

Upper Limits on the Higgs Width

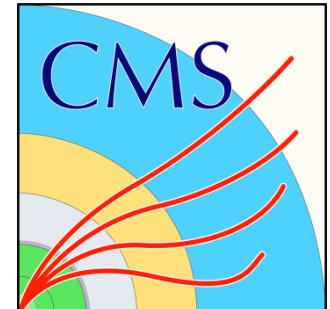
Jonathan Long

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On behalf of the ATLAS and
CMS collaborations



BSM-HW@LPC Fermilab

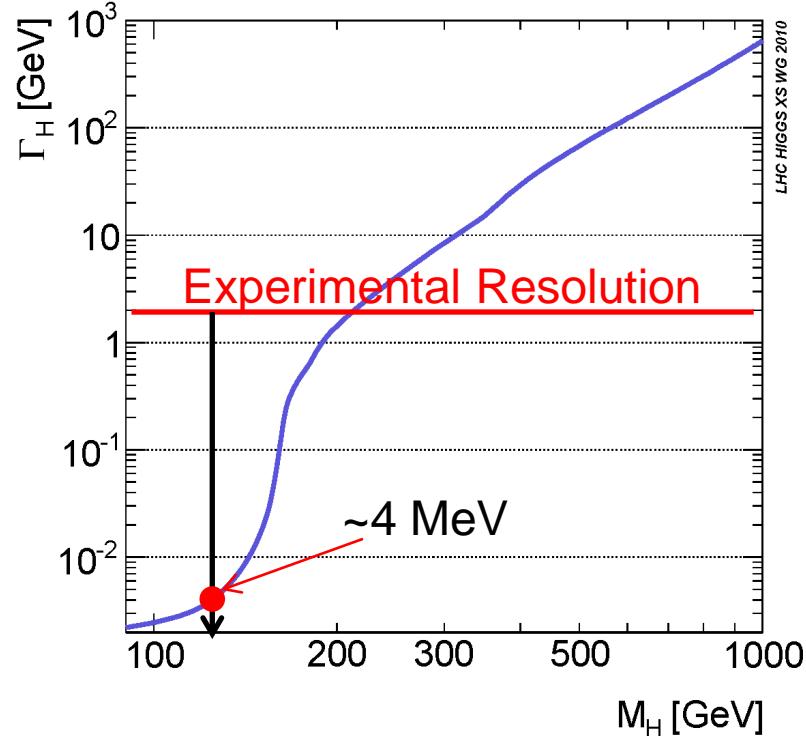


November 3rd, 2014

Introduction

- Higgs boson mass, couplings, and spin/parity have well defined measurement programs
- Width is related to strength of interactions with particles, including those not yet observed

1. Direct limits via on-shell mass spectra
2. Indirect limits via off-shell couplings



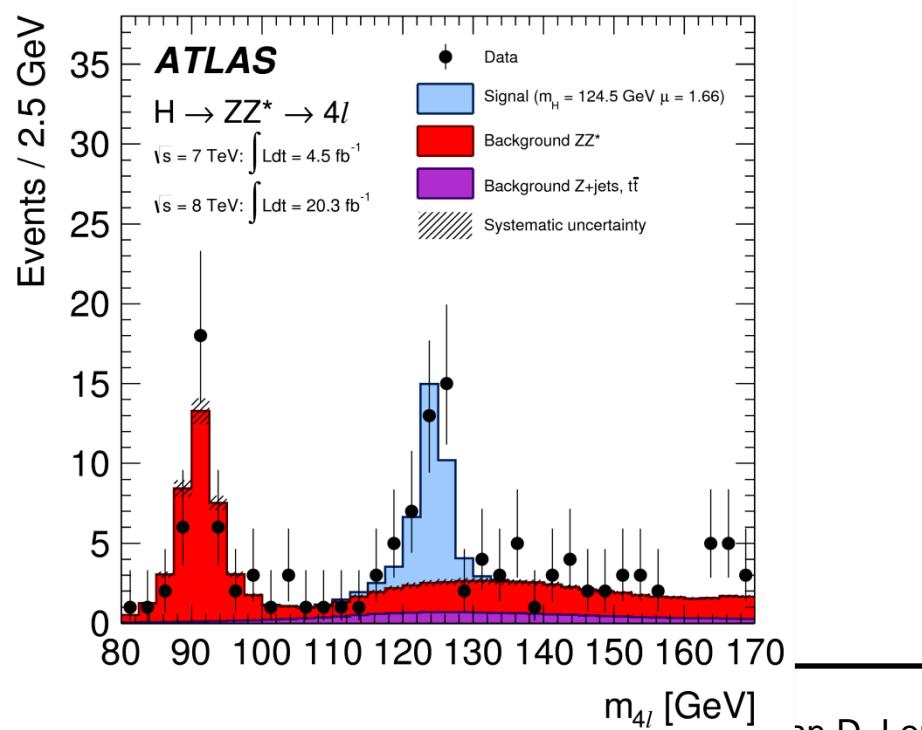
Direct Limits

- Use fully-reconstructed-mass resonance
 - $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$
- Limited by detector resolution of order GeV
- Include convolution of Gaussian (detector res.) and Breit-Wigner (Higgs boson width)
 - Included in per event errors in ZZ
- Mass and signal strength profiled
- Assume no interference between signal and background processes

$H \rightarrow ZZ \rightarrow 4\ell$

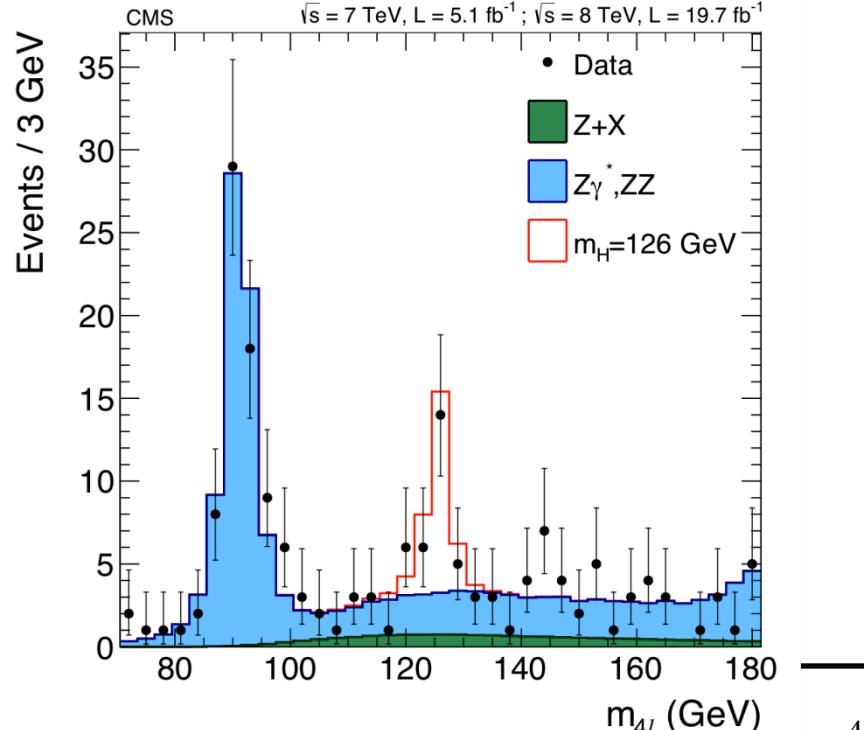
ATLAS PRD 90 (2014) 052004

- $p_T > 6(7)$ GeV $\mu(e)$
- $|\eta| < 2.7(2.47)$ $\mu(e)$
- $p_T > 20, > 15, > 10$ GeV
- $50 < m_{12} < 106$ GeV
- $m_{\min}(12 \rightarrow 50) < m_{34} < 115$ GeV
- **1.6 – 2.2 GeV mass res.**



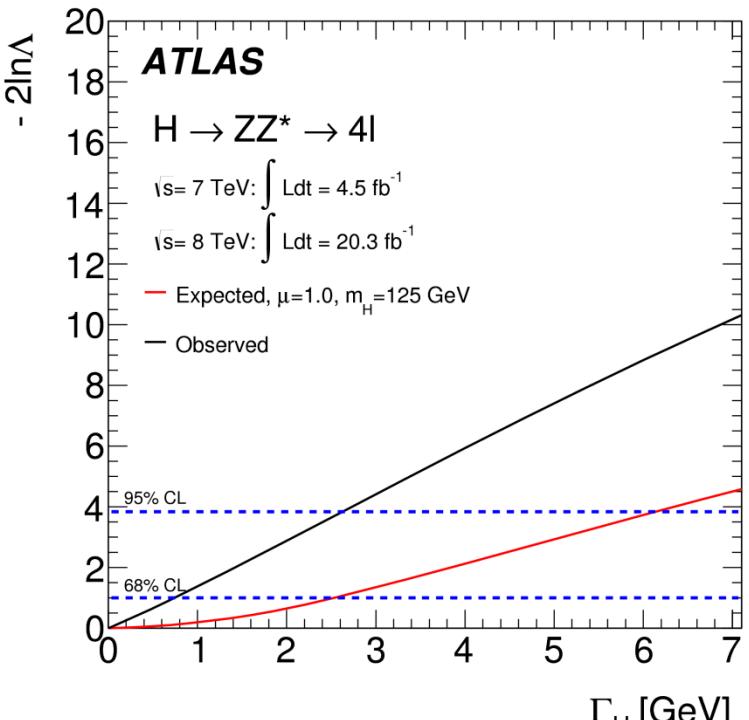
CMS PRD 89 (2014) 092007

- $p_T > 5(7)$ GeV $\mu(e)$
- $|\eta| < 2.4(2.5)$ $\mu(e)$
- $p_T > 20, > 10$ GeV
- $40 < m_{Z1} < 120$ GeV
- $12 < m_{Z2} < 120$ GeV
- **1.2 – 2 GeV mass res.**



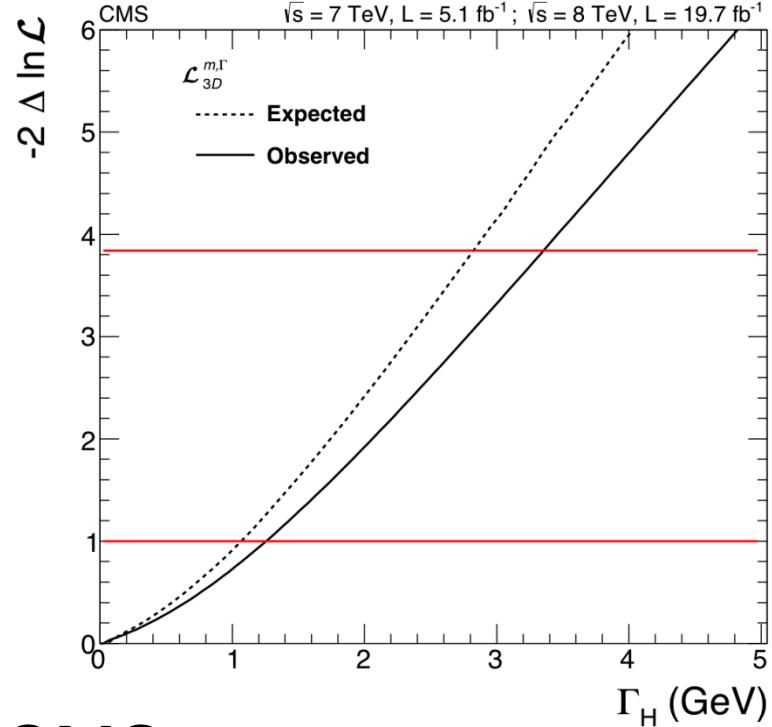
$H \rightarrow ZZ \rightarrow 4\ell$ Result

$$\mu = \sigma \cdot \text{BR} / (\sigma \cdot \text{BR})_{\text{SM}}$$



ATLAS

- $\Gamma_H < 2.6 \text{ GeV (95\% CL)}$
 - 6.2 expected
- $\mu \cong 1.66^{+0.45}_{-0.38}$



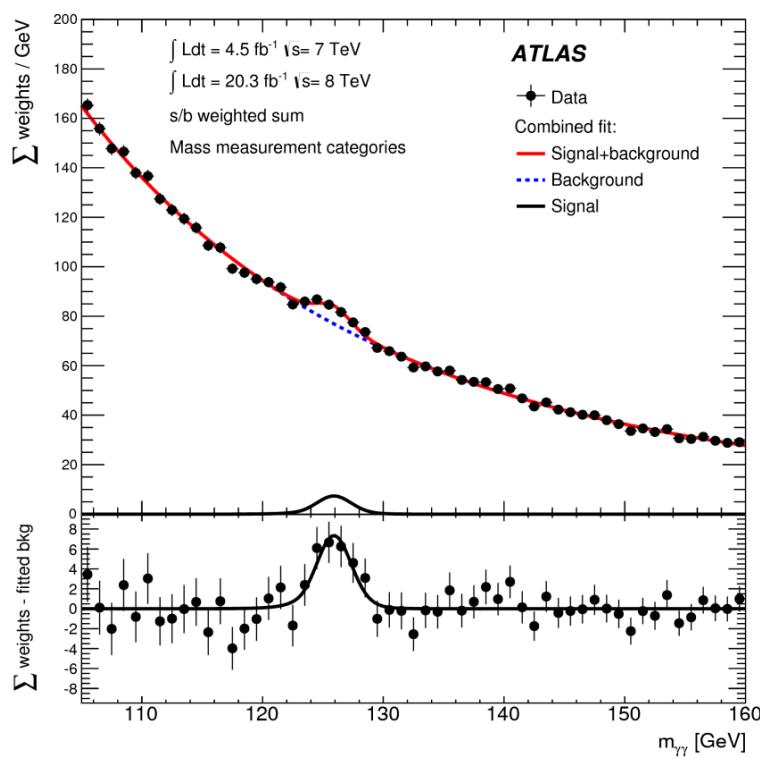
CMS

- $\Gamma_H < 3.4 \text{ GeV (95\% CL)}$
 - 2.8 expected
- $\mu \cong 0.93^{+0.26}_{-0.23}(\text{stat})^{+0.13}_{-0.09}(\text{sys})$

$H \rightarrow \gamma\gamma$

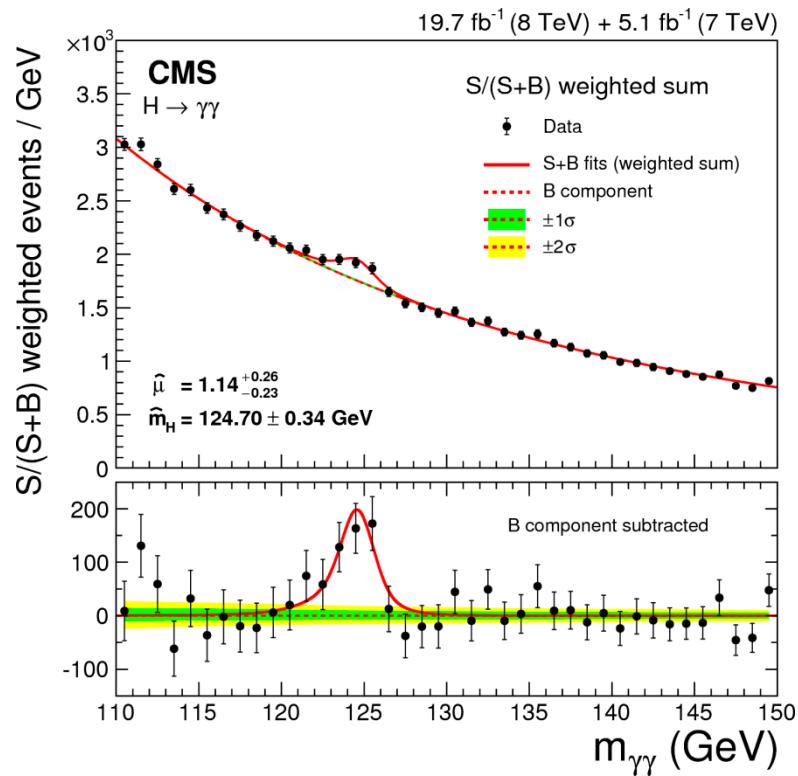
ATLAS PRD 90 (2014) 052004

- $|\eta| < 2.37$
- $E_T^1 > 0.35 \cdot m_{\gamma\gamma}$ and $E_T^2 > 0.25 \cdot m_{\gamma\gamma}$
- 10 categories



CMS (1407.0558)

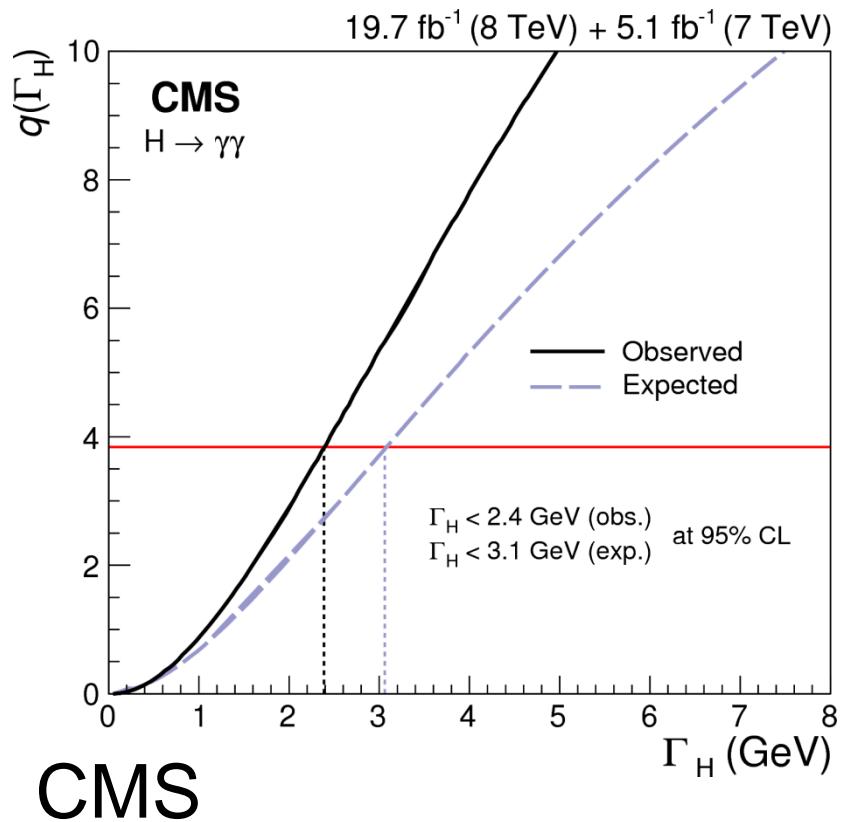
- $|\eta| < 2.5$
- $E_T^1 > m_{\gamma\gamma}/3$ and $E_T^2 > m_{\gamma\gamma}/4$
- 11(14) categories 7(8) TeV



$H \rightarrow \gamma\gamma$ Result

ATLAS

- $\Gamma_H < 5.0 \text{ GeV (95% CL)}$
 - 6.2 expected
- $\mu \cong 1.29 \pm 0.30$



CMS

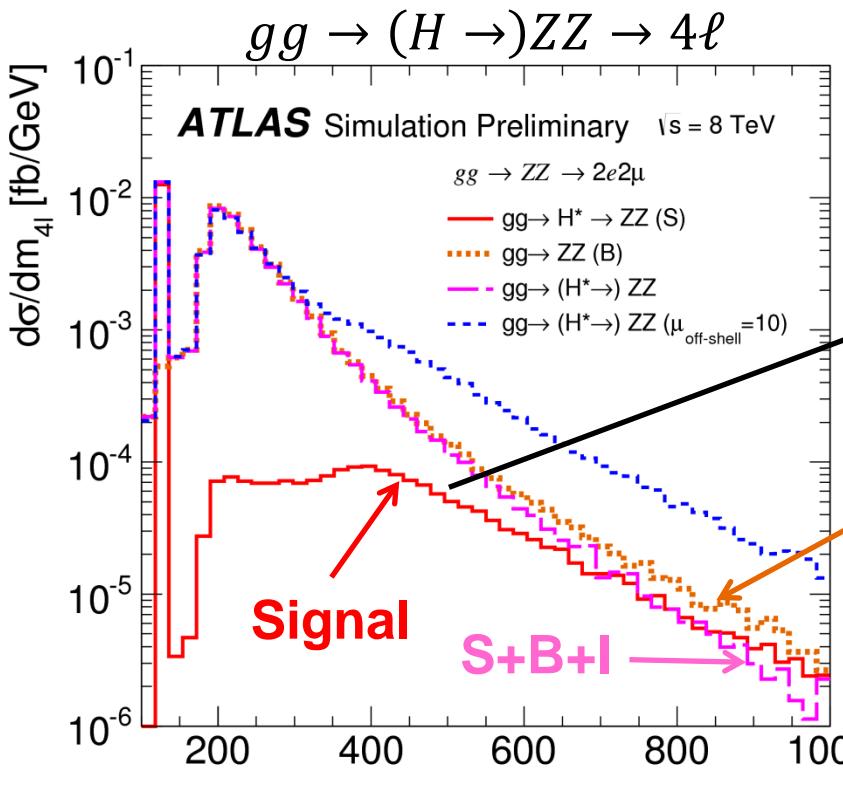
- $\Gamma_H < 2.4 \text{ GeV (95% CL)}$
 - 3.1 expected
- $\mu \cong 1.14^{+0.26}_{-0.23}$

Indirect: Off-Shell Method

Kauer and Passarino. JHEP 08 (2012) 116

Caola and Melnikov. PRD 88 (2013) 054024

Campbell, Ellis, and Williams. JHEP 04 (2014) 060



$$\frac{d\sigma_{gg \rightarrow H \rightarrow ZZ}}{dM_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(M_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

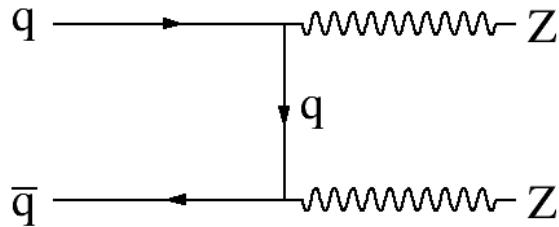
$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{off-shell}} \propto g_{ggH}^2 g_{HZZ}^2$$

$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{on-shell}} \propto \frac{g_{ggH}^2 g_{HZZ}^2}{\Gamma_H}$$

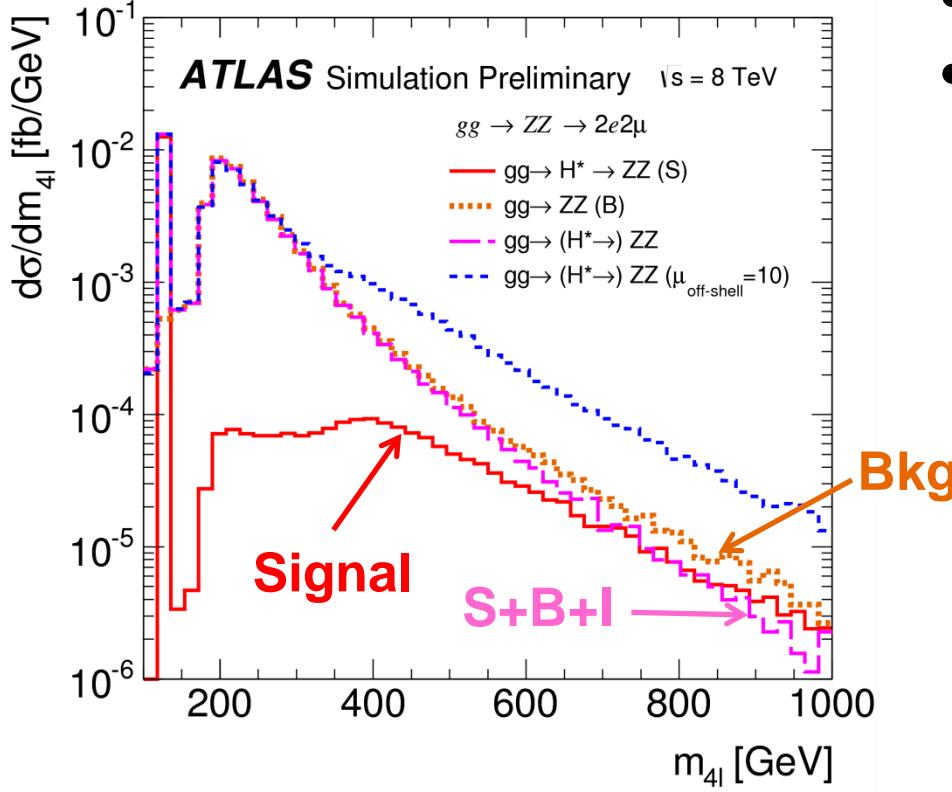
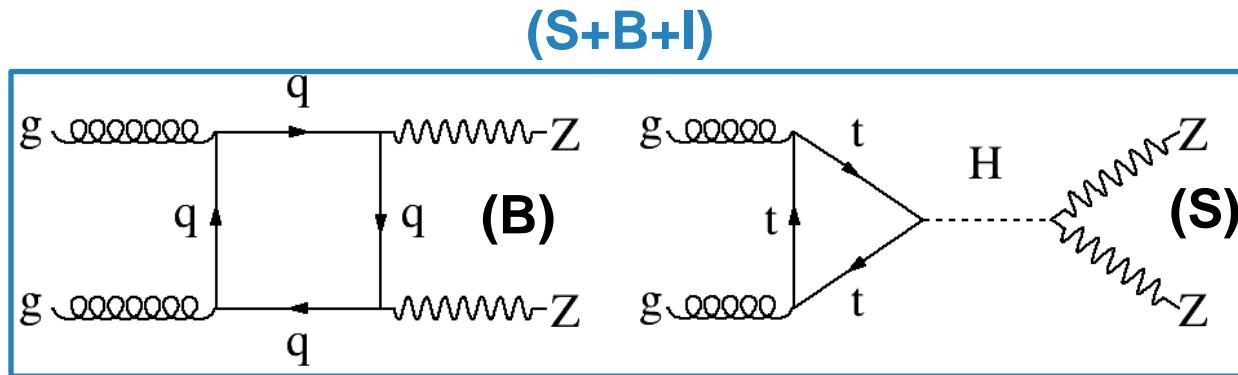
+Assumptions (later)

$$\frac{\mu^{\text{off-shell}}}{\mu^{\text{on-shell}}} = \frac{\Gamma_H}{\Gamma_H^{SM}}$$

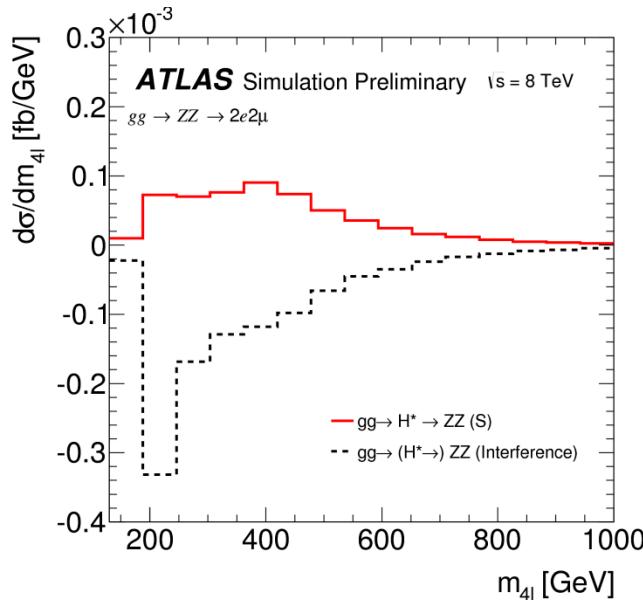
Interference



$qq \rightarrow ZZ \sim 6 \times gg \rightarrow ZZ$

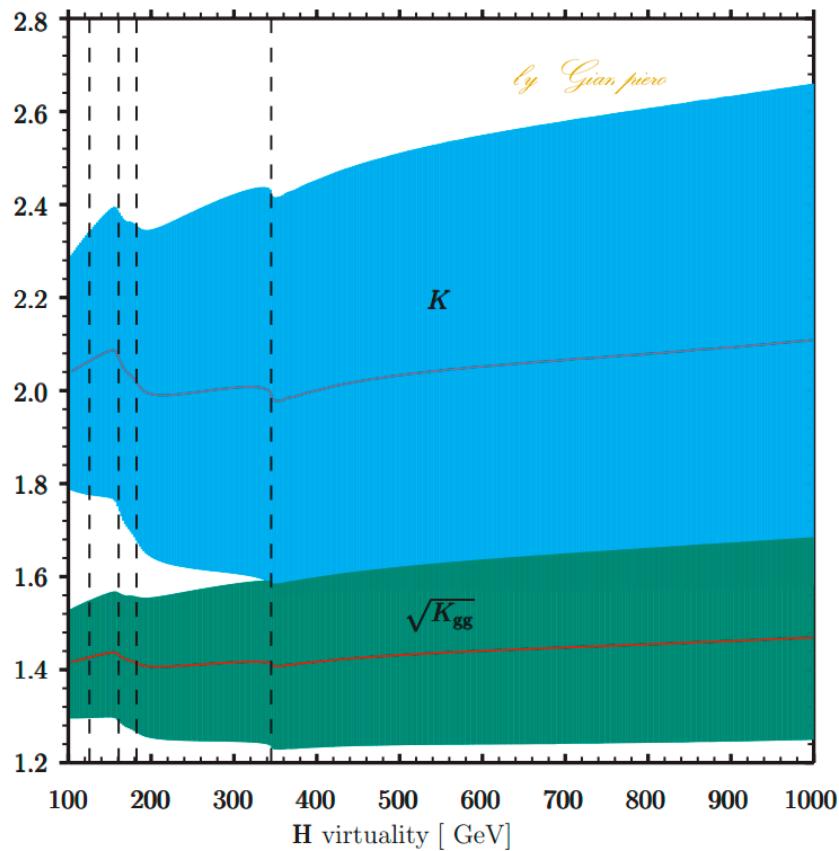


- Large negative interference
- Only LO simulation is readily available



K-Factors

NNLO/LO G. Passarino (arXiv:1312.2397)



- No higher-order QCD k-factor for LO $gg \rightarrow ZZ$ bkg
- Apply signal k-factor to bkg. and interference
 - M. Bonvini et al. (PRD 88 2013)
 - Soft-collinear approximation of corrections in $gg \rightarrow WW$ compared to $gg \rightarrow H \rightarrow WW$
 - CMS additional 10% uncert.
 - ATLAS results as a function of unknown bkg/sig k-factor

$$R_{H^*}^B = \frac{k(gg \rightarrow ZZ)}{k(gg \rightarrow H^* \rightarrow ZZ)}$$

- ATLAS additional 30% uncert. on interference

$\mu_{\text{off-shell}}$ Parameterization

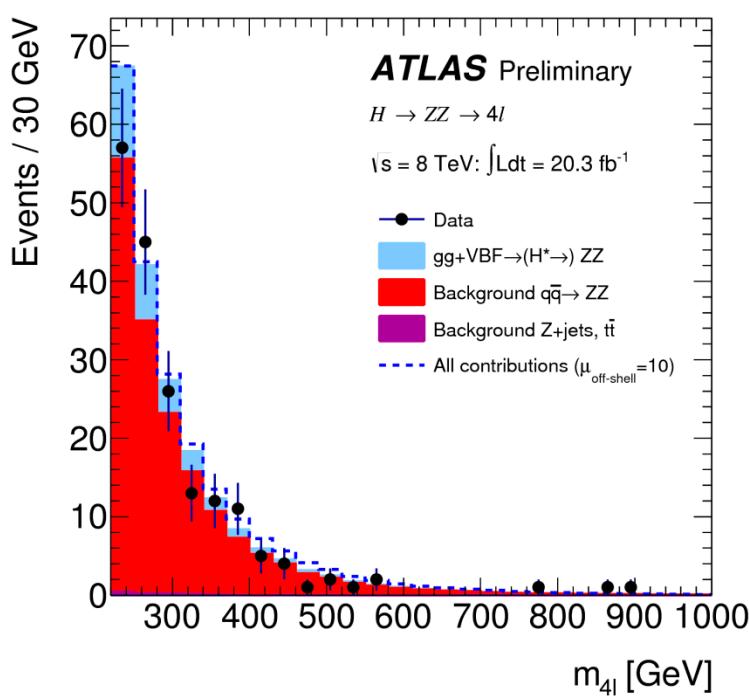
- Build prediction for arbitrary $\mu_{\text{off-shell}}$ using signal, background, and signal+background+interference
 - Including k-factors and unknown bkg/sig k-factor ratio (latter ATLAS)
 - Signal scales with $\mu_{\text{off-shell}} \cdot k_{\text{sig}}$
 - Interference term scales with $\sqrt{\mu_{\text{off-shell}} \cdot k_{\text{sig}} \cdot k_{\text{bkg}}}$
- Use MCFM or gg2VV (same results) for $gg \rightarrow H^* \rightarrow ZZ$, $gg \rightarrow ZZ$, and $gg \rightarrow (H^* \rightarrow)ZZ$
- Including EW $pp \rightarrow ZZ + 2j$ with MadGraph5 or Phantom with the same parameterization (7-10%)

Considerations

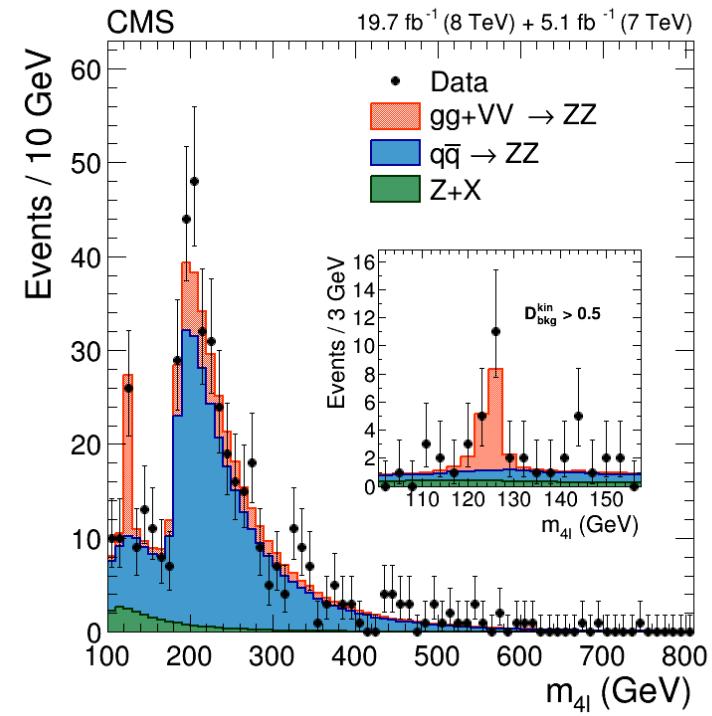
- LO MC and inclusively calculated k-factor suggest to use an inclusive analysis
- $\mu^{\text{off-shell}}$ as non-standard off-shell Higgs coupling
 - New physics which modifies off-shell couplings doesn't modify SM bkg. expectations and no new sizable signals in search region
- Interpretation as measurement of Higgs width
 - $\kappa_{i,\text{on-shell}} = \kappa_{i,\text{off-shell}}$ (couplings) $[\kappa = \frac{g}{g_{SM}}]$

$ZZ \rightarrow 4\ell$

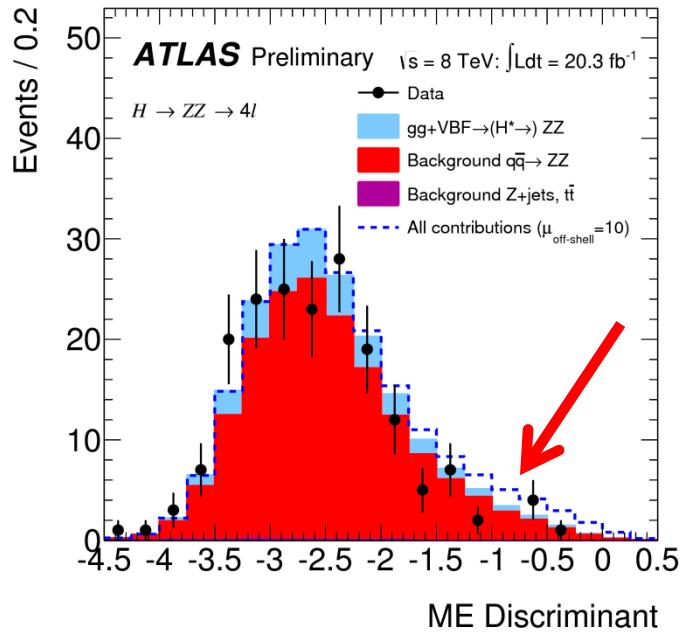
- Based on couplings analyses
- Both for on- and off-shell measurements
- Use matrix element techniques to help separate out gluon-gluon initiated signal



Including
VBF 7-10%

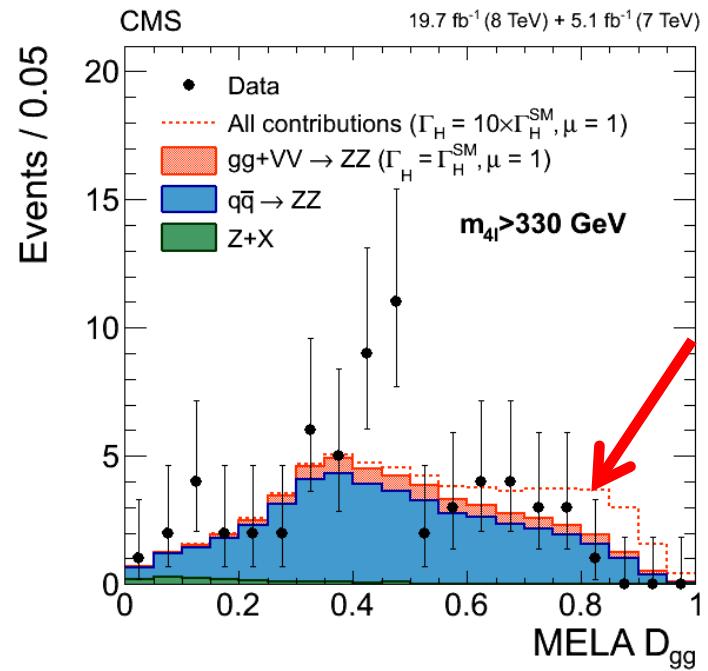


$ZZ \rightarrow 4\ell$



Obs 18 Exp 24.3 ←

Signal enriched regions



→ Obs 11 Exp 11.4

- QCD scale factor uncertainties on $gg \rightarrow (H^* \rightarrow) ZZ$ have largest impact

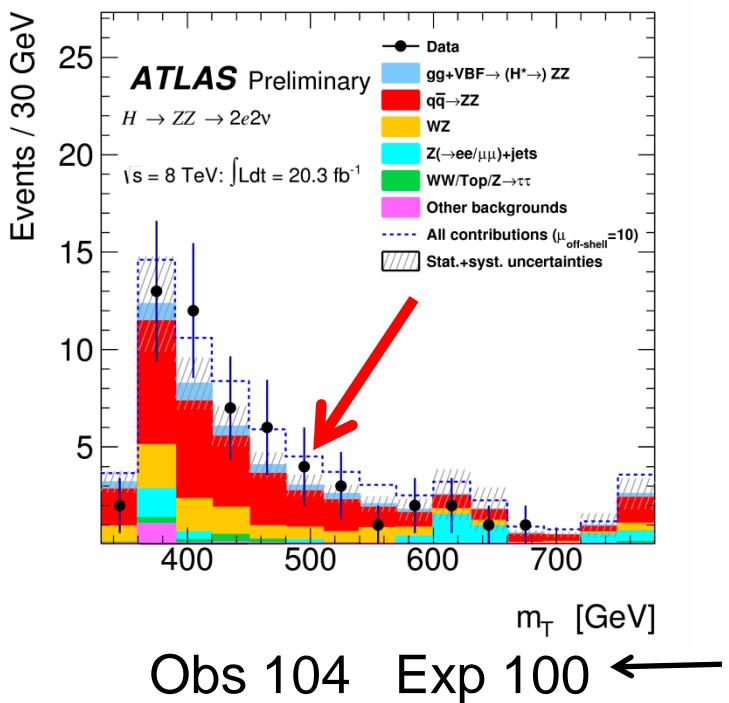
$ZZ \rightarrow 2\ell 2\nu$ (off-shell only)

ATLAS

Based on ZH->invs search

PRL 112 (2014) 201802

- $E_T^{miss} > 150$ GeV
- $350 < m_T < 1000$ GeV
- b -jet veto



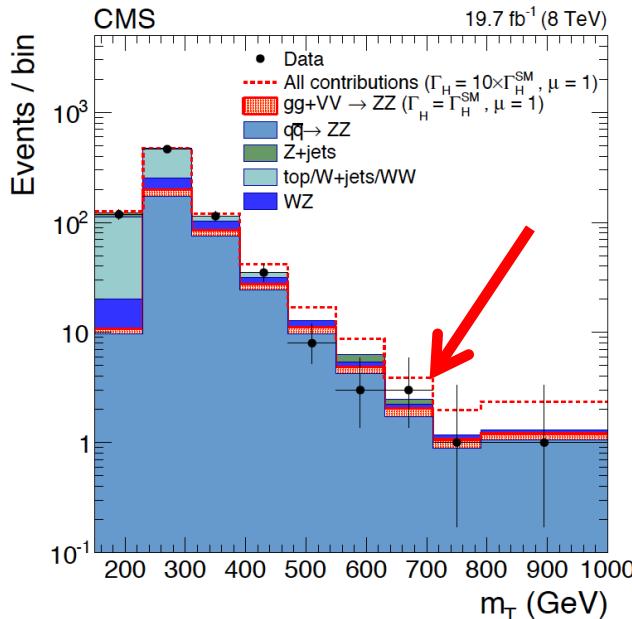
$$m_T^2 = \left[\sqrt{(p_T^{\ell\ell})^2 + m_{\ell\ell}^2} + \sqrt{(E_T^{\text{miss}})^2 + m_{\ell\ell}^2} \right]^2 - \left[\vec{p}_T^{\ell\ell} + \vec{E}_T^{\text{miss}} \right]^2$$

CMS

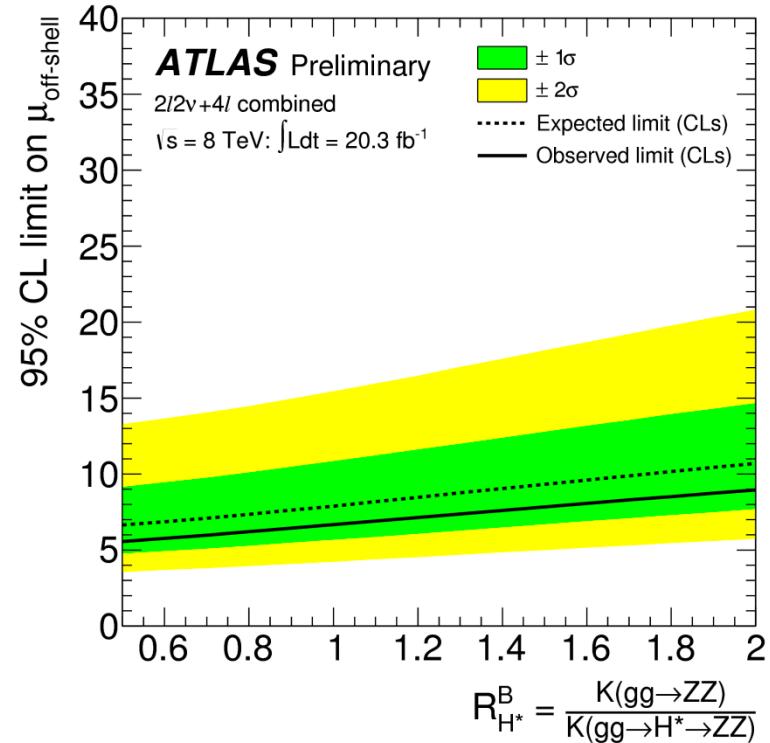
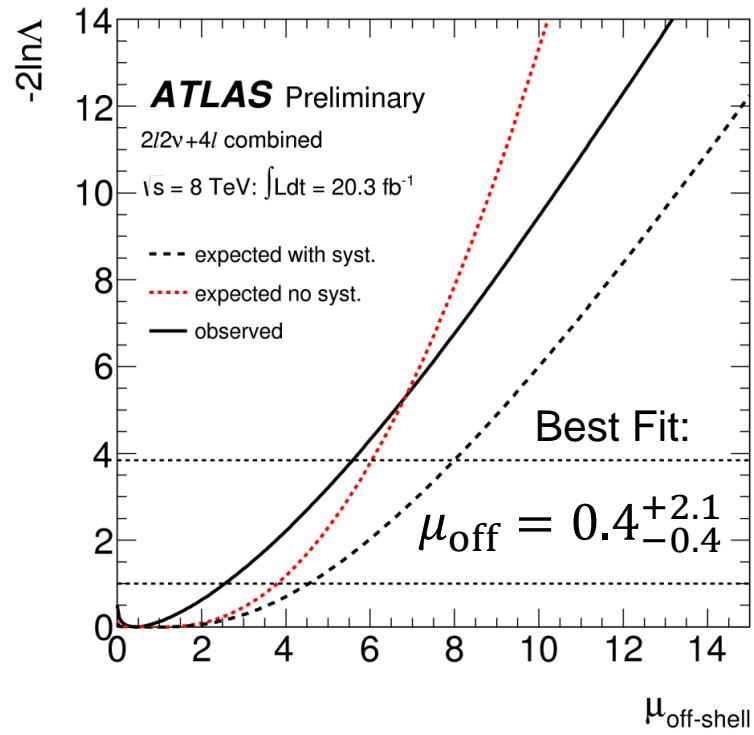
Based on high-mass analysis

Eur. Phys. J. C 73 (2013) 2469

- $E_T^{miss} > 80$ GeV
- $m_T > 180$ GeV

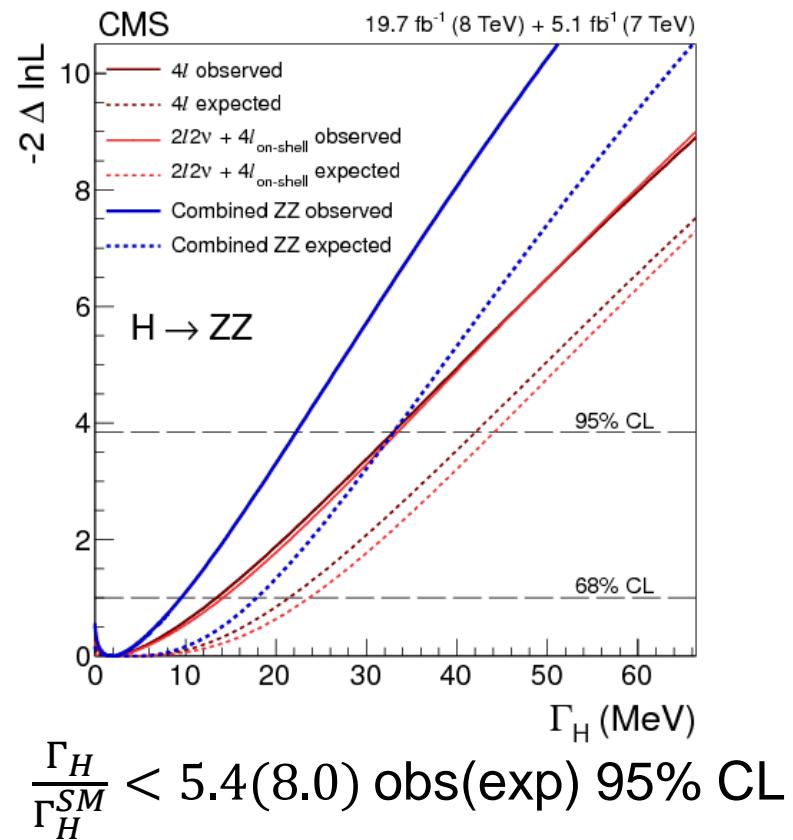
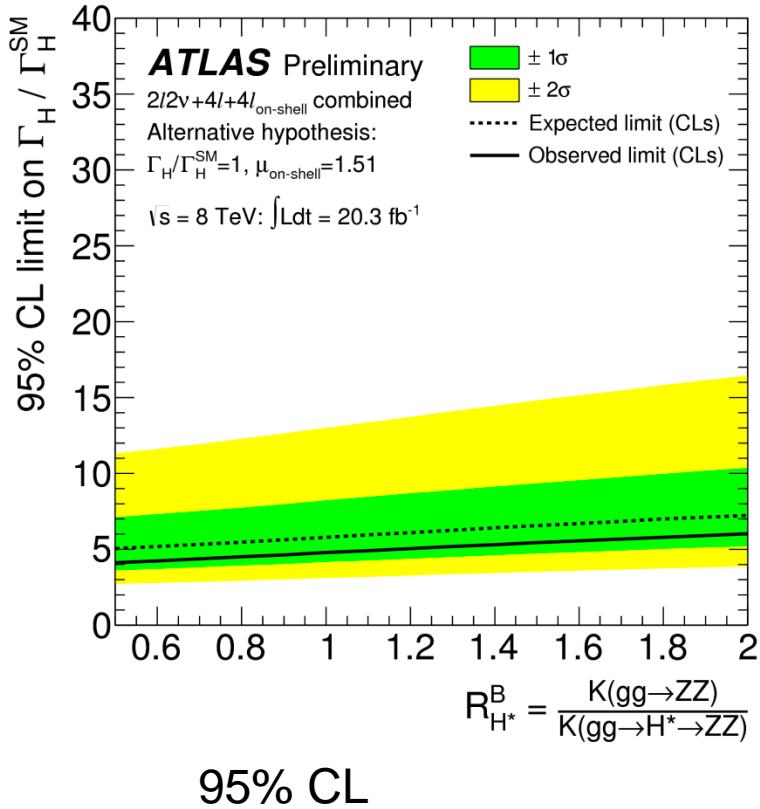


Combined $(4\ell + 2\ell 2\nu)$ Limit on $\mu^{\text{off-shell}}$



95% CL $R_{H^*}^B$	Observed			Median expected			Alternative hypothesis for CLs
	0.5	1.0	2.0	0.5	1.0	2.0	
$\mu_{\text{off-shell}}$	5.6	1.0	9.0	6.6	7.9	10.7	$R_{H^*}^B = 1, \mu_{\text{off-shell}} = 1$

Combined $(4\ell + 2\ell 2\nu)$ Limit on Width



$R_{H^*}^B$	Observed			Median expected			Alternative hypothesis for CLs
	0.5	1.0	2.0	0.5	1.0	2.0	
$\Gamma_H/\Gamma_H^{\text{SM}}$	4.1	4.8	6.0	5.0	5.8	7.2	$R_{H^*}^B = 1, \Gamma_H/\Gamma_H^{\text{SM}} = 1, \mu_{\text{on-shell}} = 1.51$
$\Gamma_H/\Gamma_H^{\text{SM}}$	4.8	5.7	7.7	7.0	8.5	12.0	$R_{H^*}^B = 1, \Gamma_H/\Gamma_H^{\text{SM}} = 1, \mu_{\text{on-shell}} = 1$

Summary

- Direct limits on Higgs width $\Gamma_H < 2.4$ GeV (95% CL) well above SM expected ~ 4 MeV width
- Upper limit on off-shell Higgs production using the $ZZ \rightarrow 4\ell$ and $2\ell 2\nu$ channels

$$\mu^{\text{off-shell}} < 5.6[6.6] - 9.0[10.7]$$

At 95% CL, obs[exp]
(For $0.5 < R_{H^*}^B < 2$)

- With assumptions on couplings, upper limit on Higgs width

At 95% CL, obs[exp]

$$\mathbf{ATLAS} \quad \Gamma_H < 4.8[7.0] - 7.7[12] \cdot \text{SM} \quad \mathbf{CMS} \quad \Gamma_H < 5.4[8.0] \cdot \text{SM}$$

(For $0.5 < R_{H^*}^B < 2$)

Backup

CMS Yields

Table 1: Expected and observed numbers of events in the 4ℓ and $2\ell 2\nu$ channels in gg-enriched regions, defined by $m_{4\ell} \geq 330 \text{ GeV}$ and $\mathcal{D}_{gg} > 0.65$ (4ℓ), and by $m_T > 350 \text{ GeV}$ and $E_T^{\text{miss}} > 100 \text{ GeV}$ ($2\ell 2\nu$). The numbers of expected events are given separately for the gg and VBF processes, and for a SM Higgs boson ($\Gamma_H = \Gamma_H^{\text{SM}}$) and a Higgs boson width and squared product of the couplings scaled by a factor 10 with respect to their SM values. The unphysical expected contributions for the signal and background components are also reported separately, for the gg and VBF processes. For both processes, the sum of the signal and background components differs from the total due to the negative interferences. The quoted uncertainties include only the systematic sources.

		4ℓ	$2\ell 2\nu$
(a)	Total gg ($\Gamma_H = \Gamma_H^{\text{SM}}$)	1.8 ± 0.3	9.6 ± 1.5
	gg Signal component ($\Gamma_H = \Gamma_H^{\text{SM}}$)	1.3 ± 0.2	4.7 ± 0.6
	gg Background component	2.3 ± 0.4	10.8 ± 1.7
(b)	Total gg ($\Gamma_H = 10 \times \Gamma_H^{\text{SM}}$)	9.9 ± 1.2	39.8 ± 5.2
(c)	Total VBF ($\Gamma_H = \Gamma_H^{\text{SM}}$)	0.23 ± 0.01	0.90 ± 0.05
	VBF signal component ($\Gamma_H = \Gamma_H^{\text{SM}}$)	0.11 ± 0.01	0.32 ± 0.02
	VBF background component	0.35 ± 0.02	1.22 ± 0.07
(d)	Total VBF ($\Gamma_H = 10 \times \Gamma_H^{\text{SM}}$)	0.77 ± 0.04	2.40 ± 0.14
(e)	$q\bar{q}$ background	9.3 ± 0.7	47.6 ± 4.0
(f)	Other backgrounds	0.05 ± 0.02	35.1 ± 4.2
(a+c+e+f)	Total expected ($\Gamma_H = \Gamma_H^{\text{SM}}$)	11.4 ± 0.8	93.2 ± 6.0
(b+d+e+f)	Total expected ($\Gamma_H = 10 \times \Gamma_H^{\text{SM}}$)	20.1 ± 1.4	124.9 ± 7.8
	Observed	11	91

ATLAS Yields 4

Process	$220 \text{ GeV} < m_{4\ell} < 1000 \text{ GeV}$	$400 \text{ GeV} < m_{4\ell} < 1000 \text{ GeV}$
$gg \rightarrow H^* \rightarrow ZZ \text{ (S)}$	2.2 ± 0.5	1.1 ± 0.3
$gg \rightarrow ZZ \text{ (B)}$	30.7 ± 7.0	2.7 ± 0.7
$gg \rightarrow (H^* \rightarrow)ZZ$	29.2 ± 6.7	2.3 ± 0.6
$gg \rightarrow (H^* \rightarrow)ZZ \text{ } (\mu_{\text{off-shell}} = 10)$	40.2 ± 9.2	9.0 ± 2.5
VBF $H^* \rightarrow ZZ \text{ (S)}$	0.2 ± 0.0	0.1 ± 0.0
VBF ZZ (B)	2.2 ± 0.1	0.7 ± 0.0
VBF $(H^* \rightarrow)ZZ$	2.0 ± 0.1	0.6 ± 0.0
VBF $(H^* \rightarrow)ZZ \text{ } (\mu_{\text{off-shell}} = 10)$	3.0 ± 0.2	1.4 ± 0.1
$q\bar{q} \rightarrow ZZ$	168 ± 13	21.3 ± 2.1
Reducible backgrounds	1.4 ± 0.1	0.1 ± 0.0
Total Expected (SM)	200 ± 15	24.3 ± 2.2
Observed	182	18

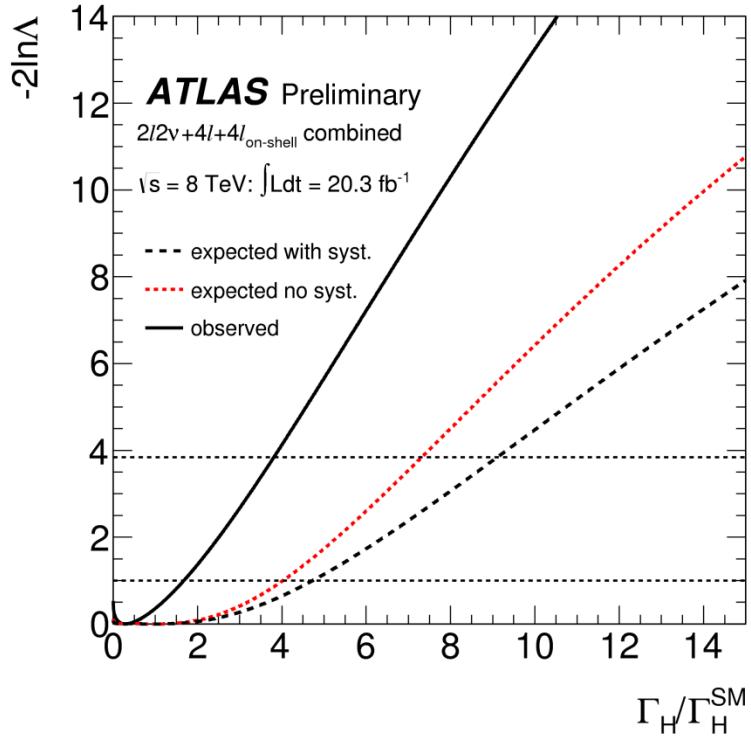
Table 1: Expected and observed number of events in the $ZZ \rightarrow 4\ell$ channel in the full off-peak region ($220 \text{ GeV} < m_{4\ell} < 1000 \text{ GeV}$) and the cut-based analysis signal region ($400 \text{ GeV} < m_{4\ell} < 1000 \text{ GeV}$). The reducible background includes contributions from the Z+jets and top quark processes. The expected events for the $gg \rightarrow (H^* \rightarrow)ZZ$ and VBF $(H^* \rightarrow)ZZ$ processes, including the Higgs boson signal, background and interference, are reported for both the SM predictions and $\mu_{\text{off-shell}} = 10$. A relative $gg \rightarrow ZZ$ background K-factor of $R_H^B = 1$ is assumed. The uncertainties in the number of expected events include the statistical uncertainties from MC samples and systematic uncertainties.

ATLAS Yields 2l2v

Process	ee	$\mu\mu$	Total
$gg \rightarrow H^* \rightarrow ZZ$ (S)	$2.6 \pm 0.03 \pm 0.8$	$2.2 \pm 0.02 \pm 0.7$	$4.8 \pm 0.04 \pm 1.5$
$gg \rightarrow ZZ$ (B)	$4.8 \pm 0.06 \pm 1.4$	$4.3 \pm 0.05 \pm 1.3$	$9.2 \pm 0.8 \pm 2.7$
$gg \rightarrow (H^* \rightarrow)ZZ$	$3.8 \pm 0.05 \pm 1.1$	$3.5 \pm 0.05 \pm 1.1$	$7.4 \pm 0.1 \pm 2.2$
$gg \rightarrow (H^* \rightarrow)ZZ(\mu_{\text{off-shell}} = 10)$	$18.7 \pm 0.1 \pm 5.6$	$16.0 \pm 0.1 \pm 4.8$	$34.7 \pm 0.2 \pm 10.4$
VBF $H^* \rightarrow ZZ$ (S)	$0.3 \pm 0.05 \pm 0.01$	$0.2 \pm 0.05 \pm 0.01$	$0.5 \pm 0.07 \pm 0.02$
VBF ZZ (B)	$1.0 \pm 0.1 \pm 0.03$	$0.8 \pm 0.1 \pm 0.03$	$1.8 \pm 0.1 \pm 0.1$
VBF $(H^* \rightarrow)ZZ$	$0.8 \pm 0.1 \pm 0.03$	$0.6 \pm 0.1 \pm 0.03$	$1.4 \pm 0.1 \pm 0.1$
VBF $(H^* \rightarrow)ZZ(\mu_{\text{off-shell}} = 10)$	$2.2 \pm 0.1 \pm 0.09$	$1.6 \pm 0.1 \pm 0.05$	$3.7 \pm 0.2 \pm 0.1$
$q\bar{q} \rightarrow ZZ$	$28.0 \pm 0.7 \pm 3.0$	$26.4 \pm 0.6 \pm 2.8$	$54.4 \pm 0.9 \pm 5.7$
WZ	$10.5 \pm 0.5 \pm 1.2$	$10.6 \pm 0.5 \pm 1.2$	$21.1 \pm 0.7 \pm 2.3$
$WW, t\bar{t}, Wt,$ and $Z \rightarrow \tau\tau$	$1.3 \pm 1.1 \pm 0.1$	$1.5 \pm 1.3 \pm 0.1$	$2.8 \pm 1.7 \pm 0.2$
$Z \rightarrow ee, \mu\mu$	$5.3 \pm 2.6 \pm 2.1$	$4.3 \pm 2.4 \pm 1.9$	$9.6 \pm 3.5 \pm 4.0$
Other backgrounds	$1.5 \pm 0.5 \pm 0.2$	$1.8 \pm 0.6 \pm 0.2$	$3.3 \pm 0.8 \pm 0.4$
Total Expected (SM)	$51.3 \pm 3.0 \pm 5.0$	$48.8 \pm 2.8 \pm 4.6$	$100 \pm 4 \pm 10$
Observed	54	50	104

Table 2: The expected yields for signals and backgrounds, with statistical and systematic uncertainties, in the $H \rightarrow ZZ \rightarrow 2\ell 2\nu$ channel corresponding to an integrated luminosity of 20.3 fb^{-1} at a collision energy of $\sqrt{s} = 8 \text{ TeV}$. The expected events for the $gg \rightarrow (H^* \rightarrow)ZZ$ and VBF $(H^* \rightarrow)ZZ$ processes, including the Higgs boson signal, background and interference, are reported for both the SM predictions and $\mu_{\text{off-shell}} = 10$. A relative $gg \rightarrow ZZ$ background K-factor of $R_{H^*}^B = 1$ is assumed. The uncertainties in the number of expected events are split into the statistical uncertainties from MC samples (or data statistical uncertainties for data-driven background estimations) and systematic uncertainties.

ATLAS LLH



$\mu_{\text{off-shell}}$ Parameterization

$$\begin{aligned} \text{MC}_{gg \rightarrow (H^* \rightarrow) ZZ}(\mu_{\text{off-shell}}) &= \left(K^{H^*}(m_{ZZ}) \cdot \mu_{\text{off-shell}} - K_{gg}^{H^*}(m_{ZZ}) \cdot \sqrt{R_{H^*}^B \cdot \mu_{\text{off-shell}}} \right) \cdot \text{MC}_{gg \rightarrow H^* \rightarrow ZZ}^{\text{SM}} \quad (\mathbf{S}) \\ &+ K_{gg}^{H^*}(m_{ZZ}) \cdot \sqrt{R_{H^*}^B \cdot \mu_{\text{off-shell}}} \cdot \text{MC}_{gg \rightarrow (H^* \rightarrow) ZZ}^{\text{SM}} \quad (\mathbf{SBI}) \\ &+ K_{gg}^{H^*}(m_{ZZ}) \cdot \left(R_{H^*}^B - \sqrt{R_{H^*}^B \cdot \mu_{\text{off-shell}}} \right) \cdot \text{MC}_{gg \rightarrow ZZ}^{\text{cont}}, \quad (\mathbf{B}) \end{aligned}$$