ATLAS + CMS: Higgs boson mass and width measurements at LHC

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On behalf of the ATLAS and CMS Collaborations

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Introduction

- In 2012 ATLAS and CMS Collaborations reported the discovery of a resonance compatible with the Higgs boson, as predicted by the Standard Model, at a mass of ~125 GeV.
- Run1 ended recording ~25 fb^{-1} at $\sqrt{s}$ = 7 and $\sqrt{s}$ = 8 TeV for ATLAS and CMS.
- Mass, width, spin, parity, couplings and cross section of the Higgs field have been measured so far.
- After Run1 new techniques have been developed to reduce systematic uncertainties and increase sensitivity, leading to more precise results.
- In this talk the combined results of ATLAS and CMS on the measurement of the Higgs boson mass are presented, as well as the limits on Higgs width.

Outline

- Run1 ATLAS and CMS results used

MASS RESULTS

- Mass measurement approach
- Individual and Combined results

WIDTH RESULTS

- Upper bound with direct width measurement
- Lower bound through Higgs lifetime
- Limits using off-shell production
- Results on Higgs width
- Limits allowing anomalous couplings

Run 1 ATLAS + CMS results

Basic sources for this presentation;

- **ATLAS**: “Measurement of the Higgs boson mass from the H→γγ and H→ZZ*→4l channels with the ATLAS detector at the LHC”, [CERN-PH-EP-2014-122, Phys.Rev. D90, 052004 (2014)]
- **CMS**: “Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV”, [CERN-PH-EP-2014-288, Eur. Phys. J. C 75 (2015) 212]
- **ATLAS+CMS**: “Combined measurement of the Higgs boson mass in pp collisions at √s = 7 and 8 TeV with the ATLAS and CMS experiments”, [CERN-PH-EP-2015-075, Phys. Rev. Lett. 114 (2015) 191803]
- **ATLAS**: “Constraints on the off-shell Higgs boson signal strength in the high-mass Z Z and WW final states with the ATLAS detector”, [CERN-PH-EP-2015-026, Eur. Phys. J C (2015) 75:335]
- **CMS**: “Constraints on the Higgs boson width from off-shell production and decay to Z-boson pairs”, [CERN-PH-EP/2013-037, Phys. Lett. B 736 (214) 64]
- **CMS**: “Limits on the Higgs boson lifetime and width from its decay to four charged leptons”, [CERN-PH-EP/2015-159]

Mass results

Mass measurement approach

- Use only H → γγ and H → ZZ → 4l channels; best mass resolution.
- Narrow peak expected over smoothly falling BG for γγ, small BG for ZZ.
- Neglect signal – BG interference (down shift ~10 MeV in γγ, much smaller in ZZ)
- **Model Independent** measurement;

  – Fitting the spectra of the reconstructed invariant masses without SM assumptions on signal, couplings and yields.

  – 3 signal strength scale factors are introduced and profiled in the fit.

$$\mu = (\sigma_{expt} \times BF_{expt}) \,/\, (\sigma_{SM} \times BF_{SM})$$

- **2 signal strengths for γγ** as this channel is sensitive to different production modes $\mu^{\gamma\gamma}_{ggF+t\bar{t}H}$ $\mu^{\gamma\gamma}_{VBF+VH}$
- **1 signal strength for ZZ** μ^{4l}

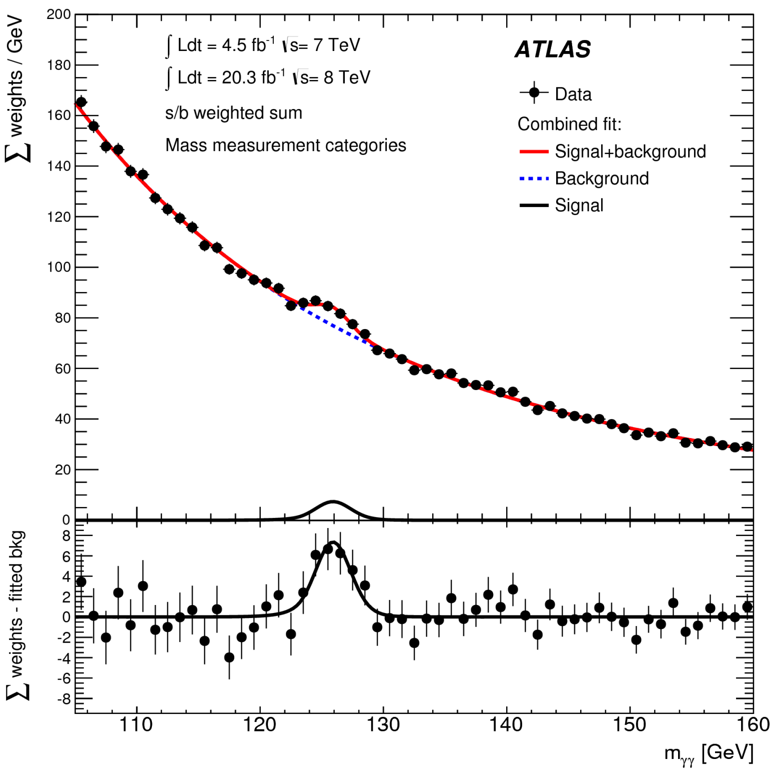
- Assumption of **same** signal strengths for ATLAS and CMS

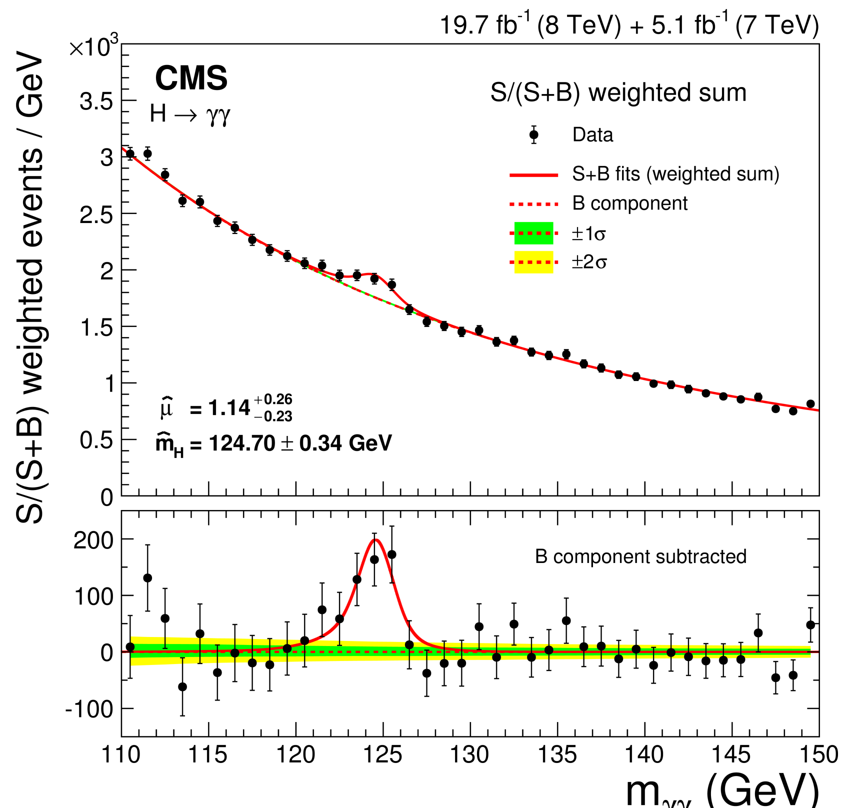
- Maximization of profile likelihood ratios; $$\Lambda(\boldsymbol{\alpha}) = \frac{L\left(\boldsymbol{\alpha}, \hat{\hat{\boldsymbol{\theta}}}(\boldsymbol{\alpha})\right)}{L\left(\hat{\boldsymbol{\alpha}}, \hat{\boldsymbol{\theta}}\right)}$$

$H \rightarrow \gamma\gamma$

- High statistics. Narrow resonant signal peak over large falling backround.
- Small S/B ratio but very good mass resolution.

- Divide the events in categories → maximizing **signal purity** and **mass resolution**;
  – **ATLAS**; converted/unconverted photons * p_T threshold * η range
  – **CMS**; event topology (from production mode) + Boosted Decision Tree classifier.



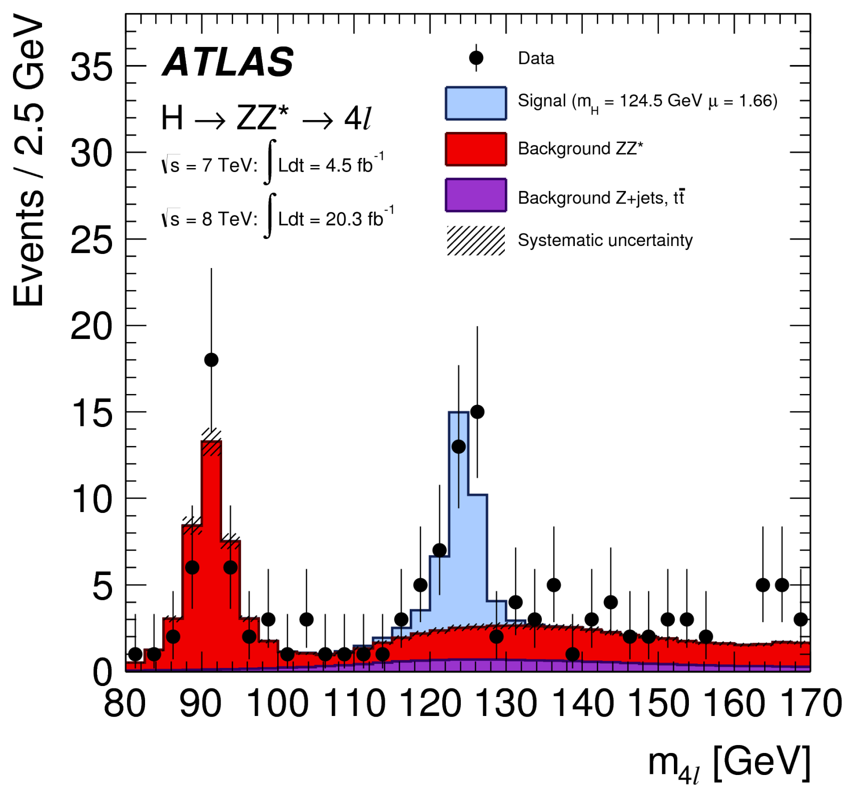


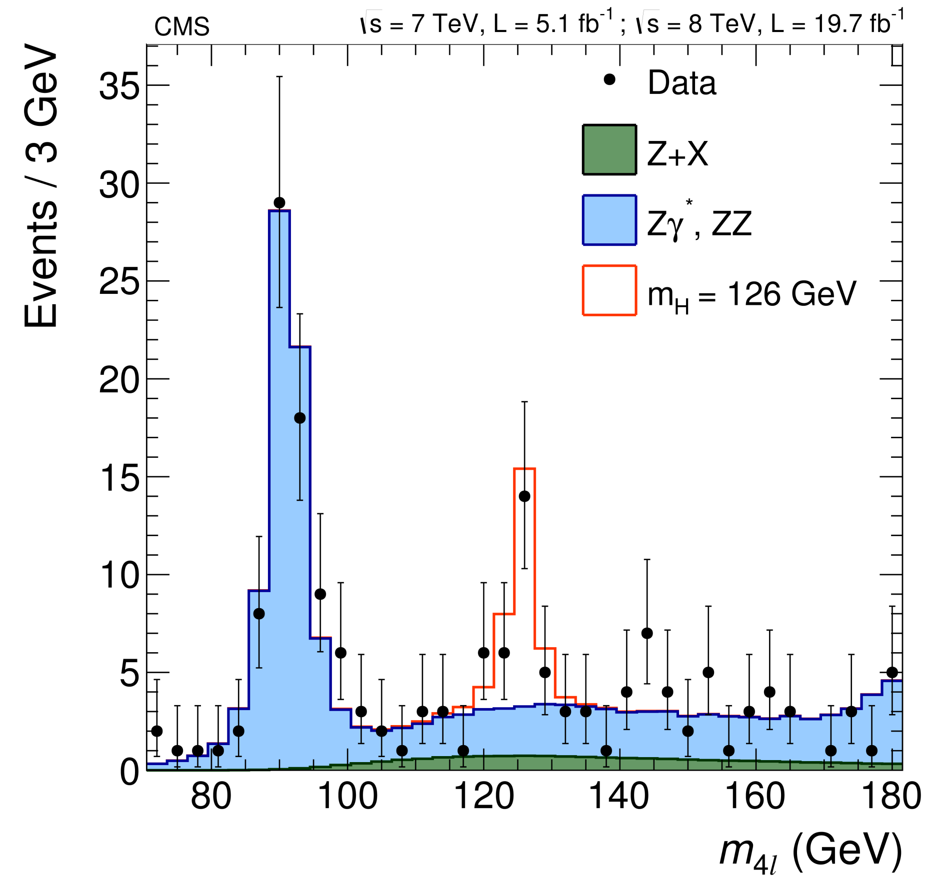
ATLAS uses different procedure for mass and couplings to reduce systematics in m_H.
CMS uses the same.

- Combined fit to all categories. **Mass** and **signal strengths** as parameters of interest.
- Background from fit to data (mostly irreducible SM γγ)

- Low statistics but high S/B ratio with very good mass resolution.

- Mass measurement through fitting m(4l) with a **multivariate discriminant.**
  – **ATLAS**; m(4l)*BDT,
  – **CMS**; m(4l)*D_{kin}*($\sigma_{m(4l)}$/m(4l))

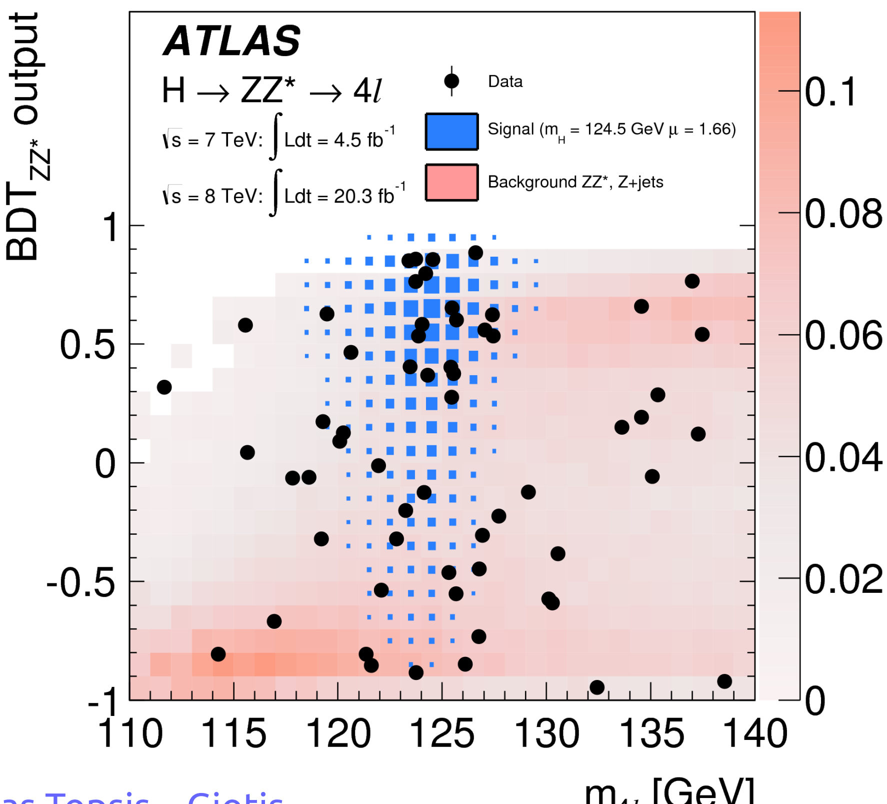




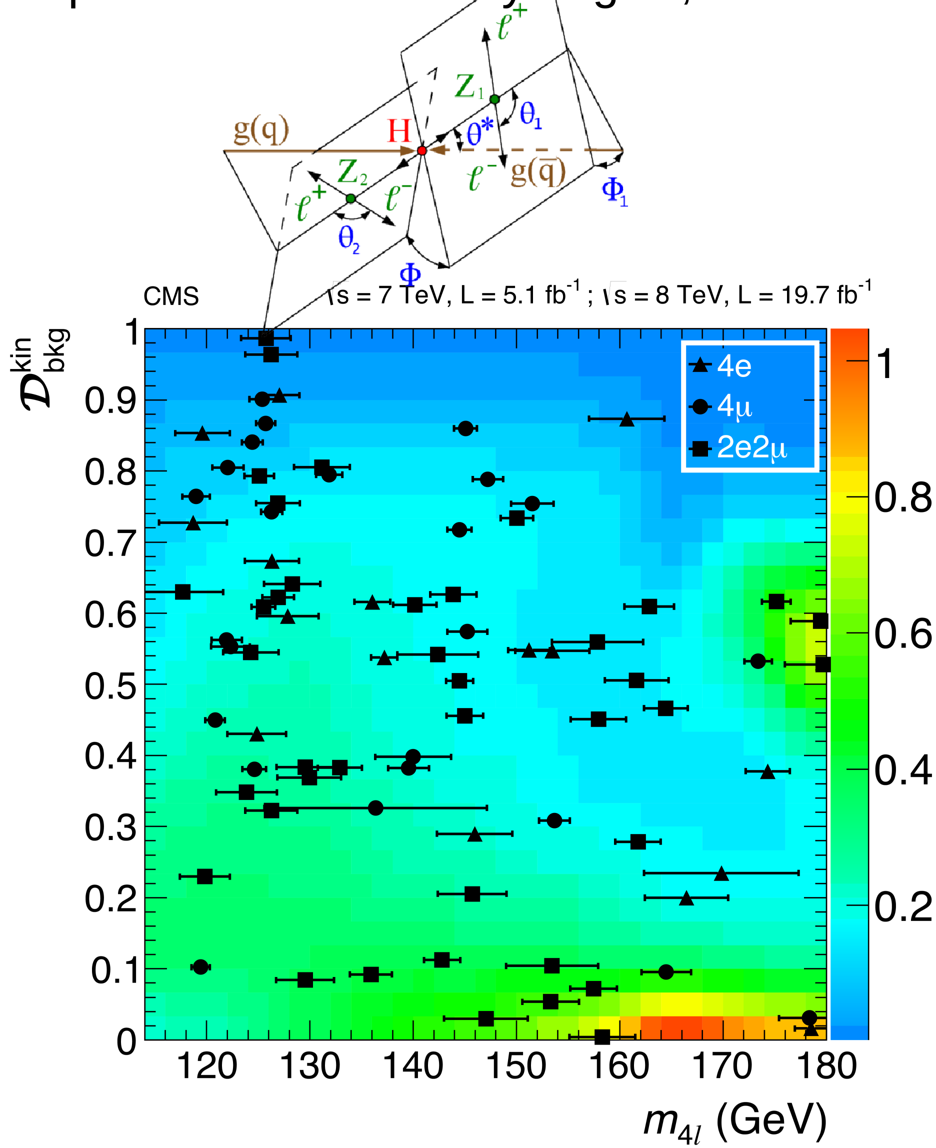
- Background estimate using **data driven** techniques for reducible cases (tt, Z+Jets), MC for ZZ case

- BDT discriminant trained against irreducible ZZ background with input;
– p_T and η of the 4l system
– Matrx Element discriminant;

$$D_{ZZ^*} = \ln\left(\frac{|\mathcal{M}_{sig}|^2}{|\mathcal{M}_{ZZ}|^2}\right)$$



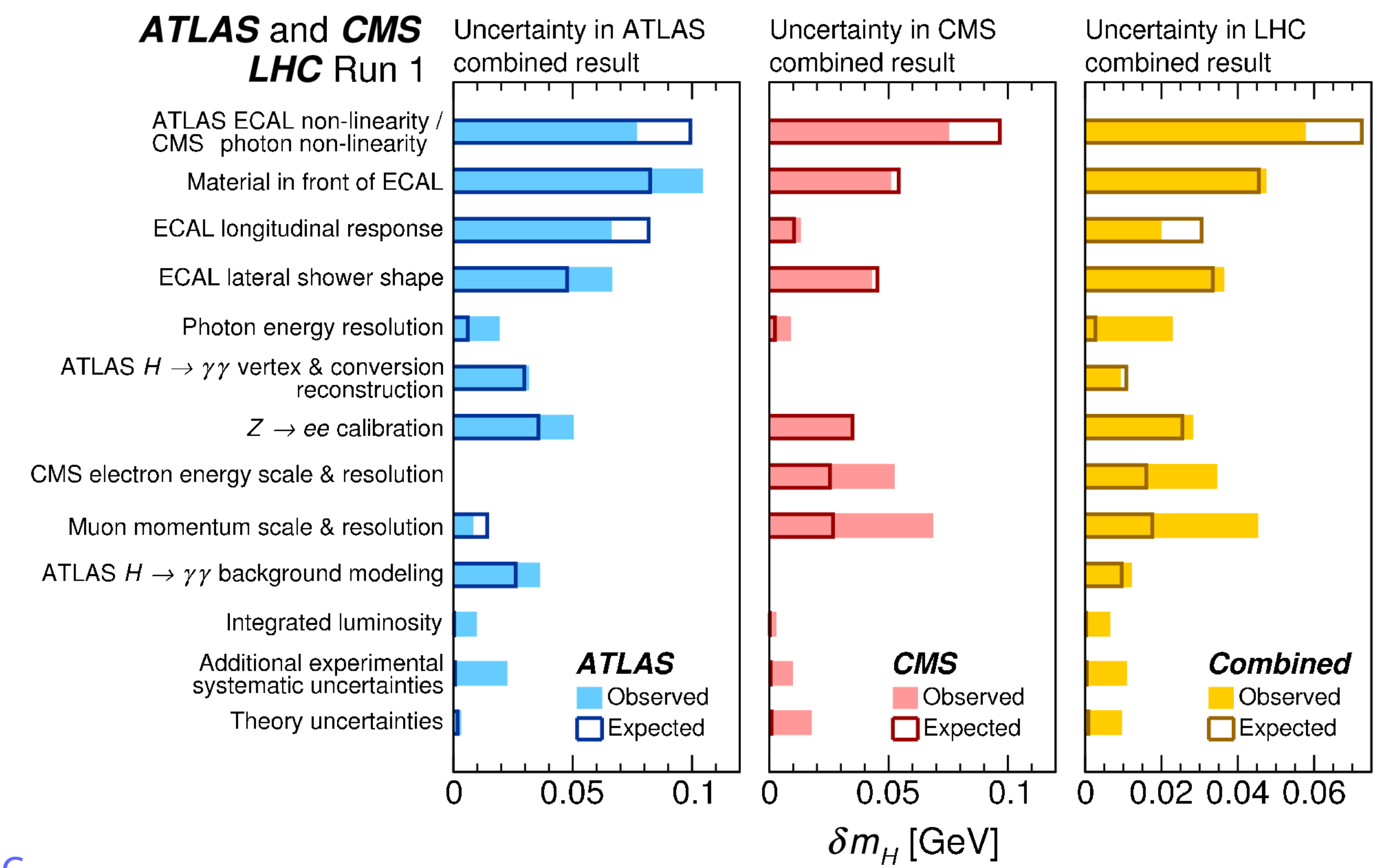
- D_{kin}; kinematical discriminant calculated from masses of the dilepton pairs and the 5 decay angles;



uncertainties

- Similar types of uncertainty dominate in each experiment independently;
  – electromagnetic energy scale and resolution
  – muon momentum and resolution
- Negligible theory uncertainties.

$$m_H = 125.09 \pm 0.21\,(stat.) \pm 0.11\,(scale) \pm 0.02\,(other) \pm 0.01\,(theory)$$



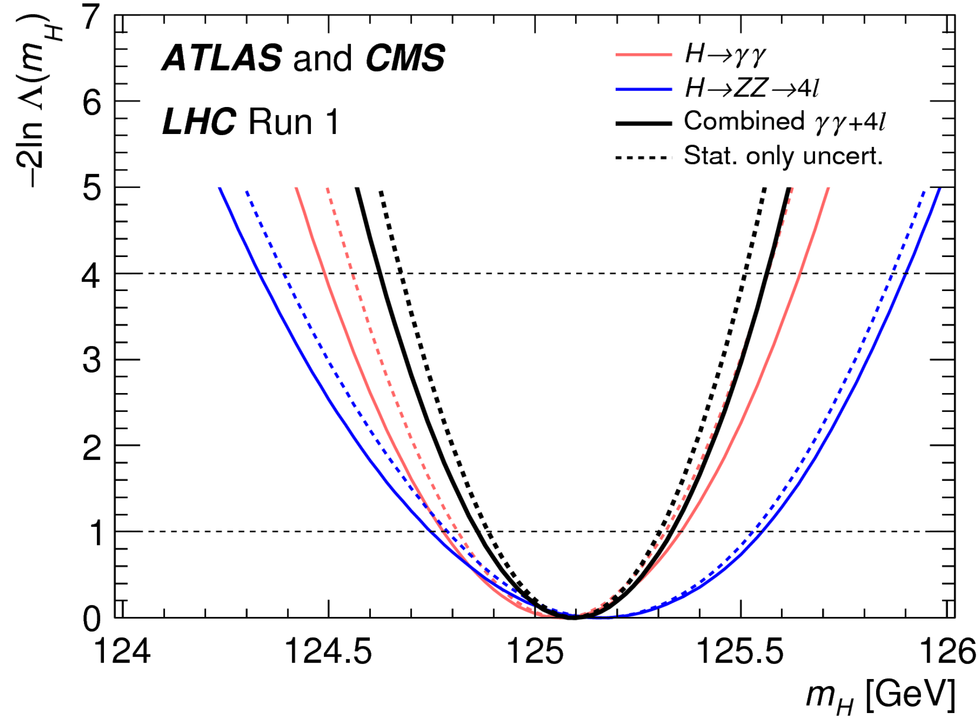
Mass results

$$\Lambda(m_H) = \frac{L\left(m_H, \hat{\hat{\mu}}^{\gamma\gamma}_{ggF+t\bar{t}H}(m_H), \hat{\hat{\mu}}^{\gamma\gamma}_{VBF+VH}(m_H), \hat{\hat{\mu}}^{4l}(m_H), \hat{\hat{\boldsymbol{\theta}}}(m_H)\right)}{L\left(\hat{m}_H, \hat{\mu}^{\gamma\gamma}_{ggF+t\bar{t}H}, \hat{\mu}^{\gamma\gamma}_{VBF+VH}, \hat{\mu}^{4l}, \hat{\boldsymbol{\theta}}\right)}$$

- Maximize profile likelihood ratio in the asymptotic regime.

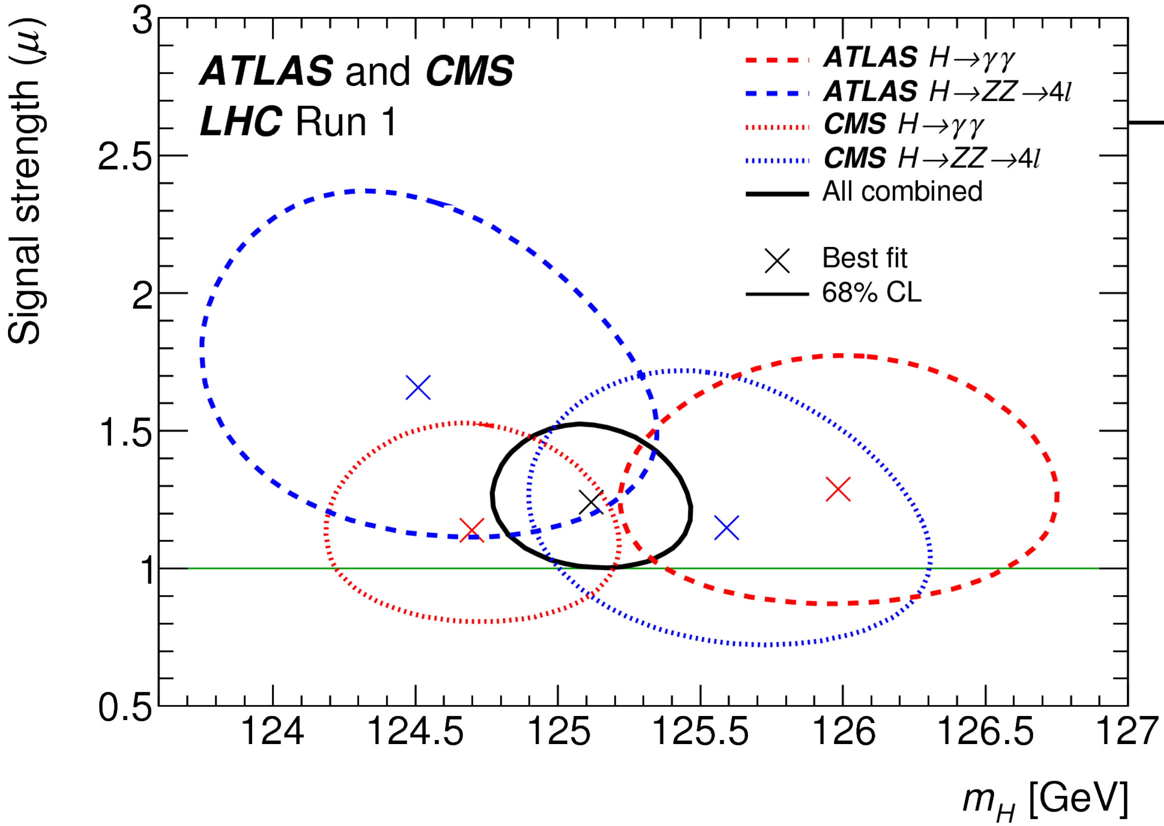
- 2 signal strengths for γγ as this channel is sensitive to different production modes
- 1 signal strength for ZZ

- Signal strengths assumed to be the same for ATLAS and CMS.



$$
\begin{aligned}
m_H &= 125.09 \pm 0.24\ GeV \\
&= 125.09 \pm 0.21\,(stat.) \pm 0.11(syst.)\ GeV
\end{aligned}
$$

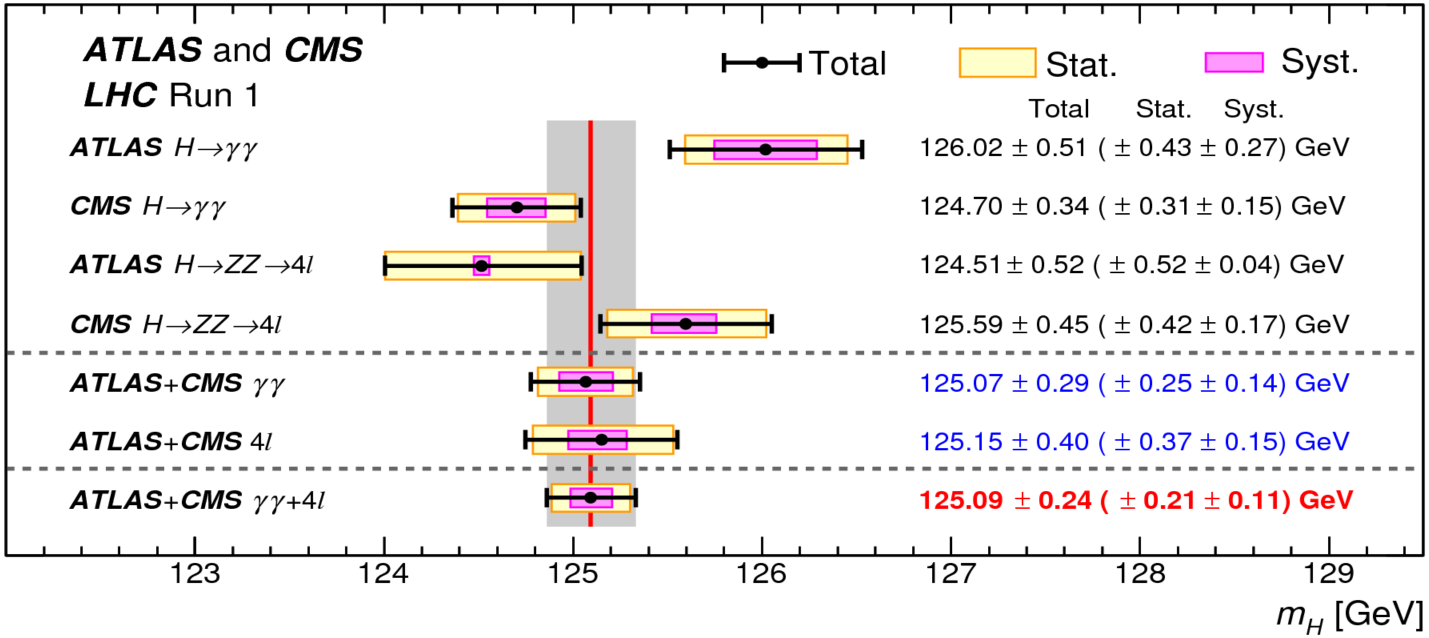
- **Total uncertainty** = width of the negative log likelihood scan with all parameters profiled
- **Statistical**; fixing nuissance parameters to their best fit values (not μs).
- **Systematic**; subtracting in quadrature stat. from total uncertainty.



Mass results

- Correlation of signal strength and mass through 2D likelihood scans of (μ, m_H).
- For the combined 2D contour (in black), the 3 signal strengths assumed to be the same, μ.
- 68% CL 2D regions assuming $-2\ln\Lambda(\mu, m_H)$ distributed as χ^2 with 2 degrees of freedom

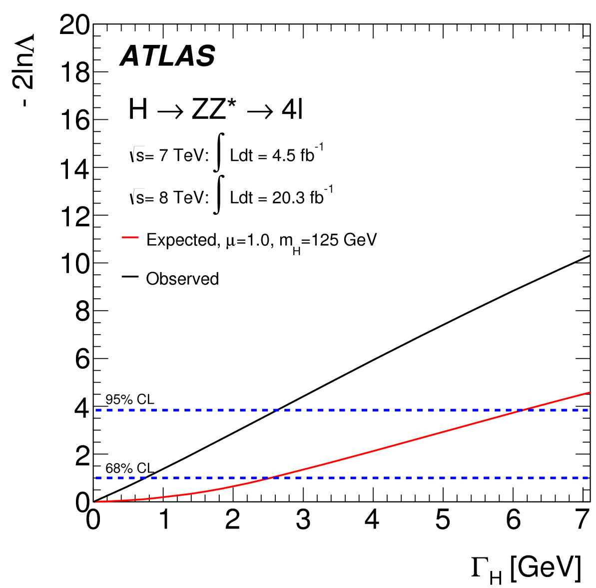
- All individual and combined results with their uncertainties.

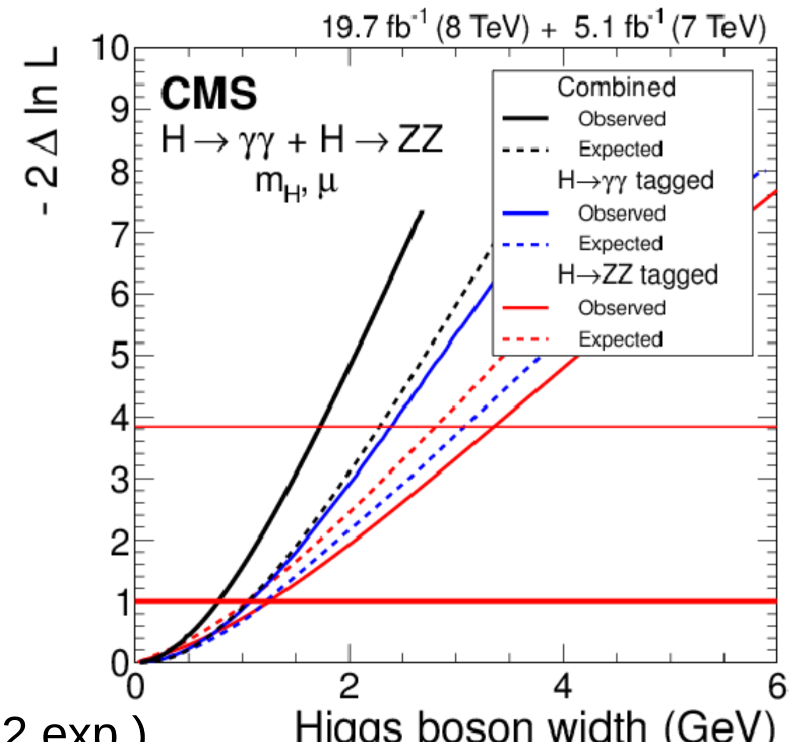


Width results

Direct Width Measurement; upper bound

- Can directly measure Higgs width Γ_H using γγ and 4l mass spectra.
- Measurement limited by experimental resolution.
- Standard Model prediction ~ **4 MeV** for mH = 125 GeV.
- Assumption of no interference of signal with backround processes.
- m_H and signal strength profiled (free parameters in the fit)





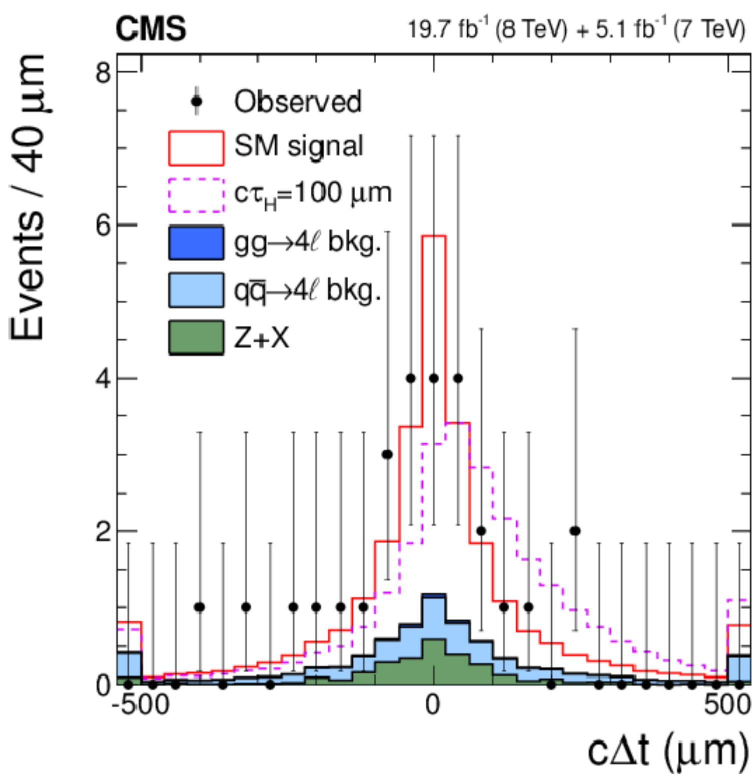
- **ATLAS** results;
  – H → γγ; $\mathbf{\Gamma_H}$ **< 5.0 GeV** obs. @ 95% CL (6.2 exp.)
  – H → ZZ → 4l; $\mathbf{\Gamma_H}$ **< 2.6 GeV** obs. @ 95% CL (6.2 exp.)
- **CMS** results;
  2 decay modes combined resulting in;
  $\mathbf{\Gamma_H}$ **< 1.7 GeV** observed @ 95% CL (2.3 expected)

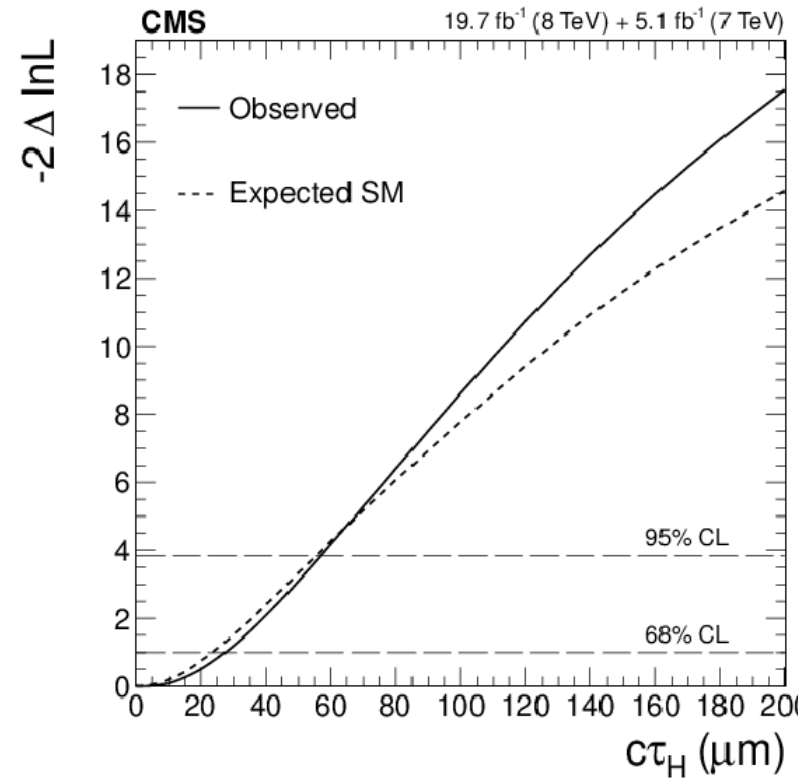
Lower bound through Higgs lifetime

- Could extract lower limits on Higgs width using its lifetime from H → ZZ → 4l;

$$\Delta t = \frac{m_{4\ell}}{p_{\mathrm{T}}} \left(\Delta \vec{r}_{\mathrm{T}} \cdot \hat{p}_{\mathrm{T}} \right) \quad \text{and} \quad \langle \Delta t \rangle = \tau_{\mathrm{H}} = \frac{\hbar}{\Gamma_{\mathrm{H}}}$$

- Standard Model gives **$\tau_H \sim 4.8\ 10^{-8}$ μm/c**, far from experimental sensitivity.





- Fit is performed to **$P(\Delta t)*P(D_{bkg})$**, where D_{bkg} the kinematic discriminant used.
- Results;
  - **$c\tau_H$ < 57 μm** observed @ 95% CL (56 μm expected)
  - **Γ_H > 3.5 x 10^{-9} MeV** observed @ 95% CL (3.6 x 10^{-9} MeV expected)

Limit width through off-shell production

- Higgs boson width could be constrained using off-shell production to 2 Z bosons away from the resonance peak. Gluon fusion is dominant.

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}.$$

- Integrating around m_H or above $2m_Z$ (where $m_{ZZ}-m_H >> \Gamma_H$);

$$\sigma_{gg\to H\to ZZ^*}^{\text{on-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H\Gamma_H} \quad \text{and} \quad \sigma_{gg\to H^*\to ZZ}^{\text{off-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(2m_Z)^2}.$$

- Taking signal strengths in terms of coupling scale factors;

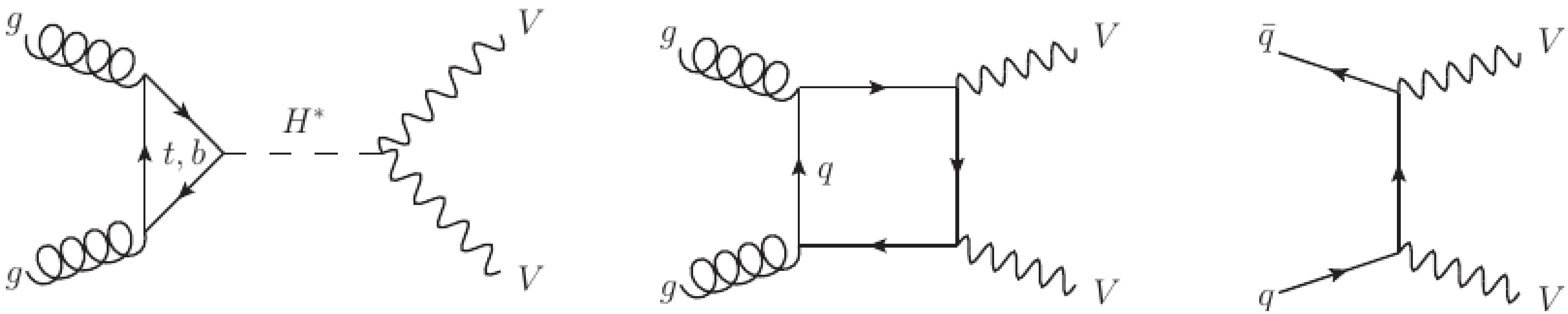
$$\mu_{\text{on-shell}} \equiv \frac{\sigma_{\text{on-shell}}^{gg\to H\to VV}}{\sigma_{\text{on-shell, SM}}^{gg\to H\to VV}} = \frac{\kappa_{g,\text{on-shell}}^2 \cdot \kappa_{V,\text{on-shell}}^2}{\Gamma_H/\Gamma_H^{SM}} \qquad \mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma_{\text{off-shell}}^{gg\to H^*\to VV}(\hat{s})}{\sigma_{\text{off-shell, SM}}^{gg\to H^*\to VV}(\hat{s})} = \kappa_{g,\text{off-shell}}^2(\hat{s}) \cdot \kappa_{V,\text{off-shell}}^2(\hat{s})$$

  - On-shell (NWA) depends on total width Off-shell does not!

- Assumption of **independence of scale factors from s** (energy scale) in high mass region considered in the analysis.
- A measurement of the relative on-shell and off-shell production provides direct information on Higgs width, assuming **coupling ratios unchanged** (no new physics).
- **NNLO K-factor for the gg → VV process unknown**. CMS assumes same NNLO K factor with the signal and adds **10% uncertainty**. ATLAS provides the result as a **function of the ratio** of these two.

Interference and MC generators

- Leading order Feynman graphs for signal and backround.
- Interference in gg → (H →) VV processes at the high mass region (off-shell)



- GGF production;

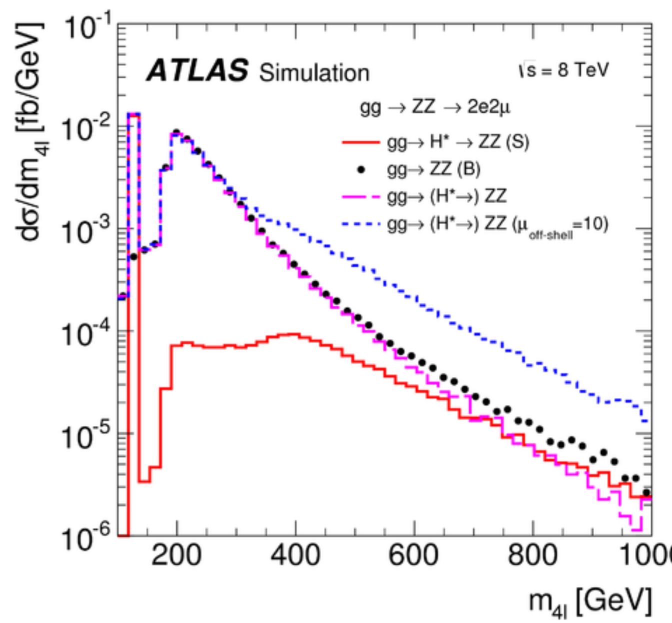
  – MCFM and GG2VV
  (LO, QCD renorm.+factor. scale = $m_{ZZ}/2$)
  – SHERPA for $p_{T,ZZ}$ description in ATLAS

- VBF production;

  – MADGRAPH and PHANTOM
  – negligible VH, ttH production mechanisms

- qqZZ production;

  – POWHEG at NLO in QCD and NLO EW corrections
  – NNLO m_{ZZ} K-factor in ATLAS



Arbitrary off-shell signal strength and K-factors

- For an arbitrary off-shell signal strength, the cross section of gg → (H* →) VV can be parametrized;

$$\begin{aligned}\sigma_{gg\to(H^*\to)VV}(\mu_{\text{off-shell}}, m_{VV}) &= \mathrm{K}^{H^*}(m_{VV})\cdot\mu_{\text{off-shell}}\cdot\sigma^{\text{SM}}_{gg\to H^*\to VV}(m_{VV}) \\ &+ \sqrt{\mathrm{K}^{H^*}_{gg}(m_{VV})\cdot\mathrm{K}^{\mathrm{B}}(m_{VV})\cdot\mu_{\text{off-shell}}}\cdot\sigma^{\text{SM}}_{gg\to VV,\,\text{Interference}}(m_{VV}) \\ &+ \mathrm{K}^{\mathrm{B}}(m_{VV})\cdot\sigma_{gg\to VV,\,\text{cont}}(m_{VV})\,.\end{aligned}$$

where;

- $\mathrm{K}^{H^*}(m_{VV}) = \sigma^{\text{NNLO}}_{gg\to H^*\to VV}/\sigma^{\text{LO}}_{gg\to H^*\to VV},$ NNLO/LO K factor for the signal.

– calculated inclusively, 20-30% QCD scale uncertainty.

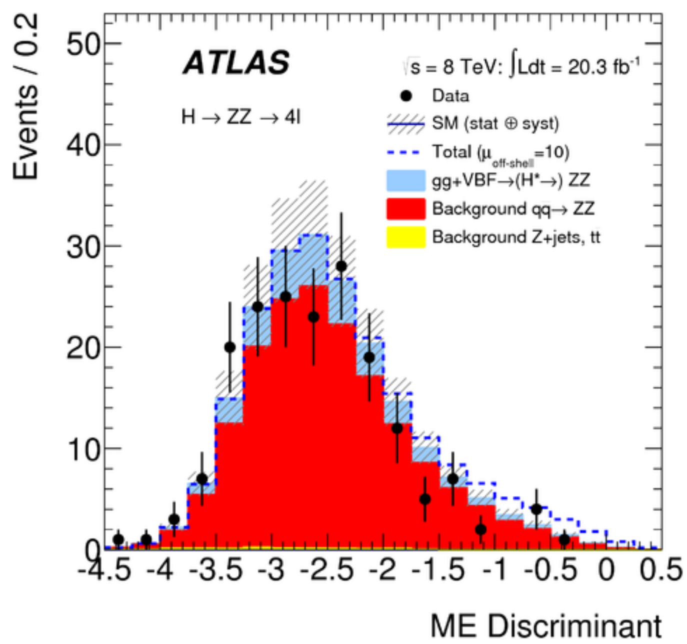
- $\mathrm{K}^{H^*}_{gg}(m_{VV})$ NNLO/LO for the gluon initiated process. Larger uncertainty.
- $\mathrm{K}^{\mathrm{B}}(m_{VV})$ K – factor for the background gg → VV process, **unknown**.

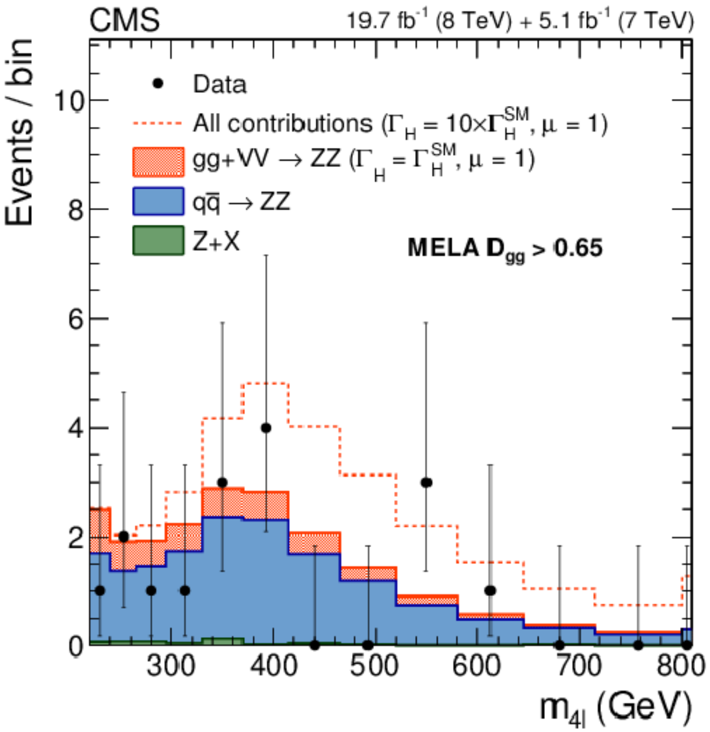
$$\mathrm{R}^{B}_{H^*} = \frac{\mathrm{K}(gg\to VV)}{\mathrm{K}(gg\to H^*\to VV)} = \frac{\mathrm{K}^{\mathrm{B}}(m_{VV})}{\mathrm{K}^{H^*}_{gg}(m_{VV})}$$

ratio between gg → VV and signal NNLO K-factors

- Similar selection to on-shell case (2 opposite sign same flavor prompt – iso leptons)
- Signal region; m_{4l} > 220 GeV for both ATLAS and CMS.
- Enhancing sensitivity using Matrix Element based discriminant;

$$\mathrm{ME} = \log_{10}\left(\frac{P_H}{P_{gg} + c \cdot P_{q\bar{q}}}\right) \qquad \mathcal{D}_{gg} = \frac{\mathcal{P}^{gg}_{\mathrm{tot}}}{\mathcal{P}^{gg}_{\mathrm{tot}} + \mathcal{P}^{q\bar{q}}_{\mathrm{bkg}}} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{\mathrm{bkg}}}{a \times \mathcal{P}^{gg}_{\mathrm{sig}} + \sqrt{a} \times \mathcal{P}^{gg}_{\mathrm{int}} + \mathcal{P}^{gg}_{\mathrm{bkg}}}\right]^{-1}$$



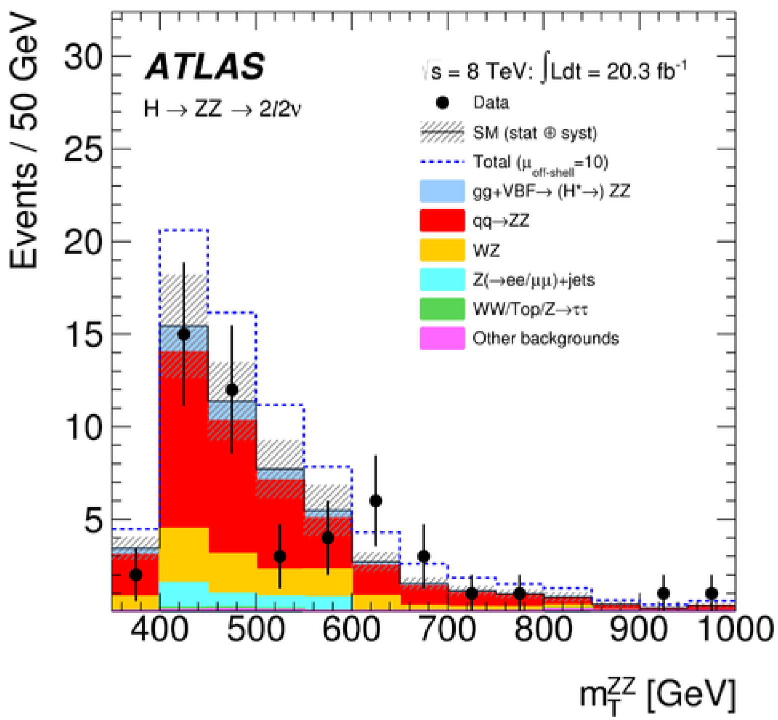


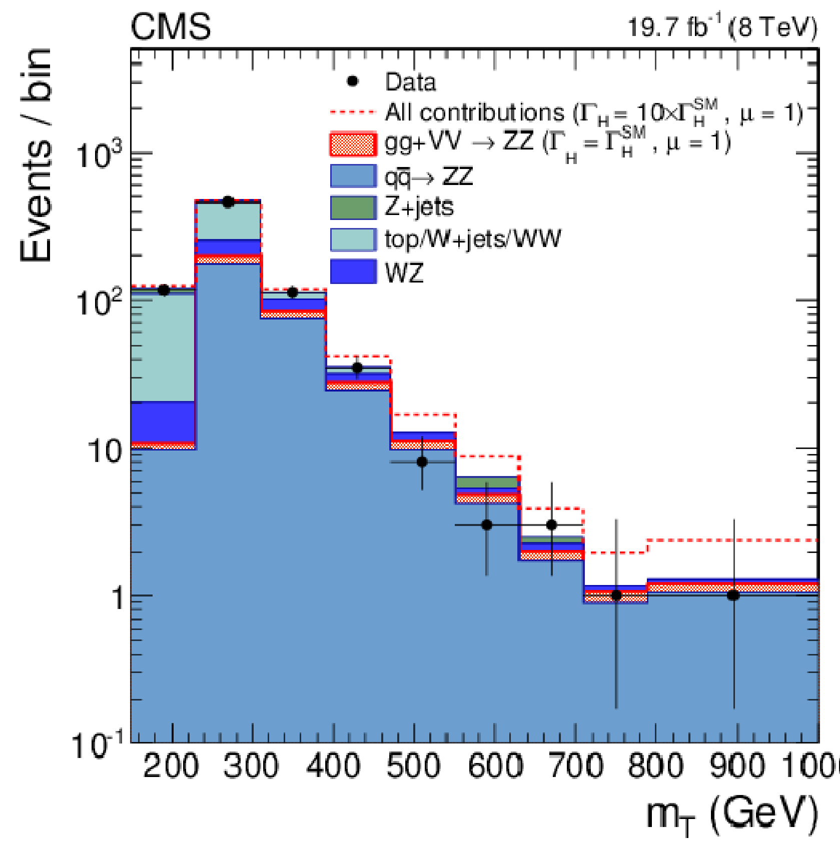
- Used **m_{4l}, m_{Z1}, m_{Z2}, 5 decay angles** to calculate Matrix Element with MCFM
- Fit **ME** discriminant shape (ATLAS), **m4l-ME** (CMS) to obtain limit on $\mu_{\text{off-shell}}$

ZZ → llνν

- Similar sensitivity to 4l but higher Branching Ratio.
- Cutting at high MET, m_{ll} in the area of the Z boson mass.

$$m_{\mathrm{T}}^2 = \left[\sqrt{{p_{\mathrm{T},2\ell}}^2 + {m_{2\ell}}^2} + \sqrt{{E_{\mathrm{T}}^{\mathrm{miss}}}^2 + {m_{2\ell}}^2}\right]^2 - \left[\vec{p}_{T,2\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right]^2,$$



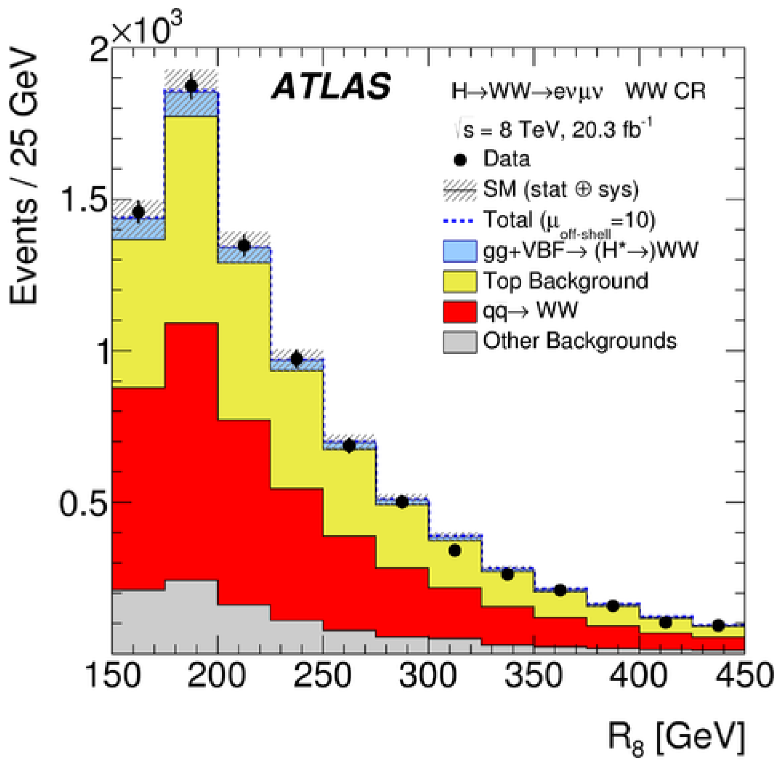


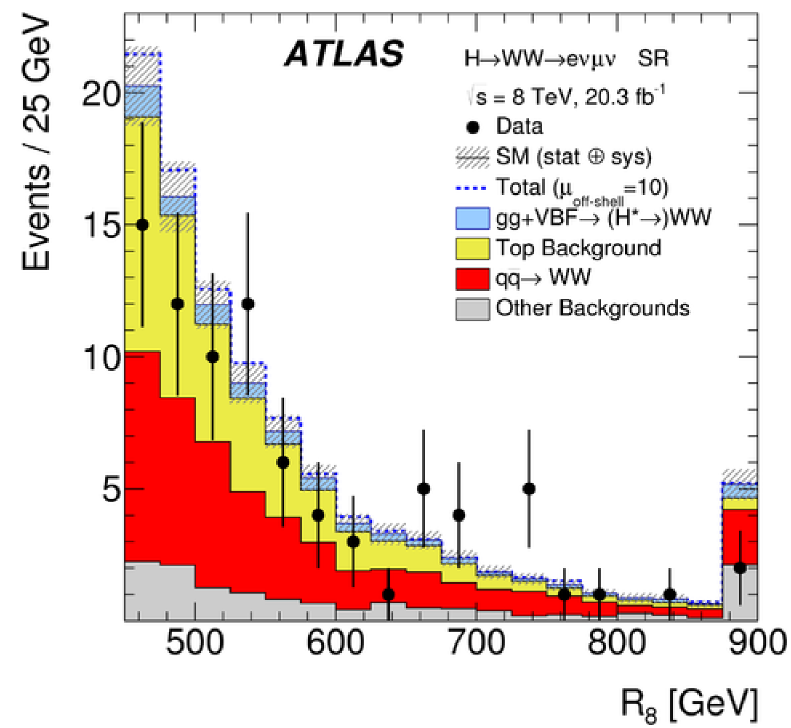
- Signal region; **350 GeV < m_T < 1 TeV** (ATLAS), **180 GeV < m_T < 1 TeV** (CMS)
- Maximum likelihood fit on m_T

WW → eνμν

- Based on inclusive on-shell H → WW* → lνlν, but inclusive in jets
- To isolate off-shell Higgs production and minimize higher order QCD effects;

$$R_8 = \sqrt{m_{\ell\ell}^2 + \left(a \cdot m_{\mathrm{T}}^{WW}\right)^2}.$$





- R8 cut and α value optimized for off-shell signal sensitivity and reject on-shell Higgs
- Maximum Likelihood fit observable; yields in signal region R_8>450 GeV and top, WW control regions.

Systematic uncertainties

- Systematic uncertainties dominated by theoretical uncertainties.

  – QCD scale uncertainty for gg → (H* →) VV and qq → VV
  – PDF for qq → VV and gg → VV
  – Unknown NNLO K-factor for the gg → VV process;
    – **ATLAS** gives result as function of the ratio between gg → VV and signal NNLO K-factor
    – **CMS** assumes same signal NNLO K-factor for the background, adding 10% systematic uncertainty.

  – Additional 30% uncertainty for the interference in ATLAS.

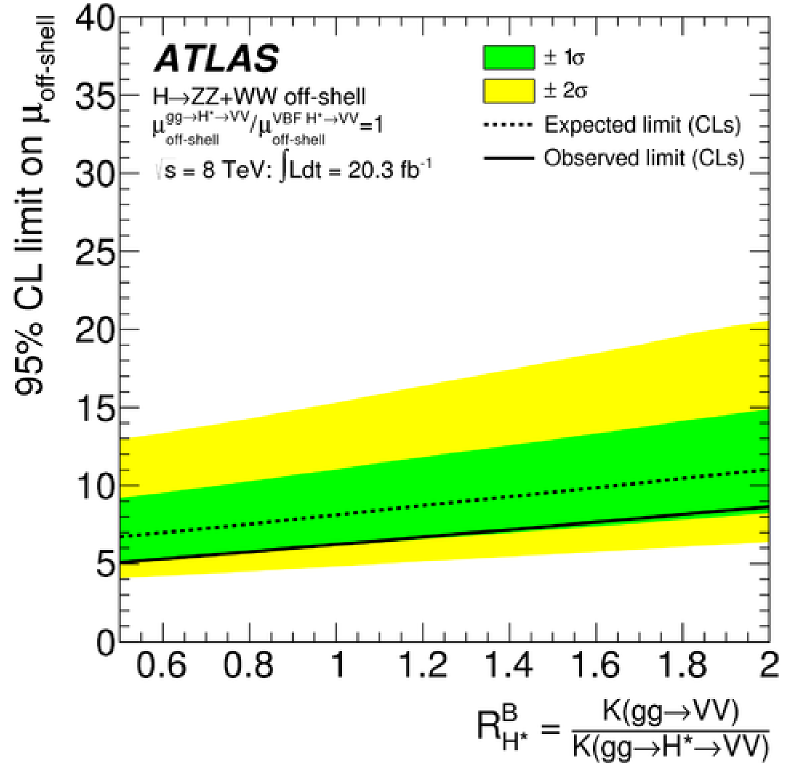
- Experimental uncertainties sub-dominant for both experiments

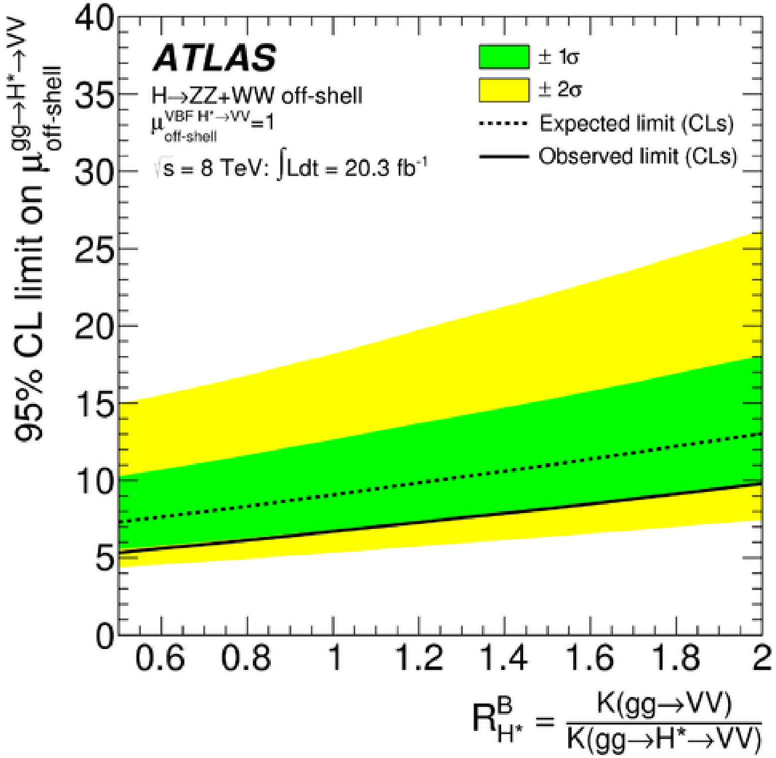
ATLAS

Systematic uncertainty	95% CL lim. (CL_s) on $\mu_{\mathrm{off-shell}}$
Interference $gg \to (H^* \to) VV$	7.2
QCD scale $\mathrm{K}^{H^*}(m_{VV})$ (correlated component)	7.1
PDF $q\bar{q} \to VV$ and $gg \to (H^* \to) VV$	6.7
QCD scale $q\bar{q} \to VV$	6.7
Luminosity	6.6
Drell–Yan background	6.6
QCD scale $\mathrm{K}^{H^*}_{gg}(m_{VV})$ (uncorrelated component)	6.5
Remaining systematic uncertainties	6.5
All systematic uncertainties	8.1
No systematic uncertainties	6.5

Limits on μoffshell

- Using two different assumptions;

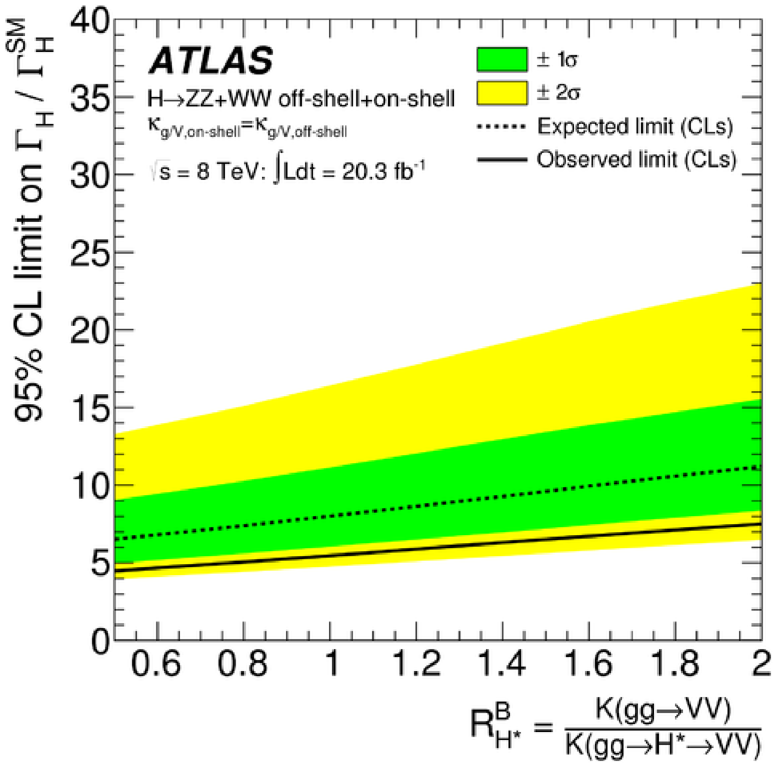


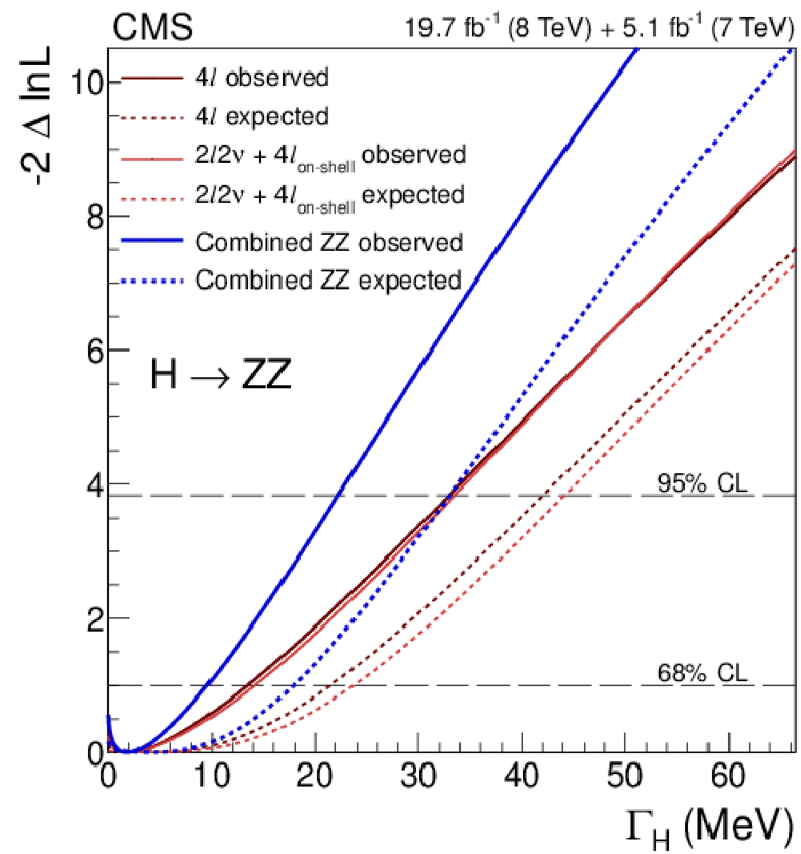


	Observed			Median expected			Assumption
R^B_{H*}	0.5	**1.0**	2.0	0.5	**1.0**	2.0	
$\mu_{\text{off-shell}}$	5.1	**6.2**	8.6	6.7	**8.1**	11.0	$\mu^{gg\to H^*}_{\text{off-shell}}/\mu^{VBF}_{\text{off-shell}}=1$
$\mu^{gg\to H^*\to VV}_{\text{off-shell}}$	5.3	**6.7**	9.8	7.3	**9.1**	13.0	$\mu^{\text{VBF }H^*\to VV}_{\text{off-shell}}=1$

Limits on Higgs width

- Obtain limits on Γ_H combining on-shell and off-shell measurements.
- Profiling μ_{ggF} and μ_{VBF} on data.
- Assuming same on-shell and off-shell couplings;





- **ATLAS** results; $\mathbf{\Gamma_H < 22.7}$ **MeV** @ 95% CL (<33 MeV expected)
- **CMS** results; $\mathbf{\Gamma_H < 22}$ **MeV** @ 95% CL (<33 MeV expected)

Limits on Higgs width allowing anomalous couplings

- Including possible anomalous couplings in HVV;

$$A(\mathrm{HVV}) \propto$$

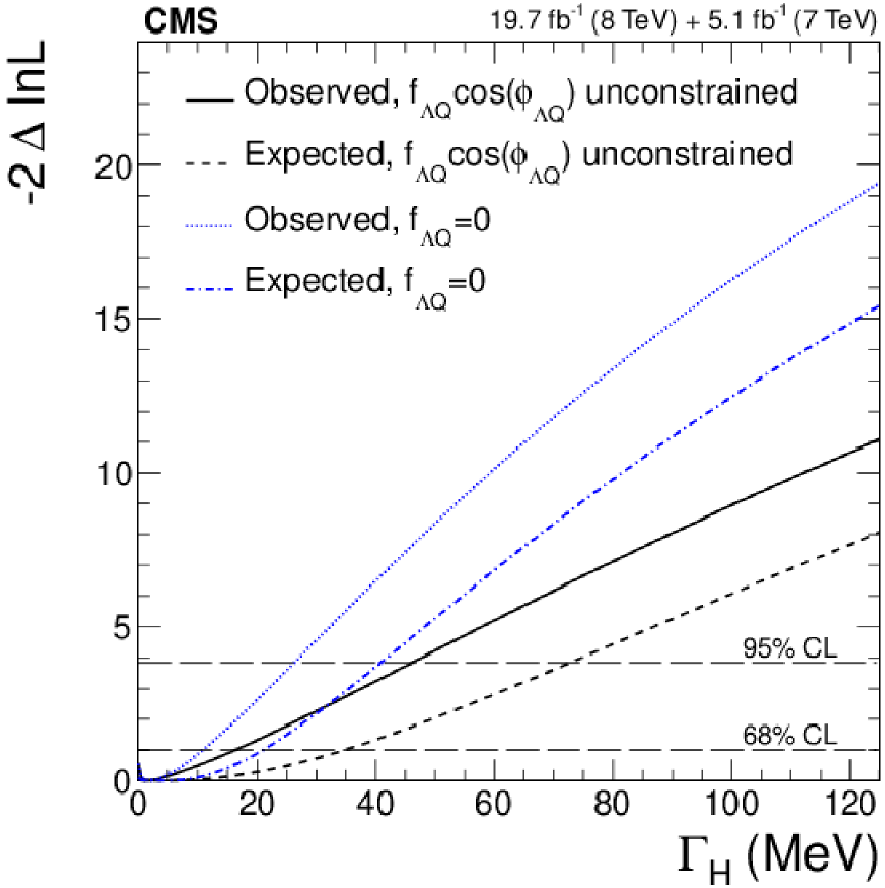
$$\left[a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_{V1}+q_{V2})^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}} \frac{(q_{V1}^2+q_{V2}^2)}{(\Lambda_1)^2}\right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^*$$

$$+ a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}.$$

- Limit as function of effective cross section;

$$f_{\Lambda Q} = \frac{m_H^4/\Lambda_Q^4}{|a_1|^2 + m_H^4/\Lambda_Q^4}.$$

- Anomalous coupling in both VBF and VH
- 2jet tag category to enhance sensitivity.



Parameter	$f_{\Lambda Q} = 0$ Observed	$f_{\Lambda Q} = 0$ Expected	$f_{\Lambda Q}$ unconstrained, $\phi_{\Lambda Q} = 0$ or π Observed	$f_{\Lambda Q}$ unconstrained, $\phi_{\Lambda Q} = 0$ or π Expected
τ_H (fs)	$[2.5 \times 10^{-8}, 190]$	$[1.6 \times 10^{-8}, 190]$	$[1.4 \times 10^{-8}, 190]$	$[9 \times 10^{-9}, 190]$
Γ_H (MeV)	$[3.5 \times 10^{-9}, 26]$	$[3.6 \times 10^{-9}, 41]$	$[3.5 \times 10^{-9}, 46]$	$[3.6 \times 10^{-9}, 73]$

conclusions

- RUN1 combined results for the Higgs boson mass measurement have been presented. The combined mass is;

$$\begin{aligned} m_H &= 125.09 \pm 0.24\ GeV \\ &= 125.09 \pm 0.21\,(stat.) \pm 0.11(syst.)\ GeV \end{aligned}$$

- First limits on the Higgs boson width have been set by ATLAS and CMS
- Direct measurement and indirect using off-shell couplings.
- New challenges with RUN2 data already coming!

The end