Measurements of the properties of the Higgs boson with the ATLAS Detector

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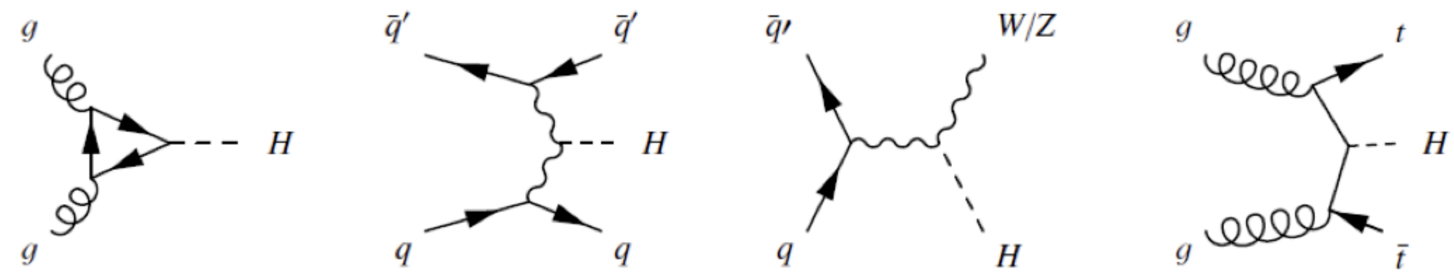
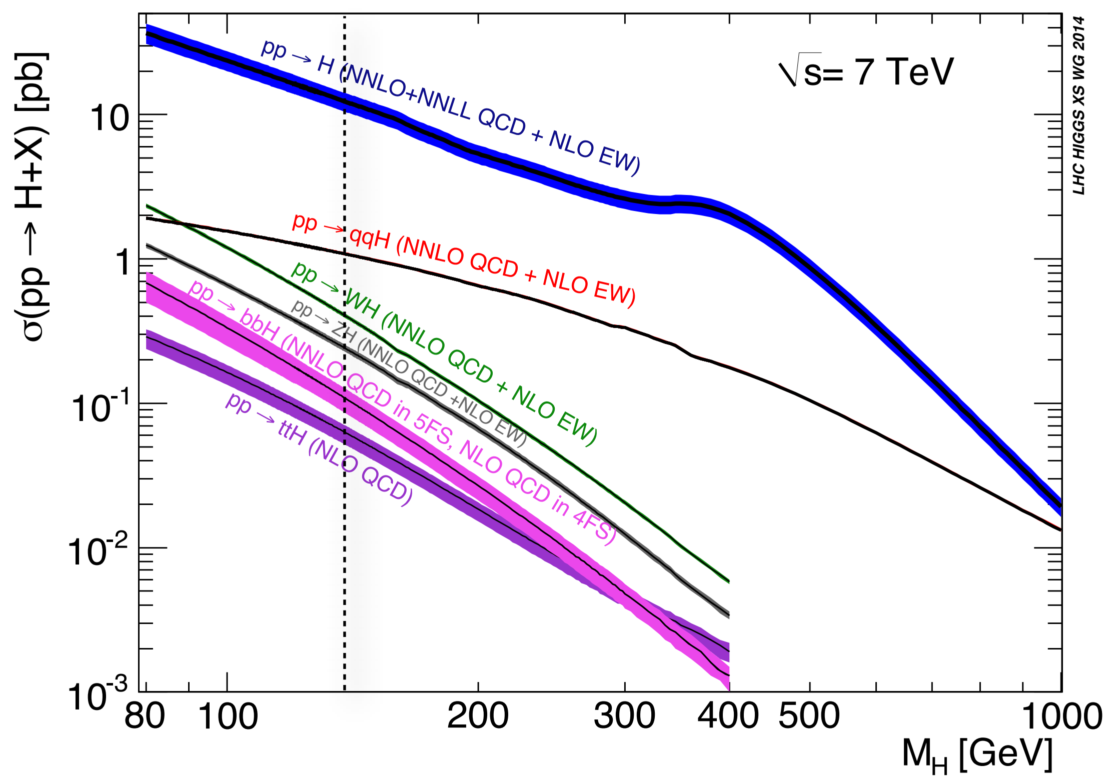
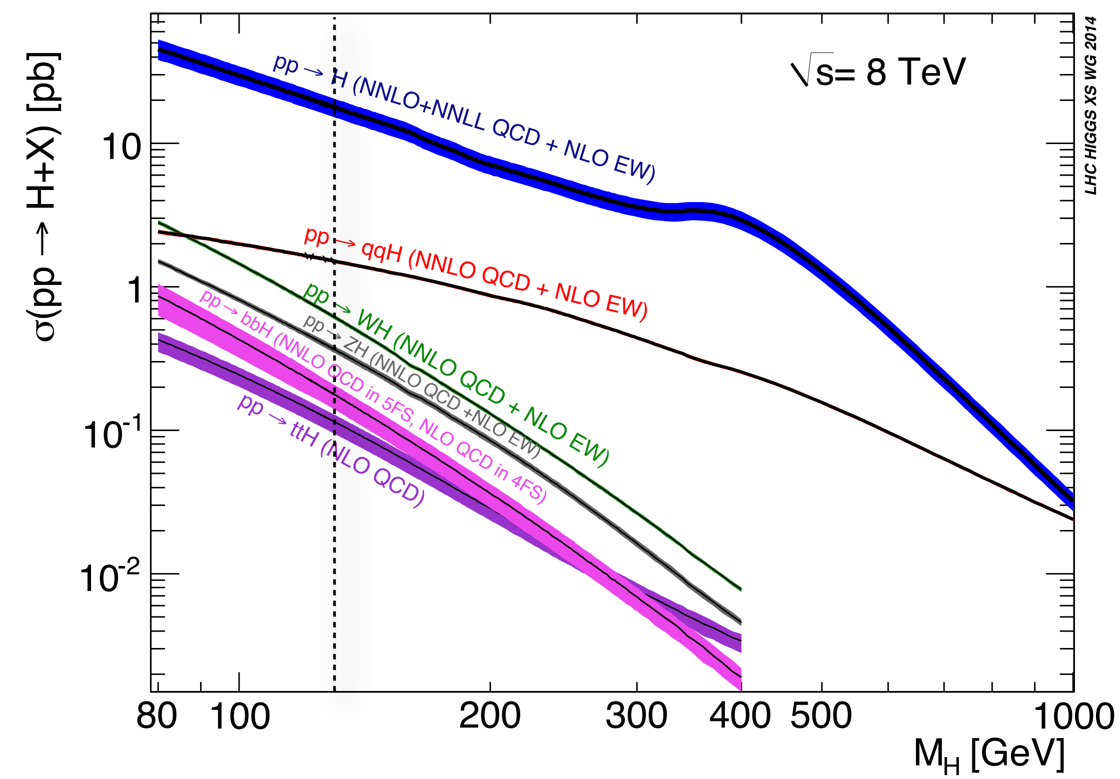
Higgs boson production at LHC







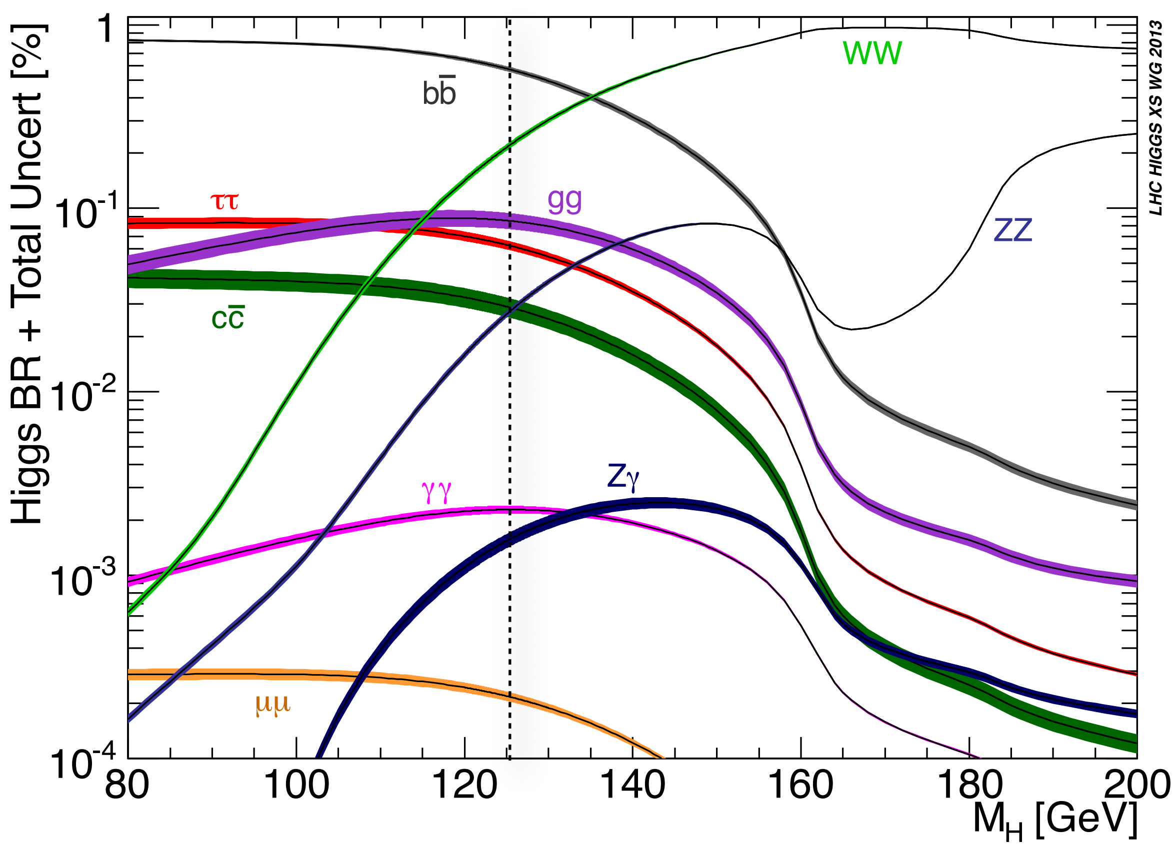
[LHC Higgs Cross Section WG - arXiv:1101.0593, arXiv:1201.3084 and arXiv:1307.1347]

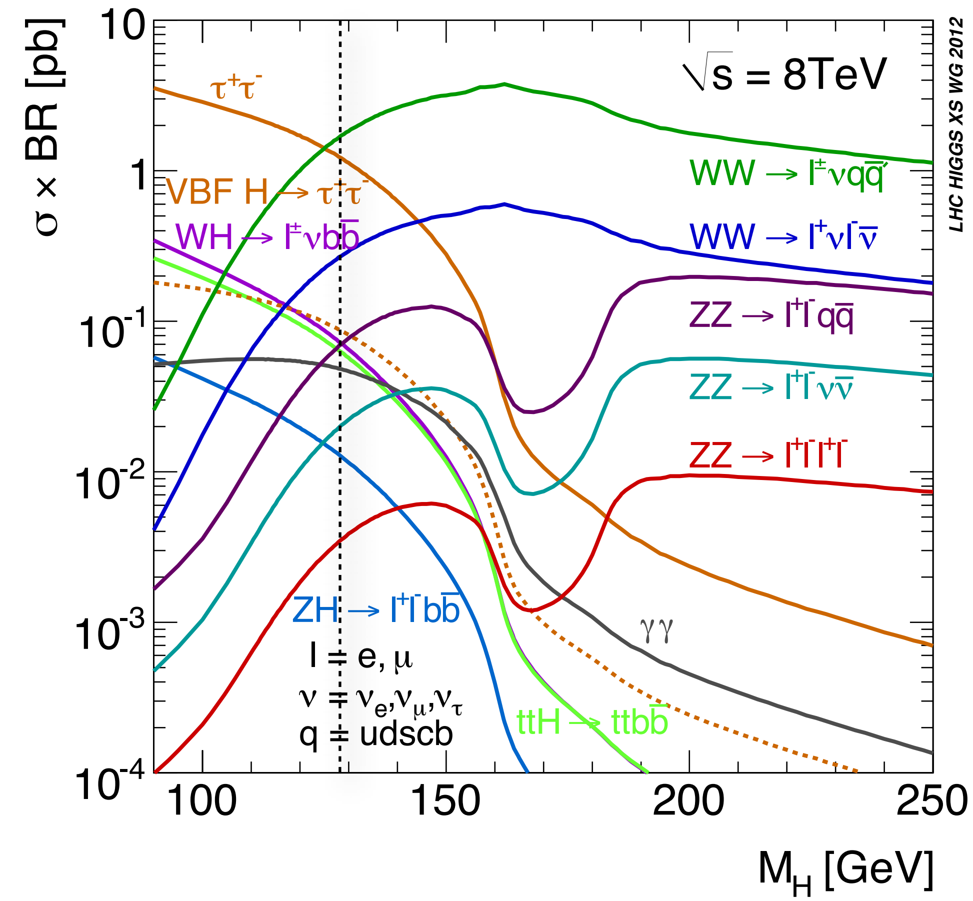
Production process	Cross section [pb] $\sqrt{s}=7$ TeV	Cross section [pb] $\sqrt{s}=8$ TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58±0.04	NLO (QCD+EW)/NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.357 ± 0.015	0.446 ± 0.019	NNLO(QCD)+NLO(EW)
$b\bar{b}$H	0.156 ± 0.021	0.203 ± 0.028	5FS + 4FS NLO(QCD)
$t\bar{t}$H	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)

- A lot of progress on cross section and BR computation
- Uncertainties O(10%) in ggF, dominated by QCD scale and PDF+α_S

Higgs boson decays

- All hadronic decay modes ($H \to b\bar{b}$ and $H \to ZZ, W^+W^- \to q\bar{q}q\bar{q}$) dominant but overwhelmed by QCD backgrounds $\to$ final states with isolated leptons, photons, missing transverse energy are the only viable ones at LHC

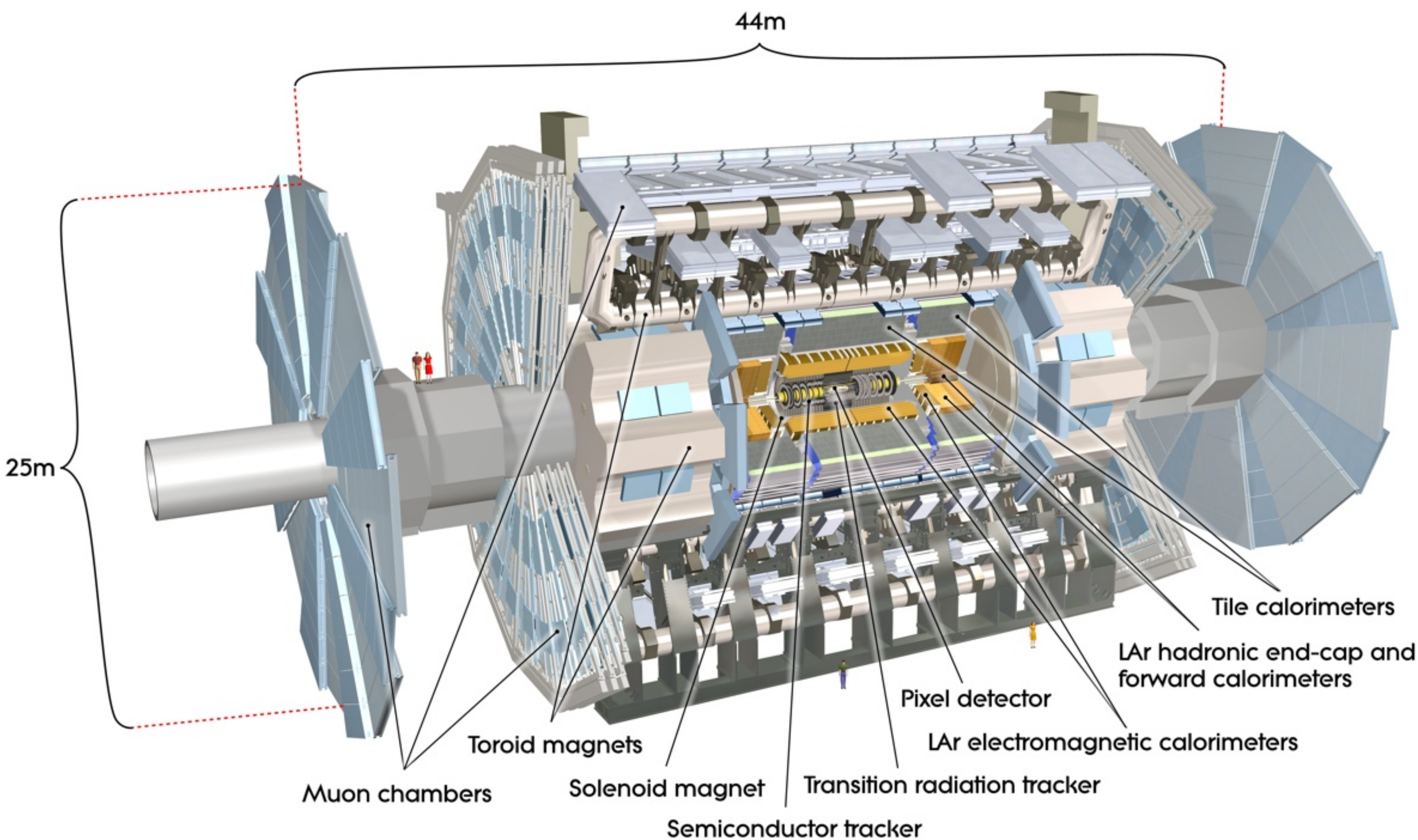




[LHC Higgs Cross Section WG - arXiv:1101.0593, arXiv:1201.3084 and arXiv:1307.1347]

$H \to$	BR (@M_H = 125 GeV)	$\sigma \cdot BR$ [fb]	events produced with 25 fb^{-1}	mass resolution	background
$\gamma\gamma$	$2.28 \cdot 10^{-3}$	50	1250	😊😊	☹
$ZZ^* \to 4l$	$1.25 \cdot 10^{-4}$	2.7	67	😊😊	😊
$WW^* \to l\nu l\nu$	$1.06 \cdot 10^{-2}$	230	5700	☹☹☹	☹
$\tau^+\tau^-$ (VBF)	$6.32 \cdot 10^{-2}$	100	2500	☹	☹☹
$b\bar{b}$ (VH)	$5.77 \cdot 10^{-1}$	106	2600	☹	☹☹

ATLAS Detector



ATLAS EXPERIMENT

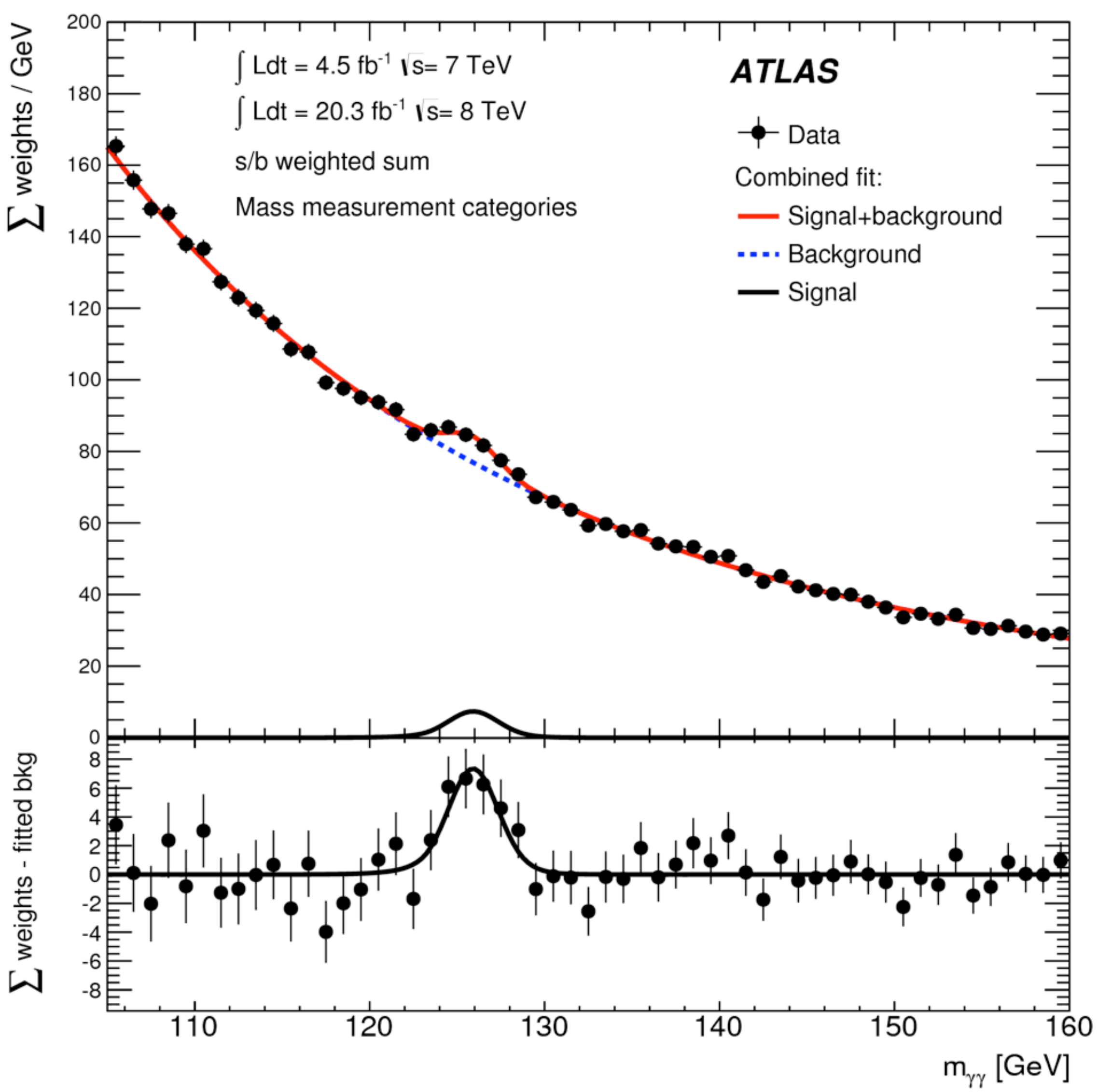
Higgs boson mass and width

[*Measurement of the Higgs boson mass from the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ channels with the ATLAS detector using 25 fb^{-1} of pp collision data* - Phys. Rev. D. 90, 052004 (2014)]

[*Constraints on the off-shell Higgs boson signal strength in the high-mass ZZ and WW final states with the ATLAS detector* - Eur. Phys. J. C (2015) 75:335]

Higgs mass measurements: $H \to \gamma\gamma$

- ATLAS M_H measurements use high resolution $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ channels and the full set of ~25 fb^{-1} data at $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV
- $H \to \gamma\gamma$: excellent mass resolution (1.7 GeV), narrow peak over smooth background

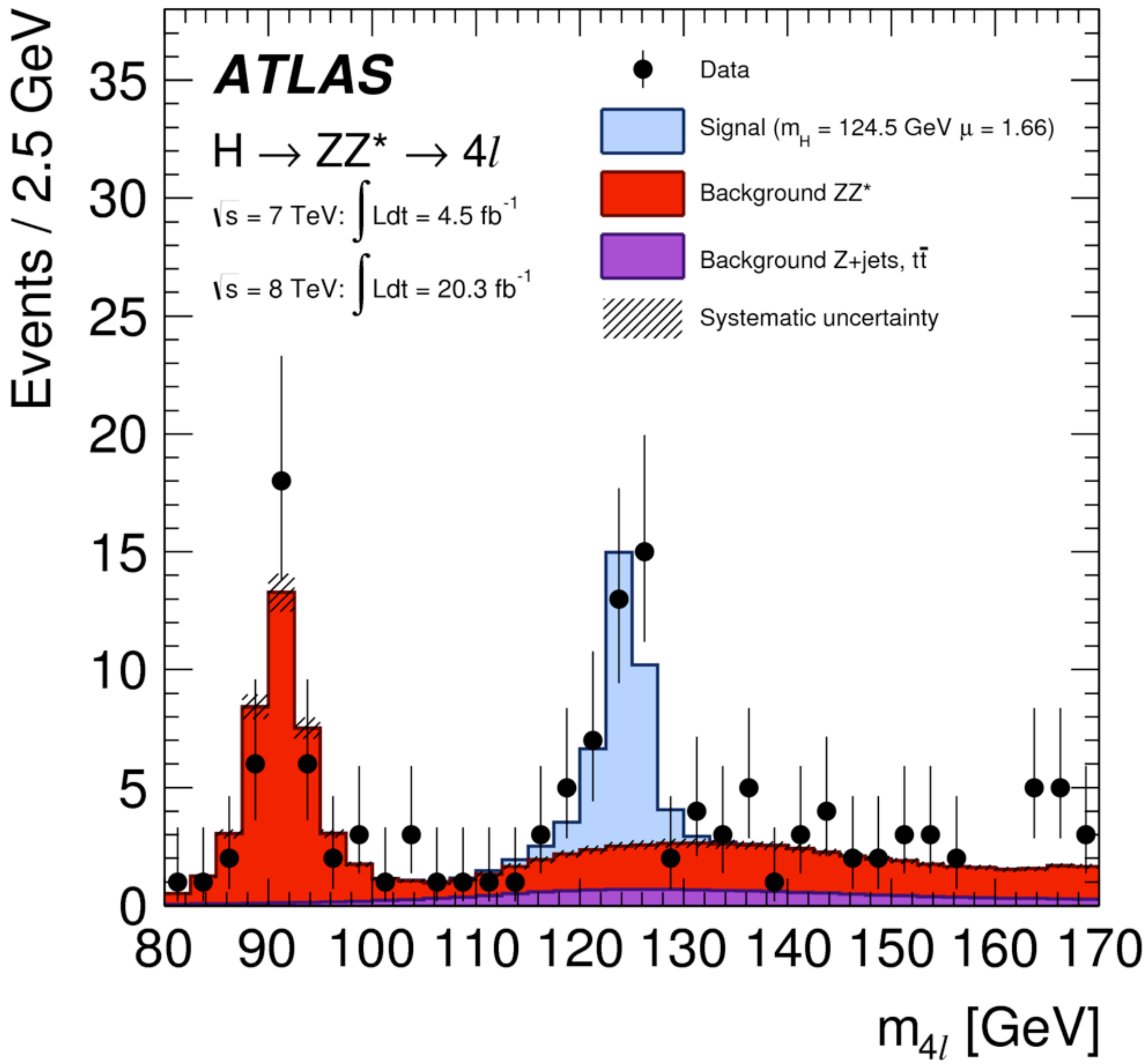


- **Mass measurement method**: simultaneous fit of mass spectra of selected diphoton events separated into 10 mutually exclusive categories - syst uncertainties treated as nuisance parameters in the likelihood
- **Signal modeling**: Crystal Ball + Gaussian
- **Background modeling and estimation**:
  - fit to diphoton mass distribution in the data over the [105, 160] GeV range
  - exponential function of first/second-order polynomial
- **Main systematics**: photon energy scale uncertainties (0.17%-0.57%)

- Results from $H \to \gamma\gamma$: **M_H = 125.98 ± 0.42(stat) ± 0.28(syst) GeV**

Higgs mass measurements: $H \rightarrow ZZ^* \rightarrow 4l$

- $H \rightarrow ZZ^* \rightarrow 4l$: high signal-to-background ratio and excellent mass resolution (1.6 - 2.2 GeV)



- **Mass measurement method**: 2D fit to m_{4l} and BDT_{ZZ} output in the [110, 140] GeV range - 1D fit to m_{4l} *as cross-check*
  - Multivariate discriminant BDT_{ZZ} reduces the impact of irreducible background
- **Background modeling**: full 2D PDF from simulation for *ZZ**, data-driven techniques for reducible background
- **Main systematics**: electron energy scale and muon momentum scale uncertainties

- Results from $H \rightarrow ZZ^* \rightarrow 4l$: **$M_H$ = 124.51 ± 0.52(stat) ± 0.06(syst) GeV**

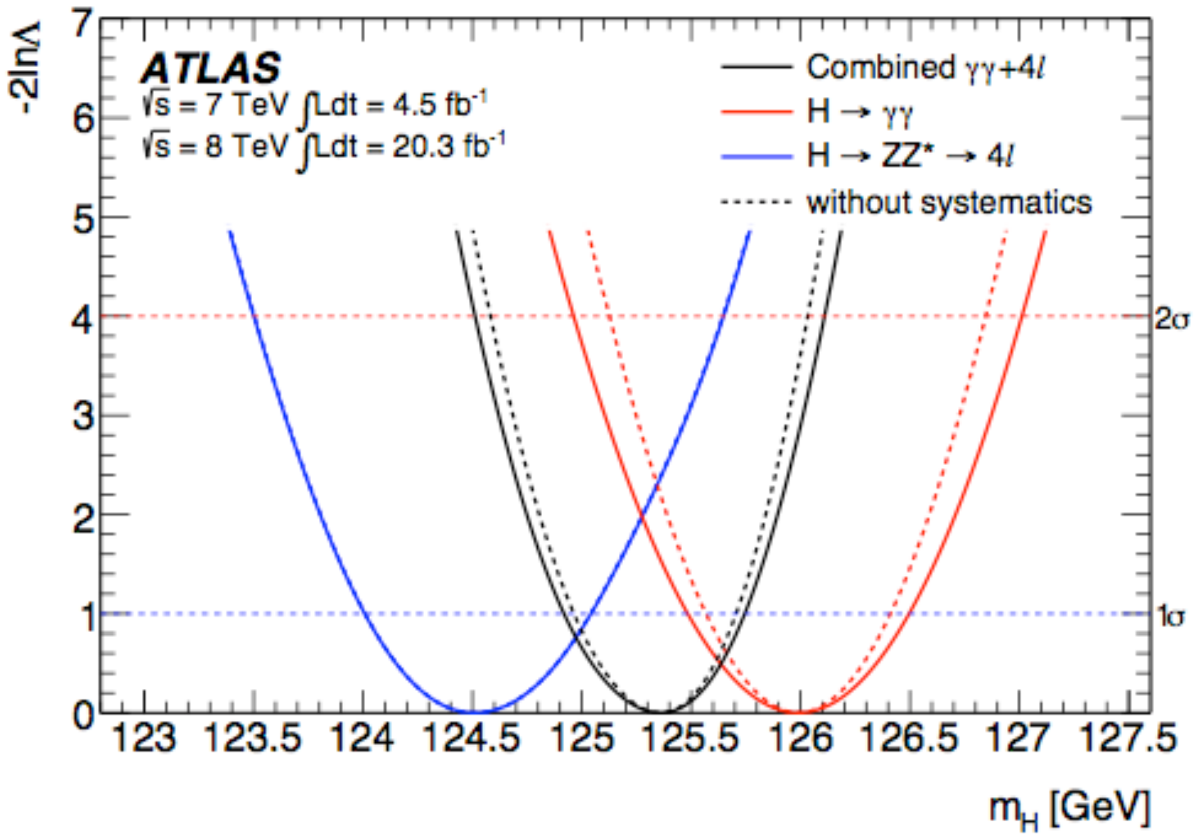
Combined mass measurement results

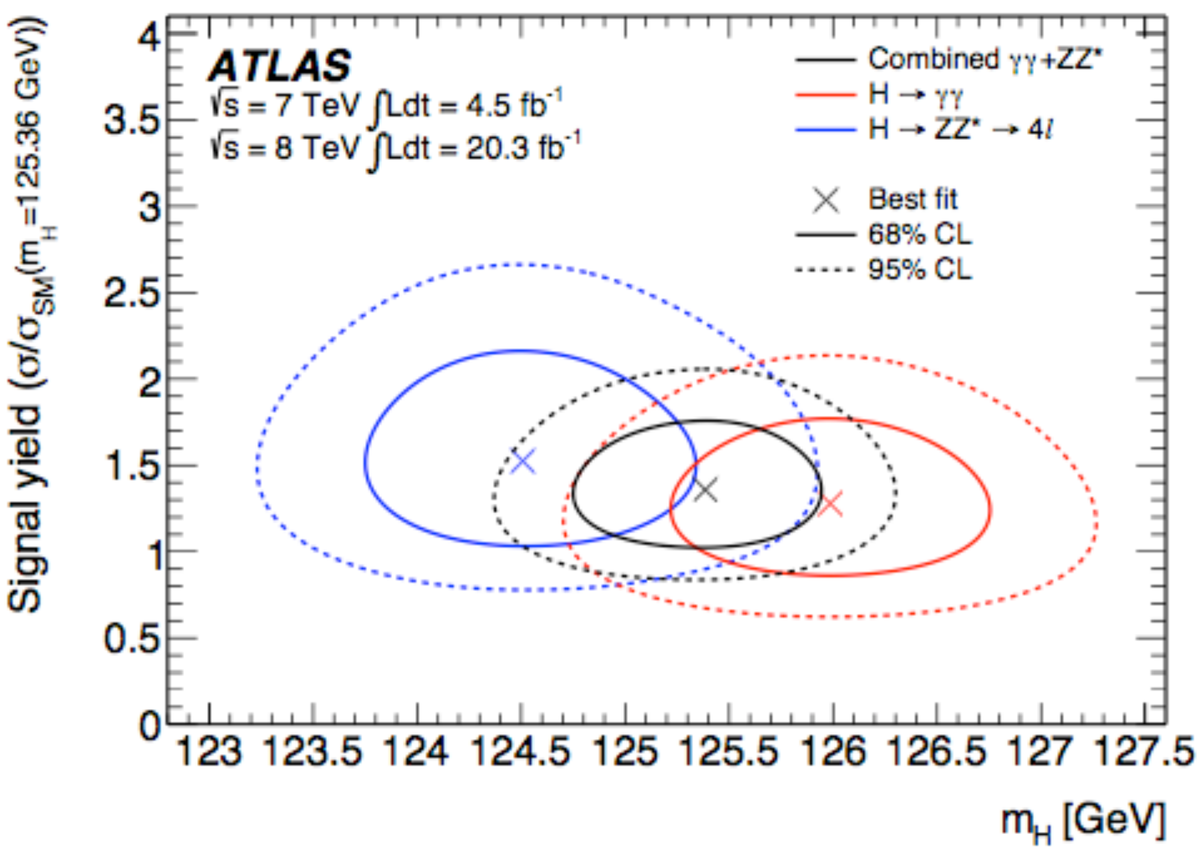
- Hypothesized values of m_H are tested using a profiled likelihood ratio:

$$\Lambda(m_H) = \frac{L(m_H, \hat{\hat{\mu}}_{\gamma\gamma}(m_H), \hat{\hat{\mu}}_{4l}(m_H), \hat{\hat{\theta}}(m_H))}{L(\hat{m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4l}, \hat{\theta})}$$

$\mu_{\gamma\gamma}$, μ_{4l} independent nuisance parameters

- Results are given in terms of $-2\ln\Lambda(\Delta m_H)$, assumed to follow a χ^2 distribution





- Compatibility between the two mass measurements at **2σ level**
- Results from the combination: **M_H = 125.36 ± 0.37(stat) ± 0.18(syst) GeV**
- No significant correlation between the two fitted variables → model-independence of the mass measurement

Limits on the Higgs boson total width

- **Indirect limits**: measure off- to on-shell ratio for $H \to ZZ \to 4l$, $H \to WW \to 2l2\nu$ and $H \to WW \to e\nu\mu\nu$ channels in the *high-mass off-peak regions* beyond 2m$_V$ ($V = Z, W$) → this allows to extract a limit on Γ_H/Γ_H^{SM} *under the assumption* that on-shell and off-shell couplings are identical i.e. independent from the production energy scale

$$\sigma^{off-shell\ (*)}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

$$\sigma^{on-shell}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \boxed{\Gamma_H}}$$

$g^2_{ggH} = H - g$ coupling

$g^2_{HZZ} = H - Z$ coupling

(*) calculation should include interference terms with $gg \to VV$ (huge negative effect for large m$_{4l}$)

- **Results**: 95% CL upper limit on Γ_H/Γ_H^{SM} in the **range [4.5, 7.5]** → Observed (Expected) 95%CL upper limit on the **Higgs boson total width of 22.7 (33.0) MeV** (Γ_H^{SM}= 4.12 MeV at M$_H$ = 125.4 GeV)

- **Direct limits**: from the width of the invariant mass peak, assuming no interference with background processes: observed (expected for μ =1) 95% CL
  - $H \to \gamma\gamma$: **5.0 (6.2) GeV**
  - $H \to ZZ^* \to 4l$: **2.6 (6.2) GeV** (due to higher signal strength observed in the data)

Higgs boson Spin/CP

[*Study of the spin and parity of the Higgs boson in di-boson decays with the ATLAS detector* - ATLAS-CONF-2015-008, arXiv:1506.05669 [hep-ex]]

[*Determination of spin and parity of the Higgs boson in the* $WW^* \rightarrow e\nu\mu\nu$ *decay channel with the ATLAS detector* - Eur. Phys. J. C75(2015) 231]

Spin/CP study framework

- Spin, parity and tensor couplings of the observed Higgs boson studied in the $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ and $H \rightarrow \gamma\gamma$ channels over the full set of ~25 fb^{-1} data at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV
- The SM $J^P = 0^+$ hypothesis has been tested against several alternative spin and parity models:
  - *the observed resonance as a spin-2 particle*
  - *the observed resonance as a pure BSM spin-0 CP-even or CP-odd Higgs boson*
  - *the observed resonance as a mixture of the SM spin-0 state and a BSM spin-0 CP-even or CP-odd state*
- $H \rightarrow \gamma\gamma$ decay forbidden by Landau-Yang theorem for a spin-1 $\rightarrow$ $J^P = 1^\pm$ not studied and ruled out at >99%CL by previous ATLAS studies
- Only **one resonance** with a mass of 125 GeV is considered and an effective field theory (EFT- valid up to a scale Λ, set to 1 TeV) approach is adopted to describe interactions with SM vector bosons

Spin-0 and -2 hypotheses

- In the **spin-0 hypothesis**, models with fixed spin and parity and models with mixed SM spin-0 and BSM spin-0 CP-even and CP-odd contributions considered (EFT approach)

$$\begin{aligned}\mathcal{L}_0^V = \{&\cos(\alpha)\kappa_{SM}[1/2 g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}]\\ &-1/(4\Lambda)[\cos(\alpha)\kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu}]\\ &-1/(2\Lambda)[\cos(\alpha)\kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}]\} X_0\end{aligned}$$

Λ = EFT scale
κ_{HVV} = BSM CP-even
κ_{AVV} = BSM CP-odd
α = mixing angle

J^P	Model	Values of tensor couplings			
		κ_{SM}	κ_{HVV}	κ_{AVV}	α
0^+	SM Higgs boson	1	0	0	0
0_h^+	BSM spin-0 CP-even	0	1	0	0
0^-	BSM spin-0 CP-odd	0	0	1	$\pi/2$

- In the **spin-2 hypothesis** (graviton-like tensor), benchmark scenarios with only QCD production for the resonance considered (EW production O(10^{-4}) in UC scenario)

$$\mathcal{L}_2 = -\frac{1}{\Lambda}\left[\sum_V \kappa_V T_{\mu\nu}^V X^{\mu\nu} + \sum_f \kappa_f T_{\mu\nu}^f X^{\mu\nu}\right]$$

κ_V/κ_f = couplings of $T^{V/f}$ to spin-2 X field

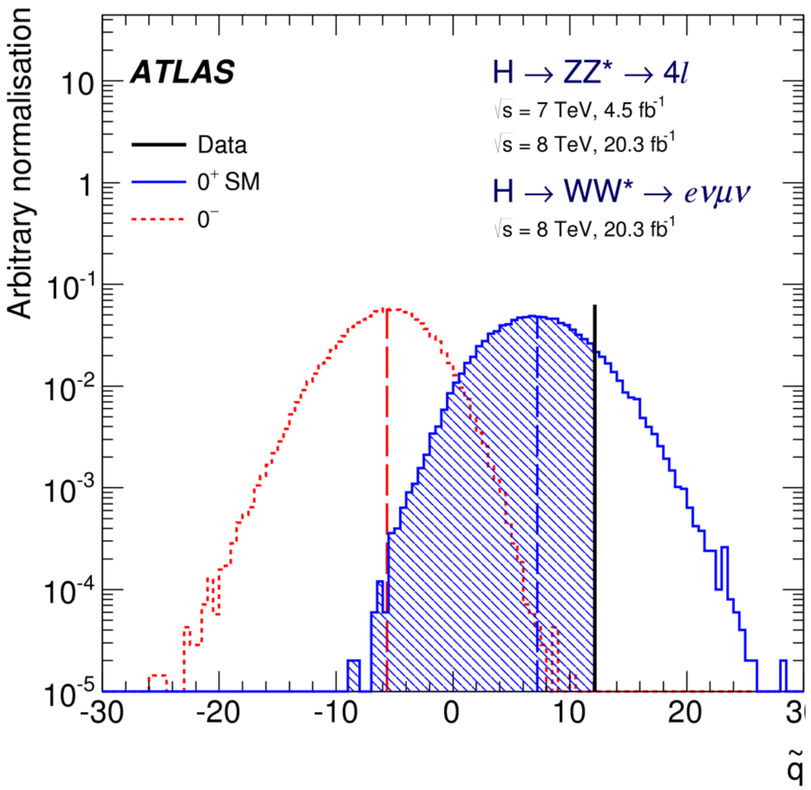
Values of tensor couplings	
$\kappa_q = \kappa_g$	Universal couplings
$\kappa_q = 0$	Low light-quark fraction
$\kappa_q = 2\kappa_g$	Low gluon fraction

Combined Spin/CP results

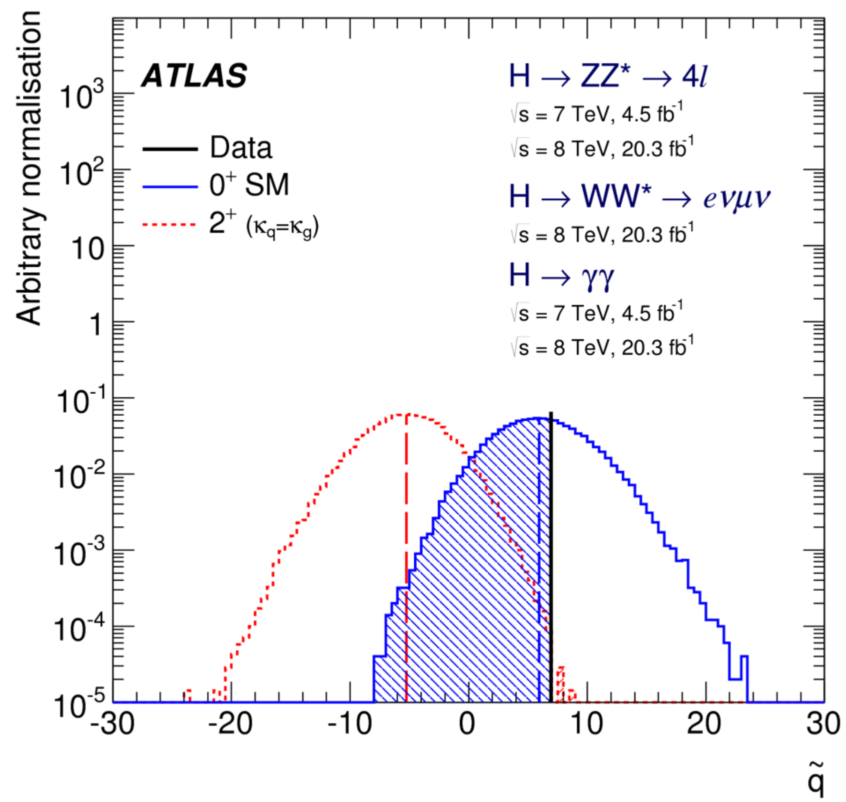
- Results given in terms of the test statistics $\tilde{q}$, to test the SM scenario against alternative spin-parity hypotheses
  - distributions of $\tilde{q}$ used to determine the corresponding *p*-values and exclusion CLs

$$\tilde{q} = \log \frac{\mathcal{L}(J^P_{SM}, \hat{\hat{\mu}}_{J^P_{SM}}, \hat{\hat{\theta}}_{J^P_{SM}})}{\mathcal{L}(J^P_{alt}, \hat{\hat{\mu}}_{J^P_{alt}}, \hat{\hat{\theta}}_{J^P_{alt}})}$$

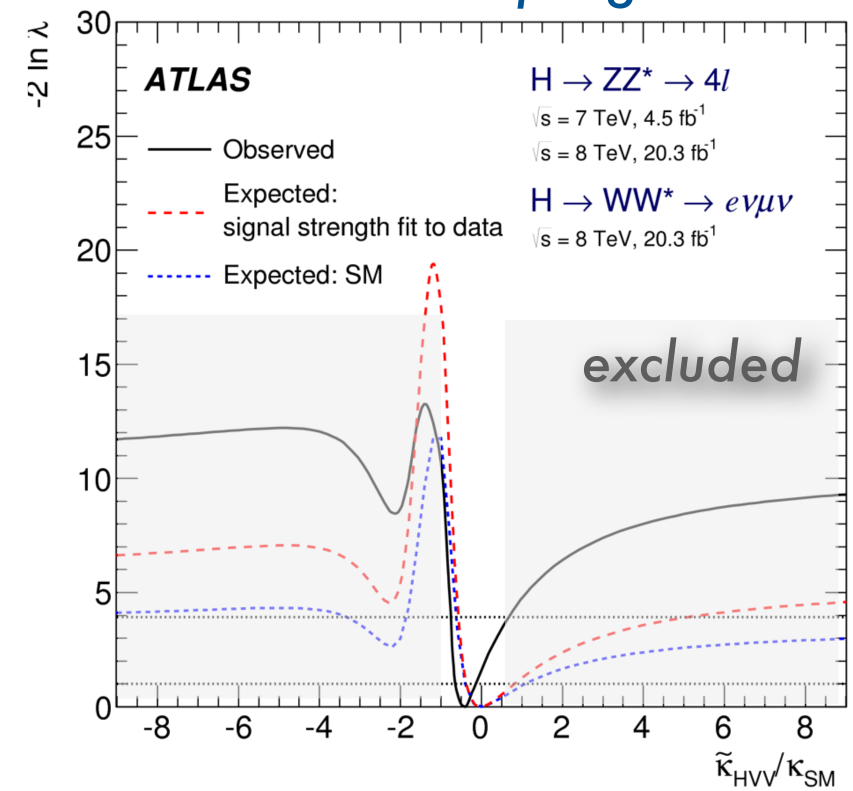
0^+ vs 0^-



0^+ vs 2^+



HVV tensor couplings to SM



Coupling ratio	Best-fit value	95% CL Exclusion Regions	
Combined	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{SM}$	-0.48	$(-\infty, -0.55] \cup [4.80, \infty)$	$(-\infty, -0.73] \cup [0.63, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$	-0.68	$(-\infty, -2.33] \cup [2.30, \infty)$	$(-\infty, -2.18] \cup [0.83, \infty)$

- **All alternative spin/CP models considered excluded at >99.9% CL in favor of the SM 0^+**

ATLAS+CMS Couplings Combination

[*Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at* $\sqrt{s}$*=7 and 8 TeV in the ATLAS experiment* - ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002, Phys. Rev. Lett. 114, 191803]

Combined coupling measurement

- Analysis based on the analysis of five production processes (*ggF, VBF, WH, ZH and ttH*) and of $H \to ZZ^*$, WW^*, $\gamma\gamma$, $\tau\tau$, *bb* and $\mu\mu$ decay modes
- Integrated luminosities per experiment of ~5 fb^{-1} at $\sqrt{s}$ = 7 TeV and ~20 fb^{-1} at $\sqrt{s}$ = 8 TeV → Combination increases sensitivity by $\sqrt{2}$
- Overall assumptions:
  - the studied particle is a **single SM-like Higgs boson** state, i.e. a CP-even scalar particle with the tensor structure of the SM interactions ($J^{CP} = 0^{++}$)
  - the total width is assumed to be small such that the **narrow-width approximation is valid** and production and decay can be decomposed
- Combined ATLAS+CMS Higgs boson mass used **M_H = 125.09 ± 0.21(stat) ± 0.11 (syst) GeV** [PRL 114 (2015) 191803, arXiv:1503.07589 [hep-ex]]
  - Measured using high resolution $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ channels
- Combination given in terms of *two generic parameterizations*:
  1. **Signal strength formalism** (ratios of cross sections and BRs)
  2. **κ-framework** (LO coupling framework which introduces coupling modifiers)

Signal strength formalism

- In this parameterisation, based on **ratios of cross sections and branching ratios**, the dominant signal TH uncertainties cancel out $\rightarrow$ no effect on the observables
- **Signal strengths** for a specific production and decay channel $i \rightarrow H \rightarrow j$

$$\mu_i = \frac{\sigma_i}{\sigma_i^{SM}} \qquad i = (ggF, VBF, WH, ZH, ttH, \ldots)$$

$$\mu^f = \frac{BR^f}{BR^f_{SM}} \qquad f = (ZZ, WW, \gamma\gamma, \tau\tau, b\bar{b}, \ldots)$$

$\mu_i = \mu^f = 1$
in the SM

- Only the product of μ_i and μ^f can be extracted experimentally (w/o any additional assumption)

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

signal strength for the combined production and decay

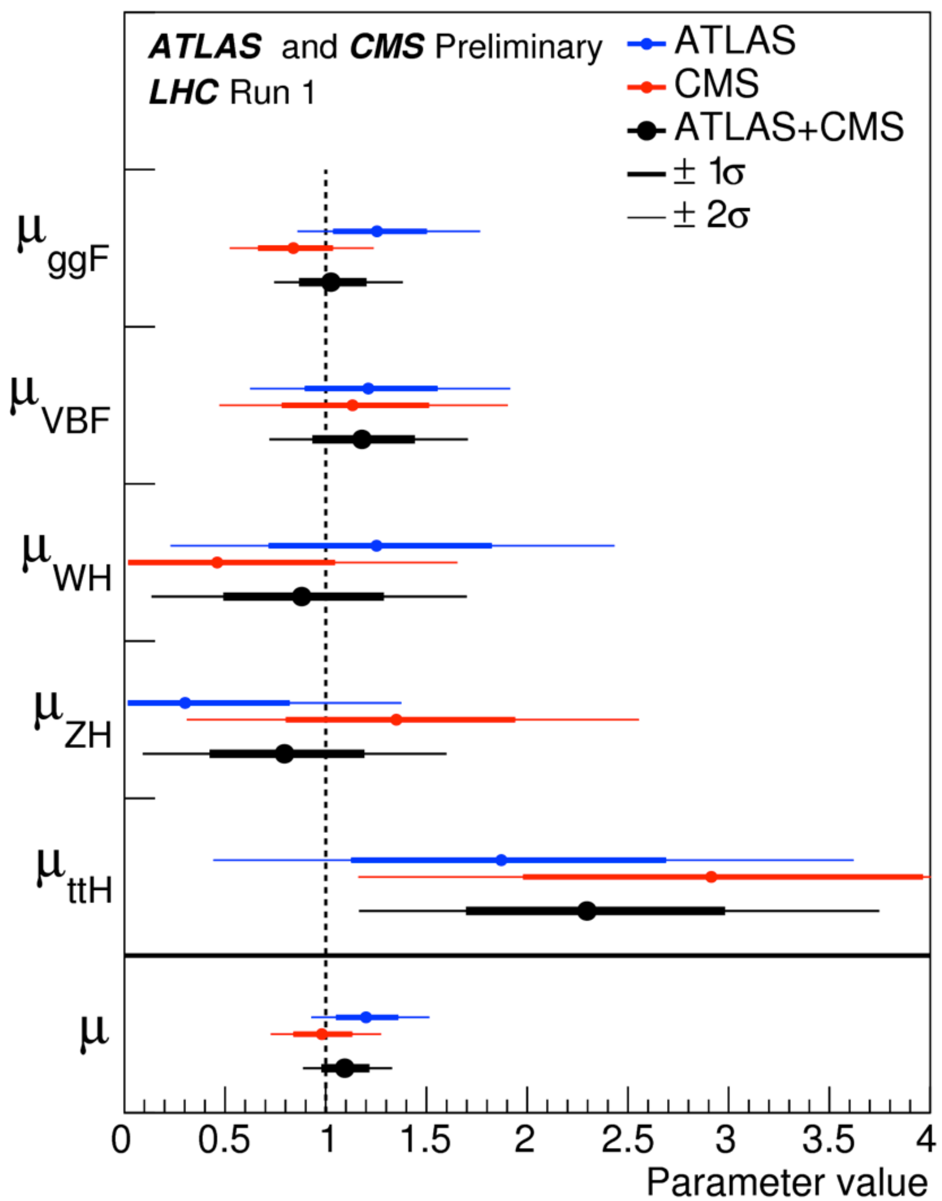
- *Most restrictive signal-strength model* : μ_i and μ^f are independent of the production process and decay mode $\rightarrow$ **one signal strength μ**
- Best fit value, combining ATLAS+CMS data at $\sqrt{7}$ and $\sqrt{8}$ TeV:

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

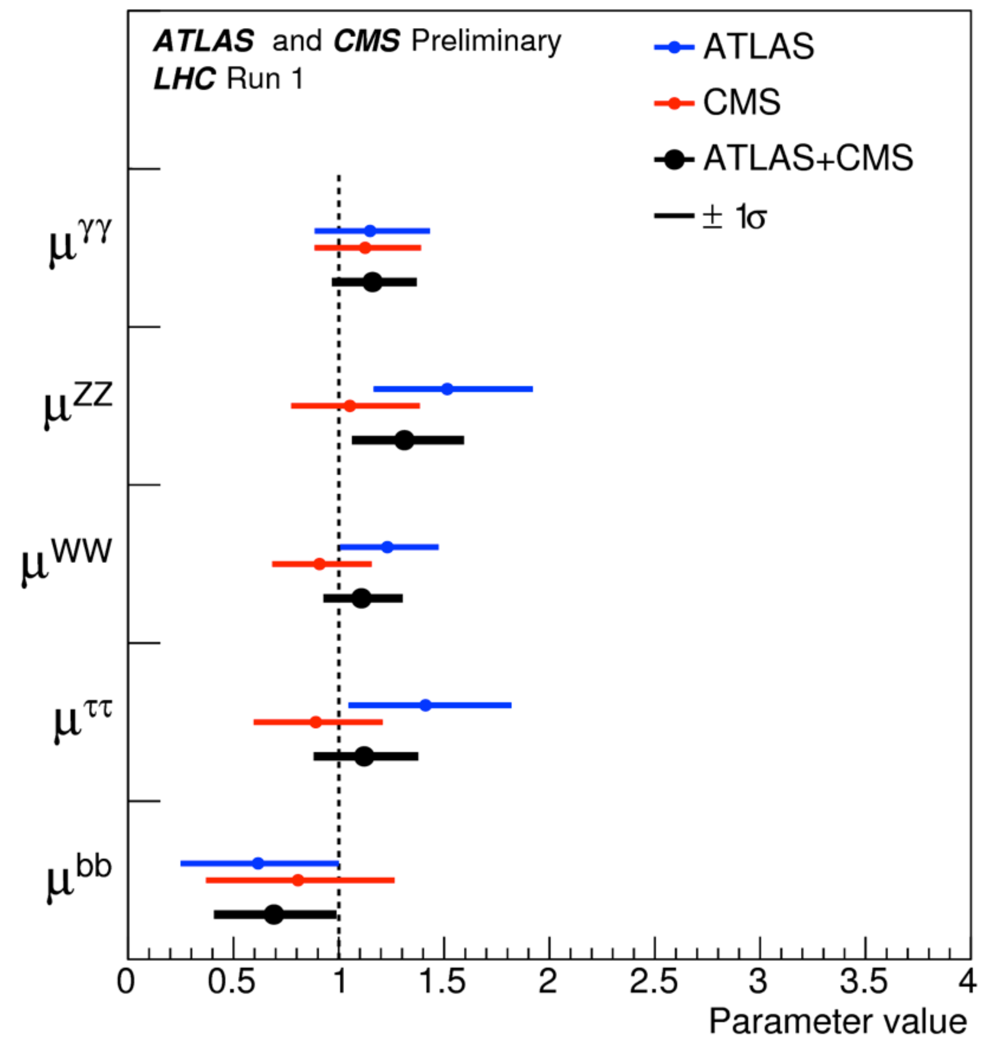
- Consistency with the SM predictions at **less than 1σ** - ***p*-value = 34%** - very model-dependent

Individual production/decay signal strengths

- Assuming $\mu^f = 1$ - **p-value = 24%**



- Assuming $\mu_i = 1$ - **p-value = 60%**



Process	Significance meas (expected)
VBF	5.4σ (4.7σ)
$t\bar{t}H$	4.4σ (2.0σ)
Decay channel	Significance meas (expected)
$H \to \tau\tau$	5.5σ (5.0σ)

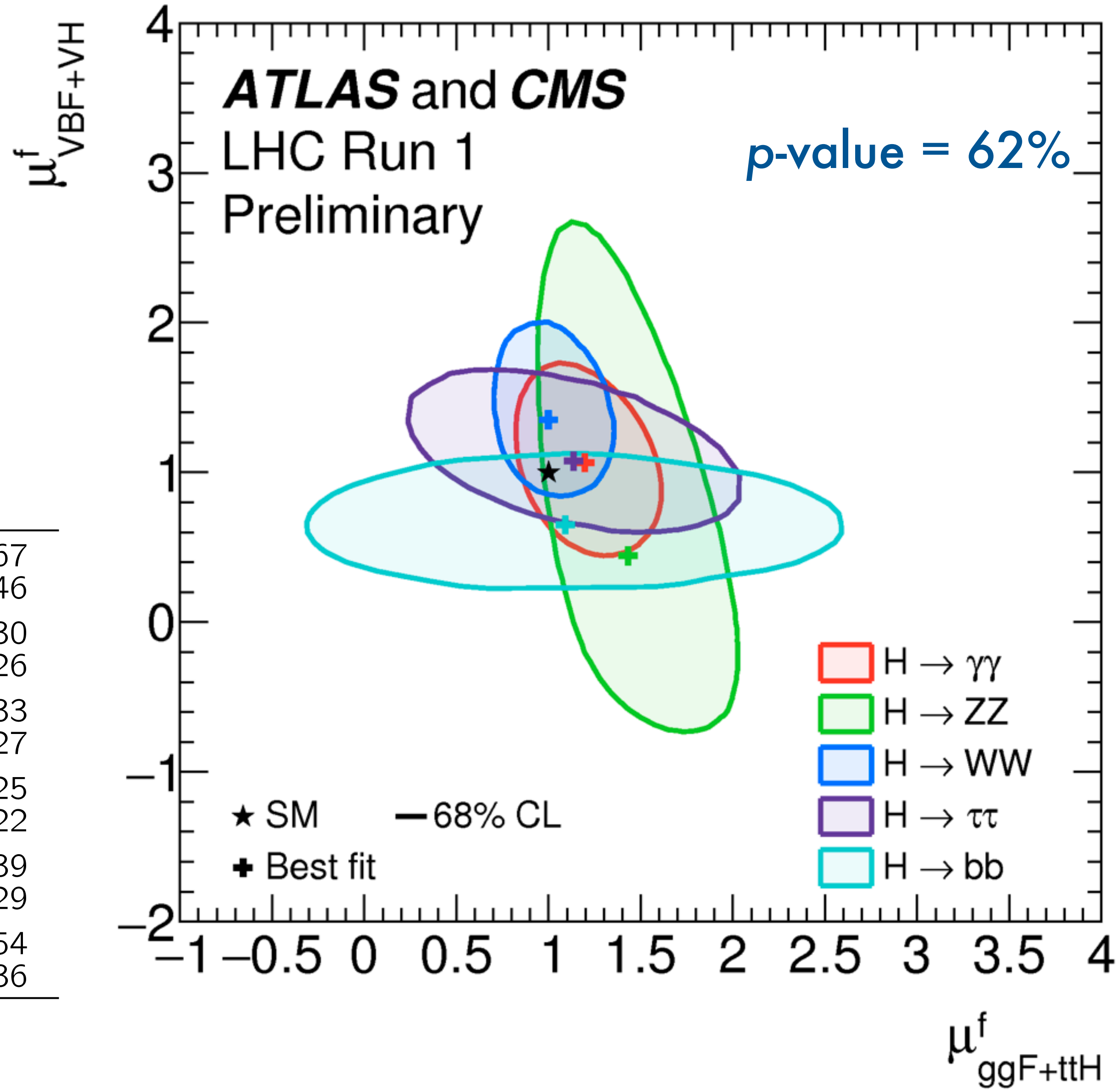
- **Signal strengths consistent with 1** (SM)
- **Largest difference in *ttH*** $\to$ 2.3σ measured excess w.r.t. SM

Boson- and fermion-mediated processes

- Potential deviations of boson and fermion couplings from the SM can be tested independently for each decay channel using $\mu^f{}_F$ (*ggF and ttH*) and $\mu^f{}_V$ (*VBF, WH, ZH*)
- 10-parameter fit of the five decay modes for ATLAS+CMS combined measurements
- Ratio $\mu^f{}_V/\mu^f{}_F$ can be measured in the different decay channels - combined result (w/o assumptions on SM decays):

$$\mu_V/\mu_F = 1.06^{+0.35}_{-0.27}$$

Parameter	ATLAS+CMS (obs/exp)	ATLAS (obs)	CMS (obs)
μ_V/μ_F	$1.06^{+0.35/+0.34}_{-0.27/-0.26}$	$0.91^{+0.67}_{-0.46}$	$1.29^{+0.67}_{-0.46}$
$\mu_F^{\gamma\gamma}$	$1.13^{+0.24/+0.21}_{-0.21/-0.19}$	$1.18^{+0.23}_{-0.29}$	$1.03^{+0.30}_{-0.26}$
μ_F^{ZZ}	$1.29^{+0.29/+0.24}_{-0.25/-0.20}$	$1.54^{+0.44}_{-0.36}$	$1.00^{+0.33}_{-0.27}$
μ_F^{WW}	$1.08^{+0.22/+0.19}_{-0.19/-0.17}$	$1.26^{+0.29}_{-0.25}$	$0.85^{+0.25}_{-0.22}$
$\mu_F^{\tau\tau}$	$1.07^{+0.35/+0.32}_{-0.28/-0.27}$	$1.50^{+0.66}_{-0.49}$	$0.75^{+0.39}_{-0.29}$
$\mu_F^{b\bar{b}}$	$0.65^{+0.37/+0.45}_{-0.28/-0.34}$	$0.67^{+0.58}_{-0.42}$	$1.03^{+0.54}_{-0.36}$



Ratio of cross sections and BRs

- If $gg \to H \to ZZ$ is chosen as reference (smallest systematic and overall uncertainties):

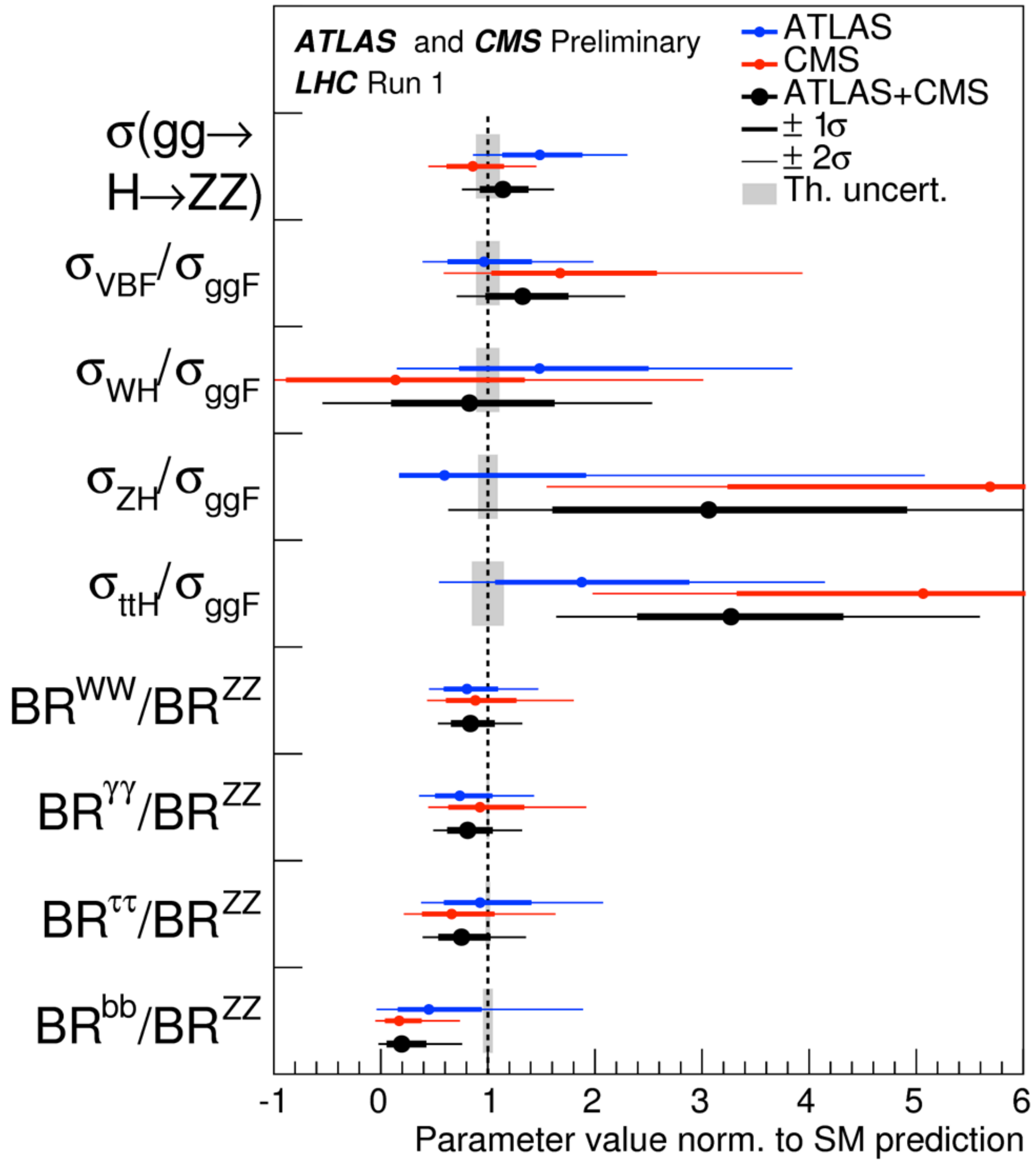
$$\sigma_i \cdot BR^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{BR^f}{BR^{ZZ}}\right)$$

$\sigma(gg \to H \to ZZ)$
4 ratios σ_i/σ_{ggF}
4 ratios BR^f/BR^{ZZ}

- Ratios do not rely on any additional assumptions and are independent of TH predictions → *most generic parameterisation*
- Fit result for each of the nine parameters normalized to the corresponding SM prediction
- Measurements are almost all consistent with the SM predictions **within less than 2σ** - **SM p-value = 16%**
- Few visible **tensions**:

$\sigma_{ttH}/\sigma_{ggF}$	$3.3^{+1.0}_{-0.9}$	2.3σ excess
σ_{ZH}/σ_{ggF}	$3.2^{+1.8}_{-1.4}$	2.2σ excess
BR_{bb}/BR_{ZZ}	$0.19^{+0.21}_{-0.12}$	2.5σ deficit

which are strongly anti-correlated



κ-framework

- Second parameterisation based on a LO framework which introduces **coupling modifiers** to probe modifications of the Higgs boson couplings due to physics BSM [arXiv:1307.1347 [hep-ph]]

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

$\vec{\kappa}$ = coupling modif
Γ^f = partial widths
Γ_H = total widths

- For a given production or decay process j, κ_j is defined as:

coupling modifiers $\boxed{\kappa_j^2 = \sigma_j/\sigma_j^{SM} \text{ or } \kappa_j^2 = \Gamma^j/\Gamma^j_{SM}}$

  - Different production processes and decay modes probe different coupling modifiers

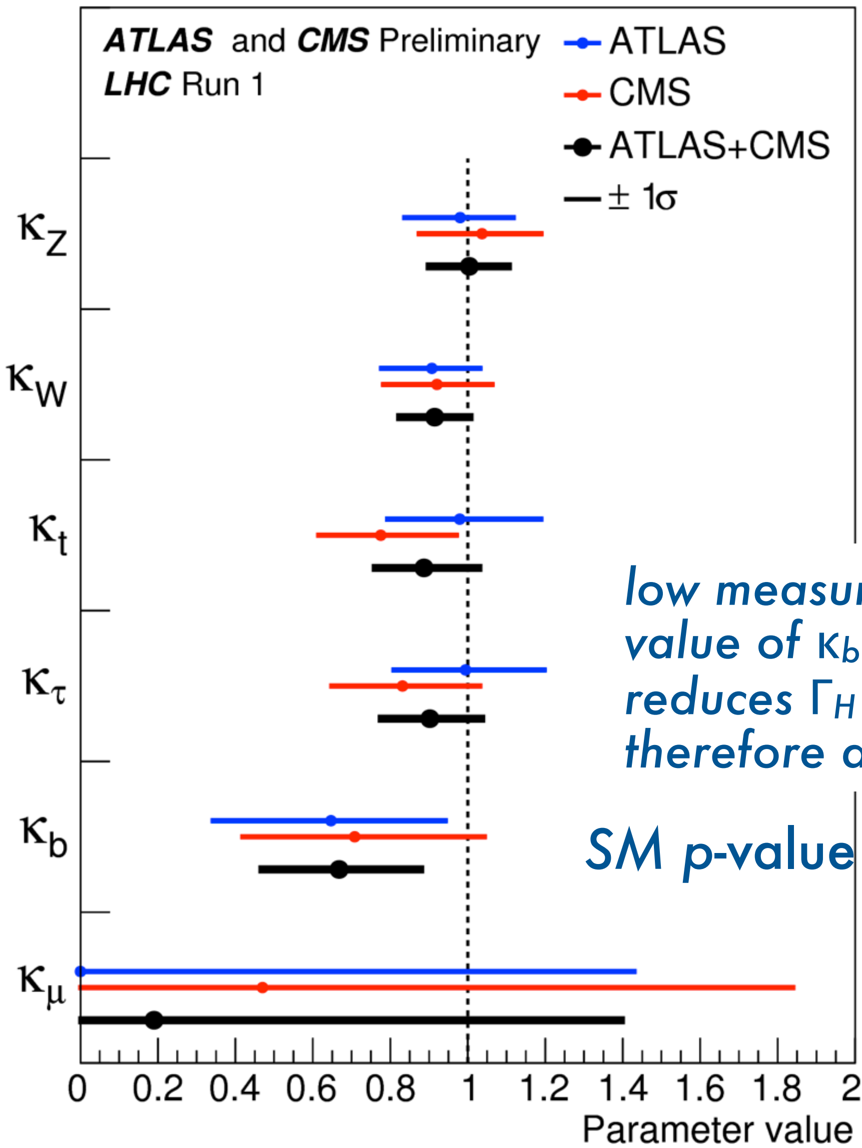
- Changes in the couplings may result in a variation of the Higgs boson width - if non-SM modification of the decays are allowed: $\Gamma_H = \dfrac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$ - $\kappa_H^2 = \sum_j BR^j_{SM}\kappa_j^2$

- Since Γ_H is not (directly or indirectly) experimentally well constrained in a model-independent way at LHC, **only ratios of coupling modifiers κ can be extracted**

- To directly measure individual κ, *assumptions on the Higgs boson width are necessary*:
  1. The Higgs boson does not have BSM decay modes, i.e. $\mathbf{BR_{BSM} = 0}$
  2. $\boldsymbol{\kappa_W \leq 1}$ **and** $\boldsymbol{\kappa_Z \leq 1}$, motivated by a wide class of BSM models ($\mathrm{BR_{BSM}}$ can be measured)

SM loops and no BSM decays

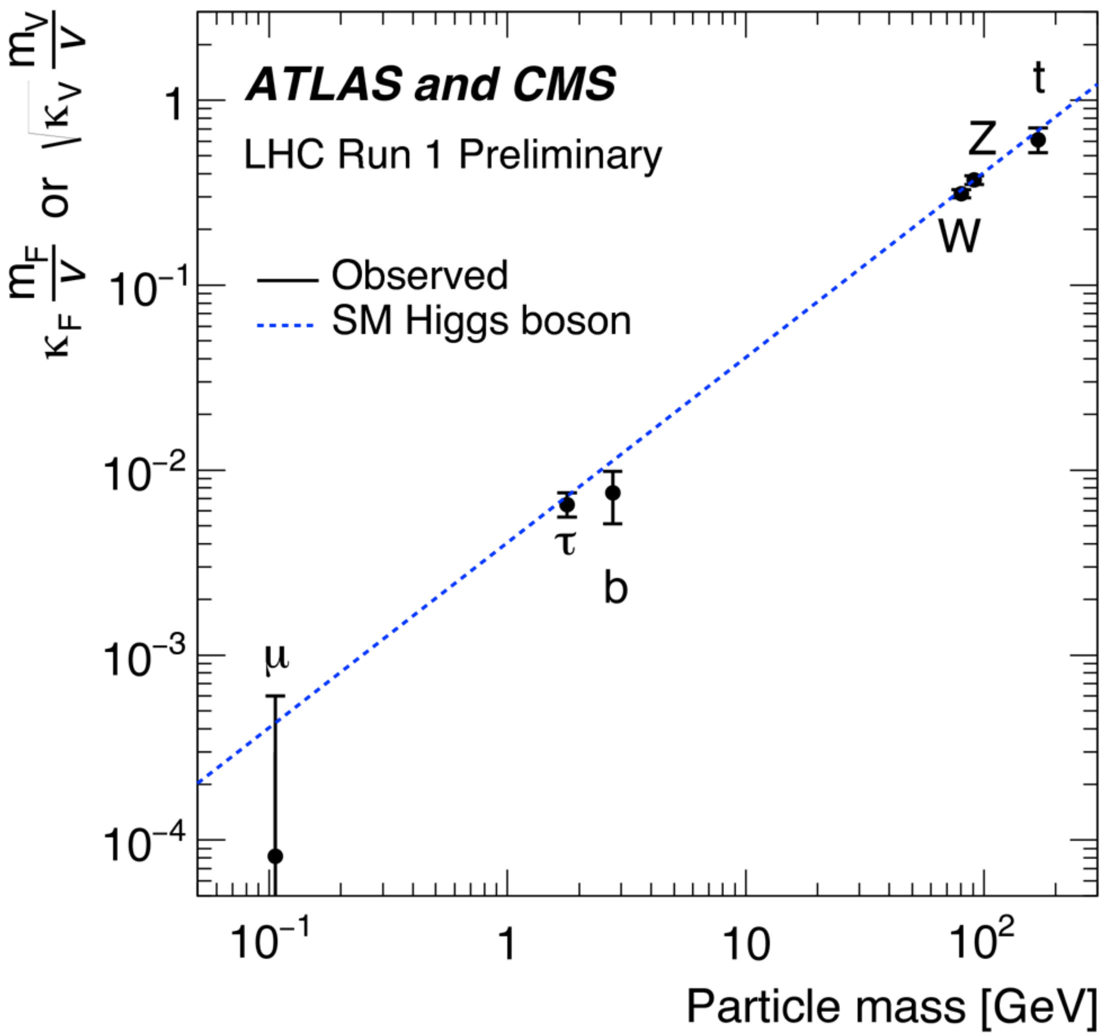
- Assuming no new particles in $gg \to H$ production and $H \to \gamma\gamma$ decay (and no invisible Higgs decays) i.e. κ_g and κ_γ consistent with the SM expectations
- This leads to a parameterisation with six free couplings modifiers: κ_W, κ_Z, κ_b, κ_t, κ_τ and κ_μ



low measured value of κ_b reduces Γ_H and therefore all κ_i

SM p-value = 65%

- Results expressed as **reduced coupling modifiers**

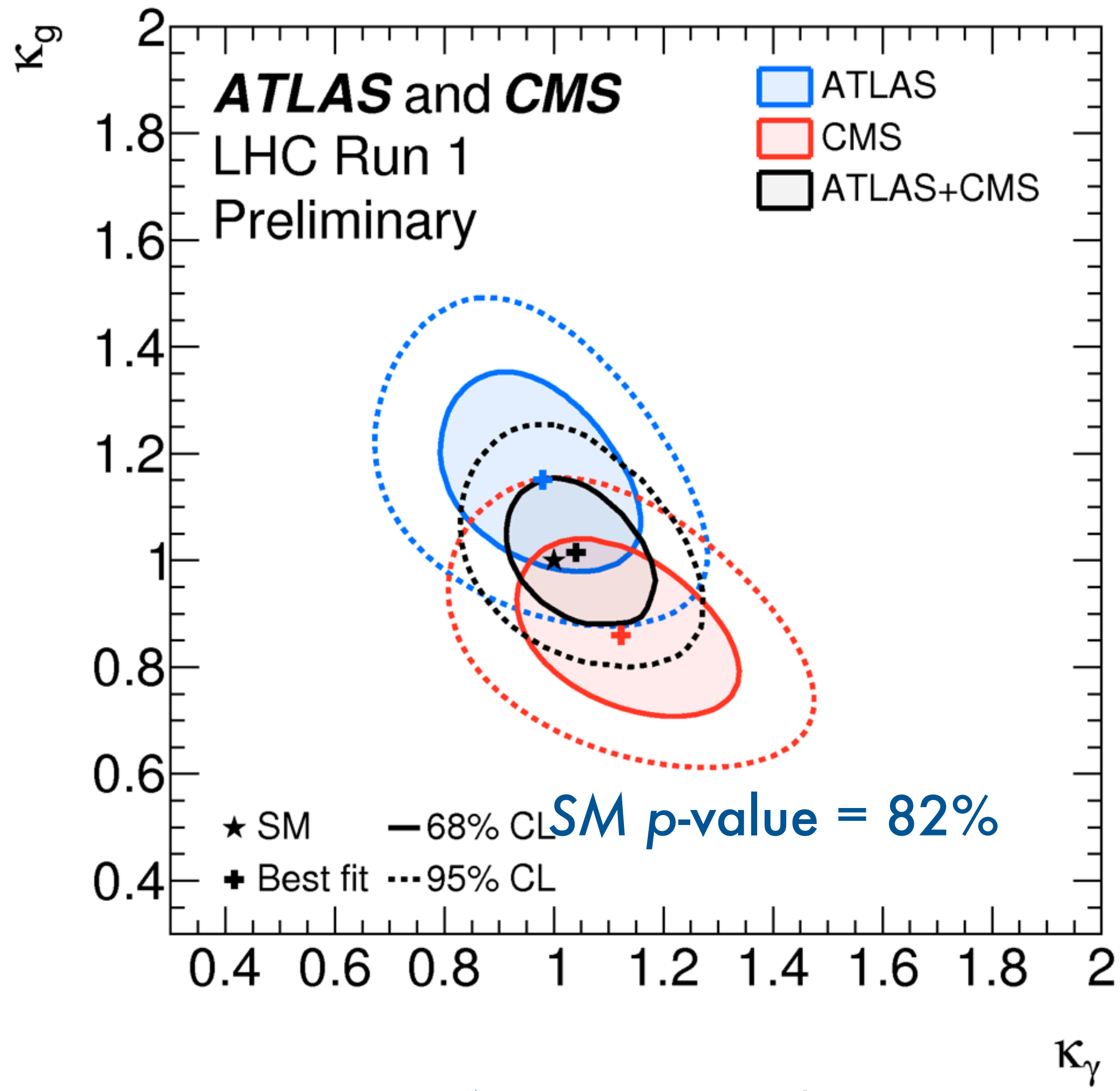


- Within current precision, **Higgs boson couplings scale with particle masses**, as in SM

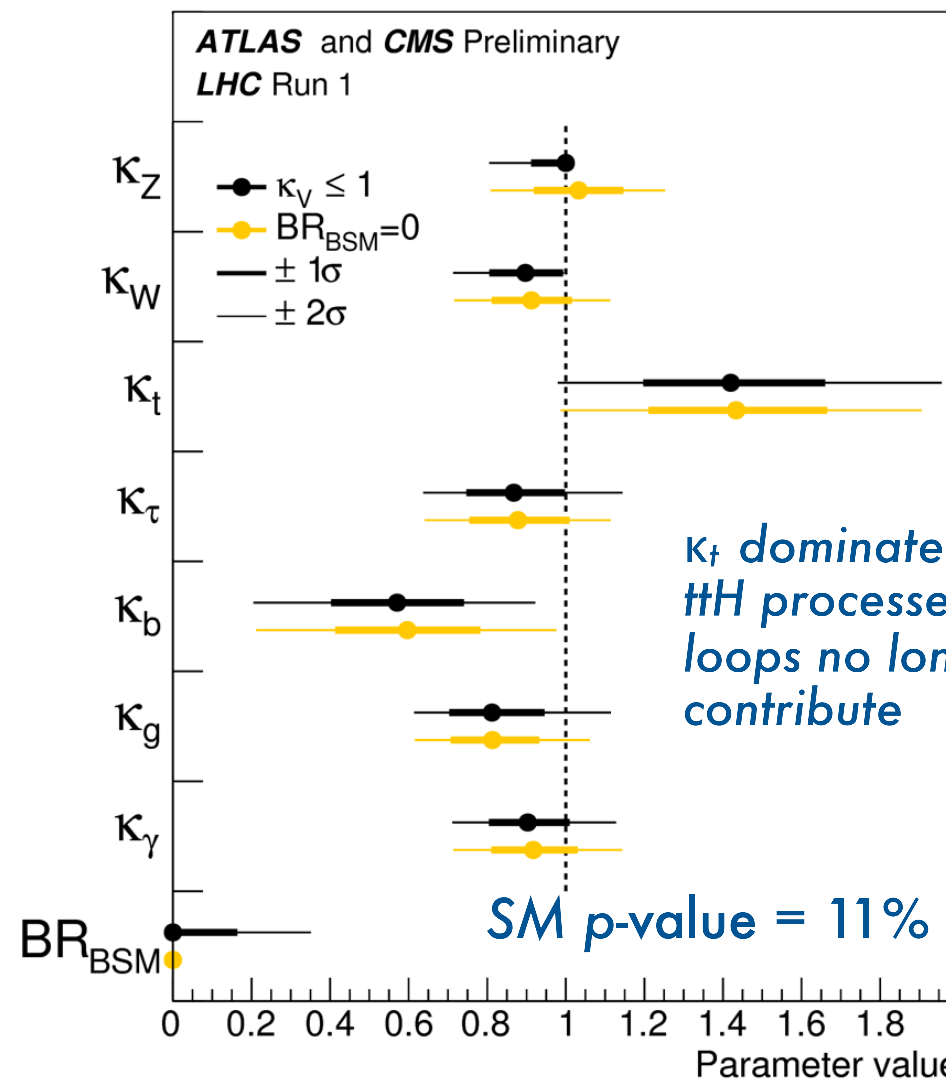
BSM particles in SM loops and BSM decays

- BSM physics may manifest in loop-induced processes of $gg \rightarrow H$ production and $H \rightarrow \gamma\gamma$ decay $\rightarrow$ **effective coupling modifiers κ_g and κ_γ**

- Fixing all other tree-level couplings to 1



- Allowing for potential deviations from the SM in the tree-level couplings to ordinary particles $\rightarrow$ 7 independent coupling modifiers κ_g ,κ_γ, κ_W, κ_Z, κ_b, κ_t and κ_τ



- **BR_{BSM} < 0.34 at 95% CL** (assuming $\kappa_V \leq 1$)
- ATLAS direct limit: **BR_{BSM} < 0.25 at 95%CL**

[arXiv:1509.00672 [hep-ex]]

Summary

- ATLAS has been successfully characterizing the Higgs boson:
  - The Higgs boson mass measured with <0.2% precision (ATLAS+CMS)
  - **Evidence of VBF production and $H\to\tau\tau$, both at the 5.5σ level** (ATLAS+CMS)
  - The new particle is **compatible with a $J^P = 0^+$ state** - several alternative states disfavored at >99.9% CL
  - All coupling measurements (both ATLAS only and combined ATLAS+CMS) show **no significant deviation from the SM prediction** (**SM *p*-value of all combined fits >10%**)- but measurements affected by statistics, experimental effects and theory uncertainties
- Many Run I studies are statistics limited, progress can be expected in Run II:
  - Cross sections increase with higher energy
  - More luminosity expected
  - Analyses extended to more channels
  - In parallel, expected progresses in theory predictions

LHC and its experiments have started Run II phase (13 TeV)
We are getting ready for Higgs boson studies with higher precision and for other surprises... Very exciting times ahead...

Backup slides

Statistical model used in the measurements

- **Extended likelihood function** $\mathcal{L}(\vec{\alpha}, \vec{\nu})$

$$\underbrace{}_{}\; -\ln \mathcal{L}(\vec{\alpha},\vec{\nu}) = (n_s + n_b) - \sum_e \left[n_s \cdot \overset{\textit{signal pdf}}{f_s(\vec{x_e}|\vec{\alpha},\vec{\nu_s})} + n_b \cdot \overset{\textit{bckg pdf}}{f_b(\vec{x_e}|\vec{\nu_b})} \right] - \overset{\textit{ancillary pdfs}}{\sum_k \ln \pi_k(\nu_k)}$$

n_s, n_b = signal/background yields
$\vec{x}$ = observables
f_s, f_b = signal/background pdfs
α = parameter of interest (mass, cross-section, couplings, ..)
$\vec{\nu}$ = "nuisance parameter" (shape parameters, systematics, ..)
π_k = pdfs from auxiliary measurements

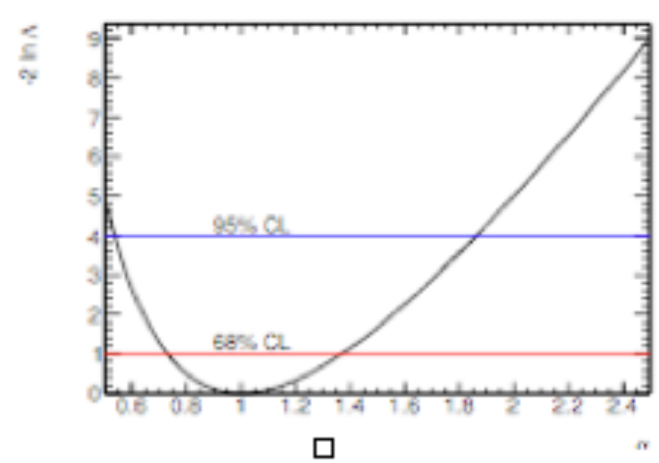
- **Test statistics**: Profiled Likelihood Ratio (PRL)

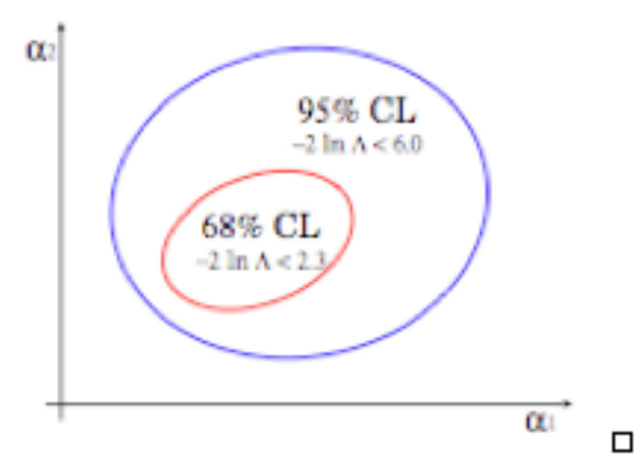
$$q_{\vec{\alpha}} = -2\ln\Lambda(\vec{\alpha}) = -2\ln\frac{\mathcal{L}(\vec{\alpha},\hat{\hat{\nu}}(\vec{\alpha}))}{\mathcal{L}(\hat{\vec{\alpha}},\hat{\nu})}$$

$\leftarrow$ likelihood for fixed $\vec{\alpha}$ and "profiled" $\vec{\nu}$
$\leftarrow$ maximum likelihood for free $\vec{\alpha}, \vec{\nu}$

- The conversion from $-2\ln\Lambda$ to the p-value is performed using a two-sided distribution with the specific number of degrees of freedom

- *Wilks' theorem*: if $\vec{\alpha} = \vec{\alpha}^{true}$, then $q_{\vec{\alpha}}$ follows a χ_D^2 distribution, with D being the number of parameters if interest $\rightarrow$ compute confidence intervals for $\vec{\alpha}$



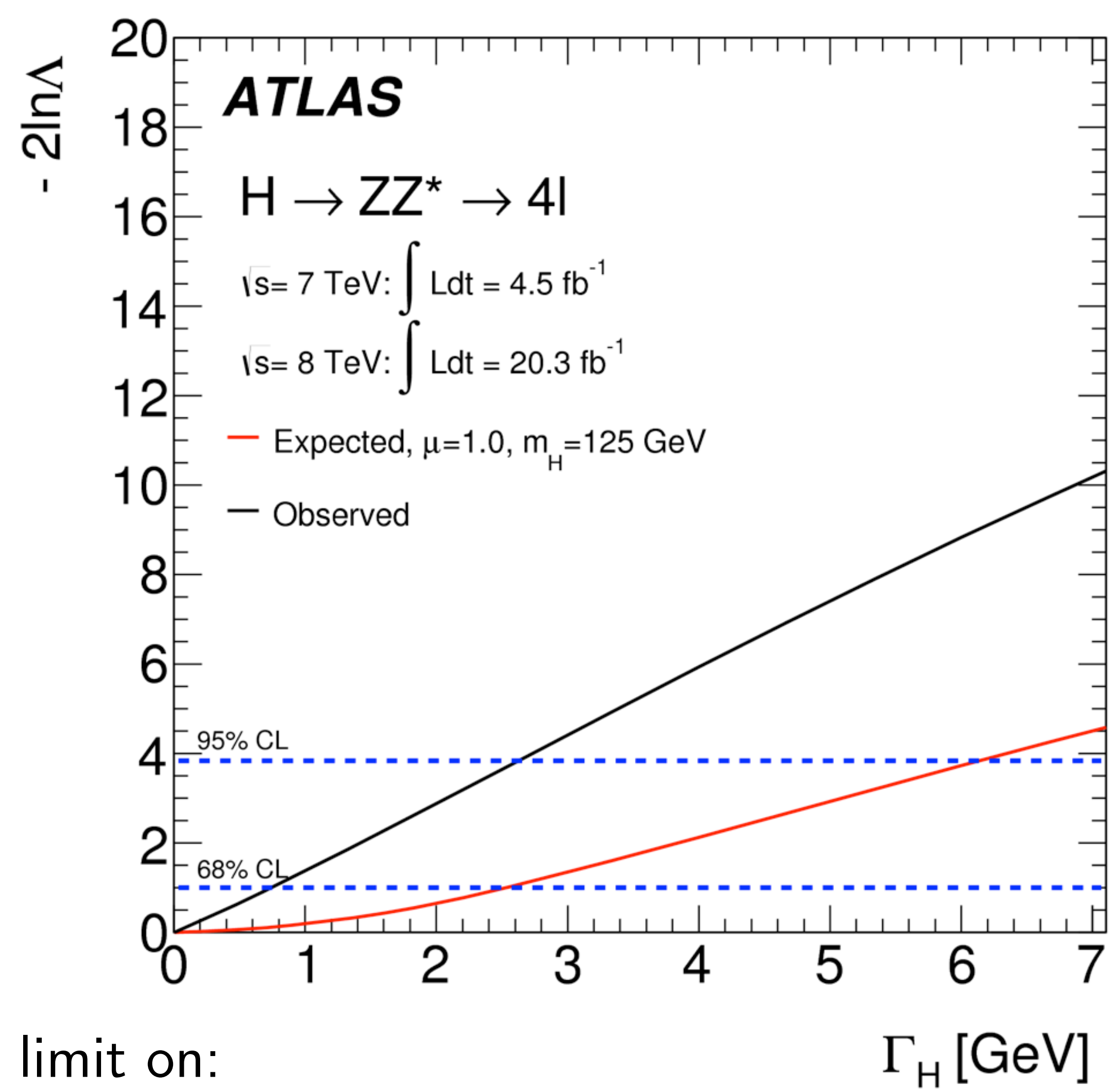


Direct limits on the Higgs boson width

- Direct limits on the decay width of the Higgs boson can be set from the observed width of the invariant mass peak (Γ_H^{SM}= 4.12 MeV at M_H = 125.4 GeV), assuming no interference with background processes

- ***$H\to\gamma\gamma$***: convolutions of detector resolution with a non relativistic Breit–Wigner distribution
  - Profile likelihood estimator with the width as main parameter

- ***$H\to ZZ^*\to 4l$*** : per-event resolution model
  - 4-lepton mass computed event-by-event by convolving detector response with nonrelativistic Breit-Wigner function describing the Higgs boson



- Observed (expected for μ =1) 95% CL upper limit on:
  - *$H\to\gamma\gamma$*: **5.0 (6.2) GeV**
  - *$H\to ZZ^*\to 4l$*: **2.6 (6.2) GeV** (due to higher signal strength observed in the data)

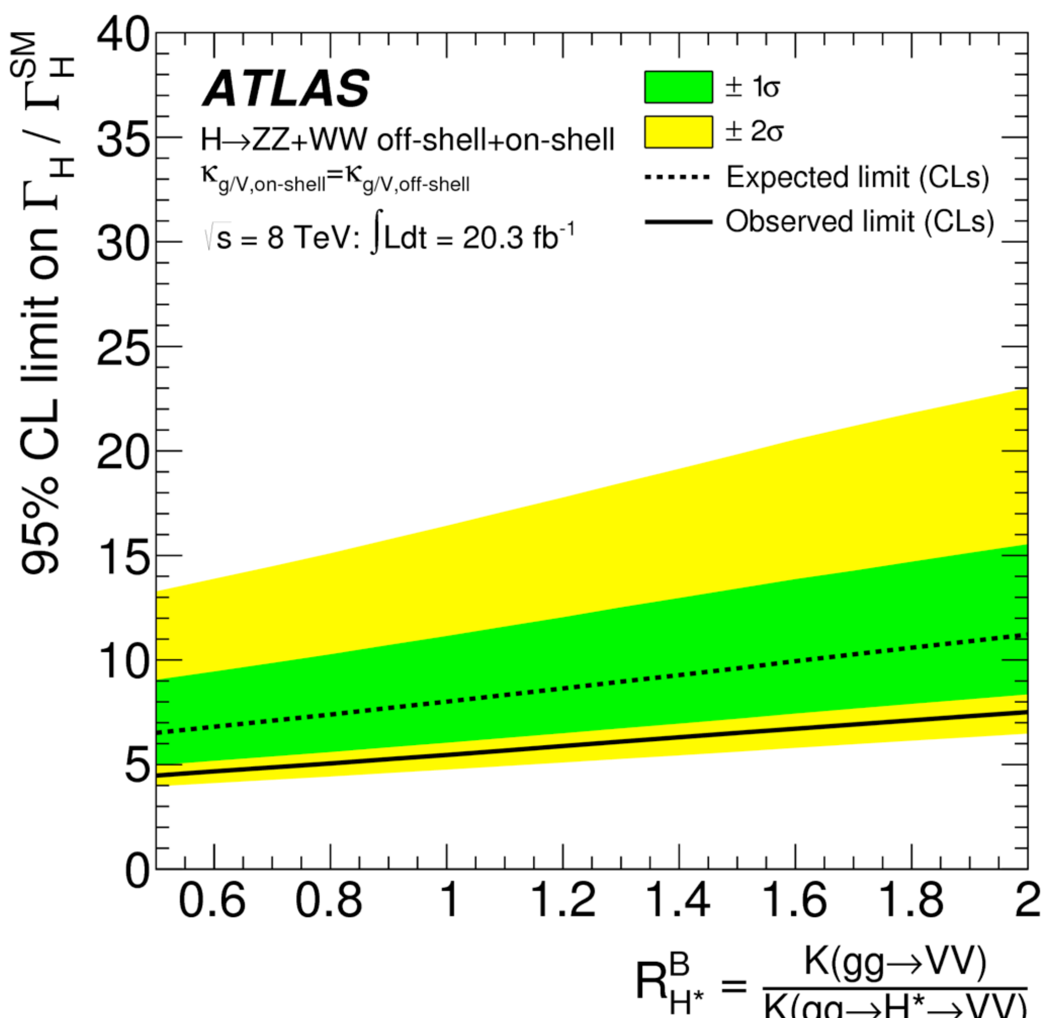
Indirect limits on the Higgs boson width

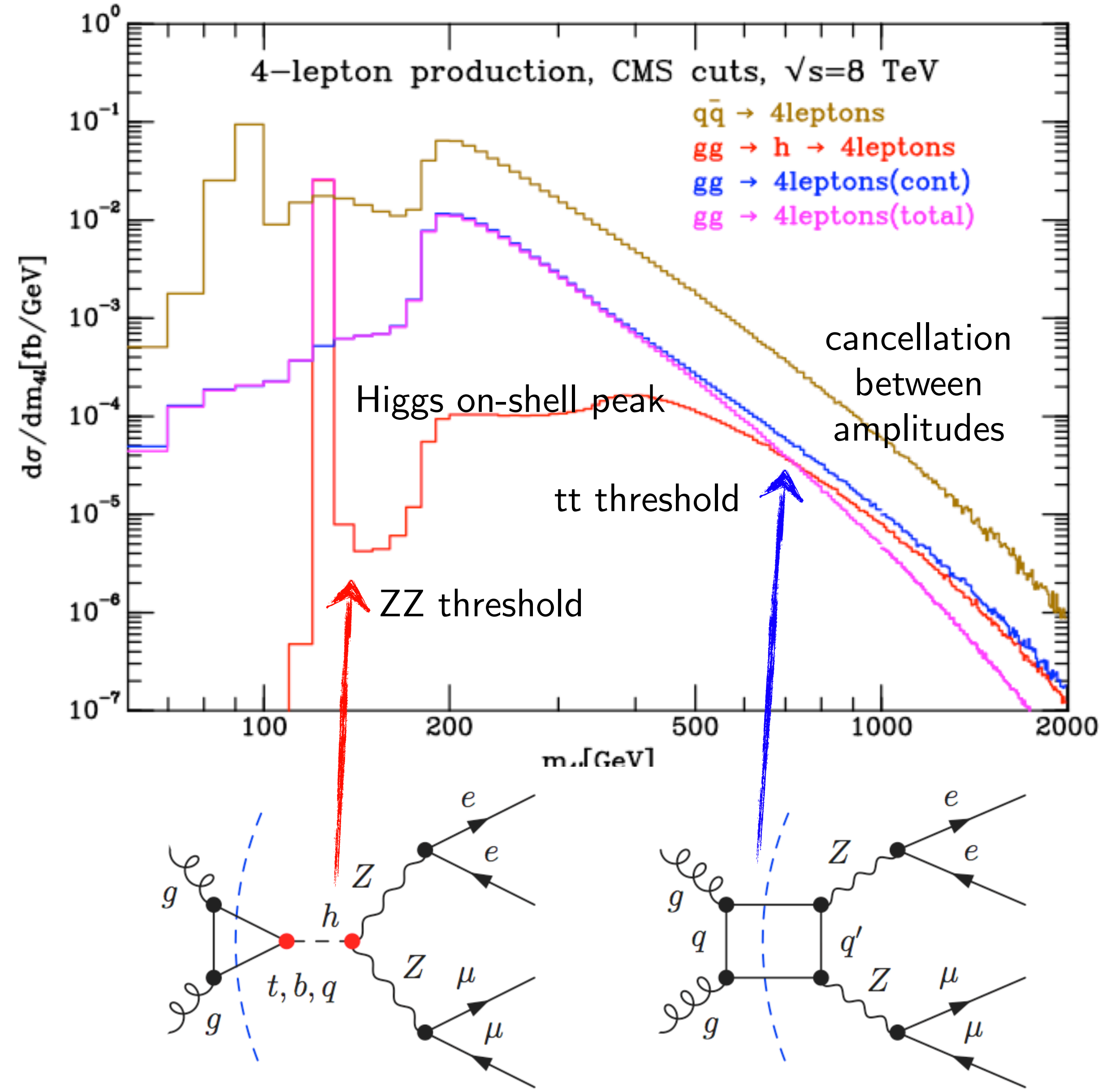
- The high-mass off-peak regions beyond $2m_V$ ($V = Z, W$) in the $H \to ZZ/WW$ channels are sensitive to Higgs boson production through *off-shell and background interference effects*

$$\sigma^{off-shell\ (*)}_{gg \to H^* \to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

$$\sigma^{on-shell}_{gg \to H \to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \boxed{\Gamma_H}}$$

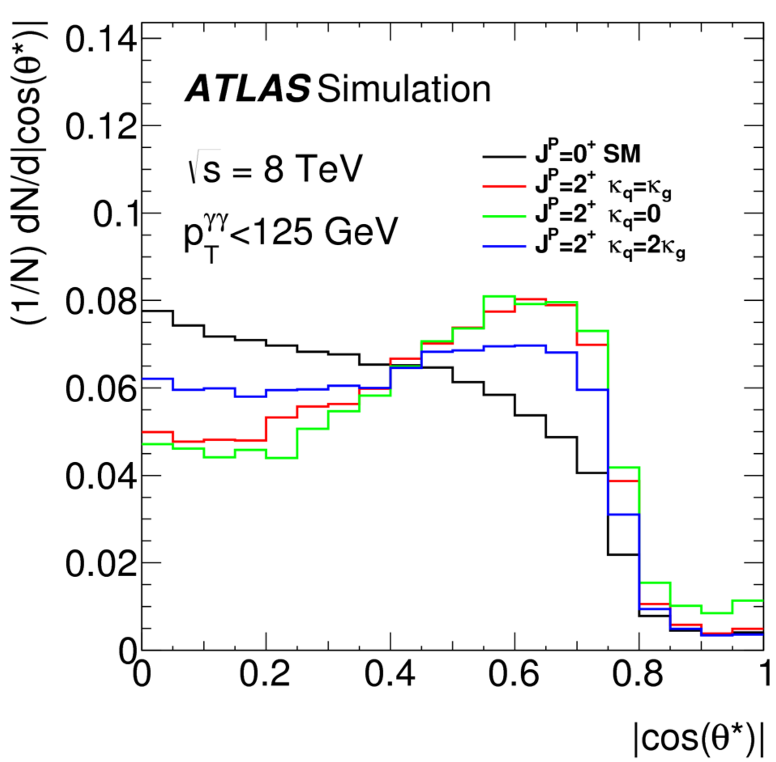
$g^2_{ggH} = H - g$ coupling $\quad g^2_{HZZ} = H - Z$ coupling



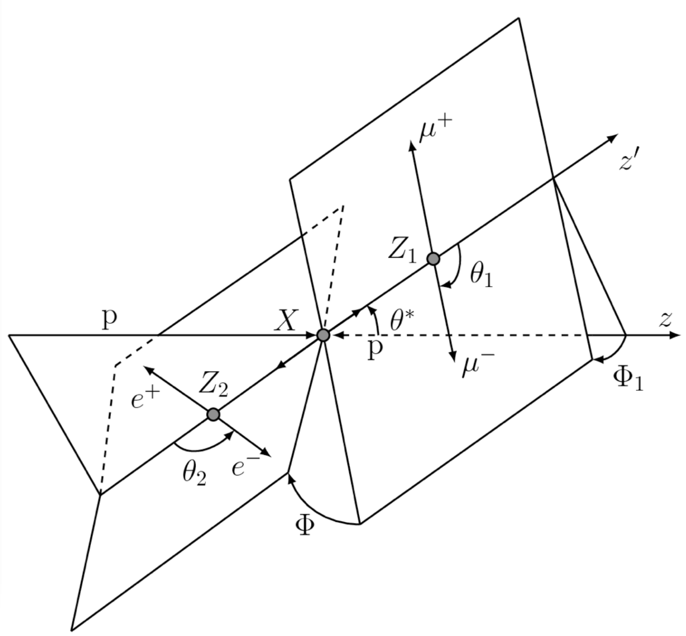


Spin/CP sensitive variables

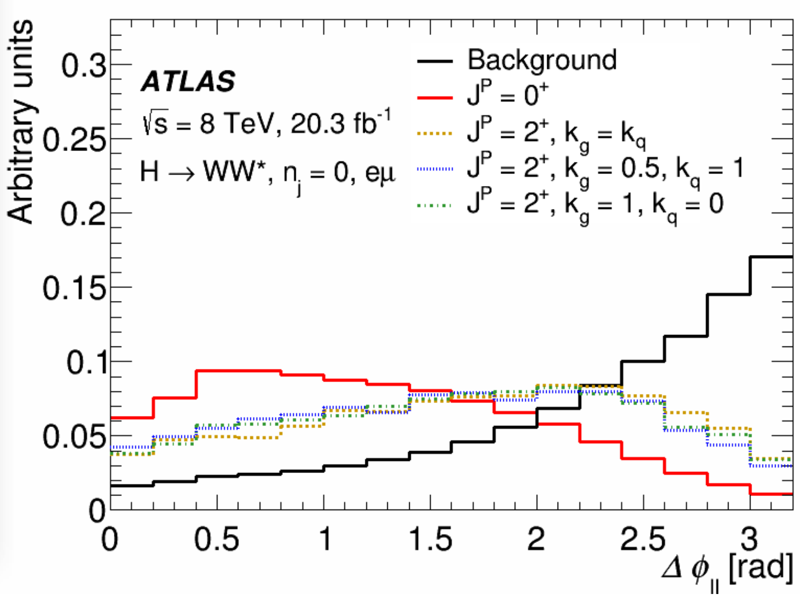
- ***H→γγ*** : diphoton $p_T^{\gamma\gamma}$ and production angle of the two photons (in the Collins-Soper frame), $|\cos(\theta^*)|$
  - 11 categories, fit on the observed $m_{\gamma\gamma}$ for each of them



- ***H→ZZ*→4l*** : two production θ^* and Φ_1 (in Higgs rest frame) plus three decay angels, Φ, θ_1 and θ_2 (in V rest frame)
  - 4 categories
  - Matrix element likelihood ratio analysis and BDT



- ***H→WW*→eνμν*** : four variables m_{ll}, $\Delta\Phi_{ll}$, p_T^{ll} and m_T
  - 5 BDTs for different spin-2 models + 1 BDT for SM 0^+
  - BDT used also to test HWW tensor structure for spin-0 fixed hypothesis



Statistical treatment - coupling combination

- For each decay mode, events are classified in different **categories**, based on their kinematic characteristics, with different purities (especially for production mode categories)
- A total of **O(100) categories (*k*)** per experiment are combined

$$n_{signal}(k) = \mathcal{L}(k) \times \sum_i \sum_f \{\sigma_i \times A_i^f(k) \times \epsilon_i^f \times BR^f\}$$
$$= \mathcal{L}(k) \times \sum_i \sum_f \mu_i \mu^f \{\sigma_i^{SM} \times A_i^f(k) \times \epsilon_i^f \times BR^f_{SM}\}$$

$\mathcal{L}(k)$ = luminosity
$A_i^f(k)$ = acceptance
ϵ_i^f = efficiency
μ_i/μ^f = signal strength

- Profile likelihood ratio test statistics:

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

$\vec{\alpha}$ = parameters
$\vec{\theta}$ = nuisances

  - For each likelihood evaluation, all systematic uncertainties (*nuisances*) are varied to maximize the profiled likelihood (*profiled*) [cdsweb.cern.ch/record/1375842]
  - Results are given in terms of $\boxed{q(\vec{\alpha}) = -2\ln\Lambda(\vec{\alpha})}$, assumed to follow a χ^2 distribution
- **O(4200) nuisance parameters** in the combined fit to describe the (systematic) uncertainties: finite MC statistics, Higgs signal TH uncertainties, TH uncertainties affecting background, other experimental uncertainties
- Most experimental uncertainties assumed to be *uncorrelated* between the two experiments

κ-framework - Overview of parameters

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

κ-framework - Fermion sector

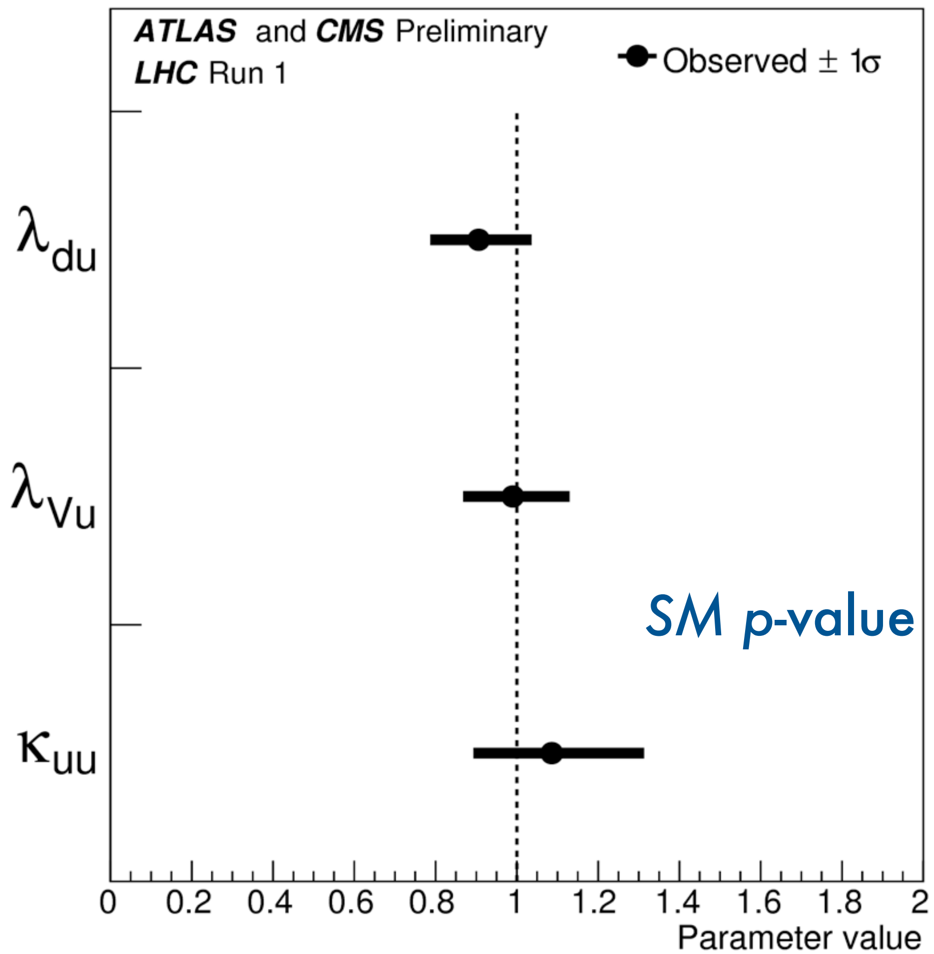
- Common coupling modifications for *up-type fermions vs down-type fermions* or for *leptons vs quarks* are predicted by many extensions of the SM (2HDM e.g.)
- Directly parametrize model in terms of ratios of coupling strength modifiers, allowing the Higgs width to vary (and assuming no BSM physics in loop processes):

$\boxed{\lambda_{du} = \kappa_d/\kappa_u}$ $\lambda_{Vu} = \kappa_V/\kappa_u$

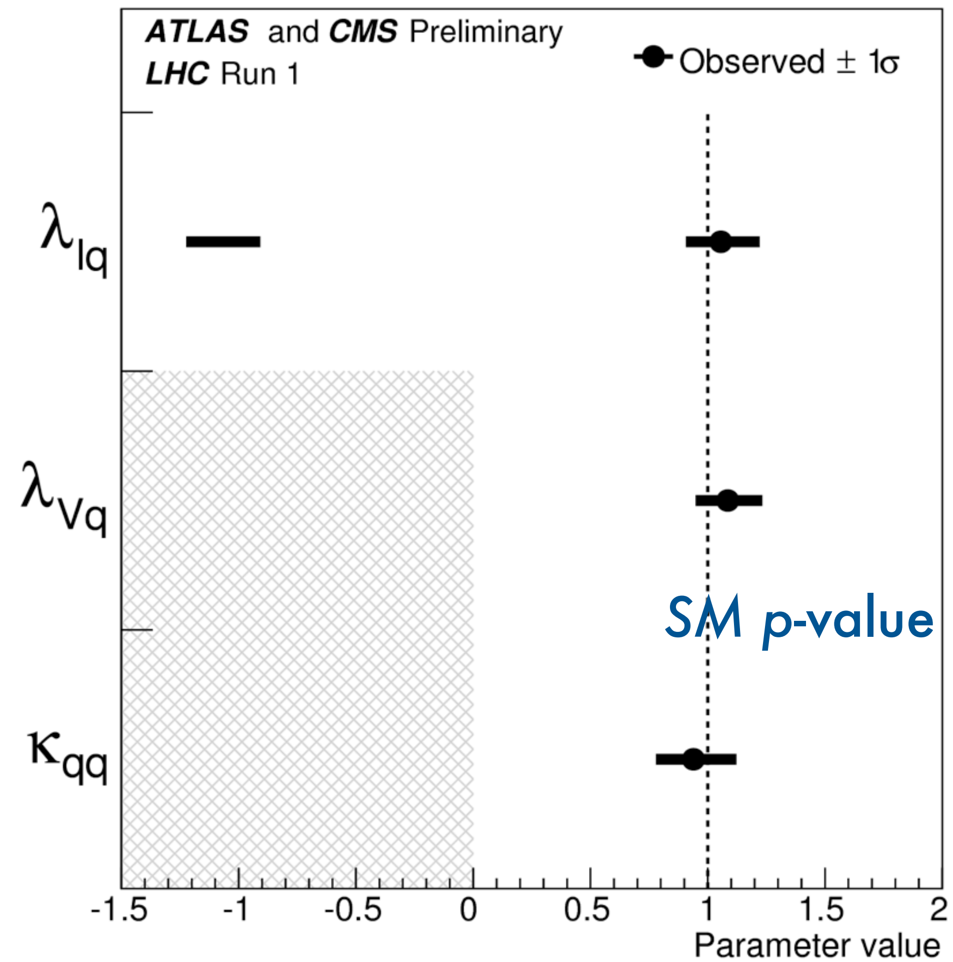
$\kappa_{uu} = \kappa_u \cdot \kappa_u/\kappa_H$

$\boxed{\lambda_{lq} = \kappa_l/\kappa_q}$ $\lambda_{Vq} = \kappa_V/\kappa_q$

$\kappa_{qq} = \kappa_q \cdot \kappa_q/\kappa_H$



SM p-value = 67%



SM p-value = 78%

- **All results are consistent with the SM**

κ-framework - Ratios of coupling modifiers

- Combined input channels span five Higgs boson decay modes and five production channels $\rightarrow$ **coupling ratios λ**

$$\lambda_{Zg} = \kappa_Z/\kappa_g \quad \lambda_{WZ} = \kappa_W/\kappa_Z$$
$$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z \quad \lambda_{bZ} = \kappa_b/\kappa_Z$$
$$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z \quad \lambda_{tg} = \kappa_t/\kappa_g$$

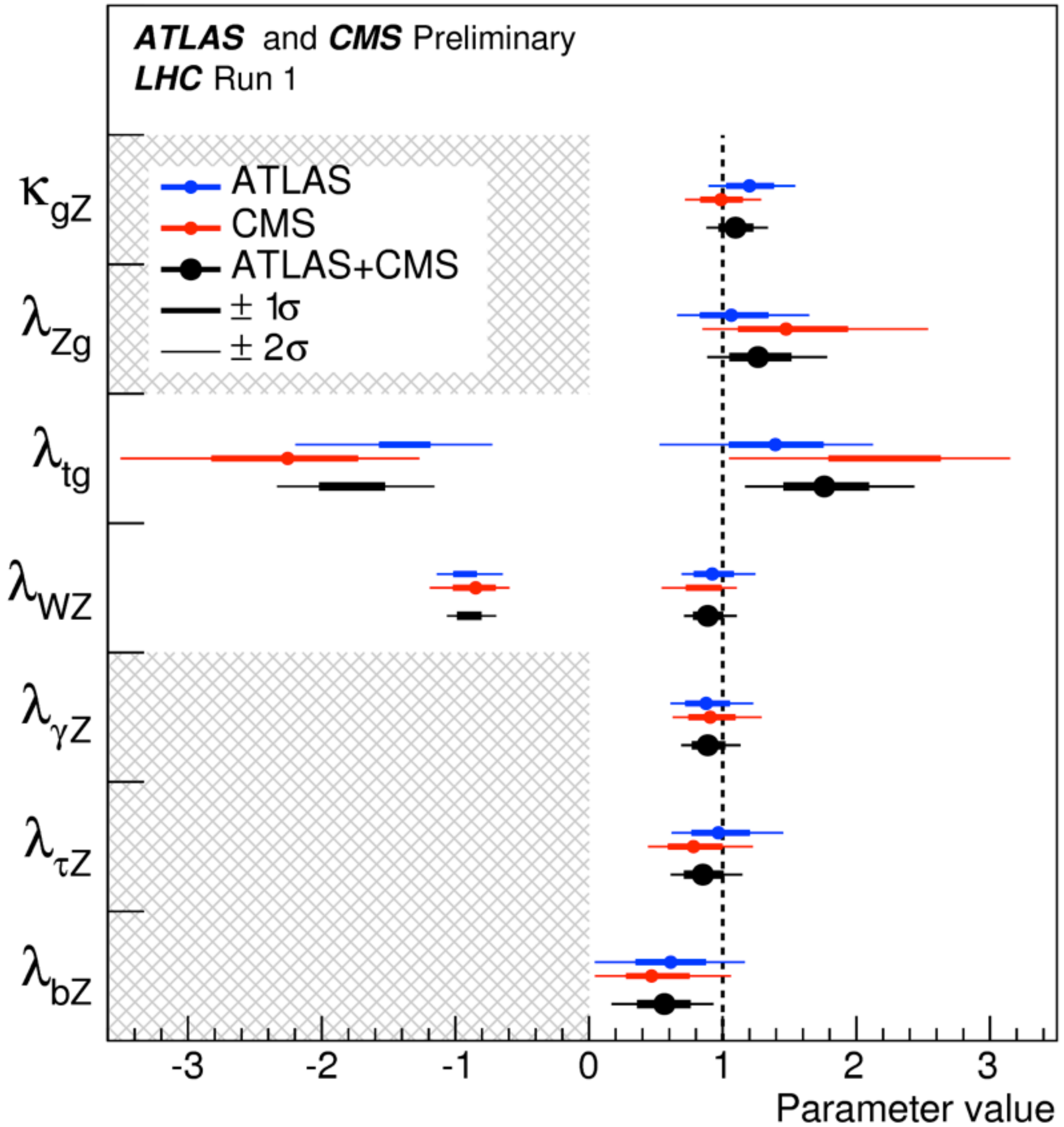
- No assumptions on Γ_H needed, as it cancels in ratios of coupling strengths

- Measurements normalized to $gg \rightarrow H \rightarrow ZZ$ in most cases

$$\sigma \cdot BR(gg \rightarrow H \rightarrow ZZ) \Longrightarrow \kappa_{gZ} = \kappa_g \cdot \kappa_z/\kappa_H$$

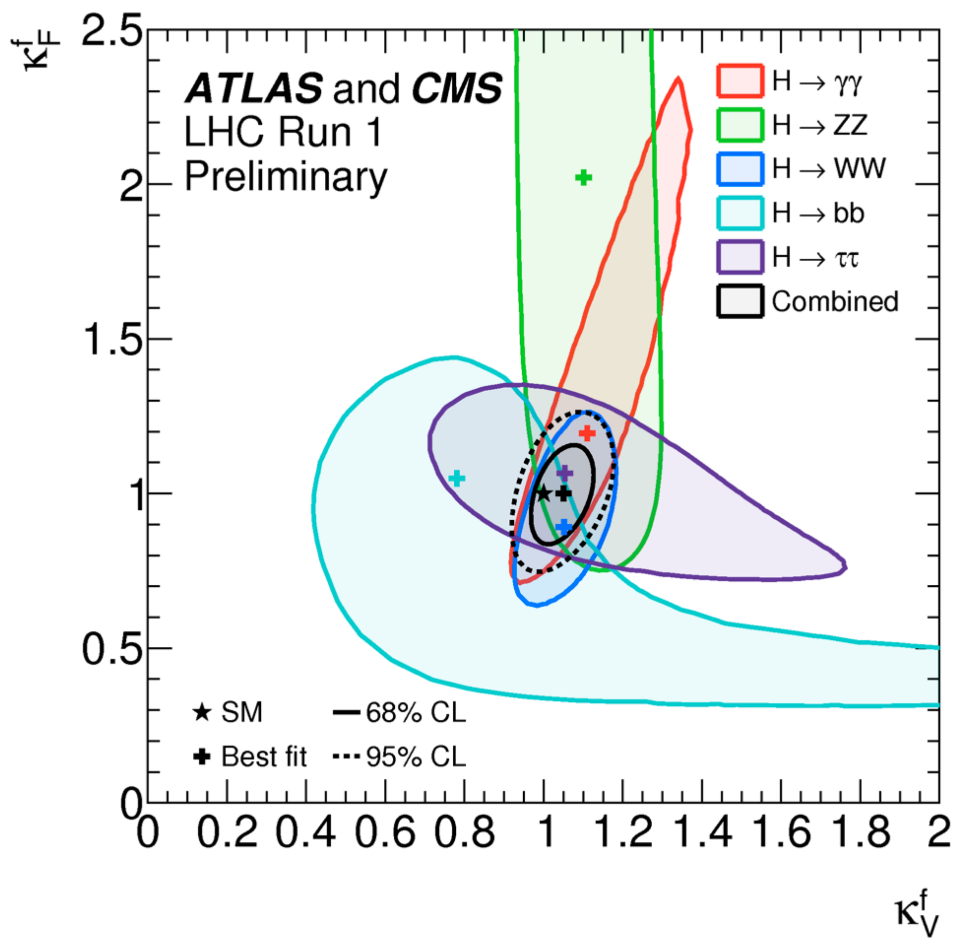
$\kappa_g =$ effective c.m. of H-g in ggF

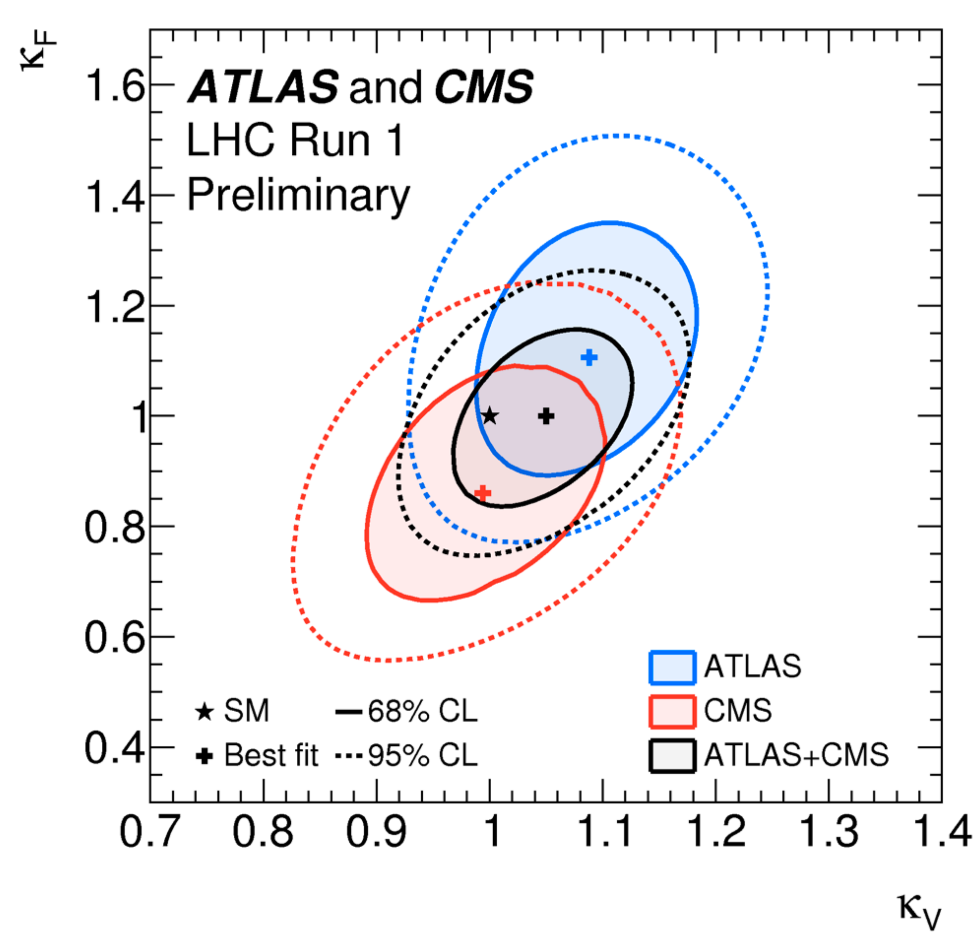
- All results are consistent with the SM predictions **within 2σ**, except for λ_{bZ} and λ_{tg}
  - This reflect the same tensions as ratios of bb and ZZ decays and of ttH and ggF production rates



Fermion and vector boson couplings

- Probe intrinsic difference between Higgs boson couplings to vector bosons and Yukawa couplings to fermions (assuming only SM physics in loops and no invisible Higgs decays)
- Assuming all boson couplings scale with κ_V while all fermions with κ_F : six fit performed, one per decay channel
  - Negative couplings would change sign of interference $\rightarrow$ *physical quantities depend on product of two κ's*





- All results are in agreement with the SM prediction of $\kappa_V{}^f = 1$ and $\kappa_F{}^f = 1$ - **almost 5σ exclusion of $\kappa_F < 0$**