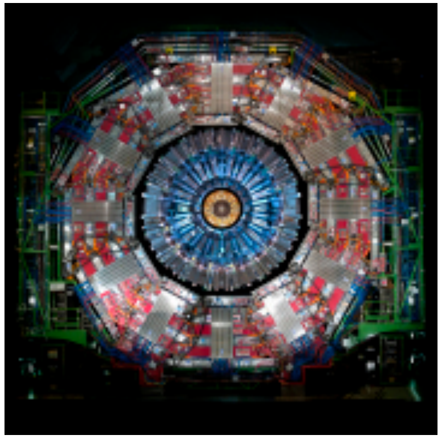
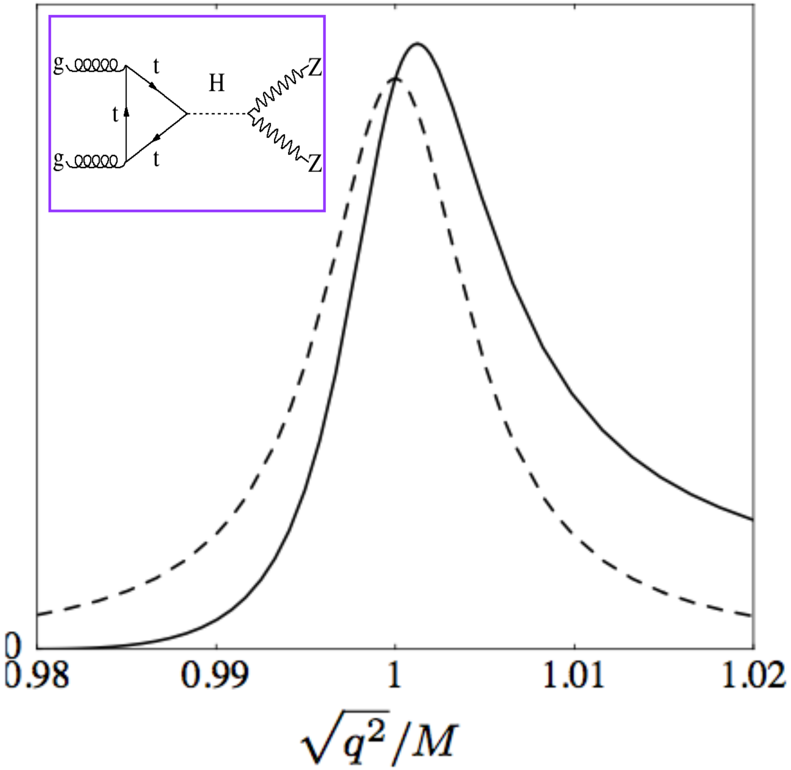
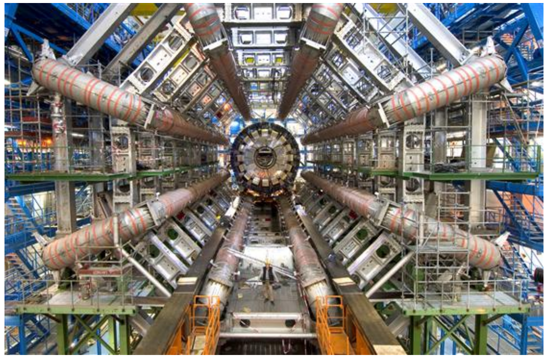
Higgs width measurements from ATLAS and CMS







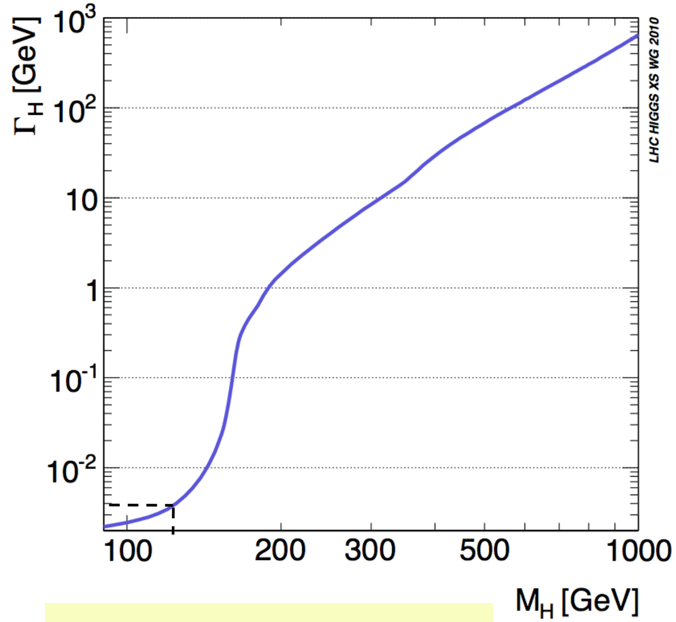
C. Charlot / LLR- École Polytechnique, on behalf of ATLAS and CMS collaborations

HC2014, Torino, 1-3 oct. 2014

The Higgs decay width

- The decay width is a fundamental parameter
  - Relates to the couplings to all (massive) particles in the spectrum, therefore sensitive to BSM physics and dark matter
- But Γ_H very small (4.15 MeV in the SM @ 125.6 GeV)

- Current (excellent) experimental resolution far off for a direct measurement
  - $\sigma_m/m \sim 1\%$ for $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$
- Only weak constraints from the measurement of the invariant mass peak
- Indirect limit from the coupling fits
  - ATLAS: $BR_{inv} < 0.41$ @95%CL ATLAS-CONF-2014-009
  - CMS: $BR_{inv} < 0.32$ @95%CL CMS PAS HIG-14-009
- Recent idea: use off-shell production to constrain the Higgs decay width



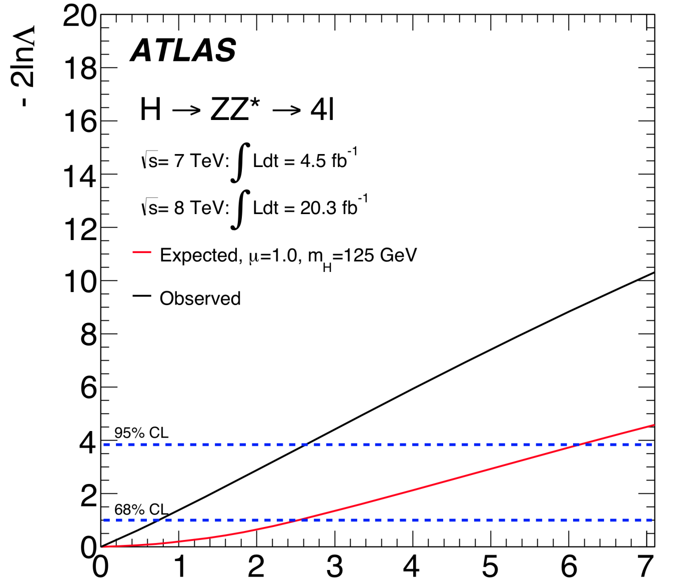
LHCXSWG, arXiv:1101.0593

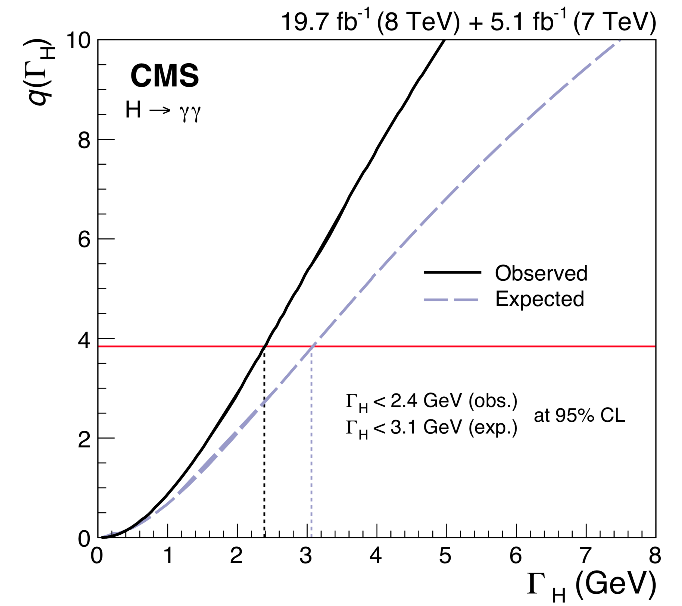
Direct constraints on Γ_H

- Measurements of the width of the invariant mass peak

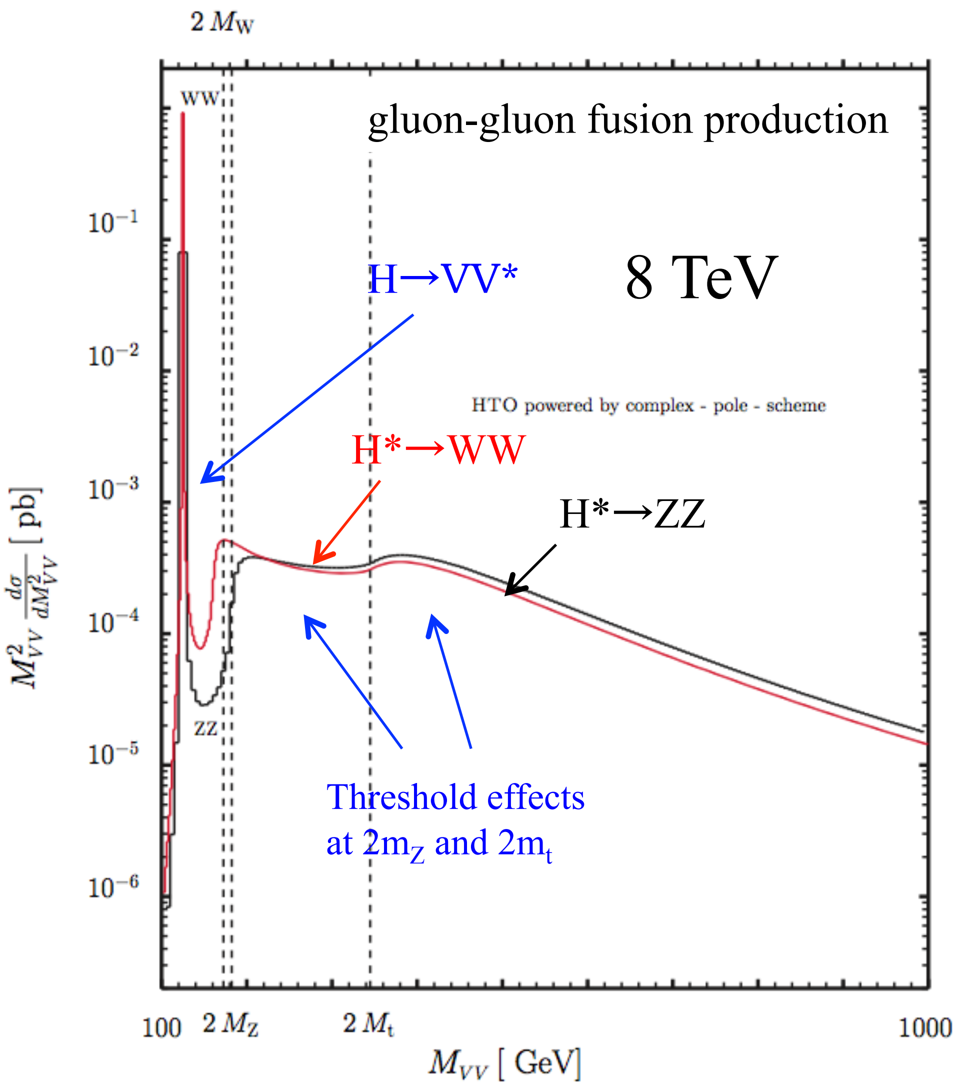
- $H \rightarrow ZZ^* \rightarrow 4l$
  - ATLAS: $\Gamma_H < 2.6$ GeV @ 95% CL ($\Gamma_H < 6.2$ GeV expected) ATLAS PRD 90 (2014) 052004
  - CMS: $\Gamma_H < 3.4$ GeV @ 95% CL ($\Gamma_H < 2.8$ GeV expected) CMS PRD 89 (2014) 092007
- $H \rightarrow \gamma\gamma$
  - ATLAS: $\Gamma_H < 5.0$ GeV @ 95% CL ($\Gamma_H < 6.2$ GeV expected) ATLAS PRD 90 (2014) 052004
  - CMS: $\Gamma_H < 2.4$ GeV @ 95% CL ($\Gamma_H < 3.1$ GeV expected) CMS PRD 89 (2014) 092007

➡ Best direct limit corresponds to $\Gamma_H < 600\ \Gamma_H^{SM}$





The Higgs lineshape



N. Kauer and G. Passarino, JHEP 08 (2012) 116

Off-shell production: $H^* \rightarrow VV$ (V = W, Z)

- Enhancement in the decay from the vicinity of the ZZ threshold
- Enhancement in the production (ggF only) at the $2m_t$ threshold
- Net result: ~8% of the total cross section above $2m_Z$ (off-shell region)
  - Enhanced by experimental cuts in the on-shell region => ~20%

Width constraint from off-shell production

- In the narrow width approximation:

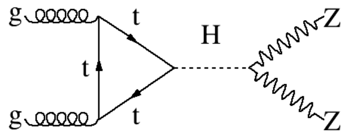
$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H}$$

- On-shell cross section depends on the ratio of the couplings (squared) and Γ_H:

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

- Off-shell cross section is independent of Γ_H:

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



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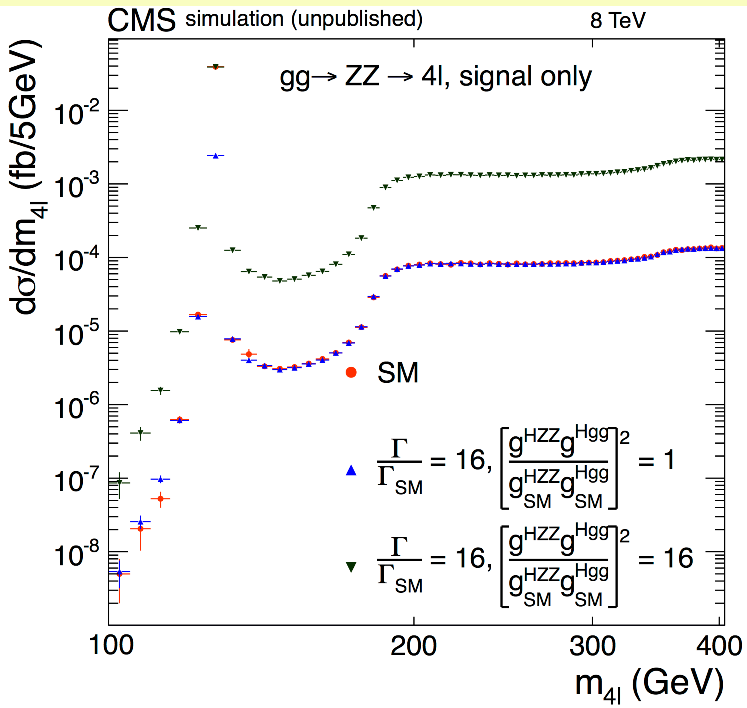


F. Caola and K. Melnikov, Phys. Rev. D 88 (2013) 054024
J. Campbell et al., arXiv.1311:3589

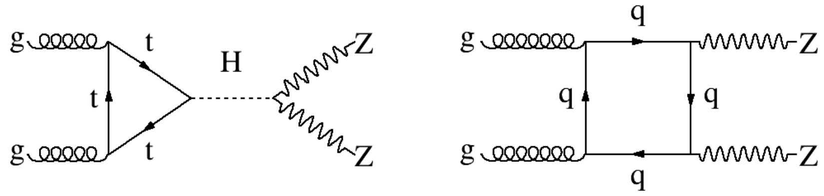
The combined measurement of the on-shell and off-shell production and decay yields is equivalent to a measurement of the width

Interference

- Non resonant gg → ZZ background production through the box diagram
- Interference between the two amplitudes is sizeable and negative
- The Higgs boson has to cancel the diboson cross section divergence (unitarization!)

- Taken into account in both ATLAS and CMS analyses
- Results in a decrease of the off-shell signal

- Similar in the VBF production mode



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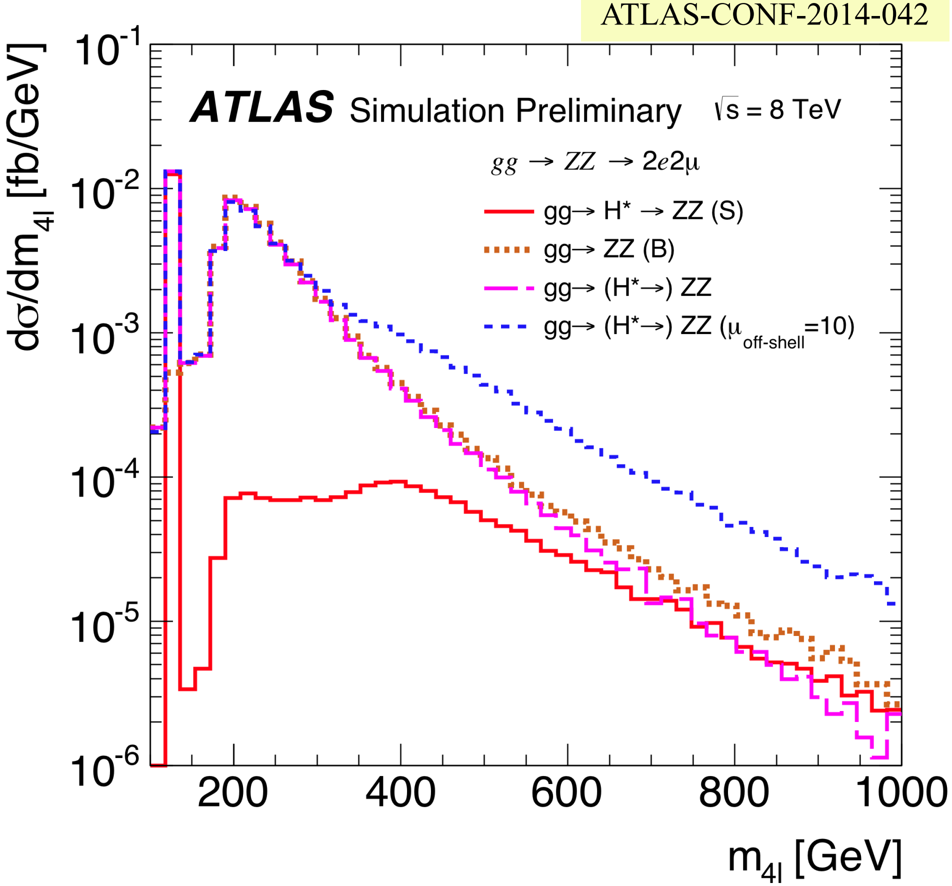
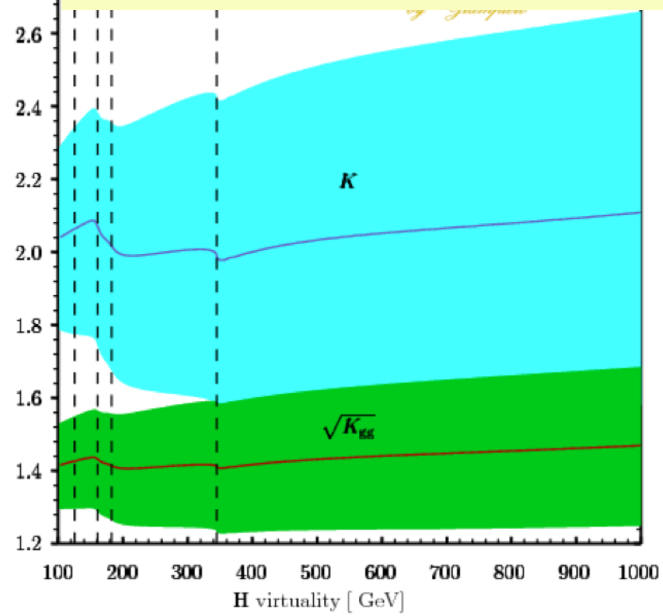


Monte Carlo simulation

gluon-gluon fusion

- Using latest versions of gg2VV and MCFM (LO in QCD)
  - Including signal H(125), background and interference
  - "Running" QCD scales (= $m_{ZZ}/2$) + scale and PDF variations for systematics
  - Signal m_{ZZ}-dependent K-factors (NNLO/LO) applied from G. Passarino (Eur. Phys. J. C 74 (2014) 2866)
  - CMS: uses results from M. Bonvini et al. (Phys. Rev. D88 (2013) 034032), use $K_{background} = K_{signal}$, assigning a 10% uncertainty on $K_{background}$
  - ATLAS: provides result as a function of $R^{B}_{H*} = K_{background} / K_{signal}$

G. Passarino, Eur. Phys. J. C 74 (2014) 2866



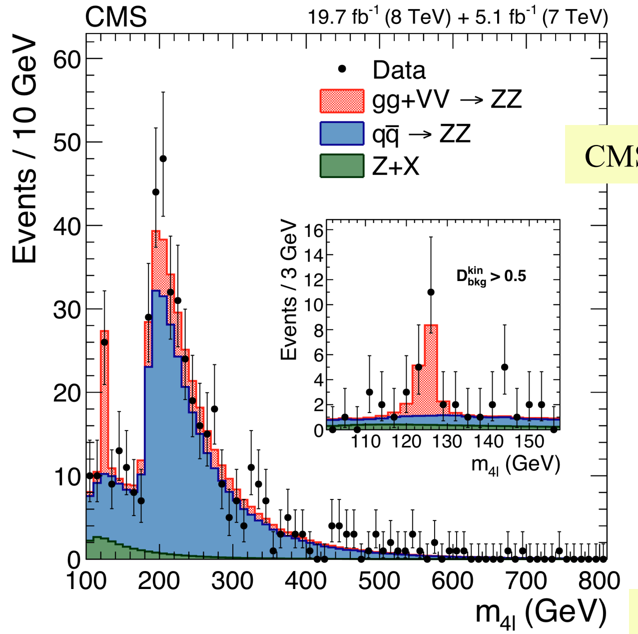
- VBF production is 7% of the total at H(126) peak
  - Slightly enhanced at high mass by trend of $\sigma_{VBF}(m_{ZZ}) \sim 10\%$
  - Using PHANTOM and MadGraph to model it
- VH and tt̄H negligible in the tail

4l analysis

- Same analyses as for the low mass Higgs measurement
  - CMS: PRD 89 (2014) 09007
  - ATLAS: PRD 90 (2014) 052004

- Four prompt and isolated leptons
  - p_T>20, 10, 7(5), 7(5) (e, μ) (CMS cuts)
- Compatible with two Z pairs
  - $40<m_{Z1}<120$, $12<m_{Z2}<120$
- Backgrounds
  - $q\bar{q}\rightarrow ZZ$: from MC
  - $gg \rightarrow ZZ$ (back.): from MC
  - Z+X: from control regions
- ME discriminants to separate the signal from $q\bar{q}\rightarrow ZZ$ in the on-shell region

- Off-shell region defined by m_{4l}>220 GeV



CMS PLB 736 (2014) 64

Observed: 223
Exp.: 217.6 ± 9.5 (syst.)

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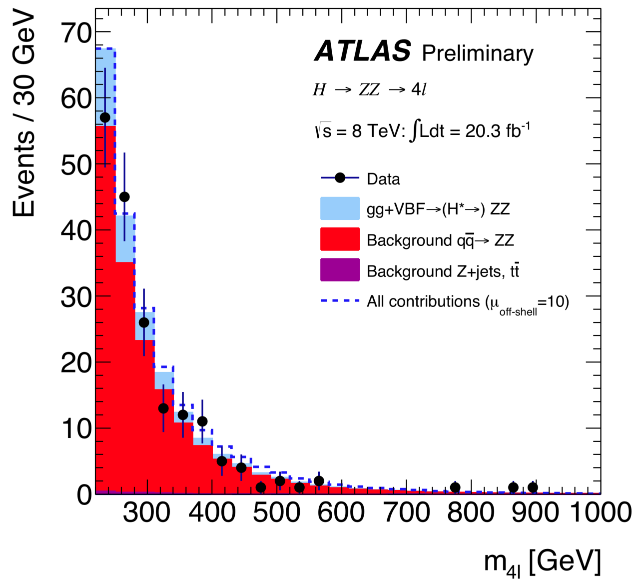


ME discriminant

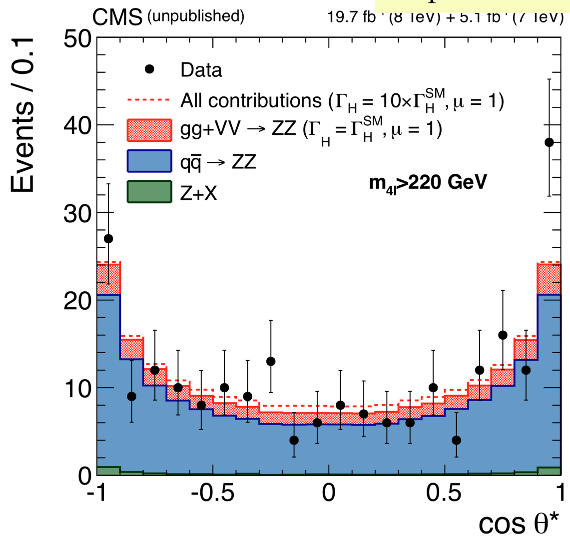
- In the matrix element likelihood approach, design specific discriminants to enhance the signal contribution in the off-shell region
- 7 kinematic variables characterize the production and decay (m_{Z1}, m_{Z2} and 5 angles) at a given m_{4l}

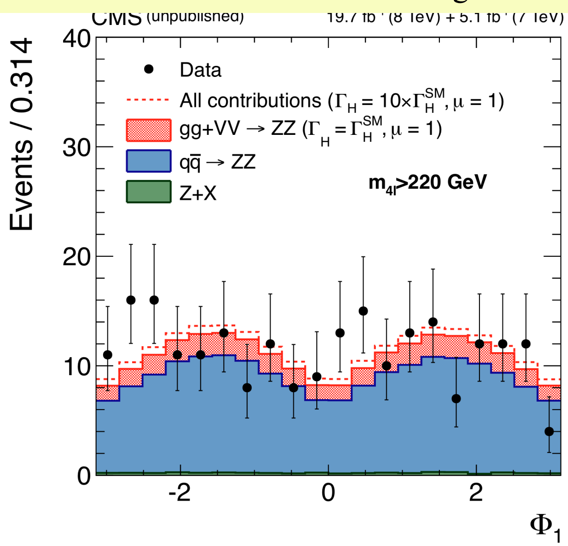
$$\mathcal{D}_{gg} = \frac{\mathcal{P}^{gg}_{\mathrm{tot}}}{\mathcal{P}^{gg}_{\mathrm{tot}} + \mathcal{P}^{q\bar{q}}_{\mathrm{bkg}}} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{\mathrm{bkg}}}{a \times \mathcal{P}^{gg}_{\mathrm{sig}} + \sqrt{a} \times \mathcal{P}^{gg}_{\mathrm{int}} + \mathcal{P}^{gg}_{\mathrm{bkg}}}\right]^{-1} \quad \text{(CMS)}$$

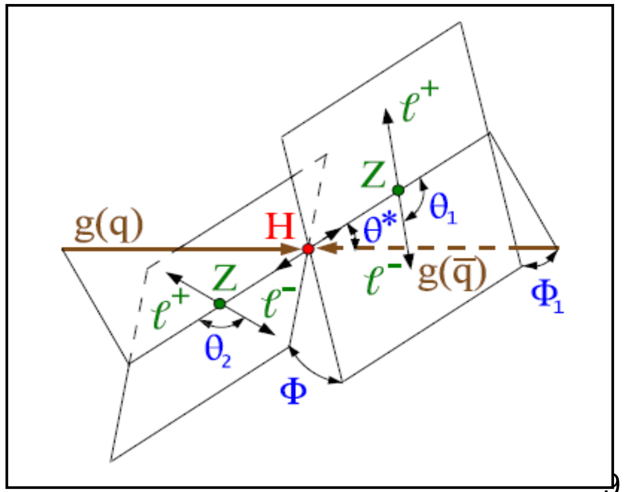
$$\mathrm{ME} = \log_{10}\left(\frac{P_H}{P_{gg} + c \cdot P_{q\bar{q}}}\right), \quad \text{(ATLAS)}$$

- Probabilities for signal, gg background and qq background from MCFM matrix elements

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig14002PubTWiki



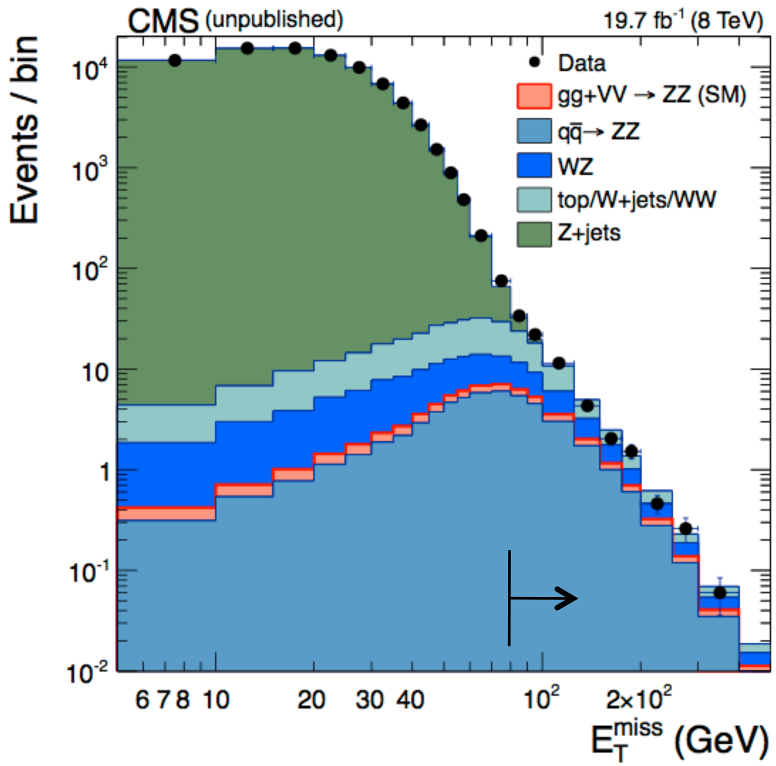




2l2ν analysis

- 6 times higher branching ratio compared to the 4l final state
  - Increased event yield in the high mass region where the rate is low
- No observation of the on-shell signal
  - Using the 4l analysis in the on-shell region
- Z+jets backgd several order of magnitude higher (fake E_T^{miss} from hadronic energy mis-measurement)
- Other backgrds
  - Irreducible: ZZ, WZ (from MC)
  - Non-resonant: top, WW
- Analysis variable: transverse mass

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig14002PubTWiki



E_T^{miss}>80 GeV

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

m_{4l} and D_{gg} distributions

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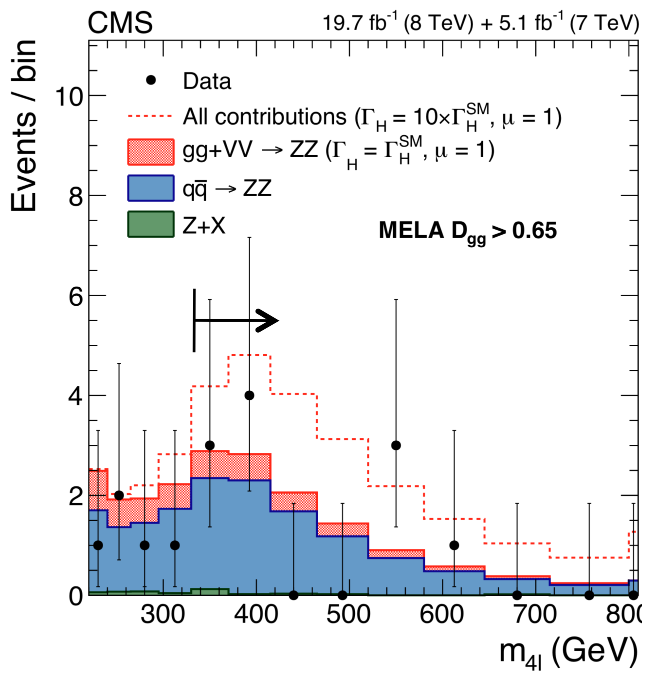

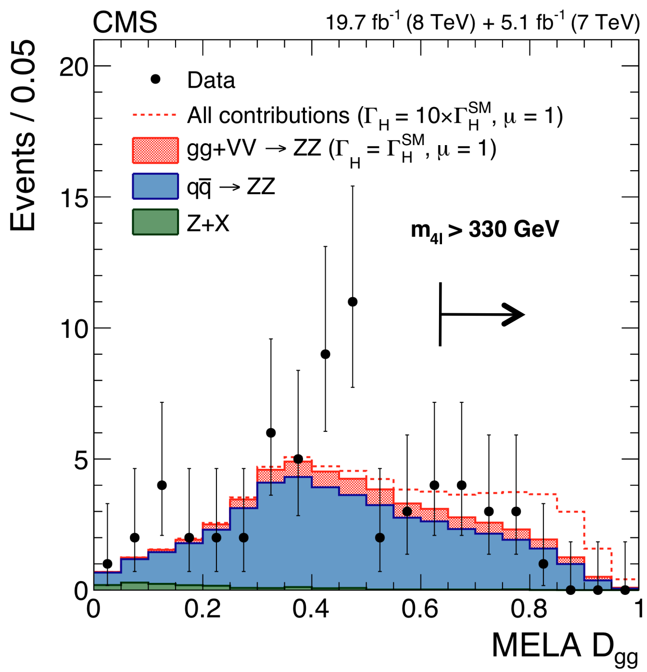

- Cut-and-count analyses performed as cross-check
- CMS: 2D (m4l, D_{gg}) cut-and count
  - m_{4l}>330 GeV, D_{gg}>0.65

Process	400 GeV < $m_{4\ell}$ < 1000 GeV
$gg \to H^* \to ZZ$ (S)	1.1 ± 0.3
$gg \to ZZ$ (B)	2.7 ± 0.7
$gg \to (H^* \to)ZZ$	2.3 ± 0.6
$gg \to (H^* \to)ZZ$ ($\mu_{\text{off-shell}} = 10$)	9.0 ± 2.5
VBF $H^* \to ZZ$ (S)	0.1 ± 0.0
VBF ZZ (B)	0.7 ± 0.0
VBF $(H^* \to)ZZ$	0.6 ± 0.0
VBF $(H^* \to)ZZ$ ($\mu_{\text{off-shell}} = 10$)	1.4 ± 0.1
$q\bar{q} \to ZZ$	21.3 ± 2.1
Reducible backgrounds	0.1 ± 0.0
Total Expected (SM)	24.3 ± 2.2
Observed	18

ATLAS-CONF-2014-042

- Main backgd: $q\bar{q}$

- ATLAS: 1D m_{4l} cut-and-count

m_T distributions

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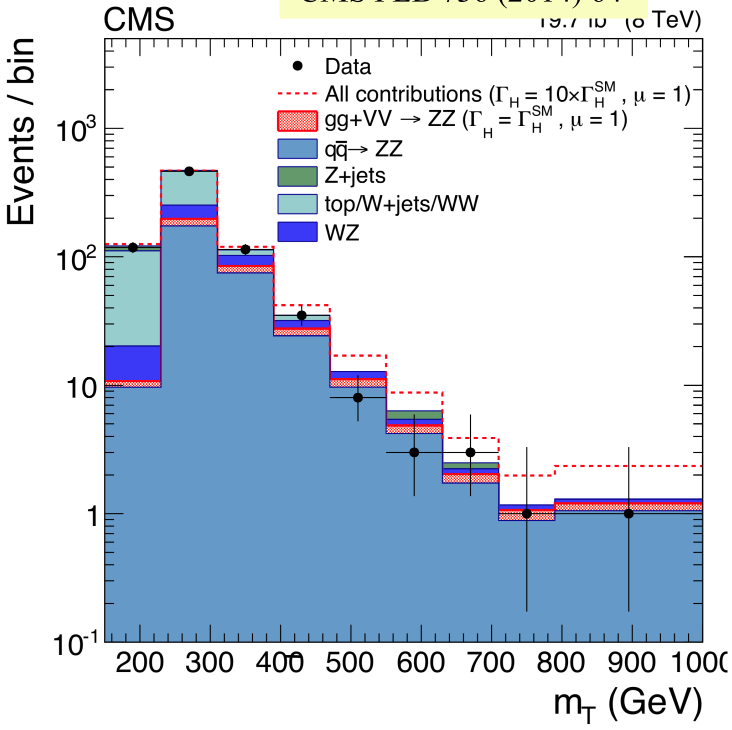

- Off-shell region in 2l2ν:
- CMS: m_T>180 GeV, E_t^{miss}>80 GeV
- ATLAS: m_T>330 GeV, E_T^{miss}>150 GeV

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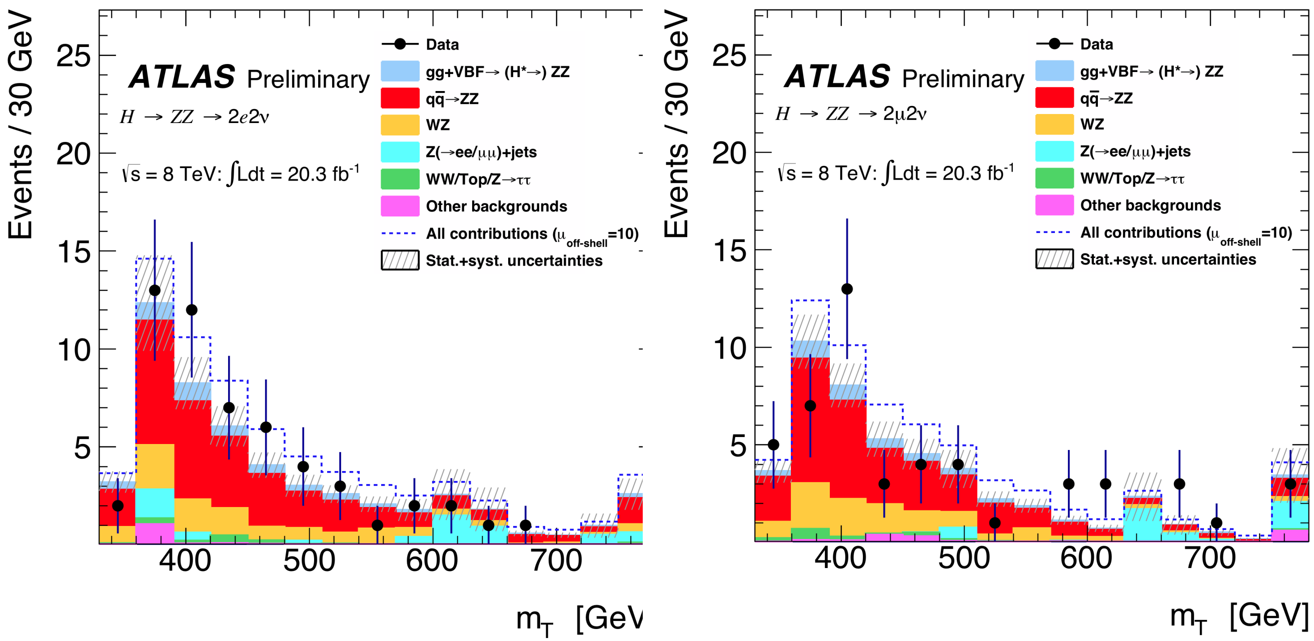

- Main backgds:
- $q\bar{q}$→ZZ, WZ, Z+jets

Statistical Analysis

- Probability density functions from MC
- Likelihood fit of the measured distributions in the on-shell and off-shell regions to extract the contribution of each component

$$\begin{aligned}\mathcal{P}_{\text{tot}}^{\text{off-shell}}(\vec{x}) = &\left[\mu_{\text{ggH}} \times (\Gamma_{\text{H}}/\Gamma_0) \times \mathcal{P}_{\text{sig}}^{\text{gg}}(\vec{x}) + \sqrt{\mu_{\text{ggH}} \times (\Gamma_{\text{H}}/\Gamma_0)} \times \mathcal{P}_{\text{int}}^{\text{gg}}(\vec{x}) + \mathcal{P}_{\text{bkg}}^{\text{gg}}(\vec{x})\right] \\ &+ \left[\mu_{\text{VBF}} \times (\Gamma_{\text{H}}/\Gamma_0) \times \mathcal{P}_{\text{sig}}^{\text{VBF}}(\vec{x}) + \sqrt{\mu_{\text{VBF}} \times (\Gamma_{\text{H}}/\Gamma_0)} \times \mathcal{P}_{\text{int}}^{\text{VBF}}(\vec{x}) + \mathcal{P}_{\text{bkg}}^{\text{VBF}}(\vec{x})\right] \\ &+ \mathcal{P}_{\text{bkg}}^{q\bar{q}}(\vec{x}) + \ldots\end{aligned}$$

- Free parameters in the fit:
  - Signal strengths scaling wrt SM expectations μ_{ggH} and μ_{VBF}
    - (assumed to be equal in ATLAS analysis $\mu = \mu_{ggH} = \mu_{VBF}$)
    - Obtained from the on-shell yield in the $H \rightarrow ZZ^* \rightarrow 4l$ channel
  - Observed Higgs width in unit of a reference value Γ_H / Γ_0
    - Obtained from the off-shell analyses in both $H^* \rightarrow ZZ \rightarrow 4l$ and $H^* \rightarrow ZZ \rightarrow 2l2\nu$ channels

Systematic uncertainties (CMS)

- Most theory systematics are correlated between on-shell and off-shell regions
  - Affect μ but not Γ in the combined measurement

- $gg \rightarrow ZZ$: QCD renormalization and factorization scales varied by a factor of two both up and down, and applied corresponding NNLO K factors (2-4%); PDF variations by using CT10, MSTW2008 and NNPDF2.1 (1%)
- Additional 10% on continuum $gg \rightarrow ZZ$ background, accounting for the limited knowledge on K-factor (30% on interference)
- QCD scales and PDF uncertainties on $qq \rightarrow ZZ$ and WZ backgrounds (4-10%) + $qq \rightarrow ZZ$ EWK corrections (2-6%)
- $2l2\nu$: background estimation for tt, tW and WW (15%+shape, 8% total backgd.)
- $2l2\nu$: Z+jets estimation from control samples (25%+shape, 3% total backgd.)

- Trigger: 1.5%, $2l2\nu$ b-jet veto: 1-3%
- Lepton reconstruction and selection: 3-4% (μ), 5-11% (e)

Systematic uncertainties (ATLAS)

- Systematic uncertainties estimated effect on $\mu_{\text{off-shell}}$

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Source of systematic uncertainties	95% CL on $\mu_{\text{off-shell}}$
QCD scale for $gg \to ZZ$	6.7
QCD scale for the $gg \to (H^* \to)ZZ$ interference	6.7
QCD scale for $q\bar{q} \to ZZ$	6.4
Z BG systematic	6.2
Luminosity	6.2
PDF for $pp \to ZZ$	6.1
Sum of remaining systematic uncertainties	6.2
No systematic	6.0
All systematic	7.9

- Dominant contribution from QCD scale for gg processes
- Backgd K-factor: results given as a function of $R^B_{H^*}$; 30% uncertainty on the interference (uncorrelated)

Results: CMS

- Very similar sensitivity between the two channels
- 4l: $\Gamma_H < 33$ MeV (8.0 x Γ_H^{SM})
  - $\Gamma_H < 42$ MeV exp.
- 2l2ν: $\Gamma_H < 33$ MeV (8.0 x Γ_H^{SM})
  - $\Gamma_H < 44$ MeV exp.

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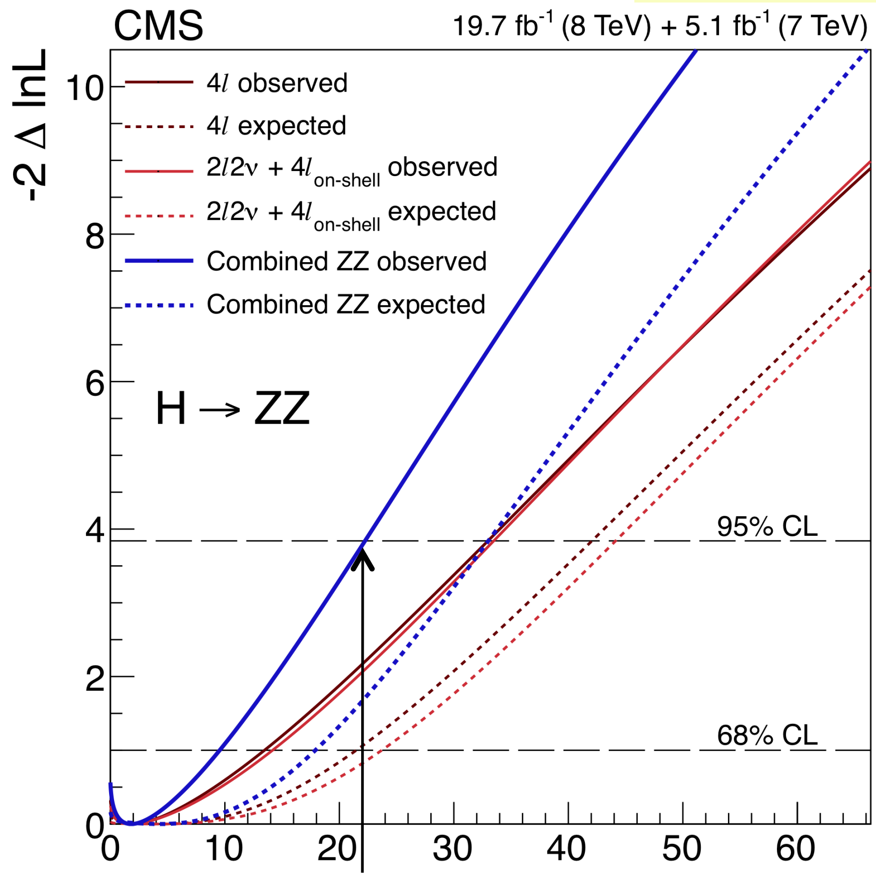


$\Gamma_H < 22$ MeV

4l + 2l2ν combined results

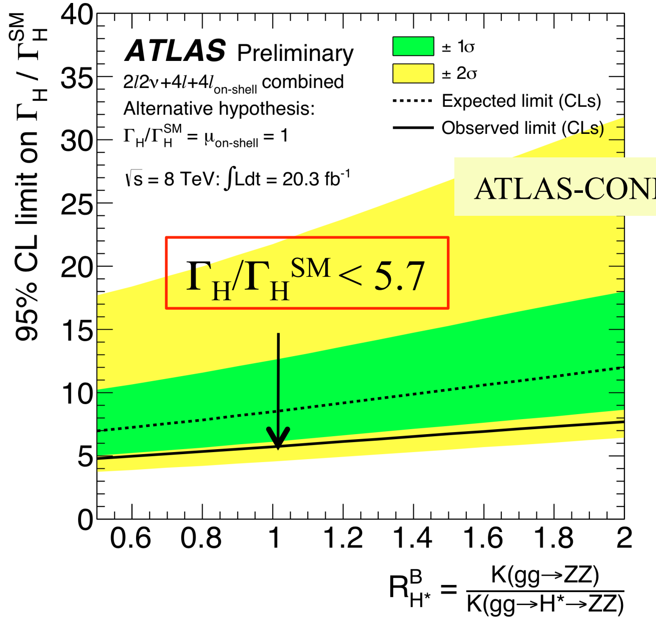
Γ_H (MeV)	Observed	Expected
Best fit value	$1.8^{+7.7}_{-1.8}$	$4.2^{+13.5}_{-4.2}$
95% CL	22	33

$\Gamma_H / \Gamma_H^{SM} < 5.4$ @ 95%CL

Results: ATLAS

- ATLAS results very similar to CMS
- Results reported as function of $R^B_{H*} = K_{background} / K_{signal}$
  - $0.5 < R^B_{H*} < 2.0$
  - $R^B_{H*} = 1$ corresponds to CMS analysis
- Model independent 95% CL limit on $\mu_{off\text{-}shell}$

Γ_H/Γ_H^{SM}	Observed	Expected
$R^B_{H*} = 0.5$	4.8	7.0
$R^B_{H*} = 1.0$	5.7	8.5
$R^B_{H*} = 2.0$	7.7	12.0



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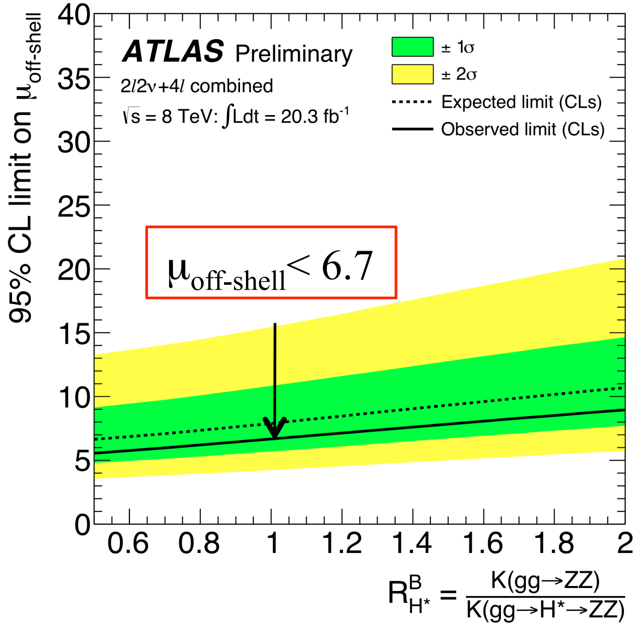


Model dependency

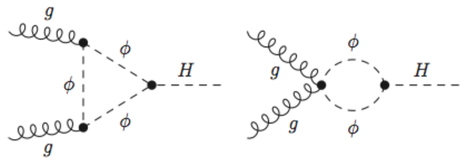
- Assume SM backgrounds: no anomalous ZZZ coupling, consistent with observations

- HVV couplings: analysis performed assuming $J^P=0^+$ with SM couplings
  - CMS studies: Anomalous couplings make the signal higher
  - Modified interference, eg ϕ_{a1}, makes the interference less destructive
  - Therefore anomalous HVV couplings would make the limit tighter

$$A(H \to ZZ) \propto \left[a_1 - e^{i\varphi_{\Lambda 1}} \frac{q_1^2 + q_2^2}{(\Lambda_1)^2} - e^{i\varphi_{\Lambda Q}} \frac{(q_1+q_2)^2}{(\Lambda_Q)^2}\right] m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

$$\mathcal{L}_i = N_{\mathrm{gg}\to\mathrm{ZZ}} \left[\mu\Gamma \times \mathcal{P}_{\mathrm{sig}}^{gg} + \sqrt{\mu\Gamma}\cos(\varphi_{a1}) \times \mathcal{P}_{\mathrm{int}}^{gg} + \mathcal{P}_{\mathrm{bkg}}^{gg}\right]$$

- Assume no strong modification of the Hgg coupling between off-shell and on-shell
  - No new particle in the gg fusion loop
  - See Englert et al., arXiv:1405.0285 for further discussion



Conclusions

- First experimental constraints on the Higgs width using off-shell Higgs production
  - Correlated measurement of $gg \rightarrow H^* \rightarrow ZZ$ and $gg \rightarrow H \rightarrow ZZ^*$ rates

- Similar results in CMS and ATLAS
  - CMS observed (expected): $\Gamma_H < 22$ MeV (33 MeV), $\Gamma_H/\Gamma_H^{SM} < 5.4$ @ 95% CL
  - ATLAS observed (expected): $\Gamma_H/\Gamma_H^{SM} < 5.7$ (8.5) @ 95% CL, $4.8 < \Gamma_H^{95\%}/\Gamma_H^{SM} < 7.7$ ($7.0 < \Gamma_H^{95\%}/\Gamma_H^{SM} < 12.0$)
  - Improves by more than 2 orders of magnitude on direct width measurements

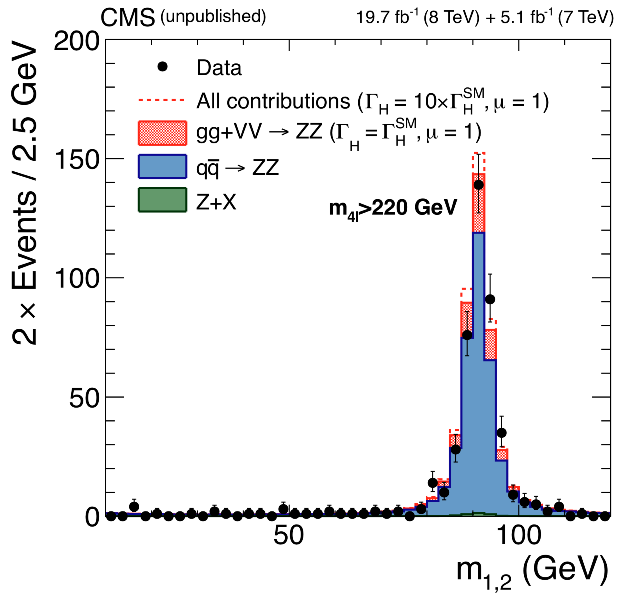
- CMS width constraint based on the Higgs propagator structure, limit holds as long as the couplings are unchanged between off-shell and on-shell
  - No new particle contributing in the gluon fusion loop

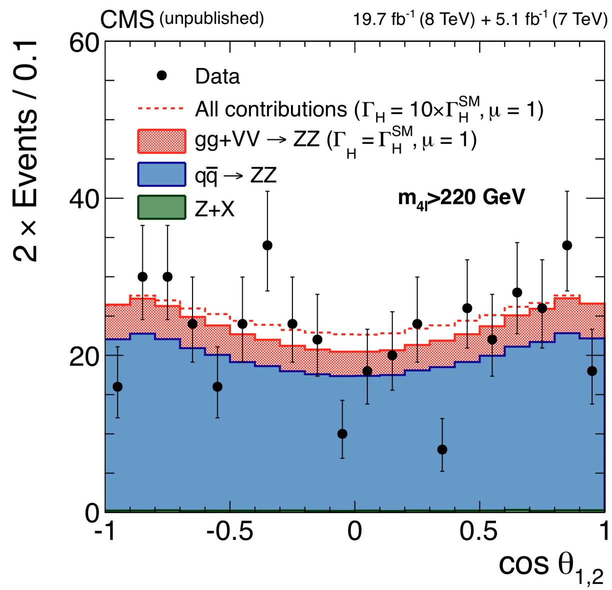
- Model independent constraint $\mu_{\text{off-shell}} < 6.7$ (7.9) provided by ATLAS

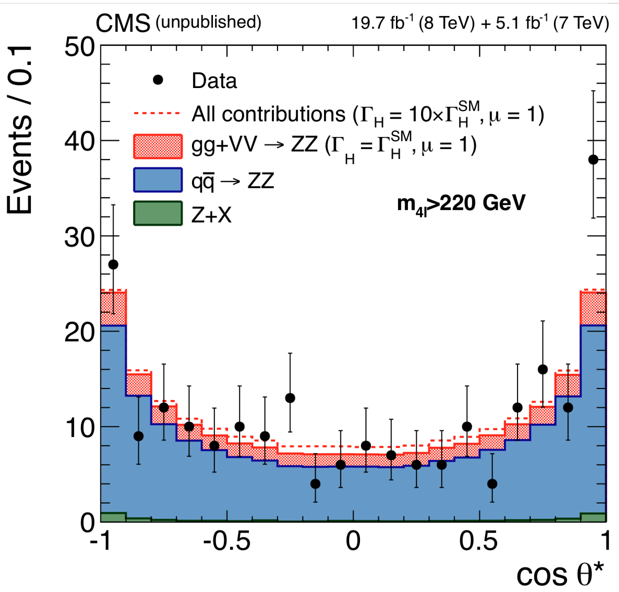
- Very striking results, worth to redo at run 2. Also a nice example of interactions between experimentalists and theoreticians.

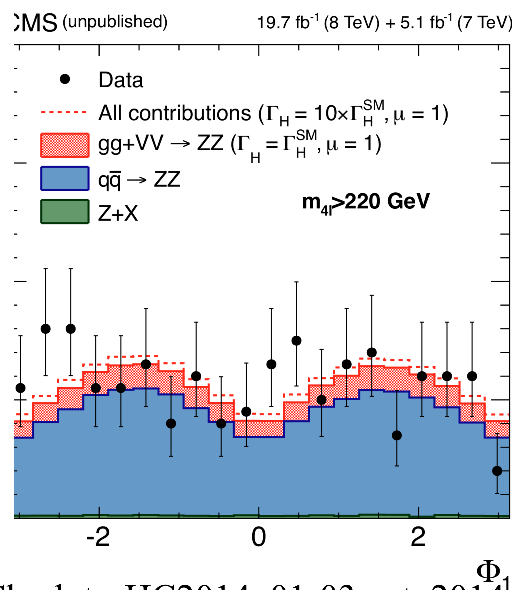
Backup

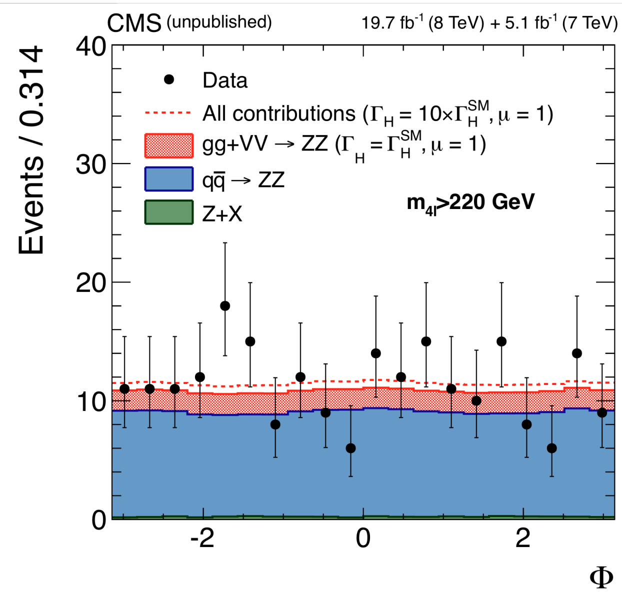
MELA discriminant









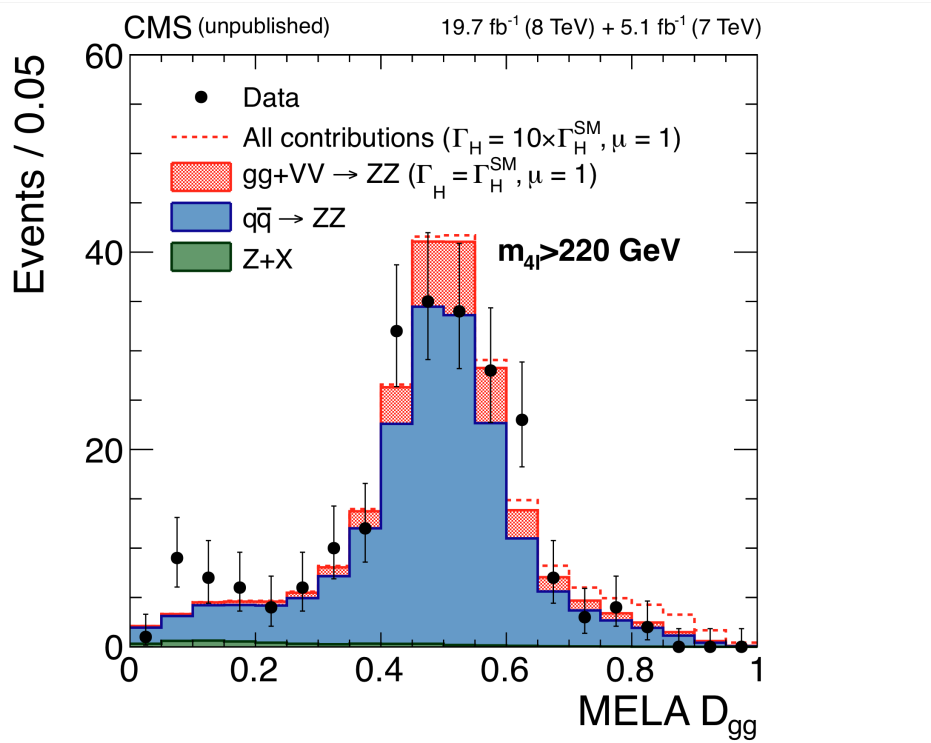


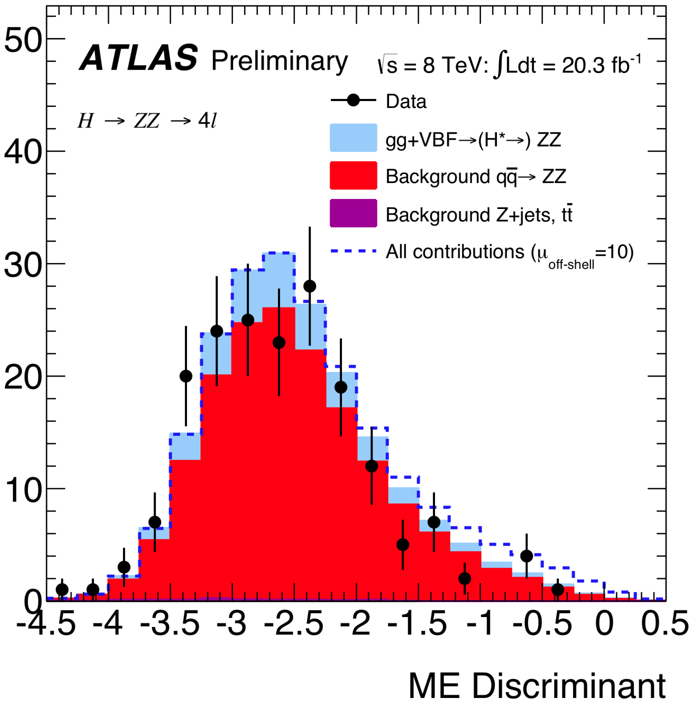
Cut and count yields: CMS

Table 1: Expected and observed numbers of events in the 4ℓ and $2\ell 2\nu$ channels in gg-enriched regions, defined by $m_{4\ell} \geq 330$ GeV and $\mathcal{D}_{gg} > 0.65$ (4ℓ), and by $m_T > 350$ GeV and $E_T^{miss} > 100$ 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 ($\Gamma_H = \Gamma_H^{SM}$) and a Higgs boson width of $\Gamma_H = 10 \times \Gamma_H^{SM}$. 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 parameters are set to $\mu = \mu_{ggH} = \mu_{VBF} = 1$.

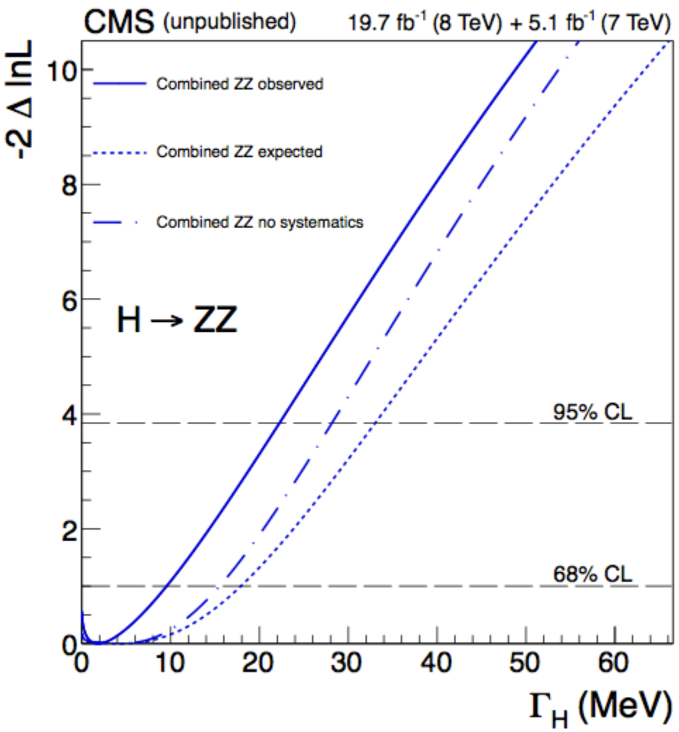
		4ℓ	$2\ell 2\nu$
(a)	total gg ($\Gamma_H = \Gamma_H^{SM}$)	1.8 ± 0.3	9.6 ± 1.5
	gg signal component ($\Gamma_H = \Gamma_H^{SM}$)	1.3 ± 0.2	4.7 ± 0.6
	gg background component	2.3 ± 0.4	10.8 ± 1.7
(b)	total gg ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	9.9 ± 1.2	39.8 ± 5.2
(c)	total VBF ($\Gamma_H = \Gamma_H^{SM}$)	0.23 ± 0.01	0.90 ± 0.05
	VBF signal component ($\Gamma_H = \Gamma_H^{SM}$)	0.11 ± 0.01	0.32 ± 0.02
	VBF background component	0.35 ± 0.02	1.22 ± 0.07
(d)	total VBF ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	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 ($\Gamma_H = \Gamma_H^{SM}$)	11.4 ± 0.8	93.2 ± 6.0
(b+d+e+f)	total expected ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	20.1 ± 1.4	124.9 ± 7.8
	observed	11	91

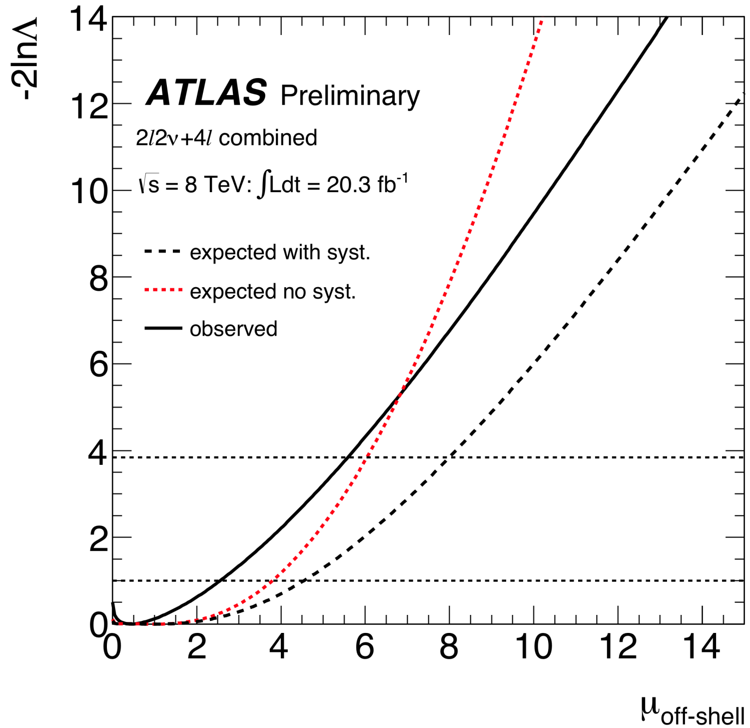
D_{gg} distributions





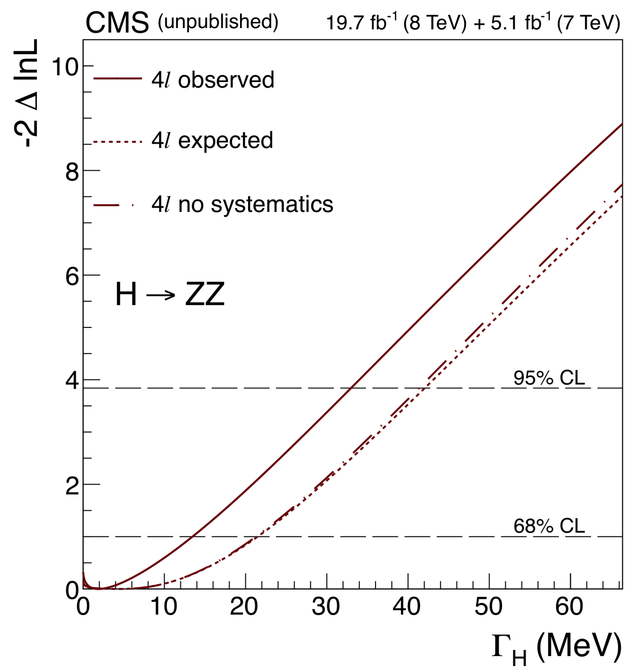
Effect of systematic uncertainties

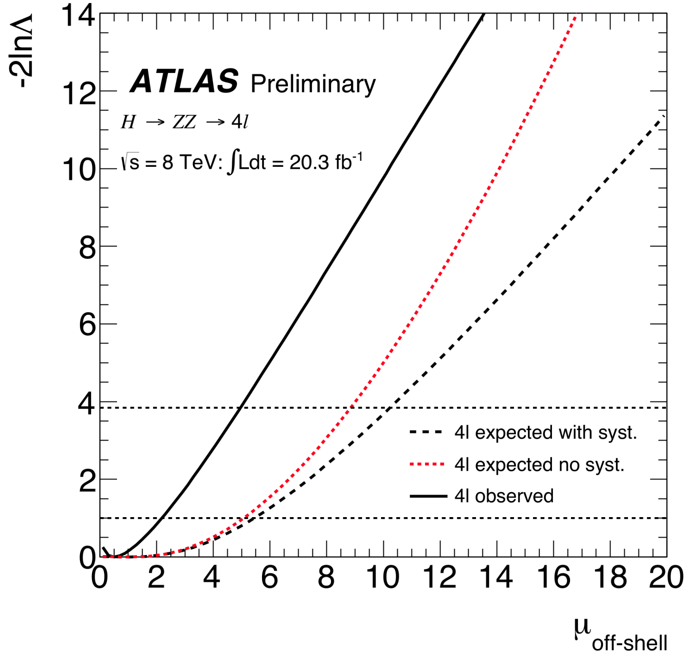




- Effect of systematics dominated by 2l2nu
- Systematic effect larger for $\mu_{\text{off-shell}}$ (most systematics cancel in the combined on-shell and off-shell measurement)

Effect of systematic uncertainties





- ❑ Very small effect of systematics in the 4l channel for the width constraint (most systematics cancel in the combined on-shell and off-shell measurement)
- ❑ Systematic effect larger for $\mu_{\text{off-shell}}$

CMS vs ATLAS analyses

CMS PLB 736 (2014) 64	ATLAS-CONF-2014-042
❑ Includes 7 TeV and 8 TeV data	❑ 8 TeV data only
❑ MELA discriminant to separate gg from qq	❑ ME discriminant to separate $gg \rightarrow H$ from gg+qq
❑ μ_F and μ_V are independent parameters of the fit	❑ $\mu = \mu_F = \mu_V$ used to constrain the high mass yield
❑ Uses $K_B = K_S$ with a 10% additional systematic uncertainty on the backgd yield for $gg \rightarrow ZZ$	❑ Provide results as a function of K_B/K_S (in [0.5-2.0]) for $gg \rightarrow ZZ$
❑ Width constraint in MeV	❑ Complementary results on the on-shell signal strength (model independent but larger uncertainty)