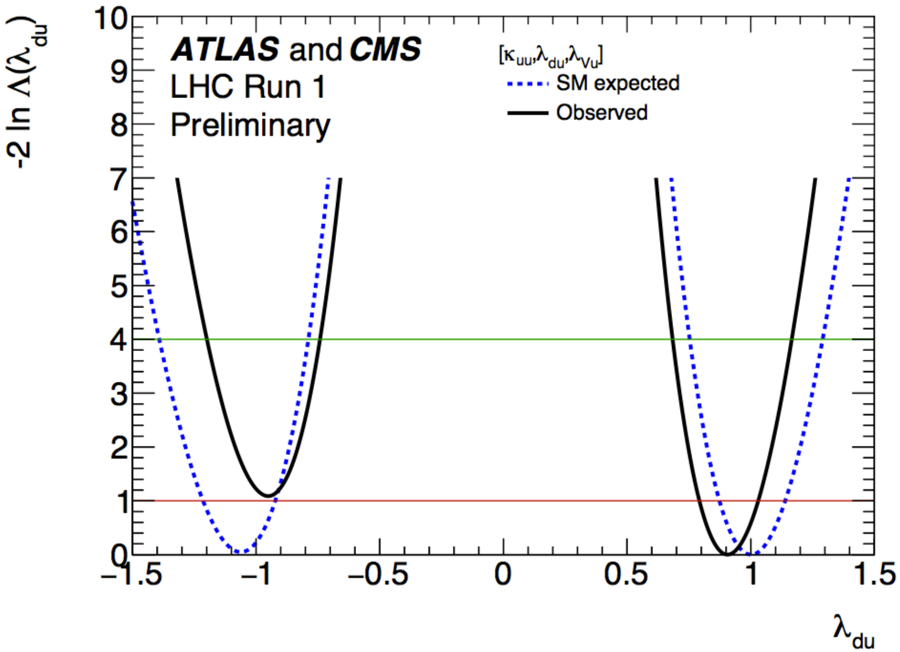


ATLAS and CMS
LHC Run 1
Preliminary
μ^f_{VBF+VH}
$\mu^f_{ggF+ttH}$
6
5
4
3
2
1
0
−1
−2
−1
0
1
2
3
4
5
★ SM
✚ Best fit
— 68% CL
··· 95% CL
H → γγ
H → ZZ
H → WW
H → ττ
H → bb

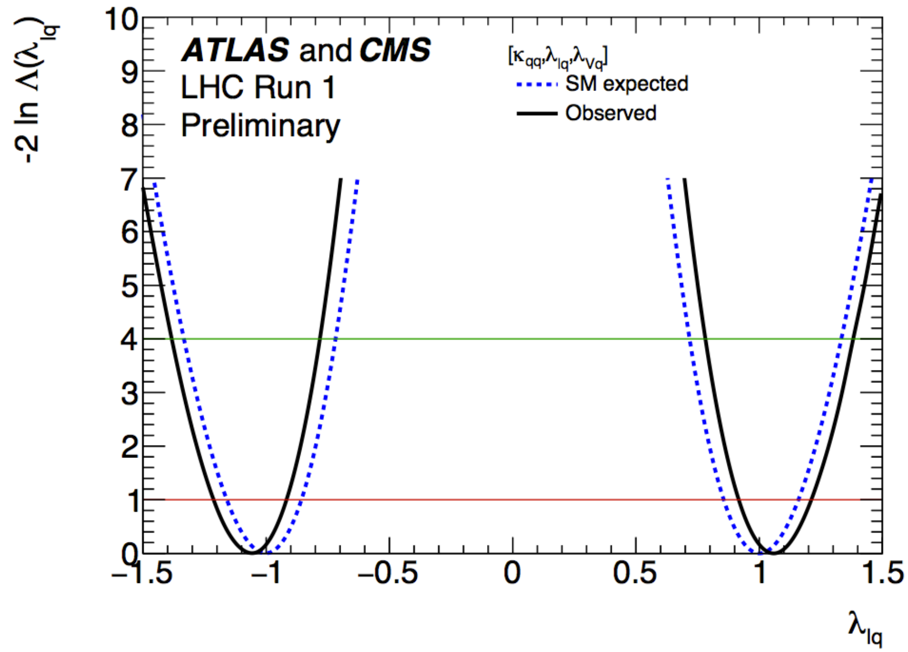
Up-down fermions and lepton-quark symmetries

- In 2HDM ratios of up/down fermions or leptons/quarks maybe different from 1 – for example in MSSM up/down fermions couplings are modified
- The ratio of coupling modifiers is checked also allowing negative values
- The results are all consistent with the SM

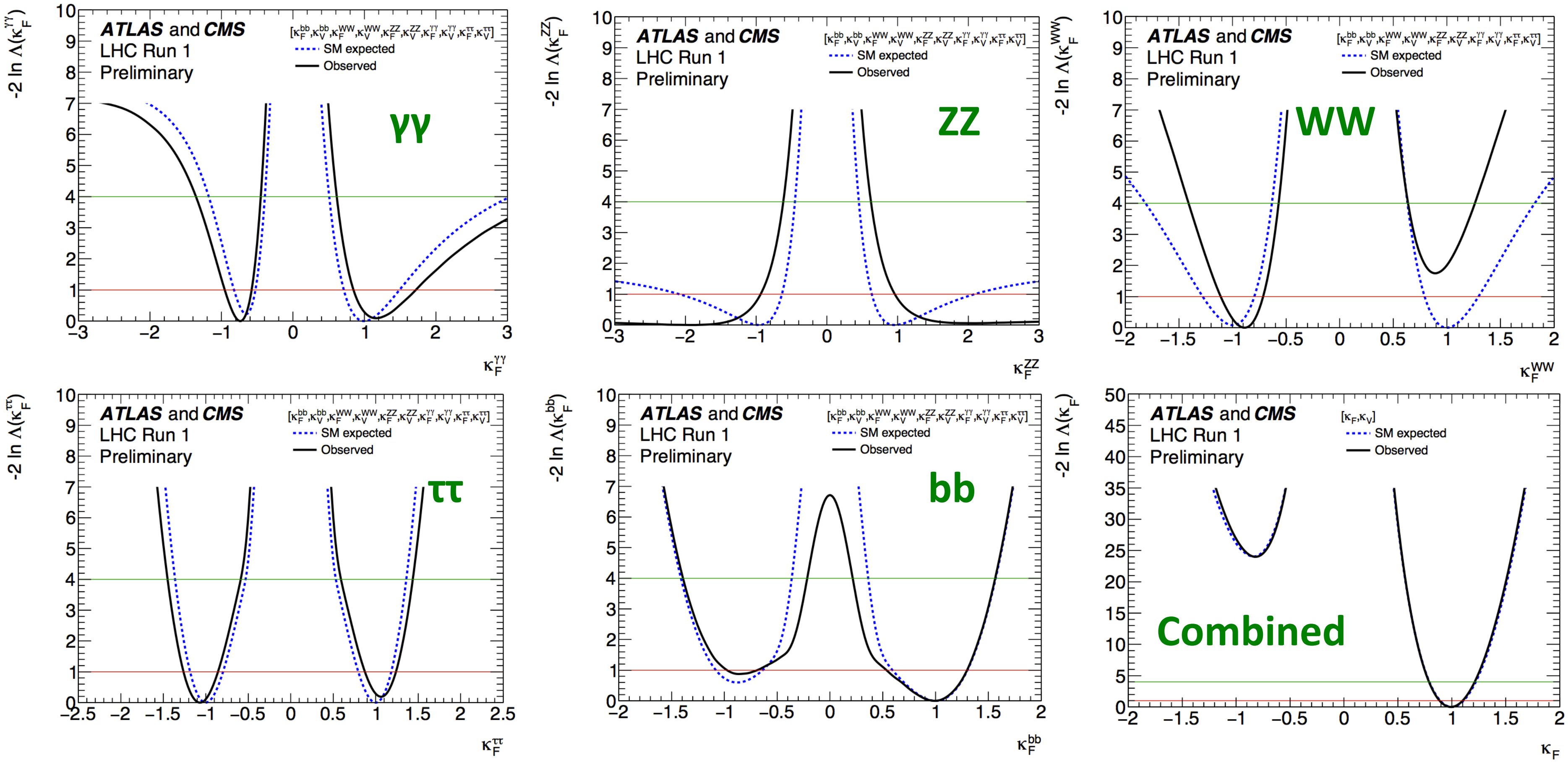
$K_{\text{down-type fermions}}/K_{\text{up-type fermions}}$



$K_{\text{leptons}}/K_{\text{quarks}}$



Scans of negative κ_F



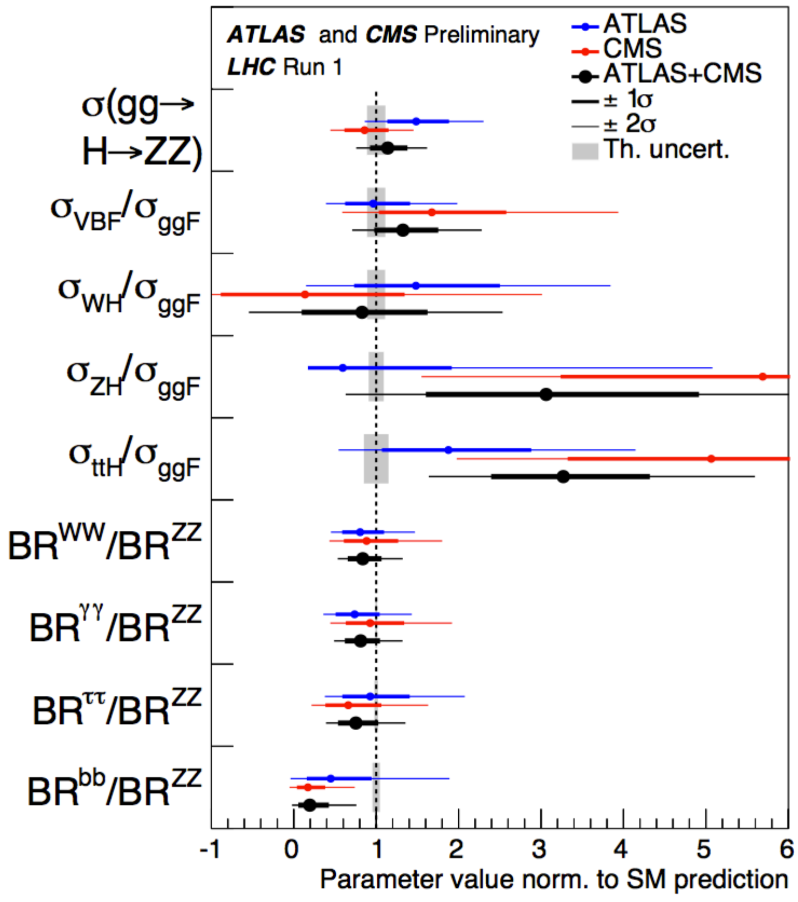
Very small sensitivity to the sign for each individual channel

Sensitivity from combination: almost 5σ exclusion of $\kappa_F<0$ from combined κ_F

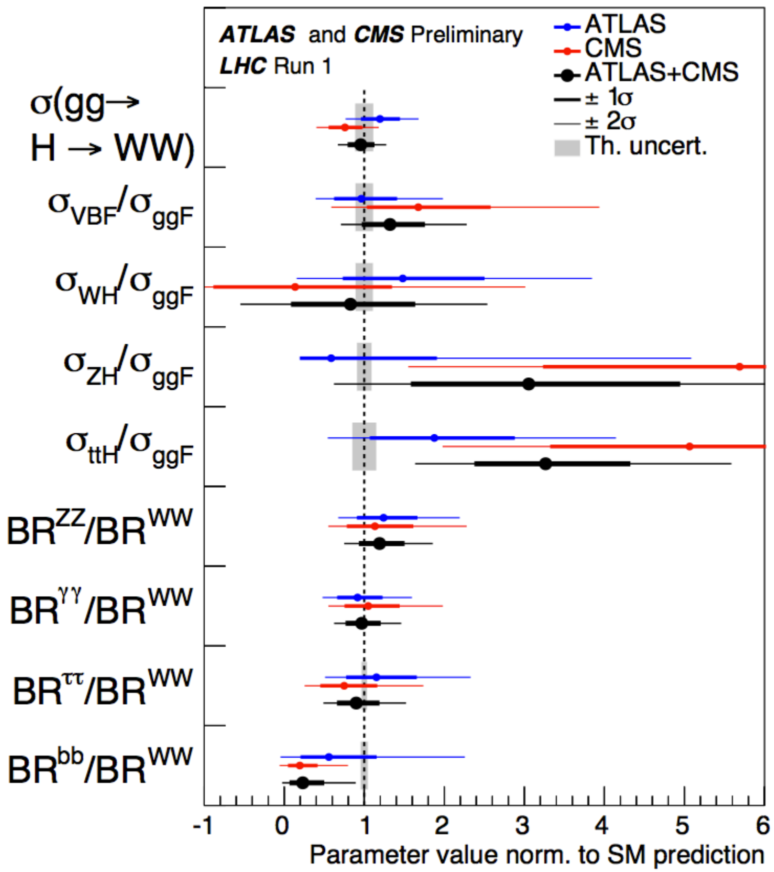
Generic parametrization relative to ZZ and WW

- Results of most generic parameterizations normalized to SM predictions

ZZ

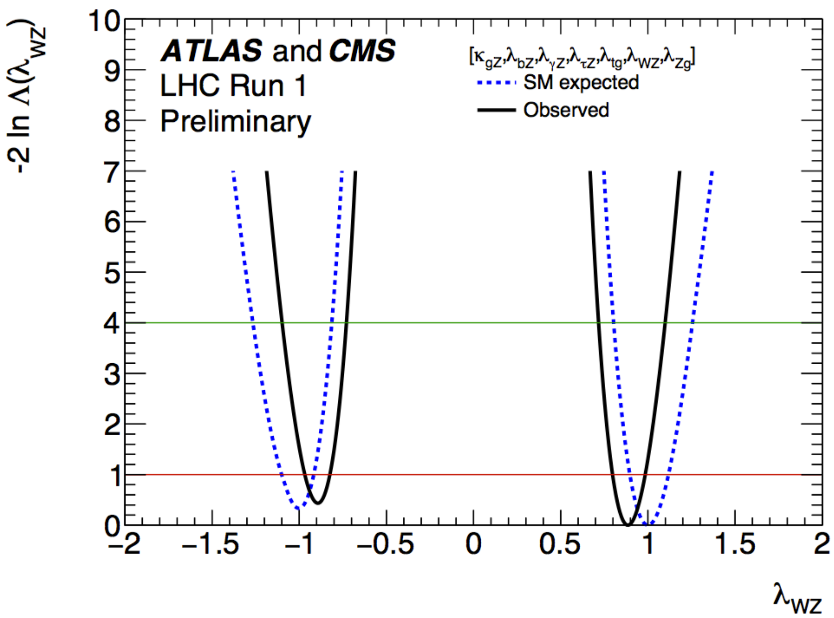


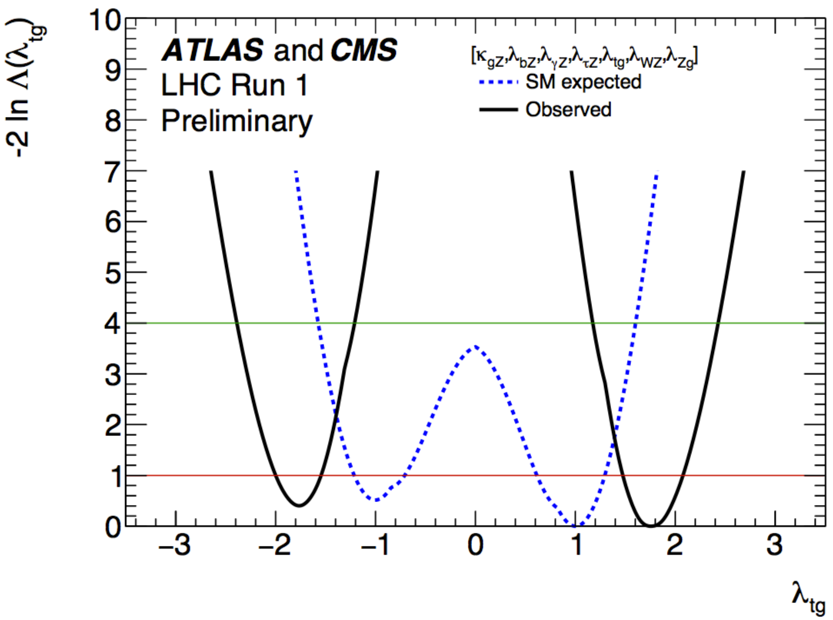
WW



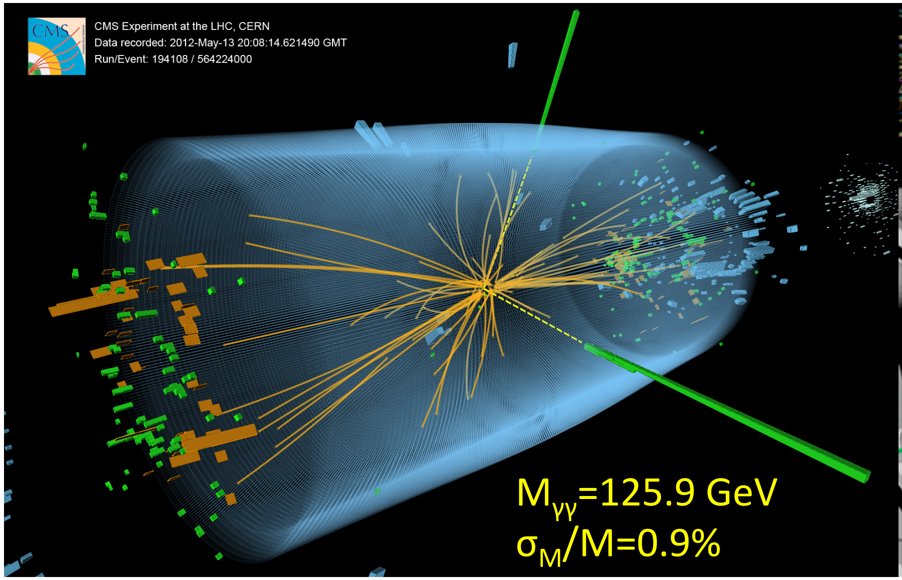
Negative κ ratios

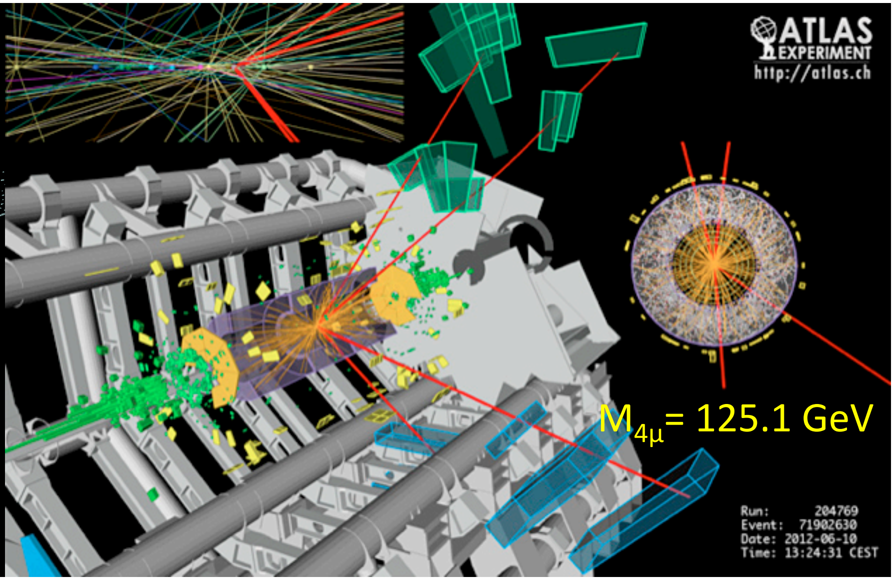
- Small sensitivity to negative coupling without interference in the H→γγ decay





July 4th 2012 discovery announced at CERN

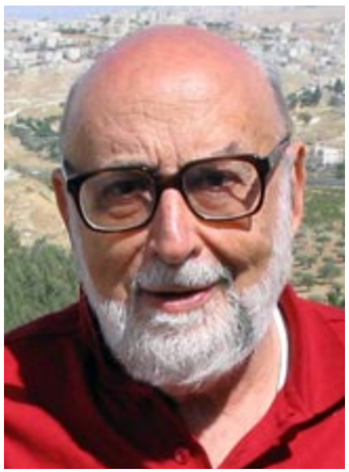




… and the Nobel Prize in physics 2013

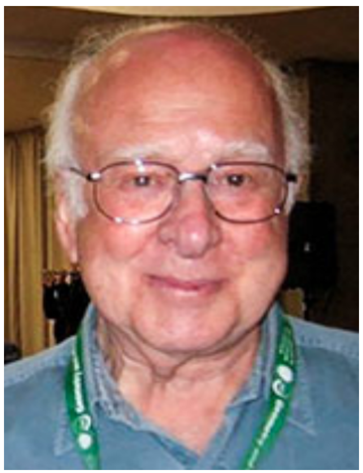
Waited some more results to make sure that it is really compatible with a Higgs boson

Tuesday 8 October 2013



François Englert
Prize share: 1/2

Peter W. Higgs
Prize share: 1/2



The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "*for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider*"