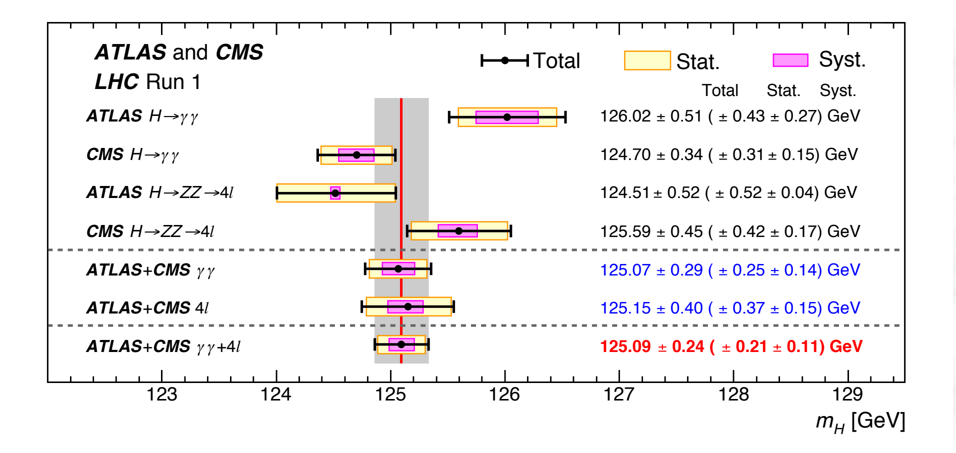
Higgs boson mass (cont.)

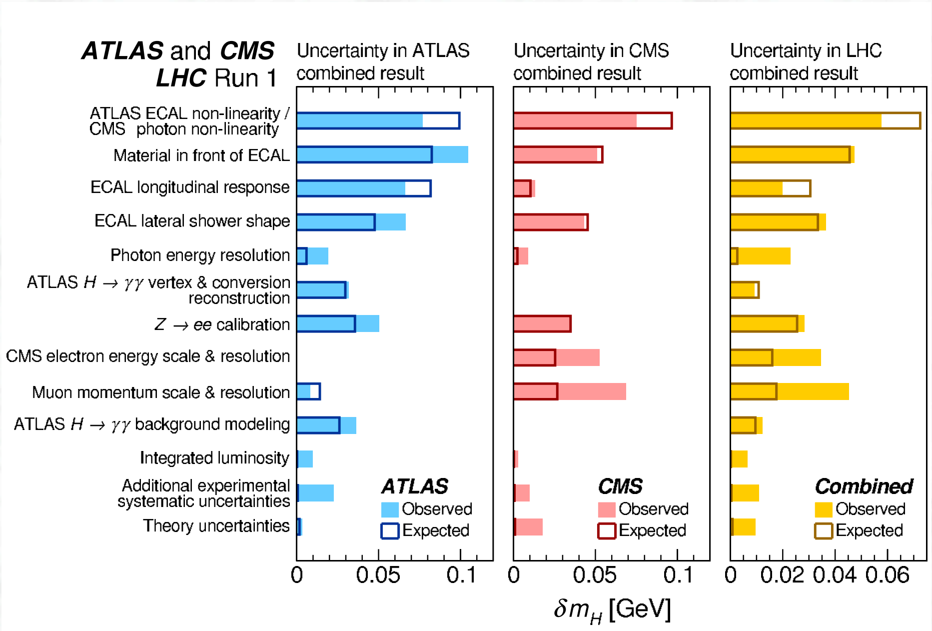
-First ATLAS and CMS combination of Higgs boson results-

PRL 114 (2015) 191803

Individual and combined results:



Uncertainties:



ATLAS + CMS:

m_H = 125.09 ± 0.21 (stat) ± 0.11 (syst) GeV

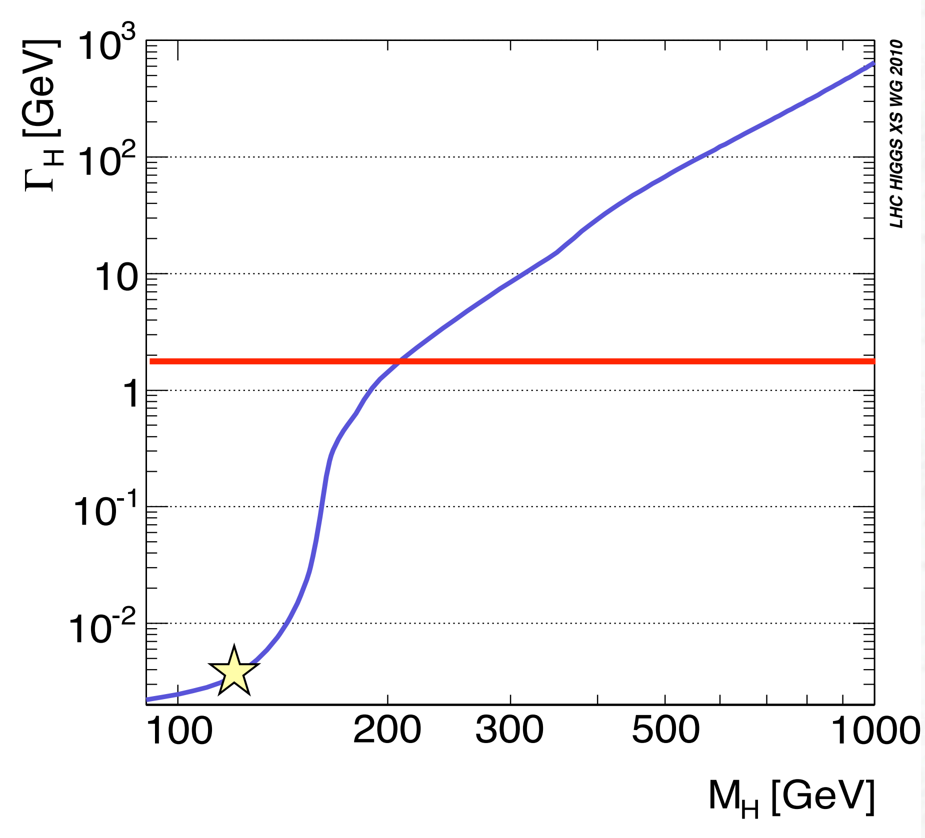
Precision of 0.2%

- Statistical uncertainty still dominant
- Major systematic uncertainties: Lepton and photon energy scales and resolutions
- Theoretical uncertainties small, γγ interference effects neglected

Higgs boson width

- The Standard Model Higgs boson width is expected to be small: $\Gamma_H \sim 4$ MeV
- Experimental mass resolution in H → γγ and H → ZZ*→4ℓ channel ~1 - 2 GeV

→ only upper limits can be extracted from the observed mass peaks



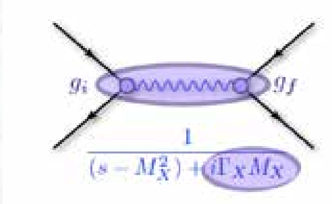
EPJ C75 (2015) 5, 212

Results: 95% CL limits

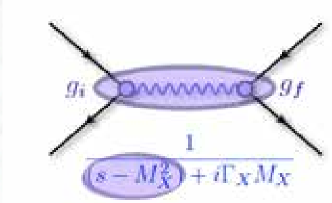
Γ_H < 1.7 GeV (2.3 expected)

Indirect constraint on the Higgs boson width from "off-shell cross sections"

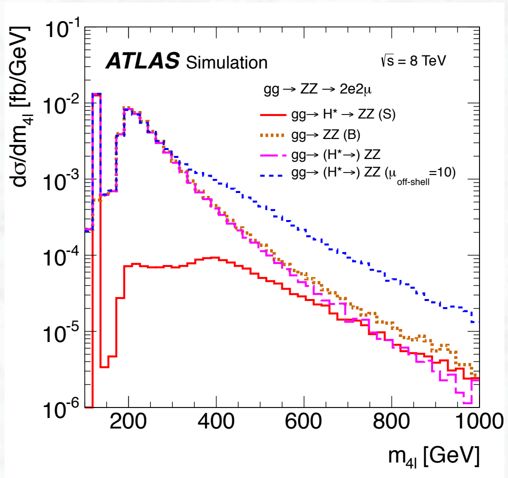
- Different sensitivity of on-shell and off-shell cross sections on the Higgs boson width
- However, model dependent: assumes that on-shell and off-shell couplings are the same
- Dependence on K-factors for signal and backgrounds (gg → VV)



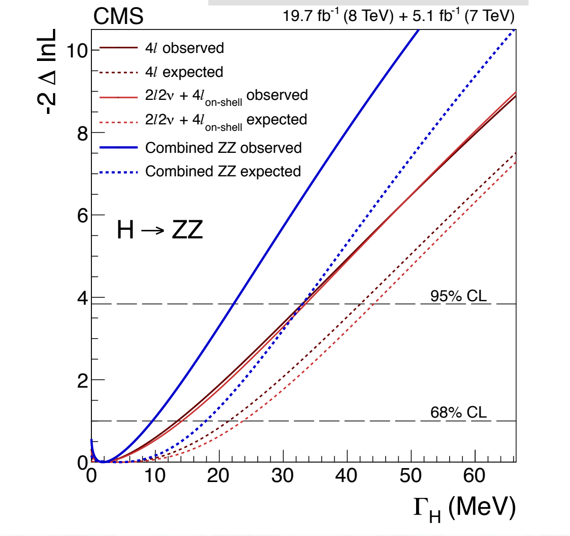
$$\sigma^{on}_{i \to X \to f} \sim \frac{g_i^2 g_f^2}{\Gamma_X}$$



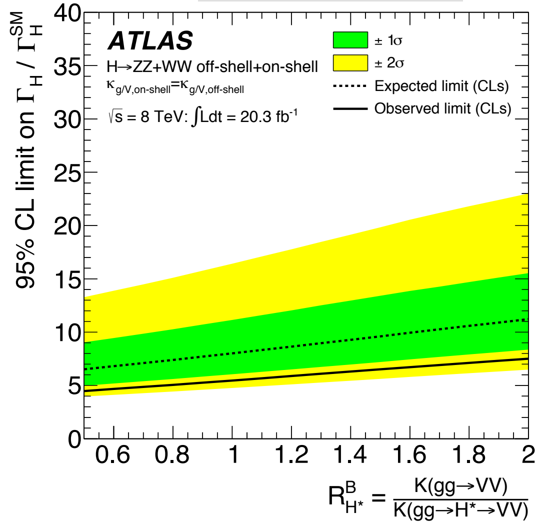
$$\sigma^{off}_{i \to X \to f} \sim g_i^2 g_f^2$$



EPJ C75 (2015) 5, 212

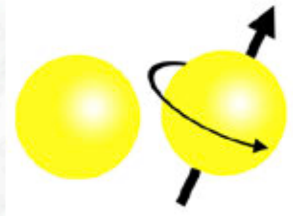


arXiv: 1503.01060



Results:	95% CL limits
CMS:	$\Gamma_H / \Gamma_{SM} < 5.4$ (= 22 MeV)
ATLAS:	$\Gamma_H / \Gamma_{SM} < 5.5$ ($R_B^{H^*} = 1$)

Spin and CP

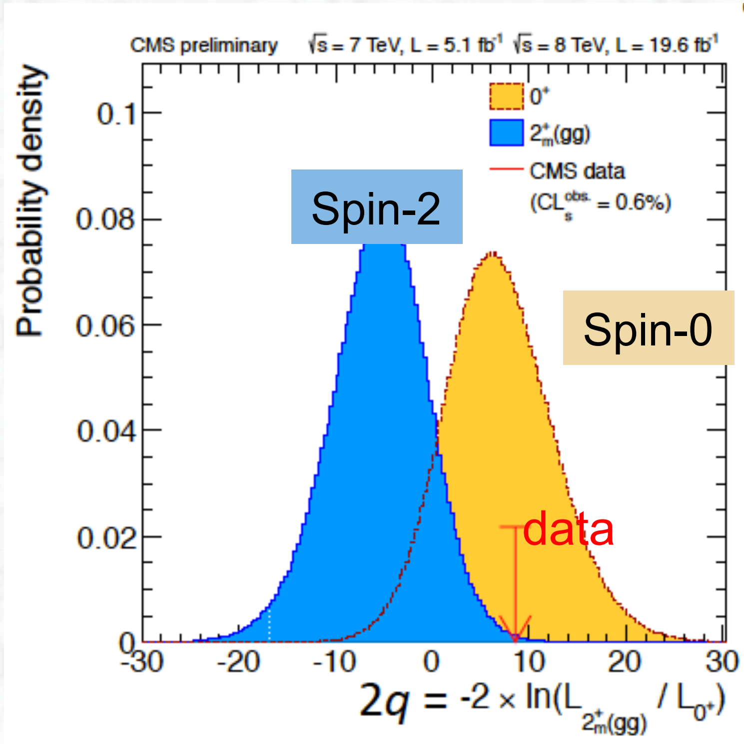


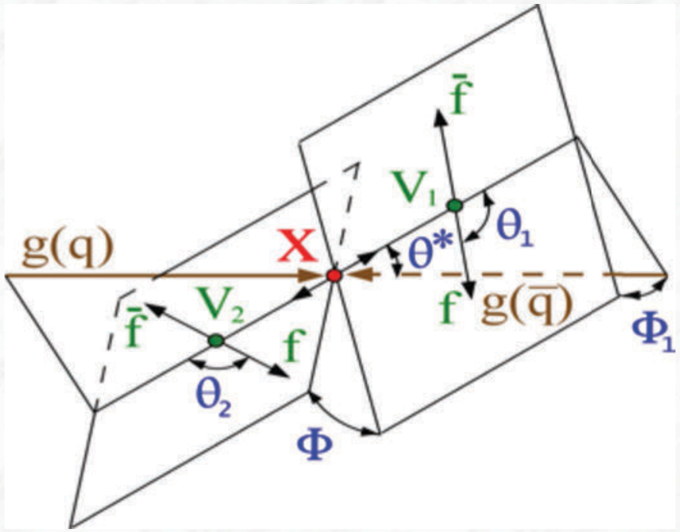
- Standard Model Higgs boson: $J^P = 0^+$

  → strategy is to falsify other hypotheses (0^-, 1^-, 1^+, 2^-, 2^+)

- Angular distributions of final state particles show sensitivity to spin

  In particular: H → ZZ* → 4ℓ decays
  (in addition: H → WW* → ℓν ℓν)



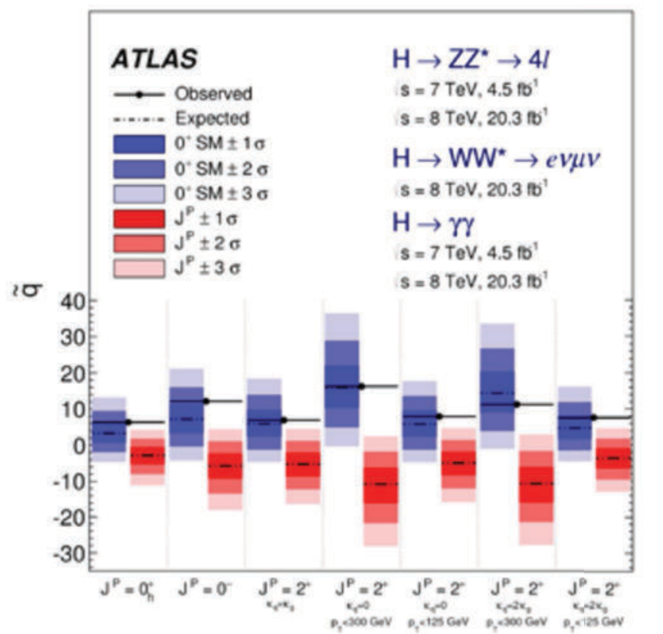


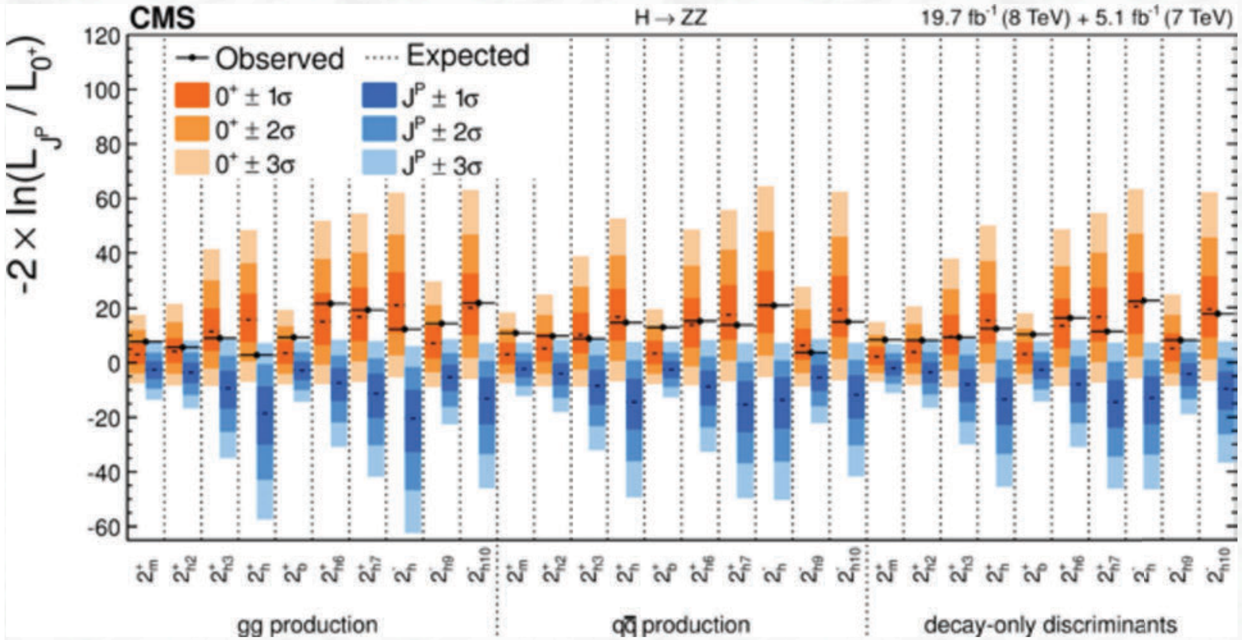
- Data strongly favour the spin-0 hypothesis of the Standard Model
- Many alternatives can be excluded with confidence levels > 99%)

Result on different J^{CP} hypothesis tests

Eur. Phys. J C75 (2015) 476

Phys. Rev. D92 (2015) 012004



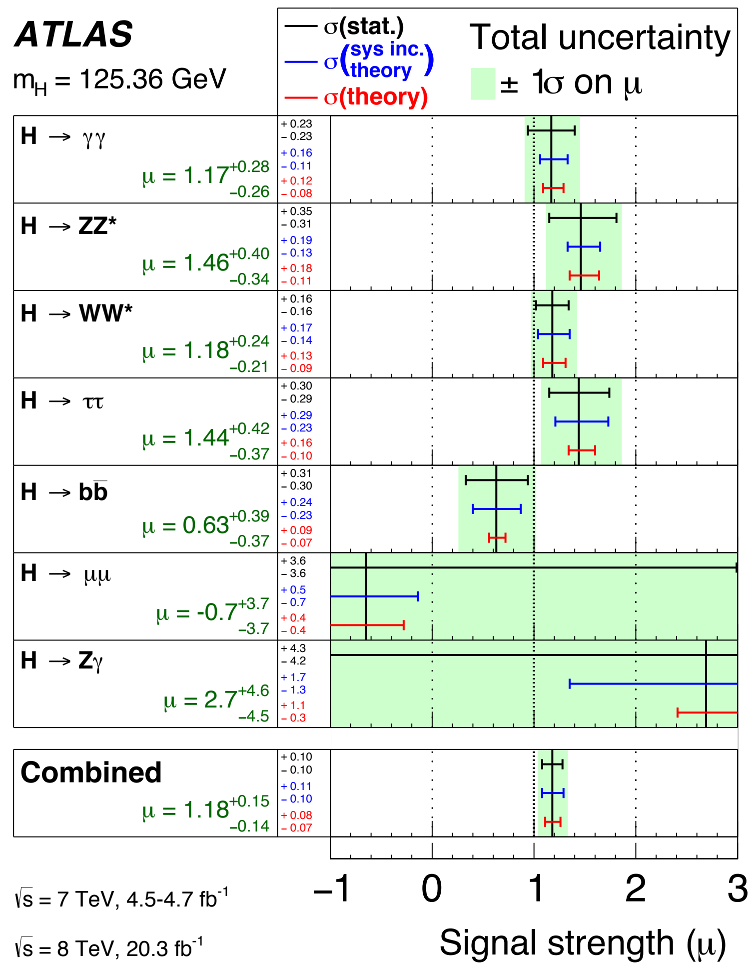


- In both experiments, data are consistent with $J^P = 0^+$ hypothesis, many alternative models are excluded with high significance

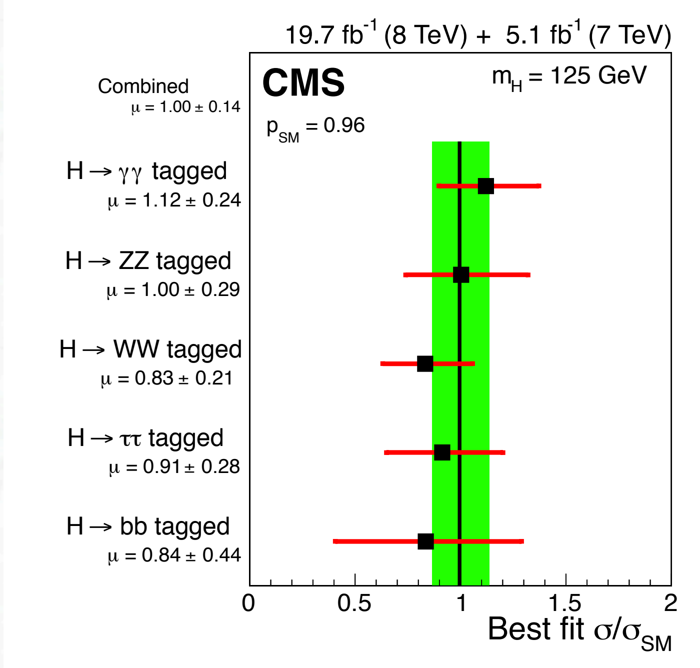
Signal strength in individual decay modes

-normalised to the expectations for the Standard Model Higgs boson-

EPJ C76 (2016) 1, 6



EPJ C75 (2015) 5, 212



Signal strengths:

ATLAS: $\mu = 1.18\,^{+0.15}_{-0.14}$

CMS: $\mu = 1.00 \pm 0.14$

Data are consistent with the hypothesis of the Standard Model Higgs boson

Signal strength Fits

Combined ATLAS + CMS results

arXiv:1606.02266

- Assuming the Standard Model and the calculated Higgs boson production cross sections, the (ATLAS + CMS) combined signal strength is:

$$\mu = 1.09\,^{+0.11}_{-0.10} \;=\; 1.09\,^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{exp})\,^{+0.03}_{-0.03}\,(\text{theo.bgd})\,^{+0.07}_{-0.06}\,(\text{theo.sig})$$

- The signal strengths have also been measured using:

  - SM cross sections and free BRs
  - Free cross sections and Standard Model BRs

$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

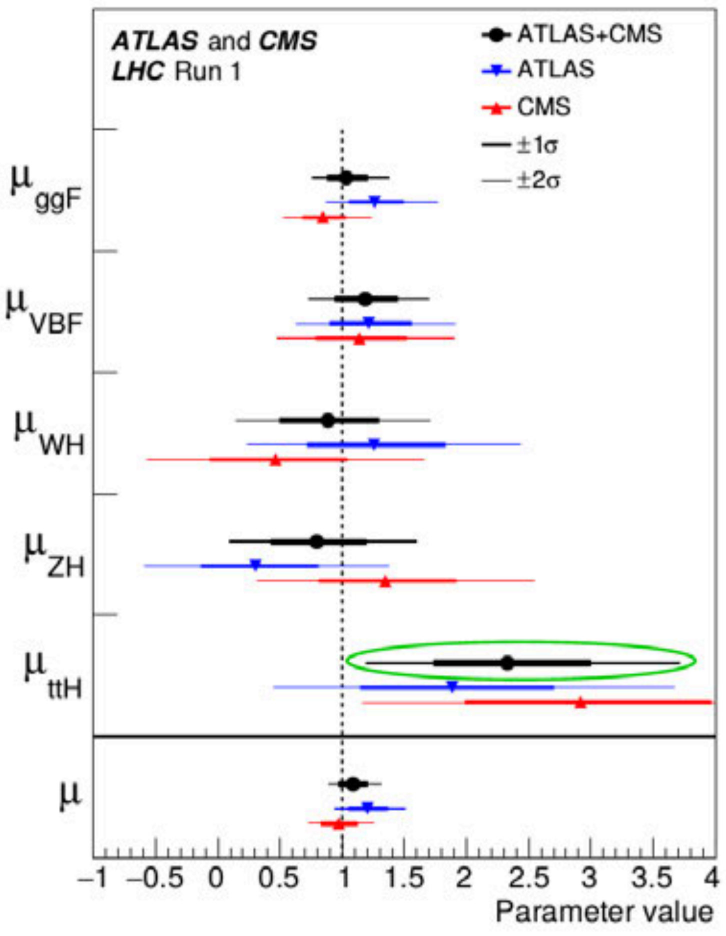
- In both cases, the data are compatible with the Standard Model with p-values of 24% and 75%, respectively

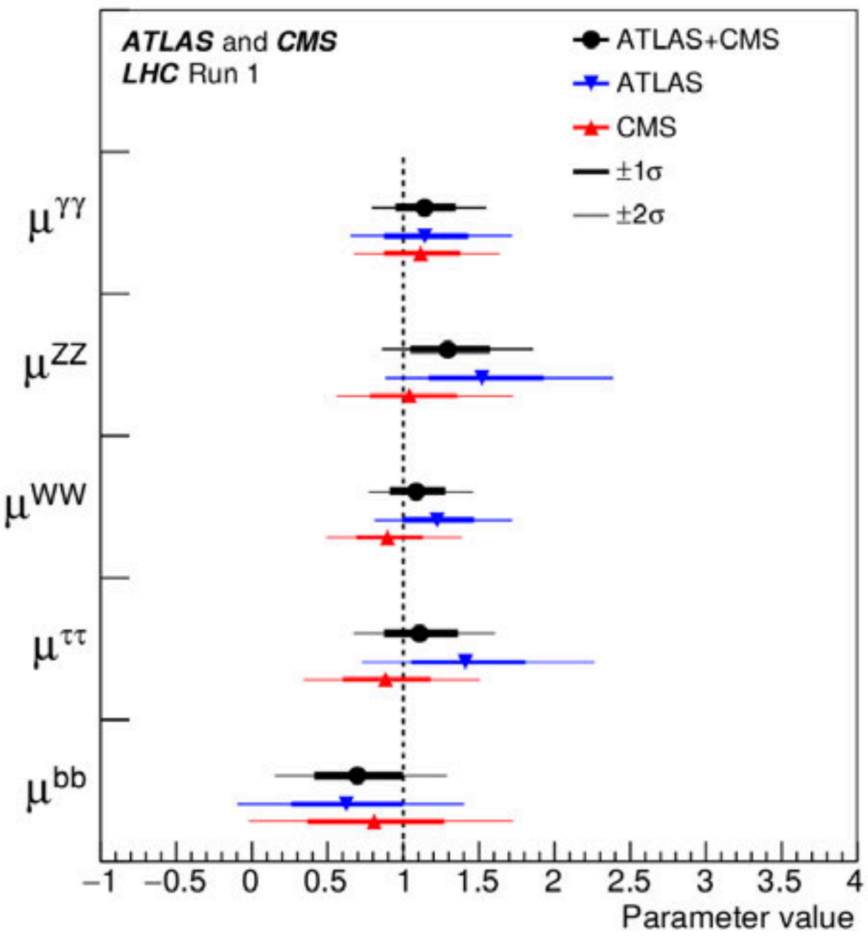
- The only "outlier" (> 2σ from the SM expectation) is: $\mu_{ttH} = 2.3\,^{+0.7}_{-0.6}$

Signal strength Fits

Combined ATLAS + CMS results

arXiv:1606.02266





Signal strength Fits

Combined ATLAS + CMS results

arXiv:1606.02266

- From the combined ATLAS + CMS results, the vector boson fusion and the $H \rightarrow \tau\tau$ decay mode reach a significance of more than 5σ

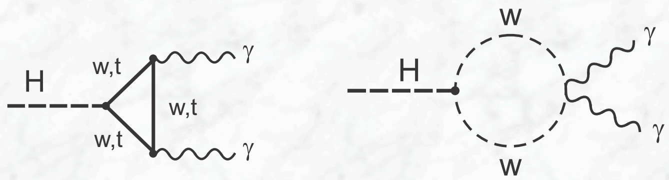
Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \rightarrow \tau\tau$	5.5	5.0
$H \rightarrow bb$	2.6	3.7

Higgs boson couplings

- Production and decay involve several couplings

Production:

Decays: e.g $H \rightarrow \gamma\gamma$ (best example)
(Decay width depends on W and top coupling, destructive interference)



- Benchmarks defined by LHC cross section working group (leading order tree-level framework: κ framework):

  - Signals observed originate from a single resonance; (mass assumed here is 125.09 GeV (ATLAS + CMS average)

  - Narrow width approximation: → rates for given channels can be decomposed as:

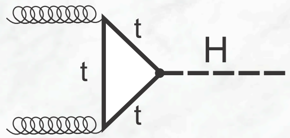
$$\sigma \cdot B\,(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

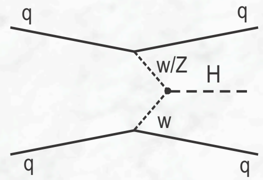
i, f = initial, final state
Γ_f, Γ_H = partial, total width

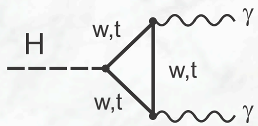
  - Modifications to coupling strength are considered (coupling scale factors κ), tensor structure of Lagrangian assumed as in Standard Model

Higgs boson couplings (in the κ framework)

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(gg\mathrm{F})$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{BSM} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

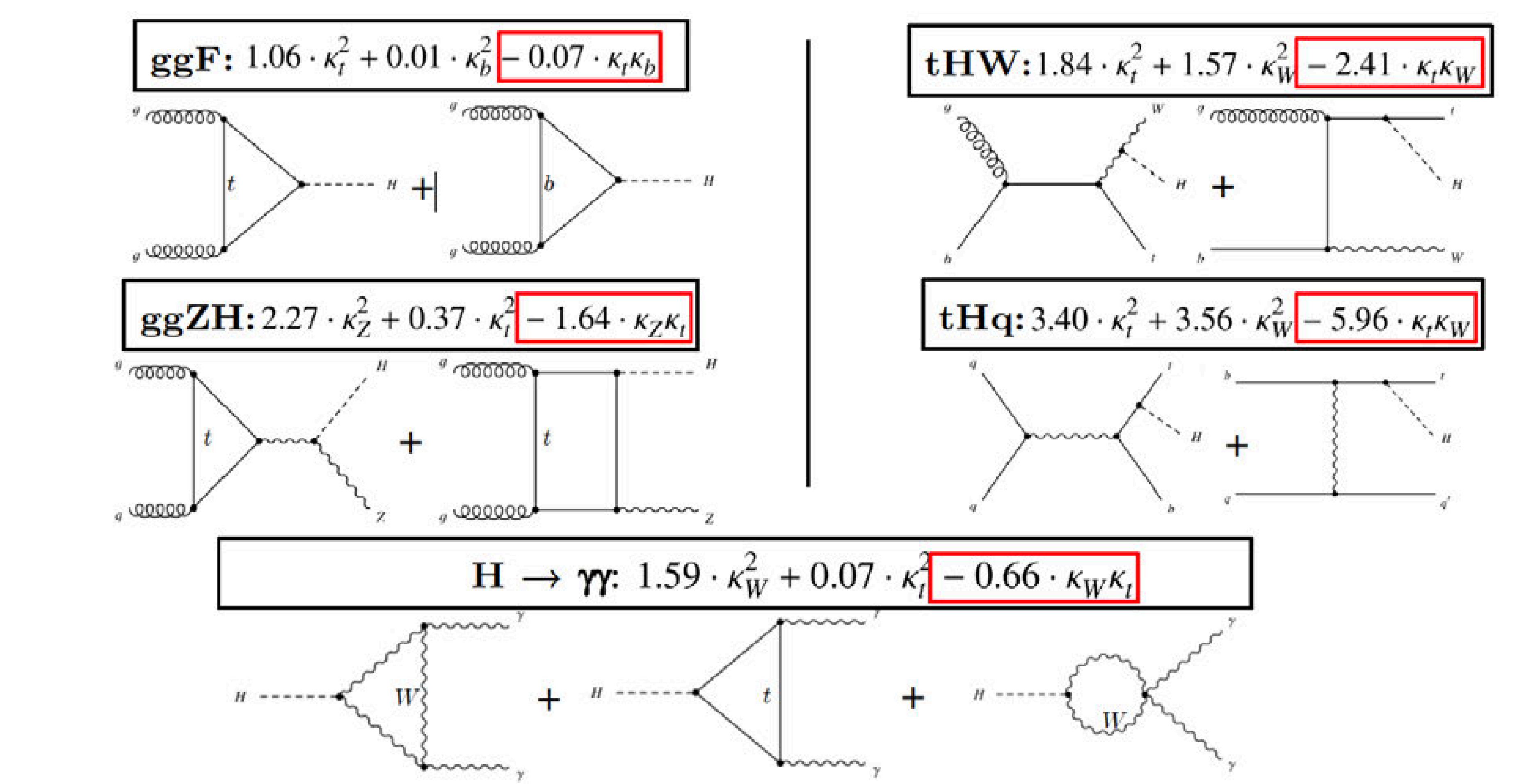






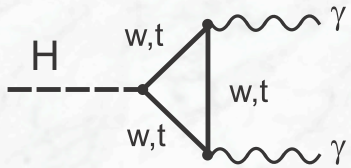
Higgs boson couplings (in the κ framework)

- The interference effects allow to determine the relative sign between two couplings

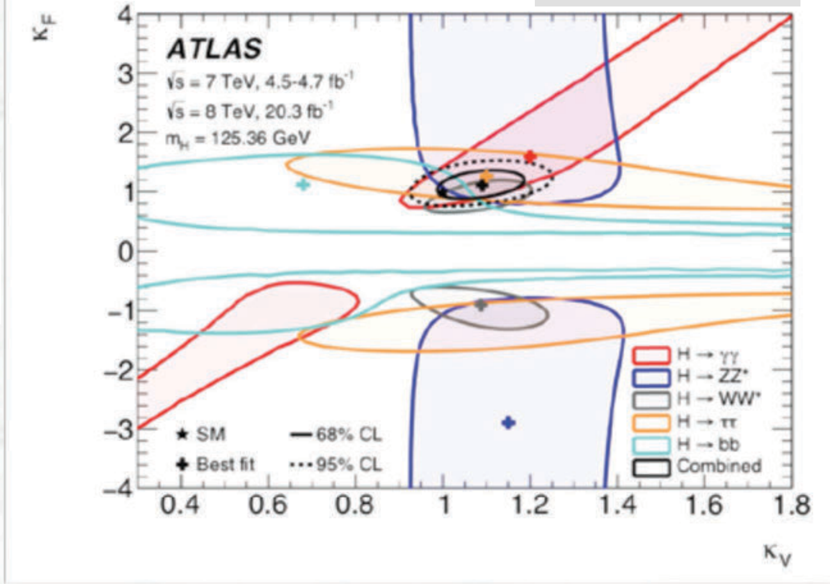


Couplings to fermions and bosons

- Assume only one scale factor for fermion and vector couplings:
  $\kappa_V = \kappa_W = \kappa_Z$ and $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$
- Assume that H → γγ and gg → H loops and the total Higgs boson width depend only on κ_V and κ_F (no contributions from physics beyond the Standard Model)
- Sensitivity to relative sign between κ_F and κ_V only from interference term in H → γγ decays (assume $\kappa_V > 0$)

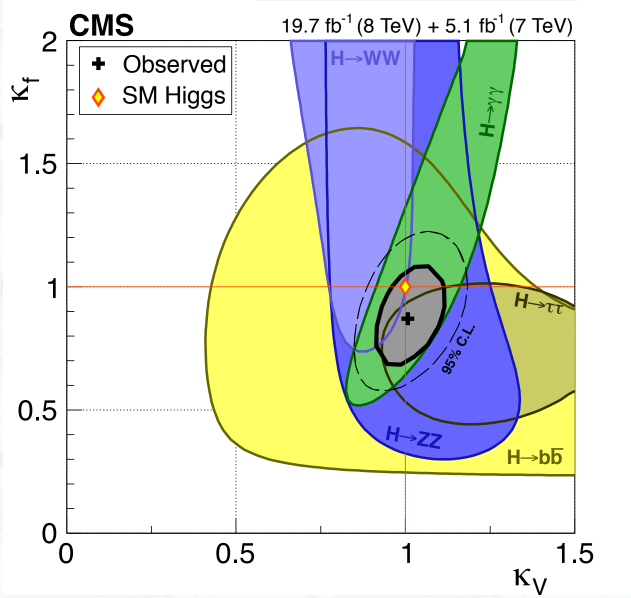


EPJ C76 (2016) 1, 6



Fit results: $\kappa_V = 1.09 \pm 0.07$
$\kappa_F = 1.11 \pm 0.16$

EPJ C75 (2015) 5, 212

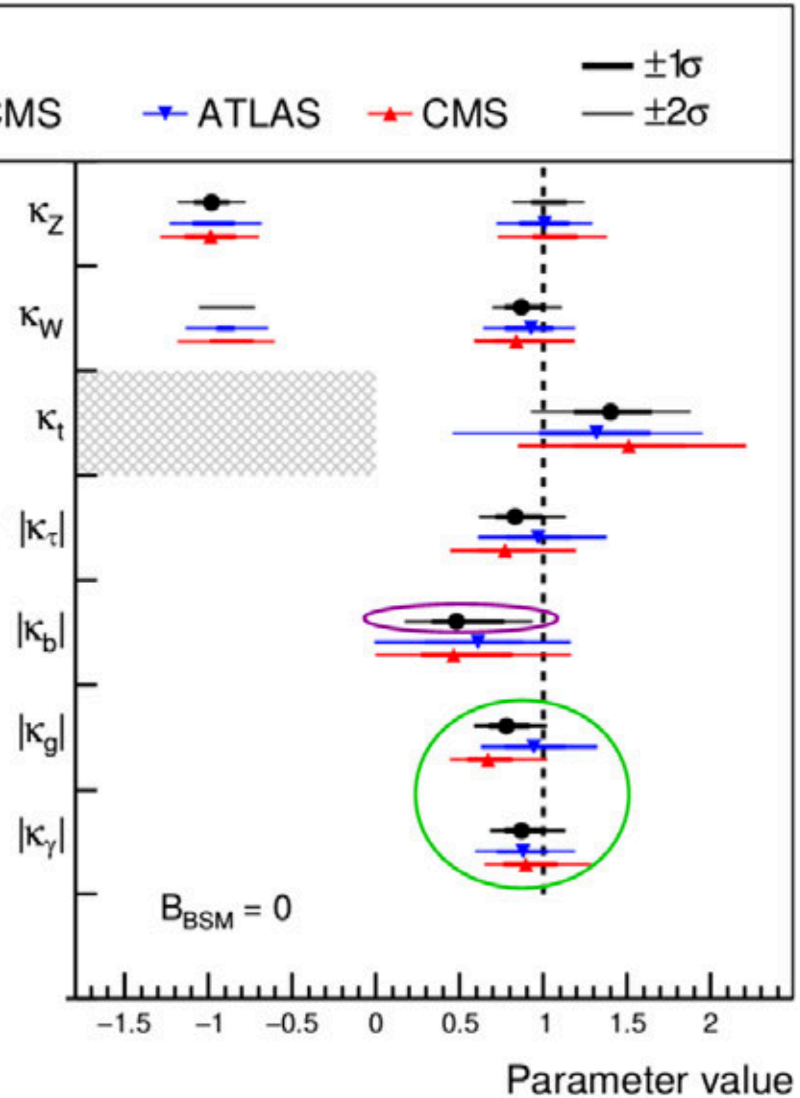


Fit results: $\kappa_V \in [0.87, 1.14]$ (95% CL)
$\kappa_F \in [0.63, 1.15]$ (95% CL)

Fits for individual κ values within the SM

arXiv:1606.02266

- All κ_i are compatible with the SM within 2σ, but $\kappa_b = 0.49^{+0.27}_{-0.15}$.
- $\kappa_{g/\gamma}$ compatible with SM:
  - $\kappa_g = 0.81^{+0.13}_{-0.10}$
  - $\kappa_\gamma = 0.90^{+0.10}_{-0.09}$
- **Global p-value compatibility with SM is 11%.**



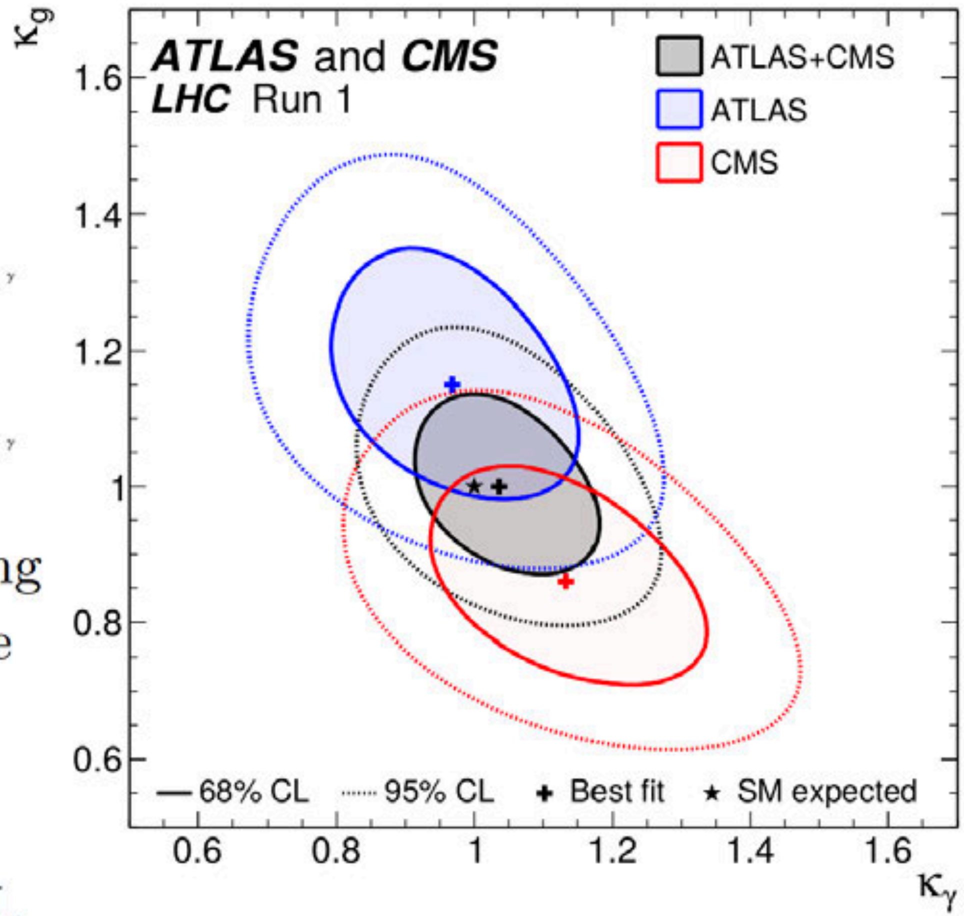
Higgs boson couplings

- Effective loop couplings-

arXiv:1606.02266

- New Physics could modify the effective Higgs-gluon and Higgs-γ couplings.

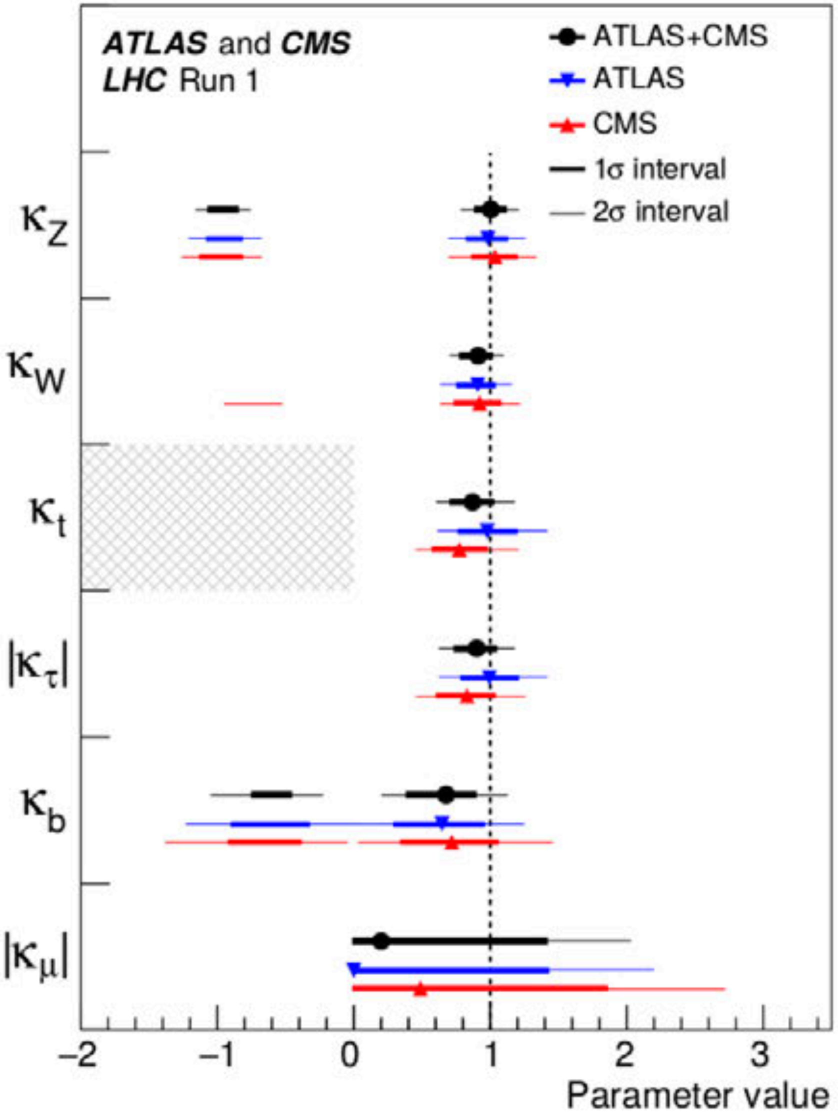
- They have been fitted fixing all other parameters to the SM prediction.
- Both κ_γ and κ_g have been found compatible with SM.



Higgs boson couplings

-The Standard Model fit-

arXiv:1606.02266



- Assuming loops with SM structures and no BSM decays, the fit is still compatible with the SM prediction.
- **The p-value compatibility data/SM is 74%.**

Higgs boson couplings

-The Standard Model fit-

arXiv:1606.02266

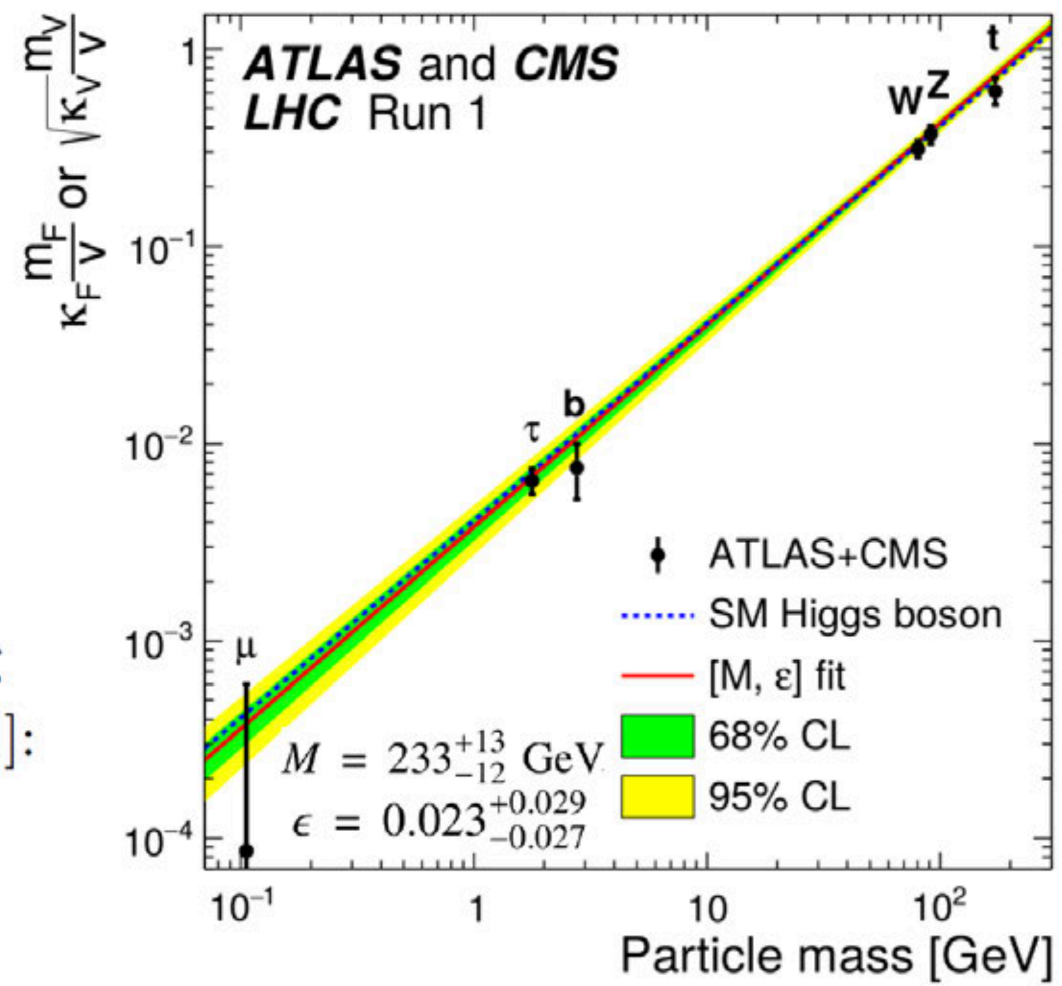
- The dependence of couplings vs particle mass have been checked using:
  - $y = k_F \frac{m_F}{v}$ (fermions);
  - $y = \sqrt{k_V} \frac{m_V}{v}$ (bosons);

  (v = 246 GeV).

- Data fitted directly using two degrees of freedom [1]:

$$\kappa_{V,i} = v \cdot m_{V,i}^{2\epsilon}/M^{1+2\epsilon}.$$

$$\kappa_{F,i} = v \cdot m_{F,i}^{\epsilon}/M^{1+\epsilon}$$



[1] JHEP **06** (2013) 103

For the first time, non-universal, mass-dependent couplings observed

Higgs boson couplings

-The most general model: ratios of coupling modifiers-

$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

- The coupling modifiers can also be fitted using σ_i and B_f, normalized to a reference process, e.g. gg → H → ZZ

  → it becomes independent from the Higgs boson width (and the corresponding assumptions, as always used so far)

  → Highest model independence at the LHC

- In this case the fit parameters correspond to ratios modifiers λ

Coupling modifier ratio parameterisation
$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$
$\lambda_{Zg} = \kappa_Z / \kappa_g$
$\lambda_{tg} = \kappa_t / \kappa_g$
$\lambda_{WZ} = \kappa_W / \kappa_Z$
$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$
$\lambda_{\tau Z} = \kappa_\tau / \kappa_Z$
$\lambda_{bZ} = \kappa_b / \kappa_Z$

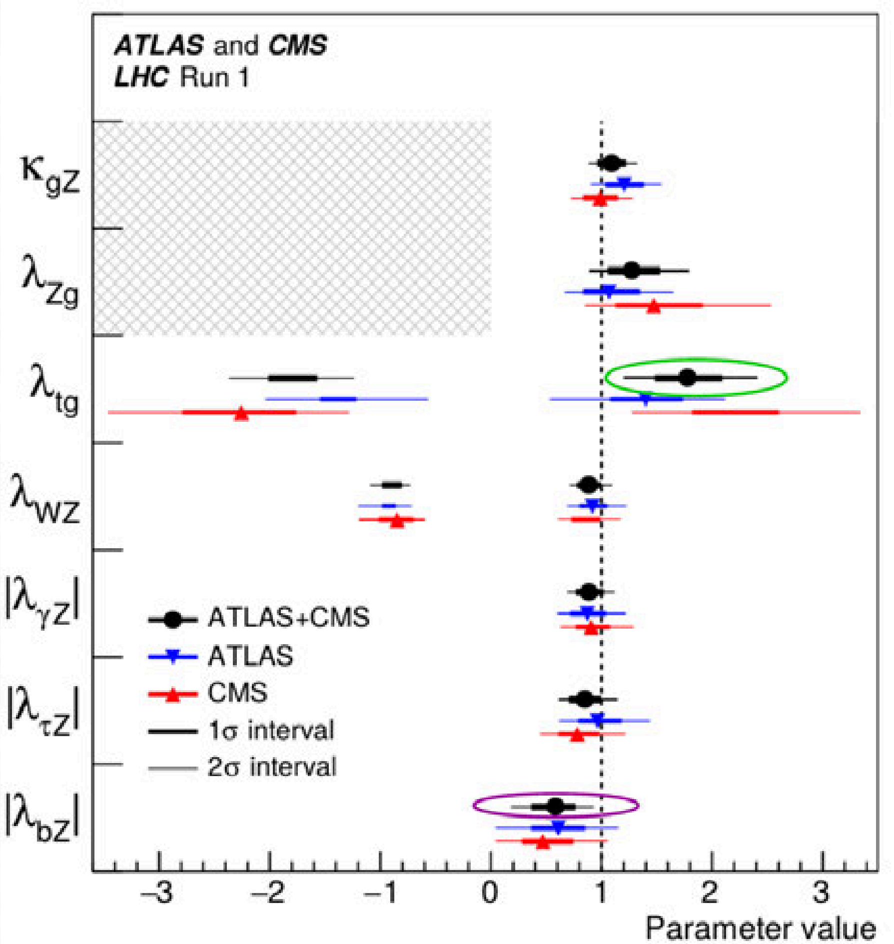
- Example: ttH → bb + X

$$\sigma_{ttH} B^{bb} / \sigma_{ggF} B^{ZZ} = k_t^2 k_b^2 / k_g^2 k_Z^2 = \lambda_{tg}^2 \lambda_{bZ}^2$$

Higgs boson couplings

-The most general model: ratios of coupling modifiers-

arXiv:1606.02266



λ_{WZ}: test of custodial symmetry
$\lambda_{\gamma Z}$: sensitive to new charged particles in H → γγ loop w.r.t H→ZZ decays
λ_{tg} : sensitive to new coloured particles contributing to gg → H production w.r.t. ttH production

- In general, good agreement with the Standard model

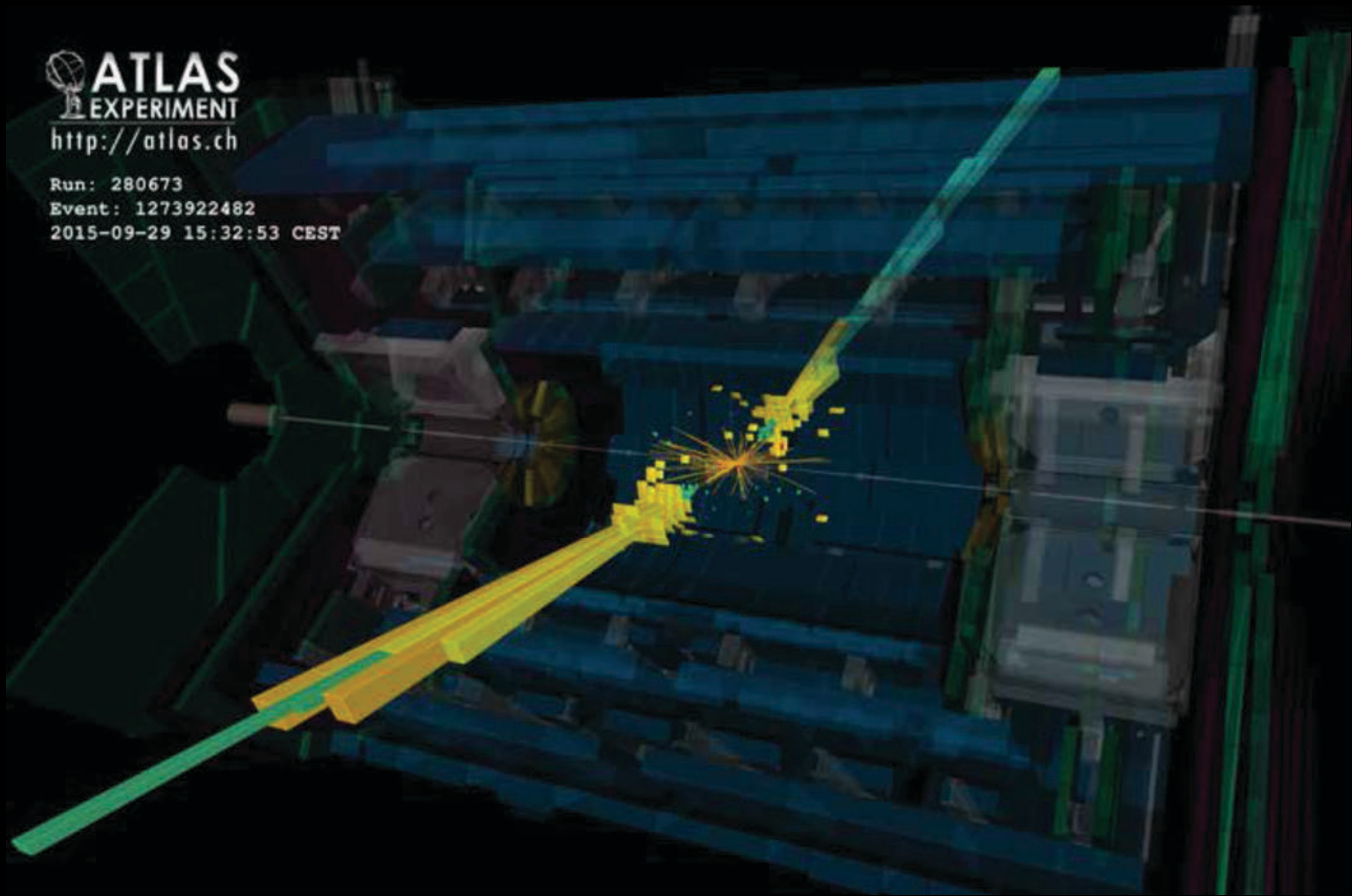
  Compatibility: 13%

- λ_{tg} somewhat high, due to the large ttH rate, but statistically not significant;
  λ_{bZ} somewhat low due to low H → bb rate;

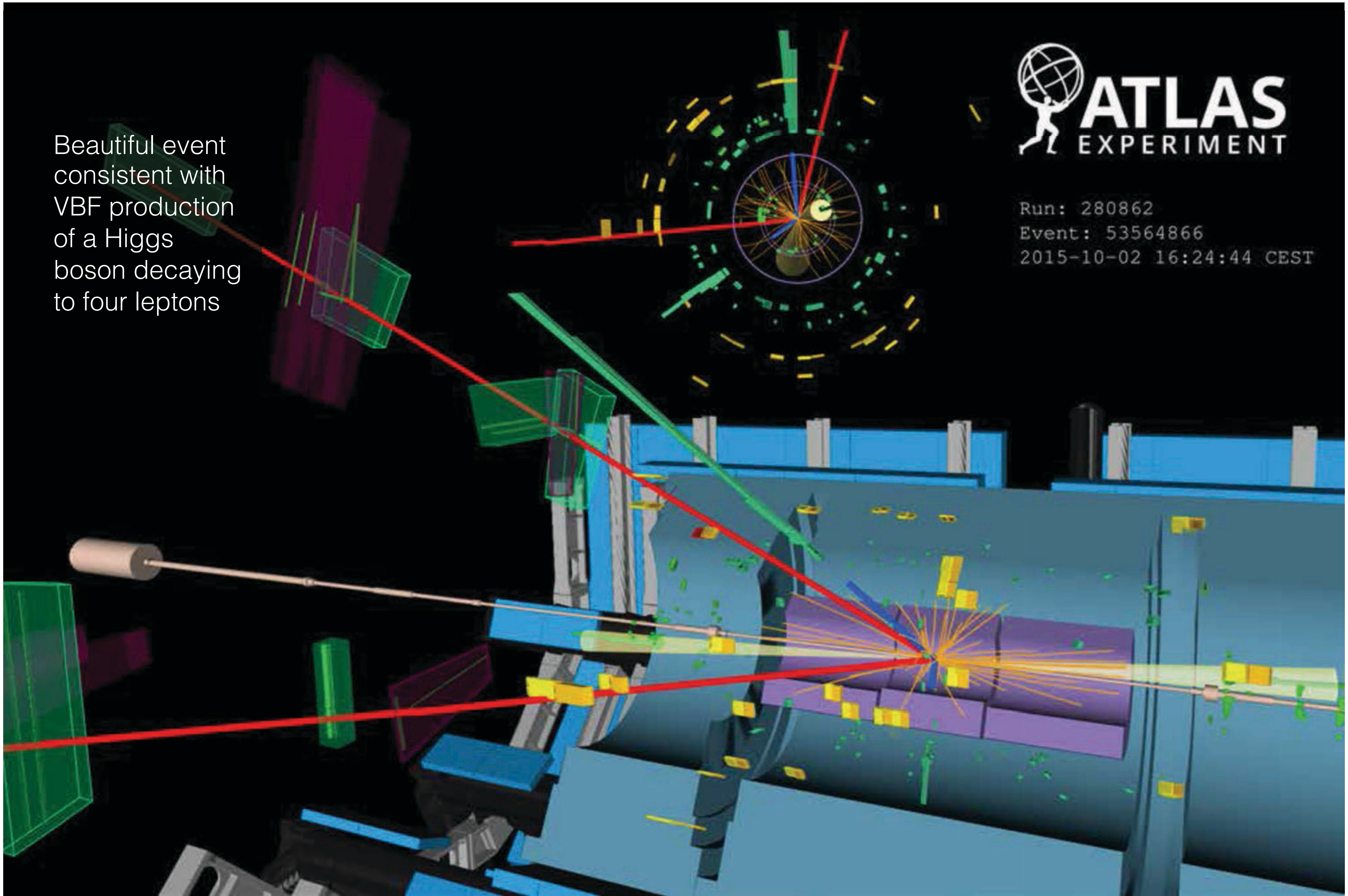
$$\lambda_{tg} = 1.78^{+0.30}_{-0.27}$$
$$|\lambda_{bZ}| = 0.58^{+0.16}_{-0.20}$$

- Large potential for increasing the overall precision in Run 2

First results from LHC Run 2



Highest mass dijet event measured by ATLAS in 2015 ($\sqrt{s}$ = 13 TeV): m_{jj} = 6.9 TeV



Display of $H \to ee\mu\mu$ candidate from 13 TeV pp collisions. The electrons have a transverse momentum of 111 and 16 GeV, the muons 18 and 17 GeV, and the jets 118 and 54 GeV. The invariant mass of the four lepton system is 129 GeV, the dielectron (dimuon) invariant mass is 91 (29) GeV, the pseudorapidity difference between the two jets is 6.4 and the dijet invariant mass is 2 TeV.

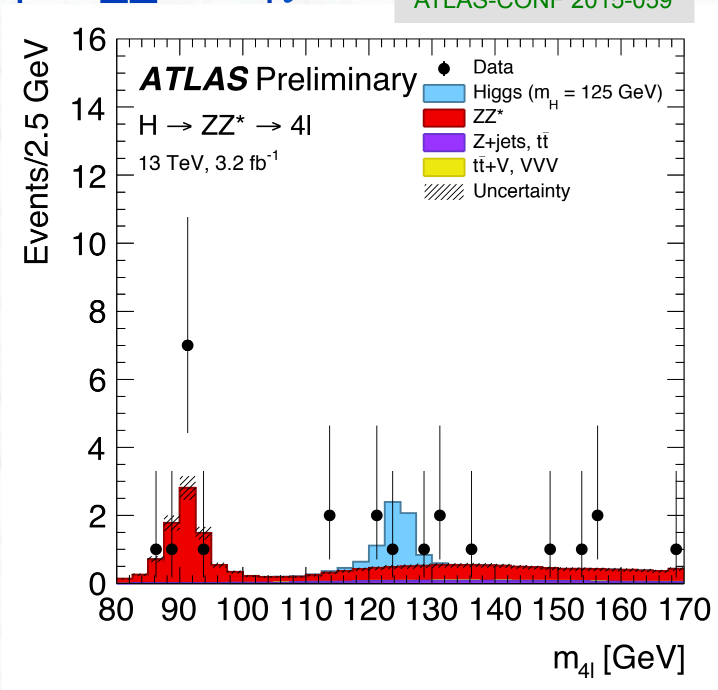
Current 13 TeV data sample still marginal for H_{125}

But important to look for the signal in an agnostic way at new CM energy

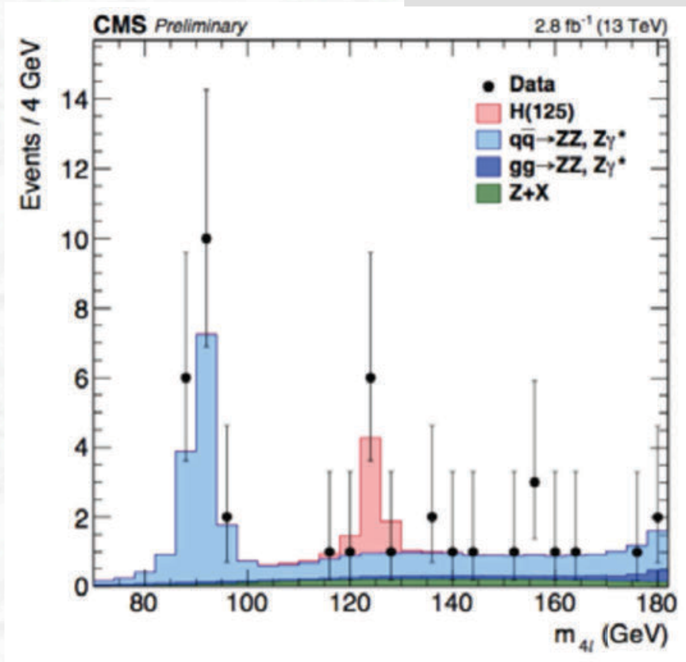
ATLAS & CMS looked for Higgs boson decays to bosonic and fermionic channels

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

ATLAS-CONF 2015-059



CMS-PAS-HIG-15-004



$\sigma_{tot,data} = 12^{+25}_{-16}$ pb

$\sigma_{tot,SM} = 51 \pm 5$ pb

Expected significance (SM): 2.8σ

$\mu = \sigma_{data} / \sigma_{SM} = 0.82^{+0.57}_{-0.43}$

Expected significance (SM): 3.4σ

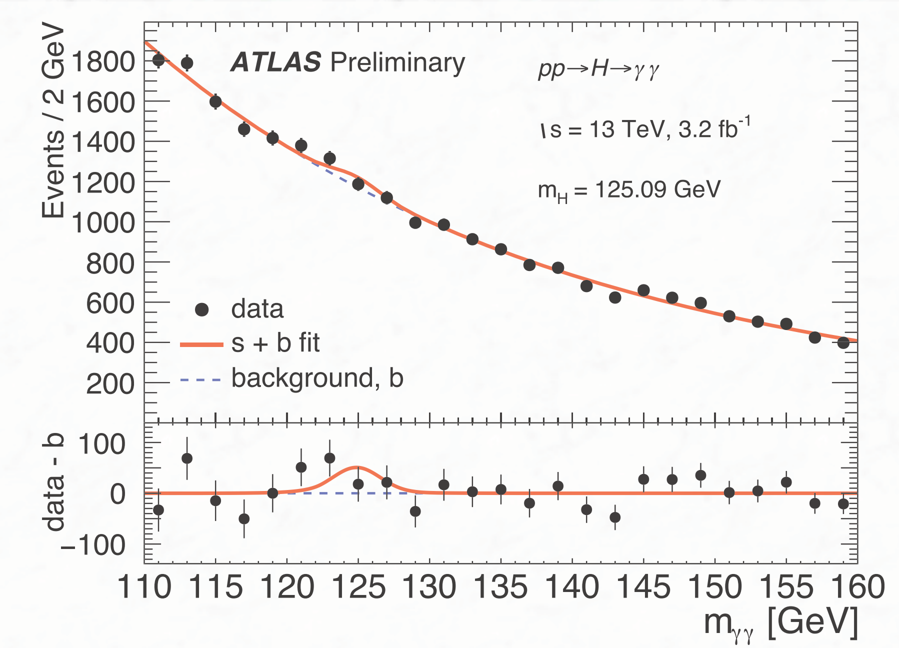
Current 13 TeV data sample still marginal for H_{125}

But important to look for the signal in an agnostic way at new CM energy

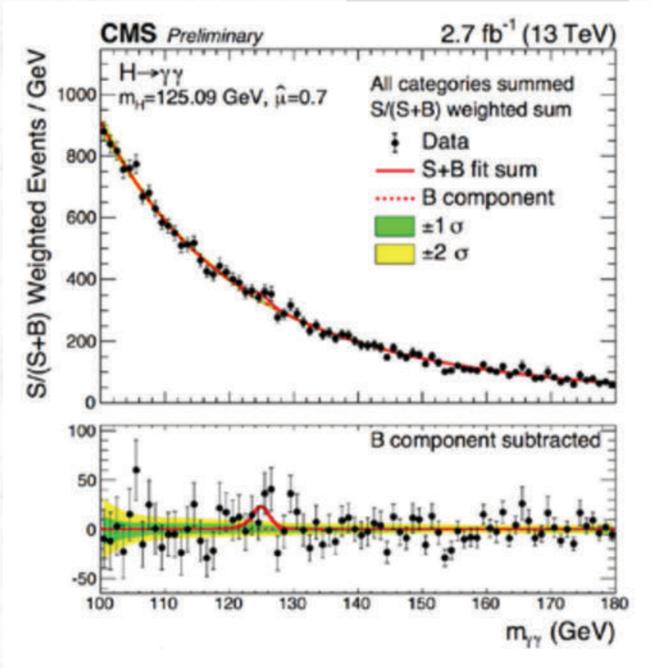
ATLAS & CMS looked for Higgs decays to bosonic and fermionic channels

$H \rightarrow \gamma\gamma$

ATLAS-CONF 2015-060



CMS-PAS-HIG-15-005



$\sigma_{tot,data} = 40 \pm 26\,^{+16}_{-10} \pm 2_{lumi}$ pb

$\sigma_{tot,SM} = 51 \pm 5$ pb

Expected significance (SM): 1.9σ

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

Expected significance (SM): 2.7σ

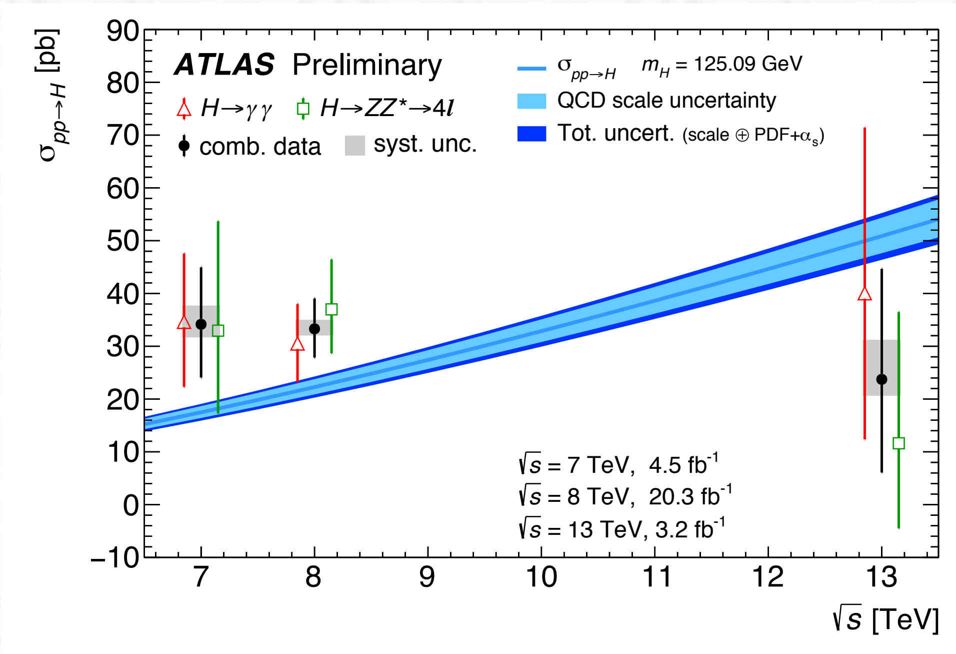
Current 13 TeV data sample still marginal for H_{125}

But important to look for the signal in an agnostic way at new CM energy

ATLAS & CMS looked for Higgs decays to bosonic and fermionic channels

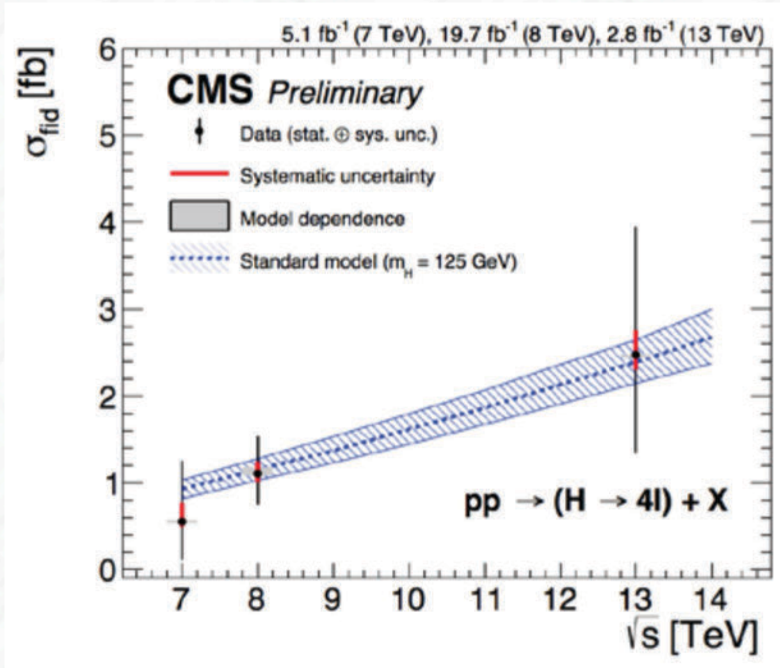
Extracted cross sections vs CM energy

Combined H → 4ℓ, γγ



ATLAS-CONF 2015-069

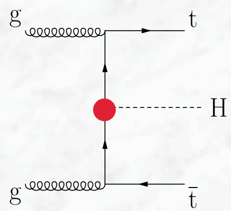
H → 4ℓ, *fiducial* cross section



CMS-PAS-HIG-15-004

Current 13 TeV data sample still marginal for H_{125}

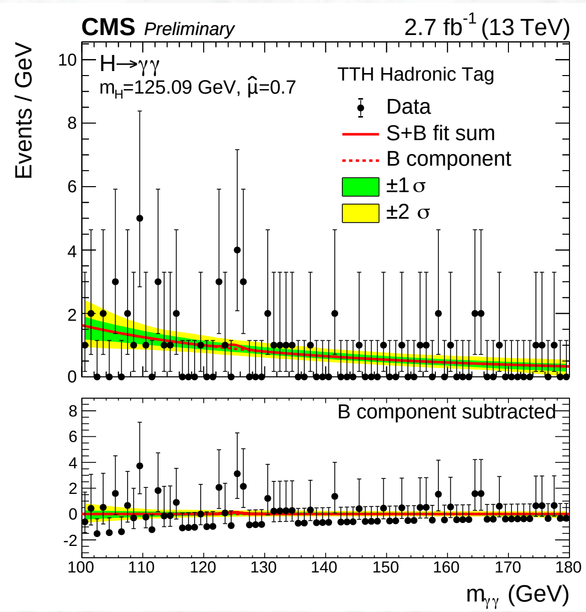
But important to look for the signal in an agnostic way at new CM energy

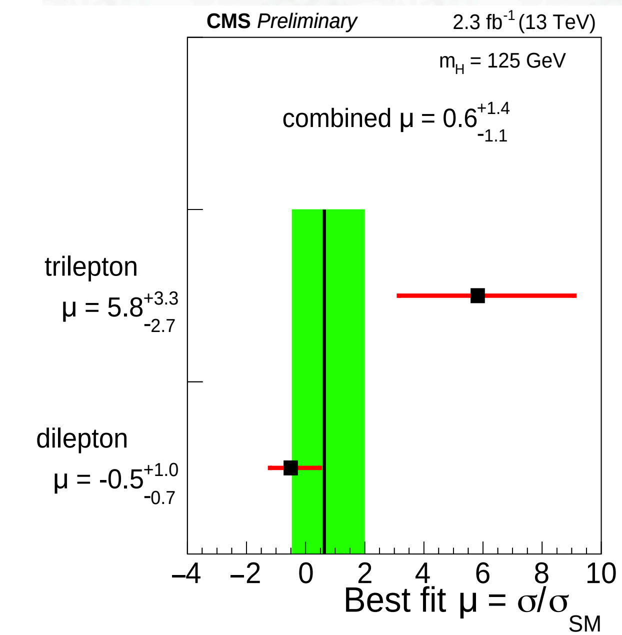


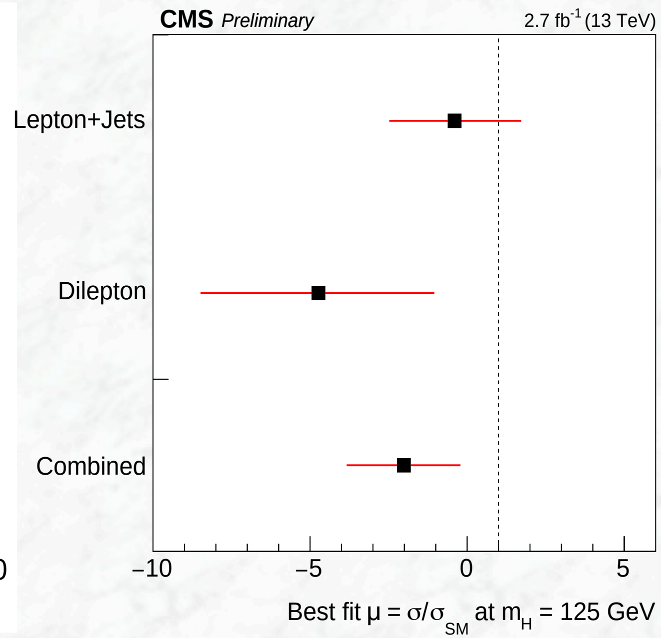
CMS showed preliminary results for ttH in all major Higgs decay channels:
H → γγ, multi-leptons, bb

Highly complex analyses, huge effort to get these done so quickly after data taking

H → γγ, tt → 0 & 1 leptons	ttH → multi-leptons, 2 same charge / 3 leptons	H → bb, tt → 1 & 2 leptons







$\mu = 3.8^{+4.5}_{-3.6}$	$\mu = 0.6^{+1.4}_{-1.1}$	$\mu = -2.0 \pm 1.8 < 2.6$ (95% CL)
CMS-PAS-HIG-15-005	CMS-PAS-HIG-15-008	CMS-PAS-HIG-16-004

Additional Higgs bosons?

Composite Higgs bosons

MSSM Higgs bosons

Dark Higgs

More Higgs bosons

Heidi Higgs

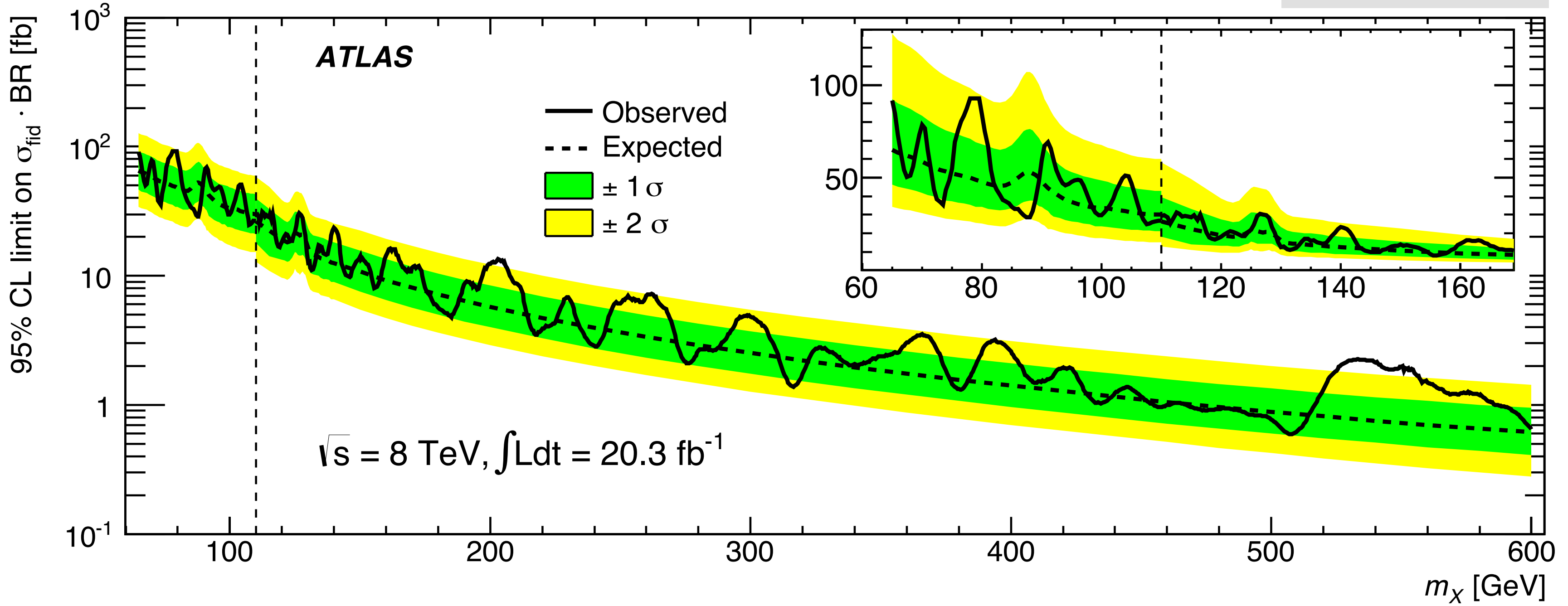
SUSY Higgs

No Higgs at the LHC

Search for Additional Higgs Bosons
-a few examples-

(i) Results of an ATLAS search on additional resonances X decaying into $\gamma\gamma$

PRL 113 (2014) 171801



Observed and expected 95% CL limits on the fiducial cross section times branching ration BR(X → $\gamma\gamma$) as a function of mass

(note: 125 GeV signal was treated as “background” and contribution was subtracted)

Diphoton resonance searches: ATLAS

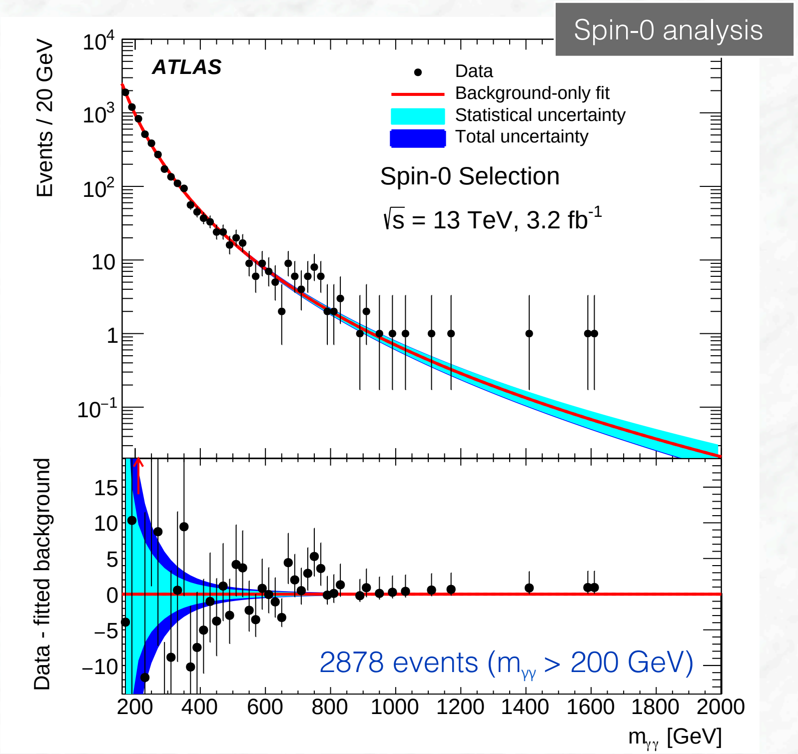
Dedicated searches for a spin-0 and a spin-2 diphoton resonance.

arXiv: 1606.03833

Main difference is acceptance: spin-0: $E_T(\gamma_1) > 0.4 \cdot m_{\gamma\gamma}$, $E_T(\gamma_2) > 0.3 \cdot m_{\gamma\gamma}$, spin-2: $E_T(\gamma_{1/2}) > 55$ GeV

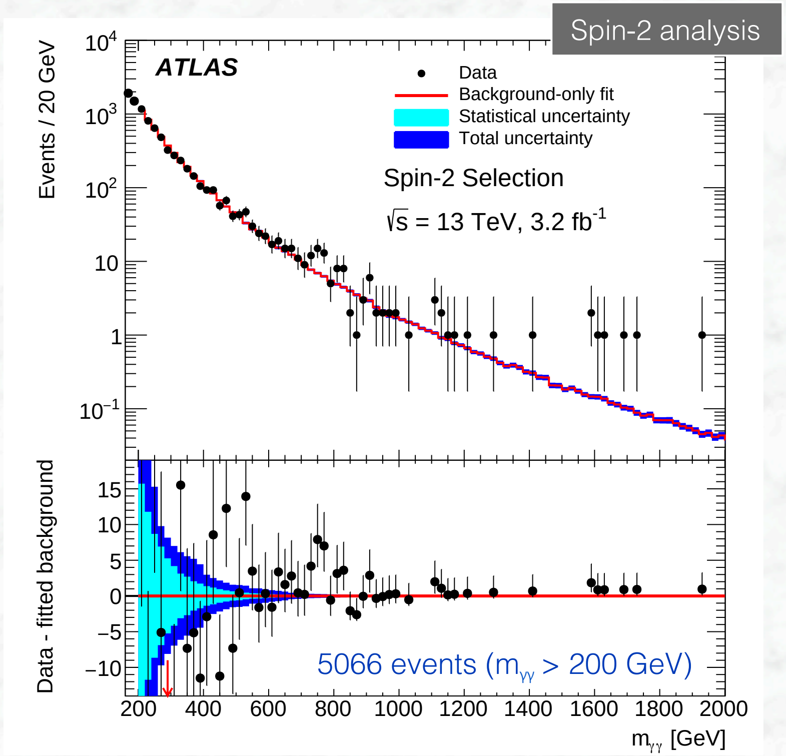
Photons are tightly identified and isolated. Typical purity ~94%

Background modelling empirical in spin-0, and (mainly) theoretical in spin-2 case (for high-mass search)



Lowest p-value at ~750 GeV, Γ ~ 45 GeV (6%)

Local / **global Z** = 3.9 / **2.1σ**



Lowest p-value at ~750 GeV, Γ ~ 7% of mass

Local / **global Z** = 3.8 / **2.1σ**

Diphoton resonance searches: CMS

Agnostic search for spin 0 and 2 bosons

arXiv:1606.04093

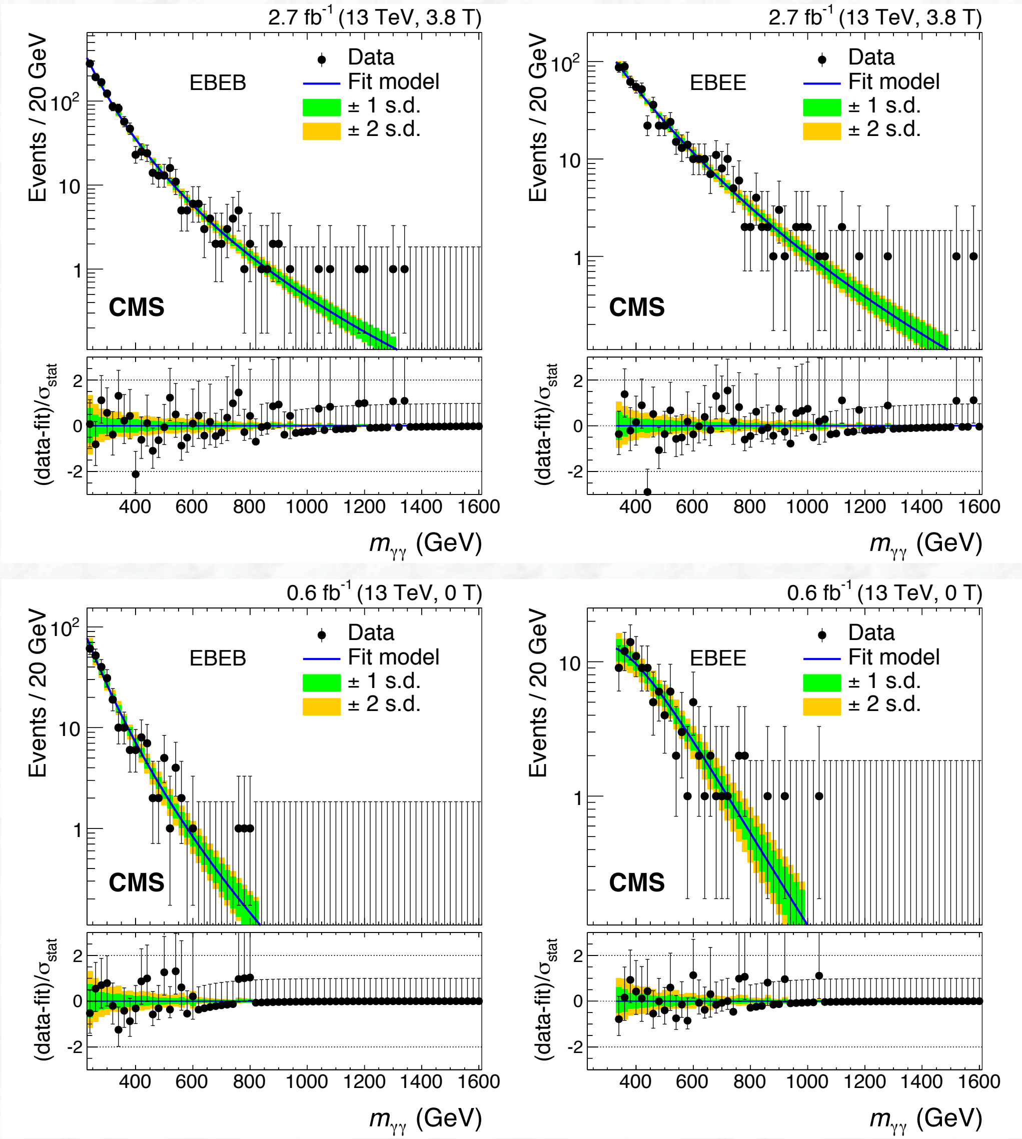
New 13 TeV analysis with improved ECAL calibration (~30% improved resolution above $m_{\gamma\gamma}$ ~ 500 GeV), and including 0.6 fb^{-1} of B-field off data

- Acceptance: $E_T(\gamma_{1/2}) > 75$ GeV, at least one γ with $|\eta| < 1.44$ (barrel), split EB-EB, EB-EE
- Dedicated calibration of B-field-off data, slightly lower γ-ID efficiency, better resolution, harder PV finding
- Empirical background modelling
- Combination of 13 & 8 TeV data (model-dependent, good compatibility)

Lowest p-value at ~750 GeV (760 for 13 TeV data only), narrow width

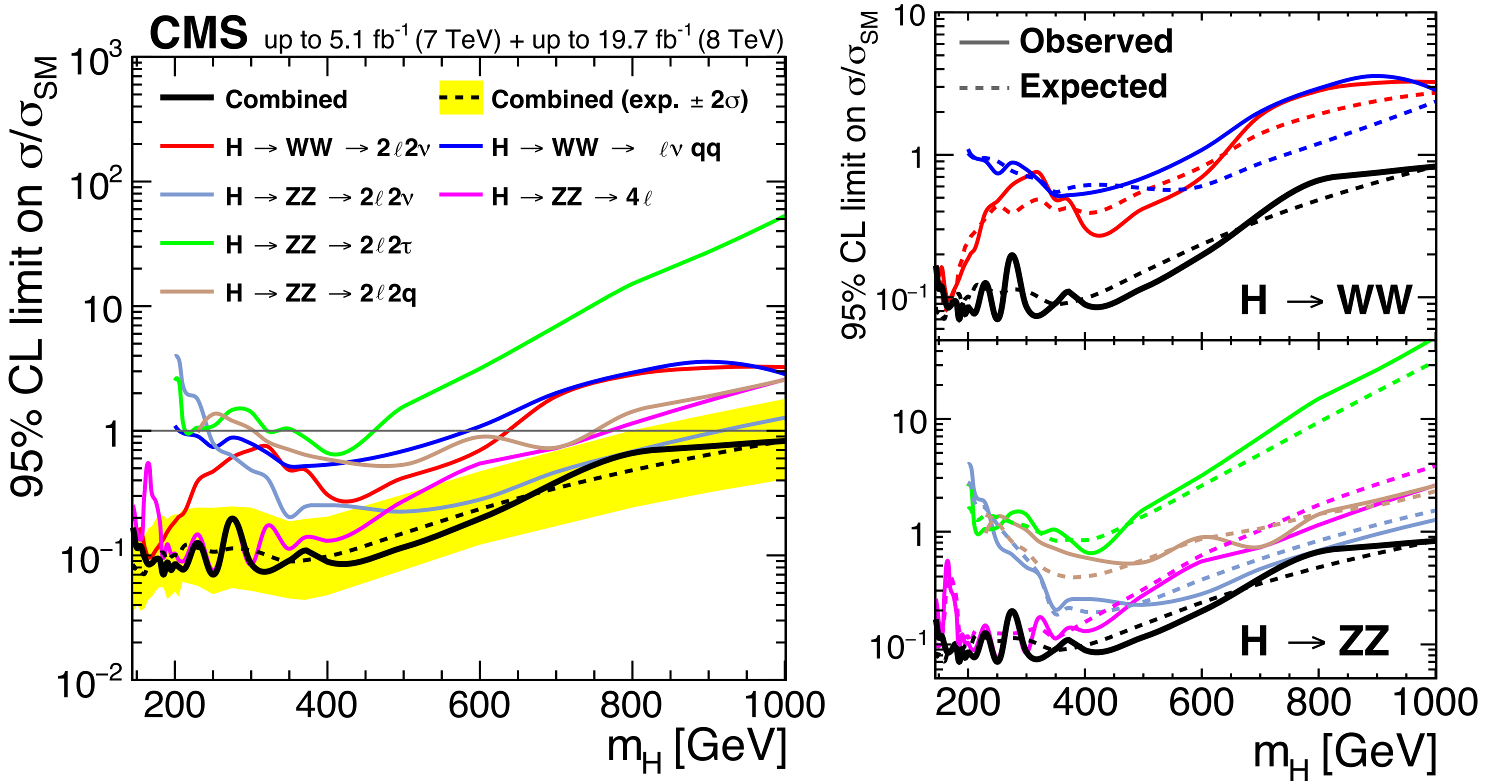
Local / **global Z** = 3.4σ / **1.6σ** (2.9σ / **< 1** for 13 TeV data only)

No compelling evidence for signal. More data needed.



(ii) Results of a CMS search on additional SM-like Higgs bosons decaying into ZZ and WW

arXiv:1504.00936

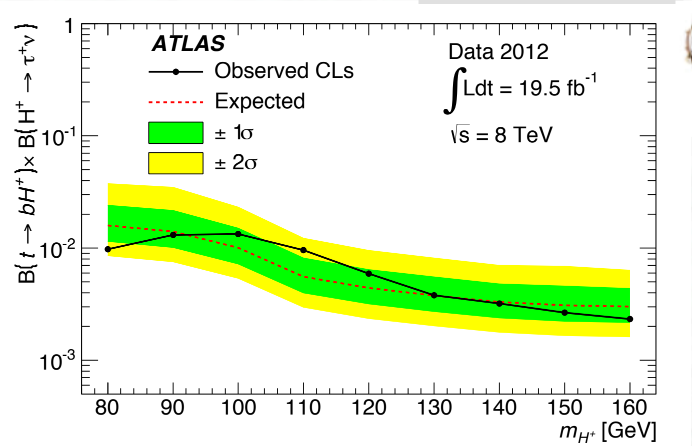


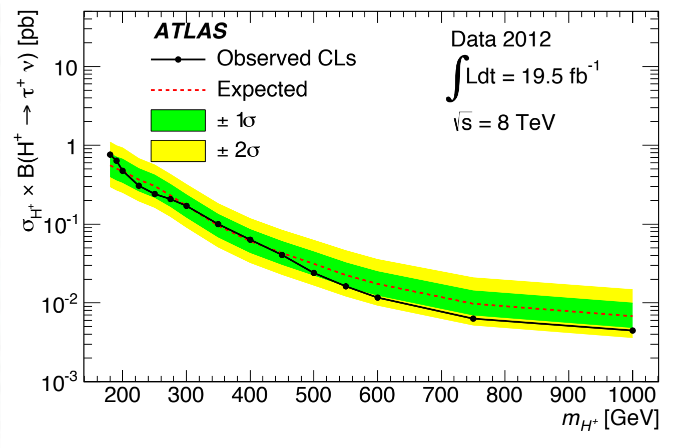
Observed and expected 95% CL limits on the cross section normalised to the SM value for individual channels and their combination

(iii) Search for charged and heavy neutral MSSM Higgs bosons

Search for $H^{\pm} \rightarrow \tau\nu$ decays via
tt production or $tH^{\pm}$ associated production

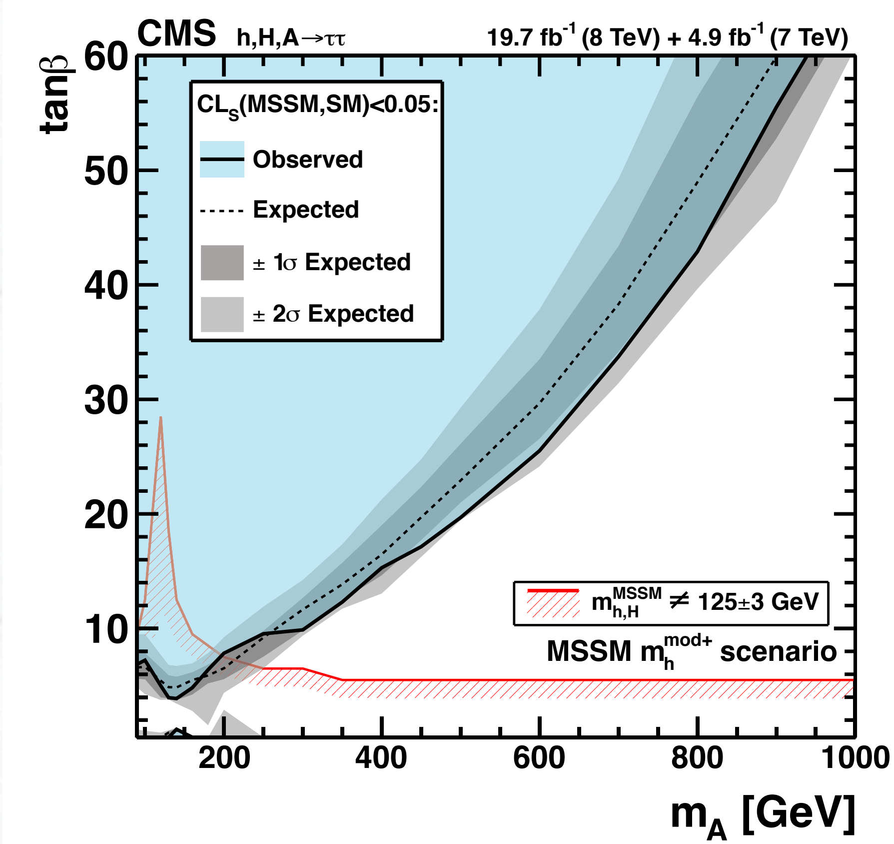
JHEP 03 (2015) 088





95% CL exclusion limits on branching ratios or cross sections times branching ratio

JHEP 10 (2014) 160



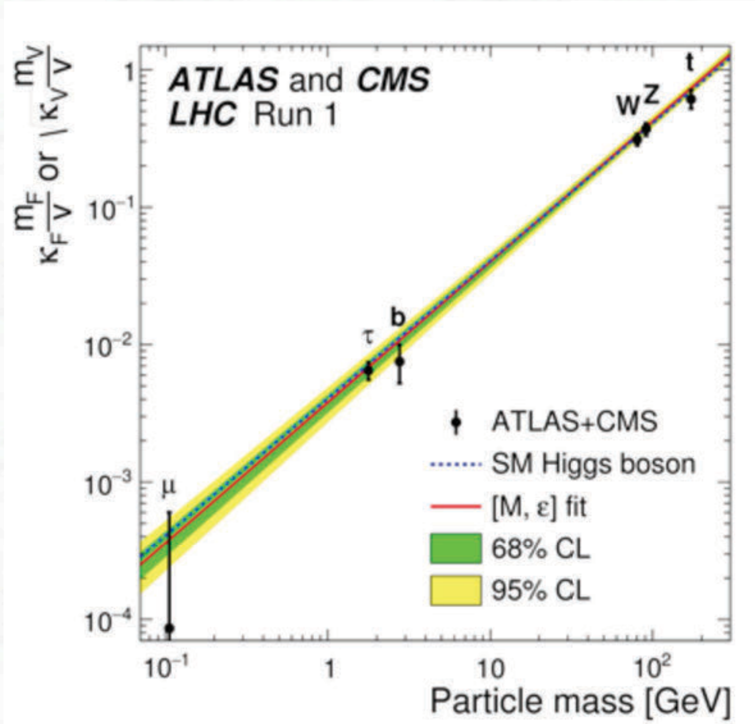
Expected and observed exclusion limits at 95% CL in the (m_A–tan β) parameter plane for the MSSM m_h^{mod+} benchmark scenario

Conclusions

- The analyses of the complete LHC Run 1 dataset by the ATLAS and CMS experiments have consolidated the milestone discovery announced in July 2012

- Properties of the particle (J^{CP}, couplings) are in very good agreement with those expected for the Standard Model Higgs boson

  The experiments have moved from the discovery to the measurement phase;



- Many measurements still statistically limited
  → significant improvements expected in Run 2 and beyond

  → Higgs particle might be the portal to new physics

- Exciting times ahead of us, with new, unexplored energy regime in reach