Scalar boson width measurements at LHC

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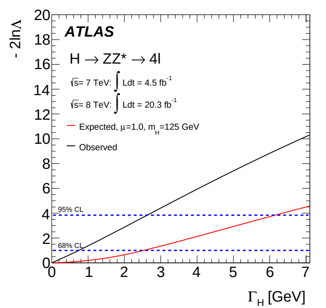
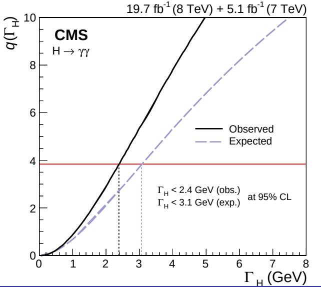
Outline

Direct width measurement

- The Higgs decay width is a fundamental parameter of the SM:
  - Relates to the Higgs couplings to all massive particles
  - Sensitive to BSM contributions
- Direct measurements of Γ_H:
  - $H \to ZZ \to 4l$
    $\Gamma_H < 3.4$ GeV (CMS) PLB 736 (2014) 64
    $\Gamma_H < 2.6$ GeV (ATLAS) arXiv:1406.3827
  - $H \to \gamma\gamma$
    $\Gamma_H < 2.4$ GeV (CMS) arXiv:1407.0558
    $\Gamma_H < 5.0$ GeV (ATLAS) arXiv:1406.3827
- 3 orders of magnitude larger than SM prediction: $\Gamma_H = 4.15$ MeV

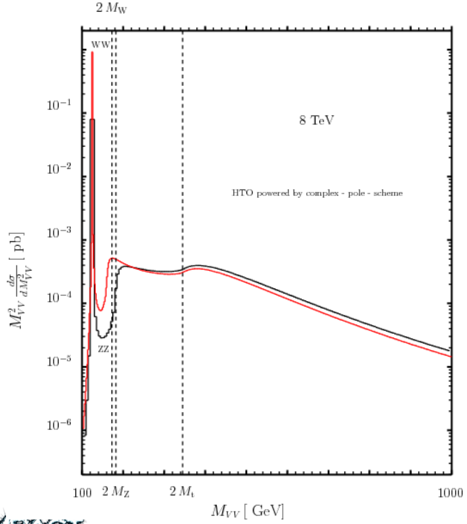




We can use indirect information from the off-shell Higgs production to put further constraints on the Higgs decay width
talk by G. Passarino on thursday

$H \to$ZZ in the off-shell region

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



- Peculiar structure of the signal distribution: enhancement of the H(126) cross-section in the high mass region
- $\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g_{ggH} g_{HZZ} \frac{F(m_{ZZ})}{(m^2_{zz} - m^2_H) + m^2_H \Gamma^2_H}$
- Destructive contribution from the interference reduce the effect
- About 7.6% of the total cross-section in the ZZ final state, but it can be enhanced by experimental selection

Constraints on the width from off-shell measurement

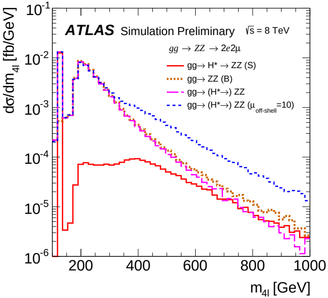
F. Caola, K. Melnikov (Phys. Rev. D88 (2013) 054024)
J. Campbell et al. (arXiv:1311.3589)

The gluon fusion production cross section can be written as

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g_{ggH}g_{HZZ}\frac{F(m_{ZZ})}{(m^2_{zz}-m^2_H)+m^2_H\Gamma^2_H}$$

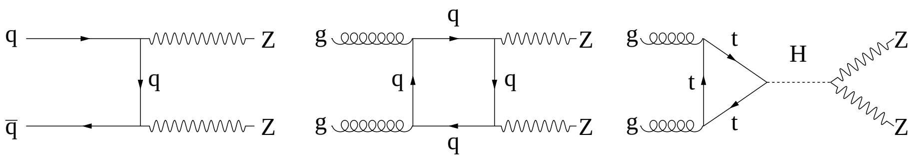
We can use this formula to set a constraint on the total Higgs width

- On peak cross-section: $\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H}$ peak yield constant if couplings scaled in the appropriate way
- high mass region: $\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}$ off-shell yield proportional to the scale
- Γ_H can be obtained from the off-shell/on-shell ratio
- Interference must be taken into account.

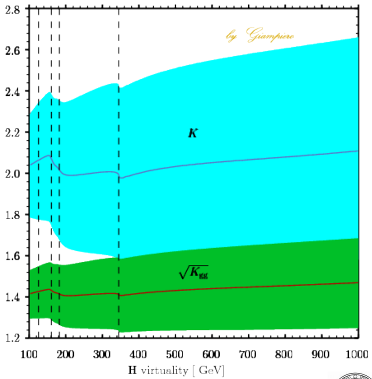


Holds for BSM as well as long as the couplings ratios are unchanged i.e. the dominant contribution to ggH is the top loop and no new particles contributions.

K-factors and ZZ production



- Signal/background/interference processes are taken into account (interference effect)
- NNLO/LO kFactors depend on m_{ZZ} Passarino, Eur.Phys.J. C74 (2014) 2866
- CMS: Same kFactors applied to signal and continuum (plus syst uncertainty) M. Bonvini et al.(Phys.Rev.D 88 2013), ATLAS provides the results as a function of sig/bkg kFactors ratio $R^B_{H^*}$
- NLO EWK corrections
  - 5% decrease of $q\bar{q} \rightarrow ZZ$ at 700 GeV
  - up to 10% uncertainty



Statistical model

Build the Probability Density Function and perform a likelihood fit on it:

$$\mathcal{P}_{\text{tot}}^{\text{off-shell}}(\vec{x}) =$$

$$\left[\mu_{ggH} \times (\Gamma_H/\Gamma_0) \times \mathcal{P}_{\text{sig}}^{gg}(\vec{x}) + \sqrt{\mu_{ggH} \times (\Gamma_H/\Gamma_0)} \times \mathcal{P}_{\text{int}}^{gg}(\vec{x}) + \mathcal{P}_{\text{bkg}}^{gg}(\vec{x})\right] +$$
$$\left[\mu_{\mathrm{VBF}} \times (\Gamma_H/\Gamma_0) \times \mathcal{P}_{\text{sig}}^{\mathrm{VBF}}(\vec{x}) + \sqrt{\mu_{\mathrm{VBF}} \times (\Gamma_H/\Gamma_0)} \times \mathcal{P}_{\text{int}}^{\mathrm{VBF}}(\vec{x}) + \mathcal{P}_{\text{bkg}}^{\mathrm{VBF}}(\vec{x})\right]$$
$$+ \mathcal{P}_{\text{bkg}}^{qq}(\vec{x}) + \ldots$$

More background contributions depending on the final state

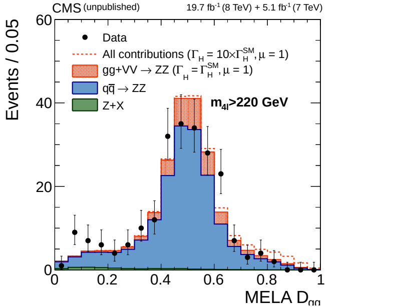
Free parameters in the fit:

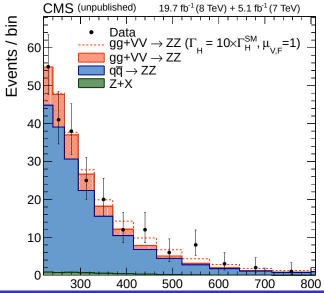
- Signal strength scaling wrt SM expectations μ_{ggH} and μ_{VBF}
  - Obtained from the on-shell H→ZZ→ $4l$ analysis
- Ratio of the observed boson width to the SM Higgs width Γ_H/Γ_0
  - Obtained from the off-shell analyses of H→ZZ→ $4l$ and $H \to ZZ \to 2l2\nu$ decays
- ATLAS: no jet splitting, $R^B_{H^*}, \mu_{\text{off-shell}}$ instead of $\mu, \Gamma_H/\Gamma_0$

The on-shell part of the spectrum is used to measure the signal strength, the off-shell to constrain the width

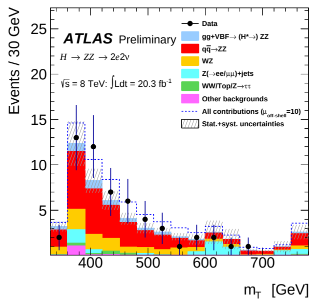
4l analysis in the off-shell region

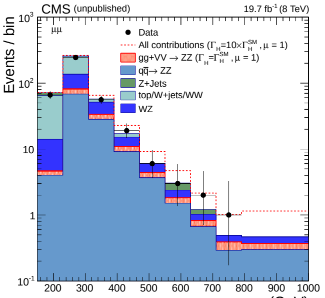
- Same experimental selection as on the on-shell analyses
  CMS:PRD 89 (2014) 092007
  ATLAS: arxiv:1406.3827
- 2-dimensional shapes are used in the likelihood fit:
  4l invariant mass: $m_{4l} > 220$ GeV
  Matrix Element Discriminant:
  $\mathcal{D}_{gg,a} = \frac{\mathcal{P}_{gg,a}}{\mathcal{P}_{gg,a}+\mathcal{P}_{q\bar{q}}} =$
  $\left[1 + \frac{\mathcal{P}^{q\bar{q}}_{\rm bkg}}{a \times \mathcal{P}^{gg}_{\rm sig} + \sqrt{a} \times \mathcal{P}^{gg}_{\rm int} + \mathcal{P}^{gg}_{\rm bkg}}\right]^{-1}$
- Based on the probabilities that an event originates from $q\bar{q}$ or gg. Includes sig, bkg and interference.
- $a = 10$: strength modifier due to Γ_H changes. Affects the maximum sensitivity, not the physics





2l2ν analysis in the off-shell region





- Analysis technique as in high mass Higgs search
  CMS: 10.1140/epjc/s10052-013-2469-8
  ATLAS: PRL 112 (2014) 201802
- ATLAS analysis further optimized the cuts in order to reduce the shape dependent theoretical uncertainties of the m_T
- Only 8 TeV data sample
- Larger BR (x6) than 4l, but larger background as well. Data driven estimation of the background
- Reaches similar sensitivity to the 4l channel

The transverse mass distribution is used as the final variable in the likelihood fit

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

Systematic uncertainties (CMS)

Theoretical

- 10% uncertainty on the $gg \to ZZ$ continuum K factor (1.0 ± 0.1)
- 2-4% QCD ren. and factoriz. scale ($\times 2$ K factor variation in gg)
- PDF shape variation (MSTW2008, CT10, NNPDF2.1): 1%
- $q\bar{q}$ QCD scales 4-10% + 2-6% from missing high order contributions
- $2l2\nu$ Bkg estimation from $t\bar{t}$, tW, WW samples: 15% (8% total bkg)
- $2l2\nu$ from Z+jets control samples: 25% on 3% total bkg
- $2l2\nu$ Parton shower and underlying event effect on MET: 6%

Experimental

- Trigger: 1.5%, $2l2\nu$ B-jet veto: 1-3%
- Lepton reconstruction: 3-4% (μ), 5-11% (e)
- $2l2\nu$ momentum scale: 1-2% (e, μ), 1% (jets)

Cancellation of normalization systematics between on and off-shell in $4l$.
Only those uncertainties affecting both shapes and yields contribute.
Dominant contribution from $2l2\nu$ sig efficiencies and bkg estimation

Systematic uncertainties (ATLAS)

- Without systematic uncertainties: $\Gamma_H < 6.0$ MeV (expected)
- Systematic uncertainties estimated effect on $\mu_{\text{off-shell}}$ determination

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
- Experimental uncertainties small wrt theoretical ones
- Results as a function of $0.5 < R^B_{H*} < 2$:
- 30% uncertainty on the interference uncorrelated to the background uncertainty on R^B_{H*}

CMS Results

- Very similar sensitivity between the two channels
- $4l$: $\Gamma_H < 33$ MeV ($8.0 \times \Gamma_{SM}$) (42 MeV expected)
- $2l2\nu$ $\Gamma_H < 33$ MeV ($8.0 \times \Gamma_{SM}$) (44 MeV expected)
- Combination:
  $\Gamma_H < 22$ MeV ($5.4 \times \Gamma_{SM}$) (33 MeV expected)
- Best fit at $\Gamma_H = 1.8^{+7.7}_{-1.8}$ MeV
- Results are compatible with the SM assumption at the $p = 0.24$ level
- Without systematic uncertainties: $\Gamma_H < 28$ MeV (exp.), most of it driven by $2l2\nu$

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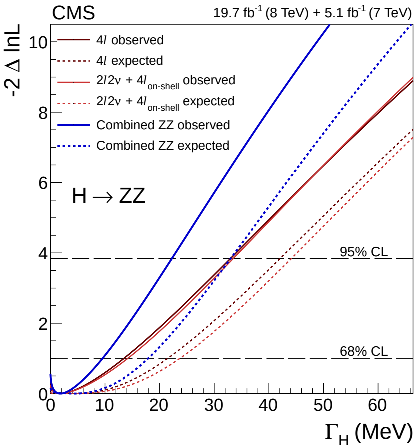
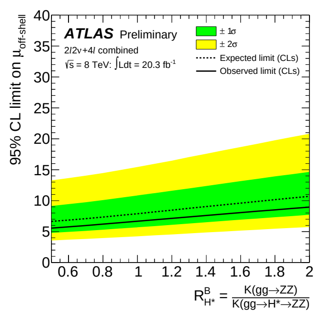
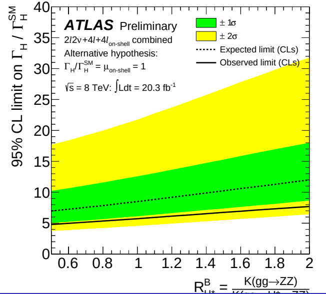


ATLAS results

- ATLAS analysis (ATLAS-CONF-2014-042) is very similar to CMS
- Reconstruction as in arXiv:1406.3827 ($4l$) and PRL 112(2014)201802 ($2l2\nu$)
- Cut-based $4l$ analysis as cross-check for the matrix element default analysis (based on m_{4l})
- Results reported as a function of
  $R^B_{H*} = \frac{K_{gg \to ZZ}}{K_{gg \to H* \to ZZ}}$
  - $0.5 < R^B_{H*} < 2$
  - $R^B_{H*} = 1$ is equivalent to CMS analysis
- 95% CLs limits on the model indipendent off-shell signal strength $\mu_{\text{off-shell}}$





R^B_{H*}	Observed 0.5	Observed 1.0	Observed 2.0	Median expected 0.5	Median expected 1.0	Median expected 2.0	Alternative hypothesis
$\mu_{\text{off-shell}}$	5.6	**6.7**	9.0	6.6	**7.9**	10.7	$R^B_{H*} = 1, \mu_{\text{off-shell}} = 1$
Γ_H/Γ_H^{SM}	4.1	**4.8**	6.0	5.0	**5.8**	7.2	$R^B_{H*} = 1, \Gamma_H/\Gamma_H^{SM} = 1, \mu_{\text{on-shell}} = 1.51$
Γ_H/Γ_H^{SM}	4.8	**5.7**	7.7	7.0	**8.5**	12.0	$R^B_{H*} = 1, \Gamma_H/\Gamma_H^{SM} = 1, \mu_{\text{on-shell}} = 1$

Conclusions

- The first experimental constraints on the Higgs total width using off-shell H(125) production were presented
- CMS: PLB 736 (2014) 64, ATLAS: ATLAS-CONF-2014-042
- This technique proved to be a powerful tool in constraining Γ_H
- Observed (Expected) $4l$ and $2l2\nu$ combined results:
    - CMS:
      $\Gamma_H = 1.8^{+7.7}_{-1.8}$, $(4.2^{+13.5}_{-4.2})$, $\Gamma_H < 22$ (33) MeV, $\Gamma_H/\Gamma_{SM} < 5.4$ (8.0)
    - ATLAS:
      $\Gamma_H/\Gamma_{SM} = 0.3^{+1.4}_{-0.3}$, $\Gamma_H/\Gamma_{SM} < 5.7$ (8.5), $4.8 < \Gamma_H^{95\%}/\Gamma_{SM} < 7.7$ $(7.0 < \Gamma_H^{95\%}/\Gamma_{SM} < 12.0)$
    - Very similar results from the 2 experiments
- 3 orders of magnitude improvement wrt to direct limits
- The CMS results hold for BSM models as long as the couplings ratios between on and off-shell contributions are unchanged
- Model independent constraint on $\mu_{\text{off-shell}} < 6.7$ (7.9) from ATLAS
- The presence of anomalous HVV coupling would enhance the off-shell contributions, making the constraint tighter

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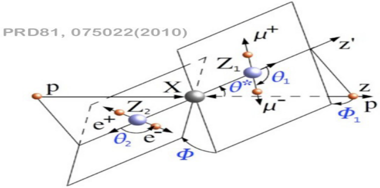
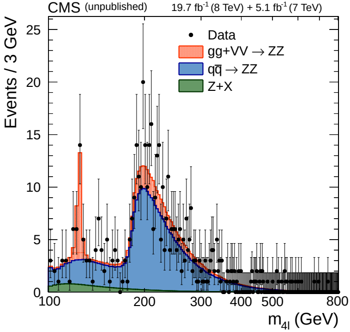
BACKUP

$H \to ZZ \to 4l$ on-shell analysis

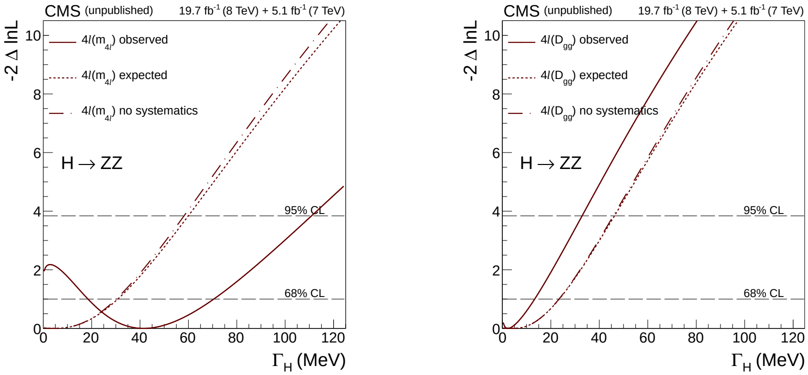
5 angles and 2 masses fully describe the H→ZZ→ 4l decay
Golden channel for discovery and spin-parity
Sensitive to different $q\bar{q}/gg$ production fractions.





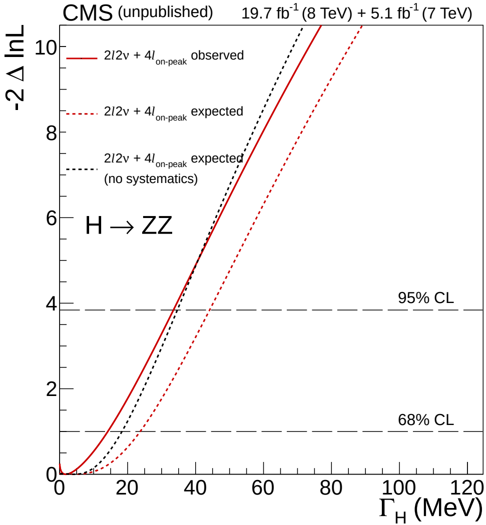
- 4 isolated leptons
- Lepton $p_T > 20, 10, 5, 5$ GeV
- 2 OS/SF pairs, $m_{4l} > 4$ GeV
- $40 < m_{Z_1} < 120$GeV
  $12 < m_{Z_2} < 120$GeV
- Matrix Element Discriminant based on system kinematics

4l 1D likelihood scans



Most of the sensitivity from the D_{gg} contribution.
Very small effect of systematic uncertainties, because of cancellations with the on-peak analysis.

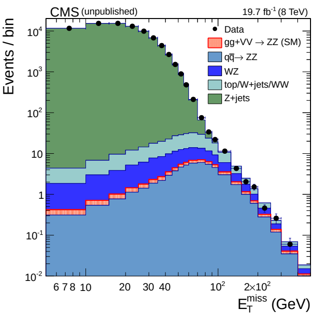
Systematics effect on $2l2\nu$

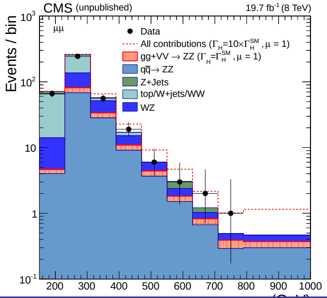


Yields

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

2l2ν analysis in the off-shell region at CMS





- Analysis technique as in high mass Higgs search 10.1140/epjc/s10052-013-2469-8
- Only 8 TeV data sample
- Larger BR (x6) than 4l, but larger background as well. Data driven estimation of the background

- 2 OS/SF isolated leptons with $p_T > 20$ GeV making a pair compatible with a Z
- missing $E_T^{miss} > 80$ GeV
- $m_T > 180$ GeV

The transverse mass distribution is used as the final variable in the likelihood fit

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