Constraints on Higgs-boson width using $H^*(125) \to VV$ events

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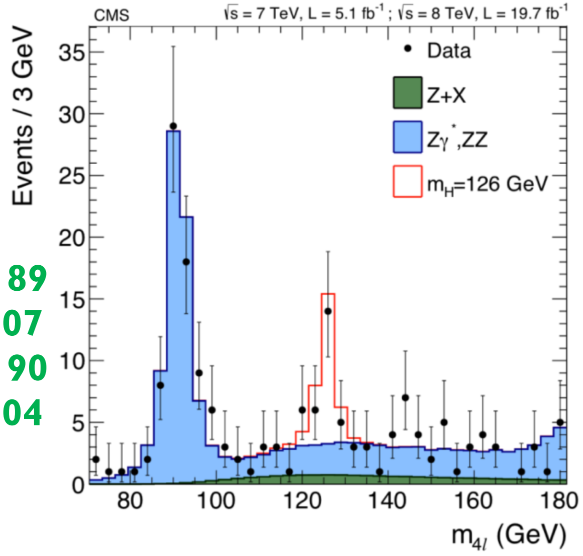
on behalf of the CMS and ATLAS collaborations

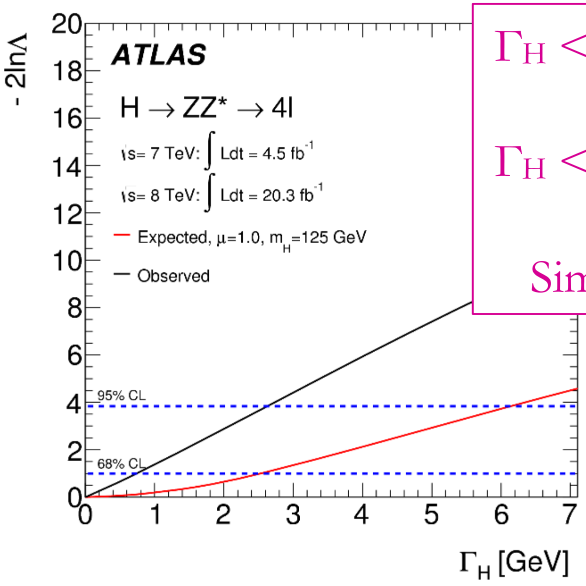
25th International Workshop on Weak Interactions and Neutrinos (WIN2015)
MPIK Heidelberg, 8-13 June 2015

The Higgs width at the LHC

- Direct decay width measurements at the peak limited by experimental resolution:
  - $f(m) \sim BW(m, \Gamma) \otimes R(m, \sigma)$
  - If $\Gamma \ll \sigma$, not possible to disentangle natural width
    - SM Higgs width at m_H = 125 GeV is Γ_H = 4.07 MeV
    - Experimental resolution is $\sigma \sim$ 1-3 GeV for $H \rightarrow ZZ^* \rightarrow 4l$

Phys. Rev. D 89 (2014) 092007
Phys. Rev. D 90 (2014) 052004



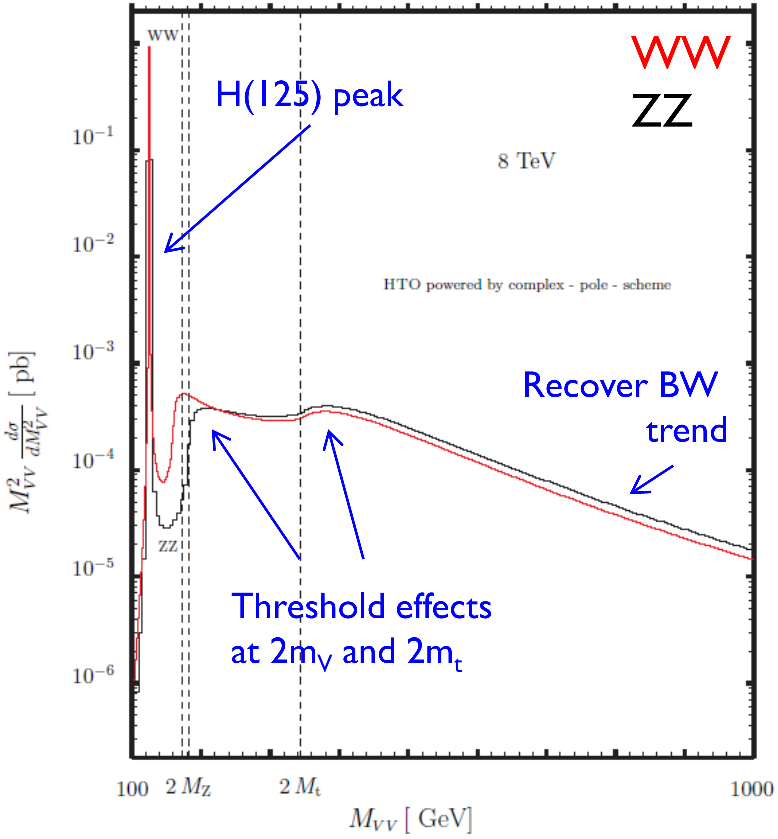


Γ_H < 3.4 GeV @ 95% CL
(CMS)
Γ_H < 2.6 GeV @ 95% CL
(ATLAS)
Similar results from γγ

The idea

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

gluon-gluon fusion production



- Off-shell H* → VV (V = W, Z)
  - Peculiar cancellation between BW trend and decay amplitude creates an enhancement of H(125) cross-section at high m_{VV}

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

(Analogously for WW)

  - About 7.6% of total cross-section in the ZZ final state, but can be enhanced by experimental cuts

	Tot[pb]	$M_{ZZ} > 2\,M_Z$ [pb]	R[%]
$gg \to H \to$ all	19.146	0.1525	0.8
$gg \to H \to ZZ$	0.5462	0.0416	7.6

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

$\mu_{\text{off-shell}}$ and width

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(<u>Analogously for WW</u>)

Can it be used to set a constraint on the total Higgs width?

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} = \frac{\kappa^2_g\kappa^2_Z}{r}(\sigma\cdot\text{BR})_{\text{SM}} \equiv \boxed{\mu}(\sigma\cdot\text{BR})_{\text{SM}}$$

$$\frac{d\sigma^{\text{off-peak}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \boxed{\kappa^2_g\kappa^2_Z}\frac{d\sigma^{\text{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

$$\kappa_g = g_{ggH}/g^{\text{SM}}_{ggH}$$
$$\kappa_Z = g_{HZZ}/g^{\text{SM}}_{HZZ},$$
$$\boxed{r = \Gamma_H/\Gamma^{\text{SM}}_{H}}$$

- Couplings can scale by arbitrary values as a function of m_{VV} (generic New Physics assumption)
  - A new signal strength $\mu_{\text{off}} = \kappa_g^2\kappa_Z^2$ is extracted from off-shell data

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$$\kappa_g = g_{ggH}/g_{ggH}^{\text{SM}}$$

$$\kappa_Z = g_{HZZ}/g_{HZZ}^{\text{SM}}$$

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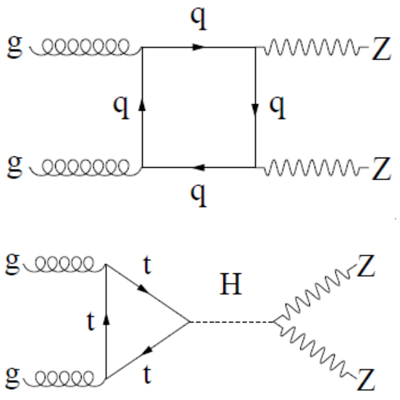
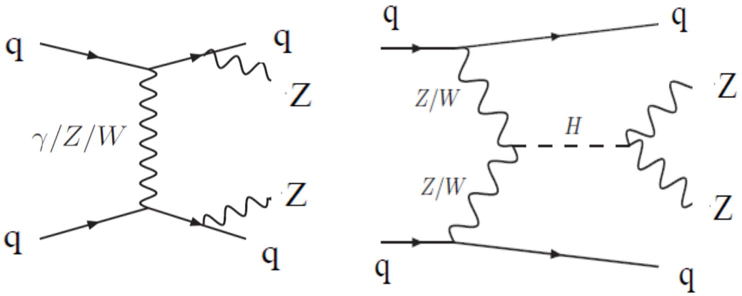
- Couplings can scale by arbitrary values as a function of m_{VV} (generic New Physics assumption)
  - A new signal strength $\mu_{\text{off}} = \kappa_g^2\kappa_Z^2$ is extracted from off-shell data
- On-shell and off-shell couplings scale by the same amounts
  - Fitting simultaneously the on-shell and off-shell regions yields a determination of Γ

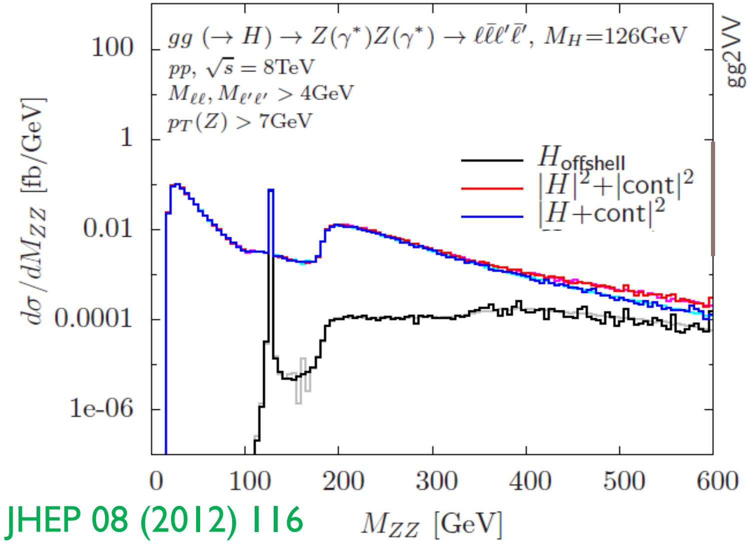
Interference



- Since both Higgs and non-resonant VV production may start from gg initial states, the two processes interfere
- The same is true for VBF production



- Effect of interference is very small for m_{VV} ~ 125 GeV, important for large m_{VV}
  - Affects off-shell measurements
- Background and interference calculations only available at LO QCD
- VH and ttH off-shell effects are suppressed by rapid fall of inclusive cross-section vs. H mass
  - Do not contribute at high m_{VV}

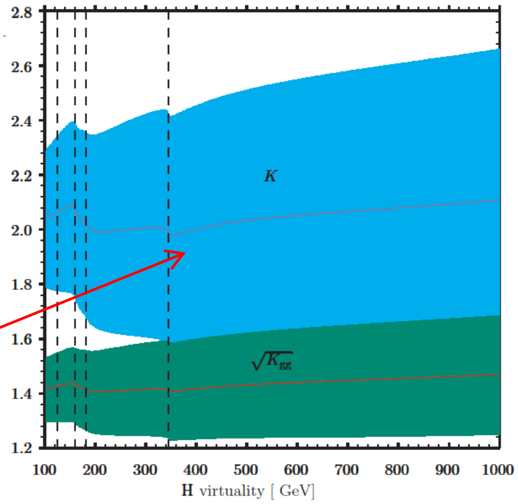


N. Kauer and G. Passarino, JHEP 08 (2012) 116

Monte Carlo simulation

gluon-gluon fusion

- Using MC event generators gg2VV and MCFM (LO in QCD)
  - Including Higgs signal, continuum and interference
  - Signal m_{VV} -dependent k-factors (NNLO/LO) applied G. Passarino (Eur. Phys. J. C 74 (2014) 2866)
  - Using results from M. Bonvini et al. (Phys. Rev. D88 (2013) 034032), assume $k_{continuum} = k_{signal}$ as central value



$q\bar{q} \rightarrow$ ZZ / WZ / WW dominant backgrounds

- Use POWHEG at NLO QCD
  - NLO EW corrections from external calculations (S. Gieseke et al, Eur. Phys. J. C 74 (2014) 2988) applied as a function of m_{VV}
  - ATLAS also applies corrections for NNLO QCD effects (Phys. Lett. B 735 (2014) 311, Phys. Rev. Lett. 113 (2014) 212001)

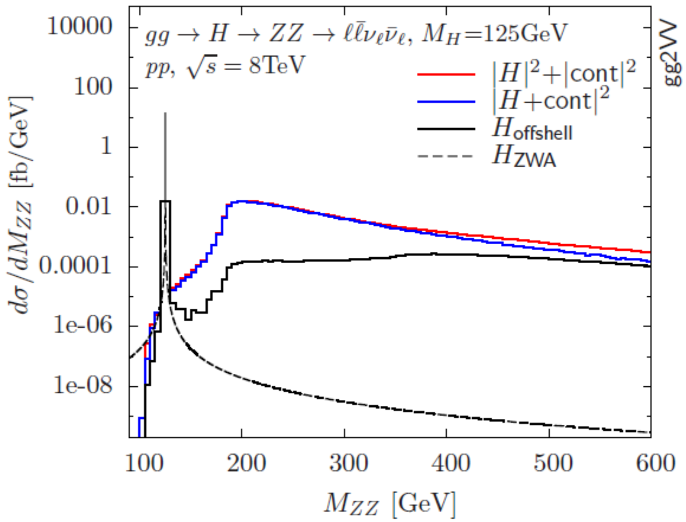
VBF production

- Using PHANTOM and MadGraph
  - VBF production is 7% of the total at peak, slightly enhanced at high mass by trend of $\sigma_{VBF}(m_{ZZ})$ ~ 10%
  - Higher order effects very small (~6%)

CMS collab., Phys. Lett. B 736 (2014) 64
ATLAS collab., arXiv:1503.01060

Experimental analysis

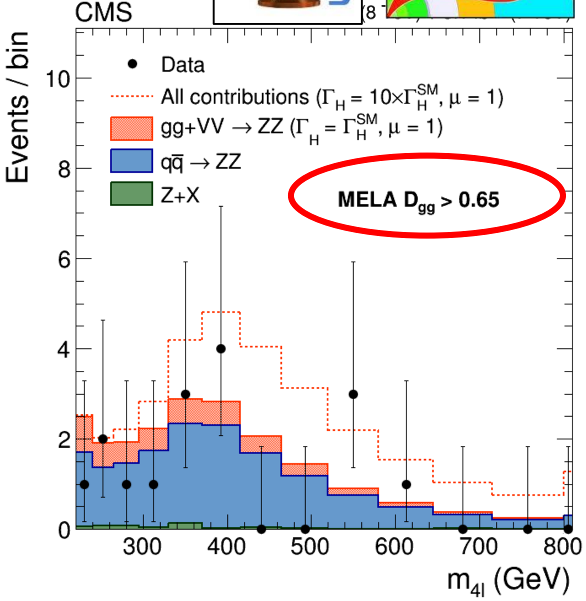
- ZZ → 4l final state (l = e, μ)
  - At high mass, basically only background is $q\bar{q}$ → ZZ
  - Fully reconstructed state → can use matrix element probabilities of lepton 4-vectors to distinguish between signal and background
- ZZ → 2l2ν final state (l = e, μ)
  - Much larger BR (x6) but smaller acceptance
    - tight p_T selection → no access to on shell-region
  - Rely on transverse mass distributions

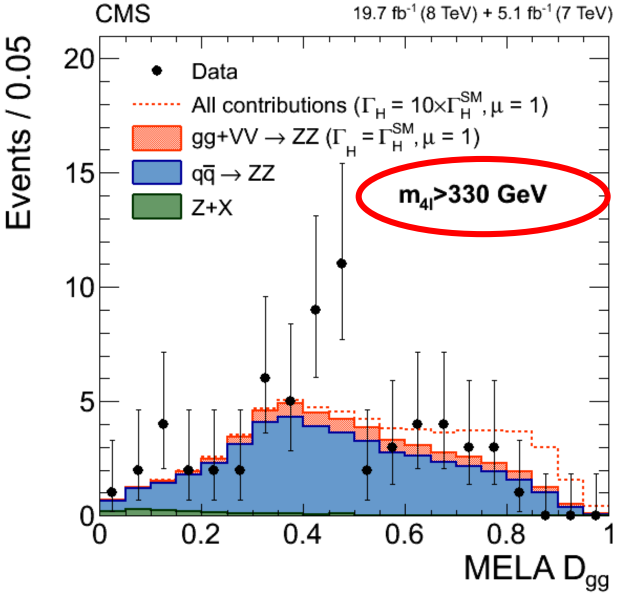


- WW → eμ2ν final state
  - Signal yields similar to ZZ, but important non-VV backgrounds ($t\bar{t}$)
  - Not trivial to achieve a full separation of on-/off-shell regions

Analysis of ZZ → 4l

- Event selections:
  - Two pairs of leptons (electrons or muons), isolated and prompt, of opposite sign and same flavor
  - Requirements on lepton p_T and di-lepton masses
  - Off-shell analysis region: $m_{4l} > 220$ GeV
- Kinematic discriminants:
  - Use 7 variables completely describing decay kinematics (m_{Z1}, m_{Z2}, five lepton angles)
  - Build joint probabilities for various contributing processes ($gg \to 4l$ signal, $gg \to 4l$ total, $q\bar{q} \to 4l$ etc.) from MCFM matrix elements





ATLAS

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

CMS

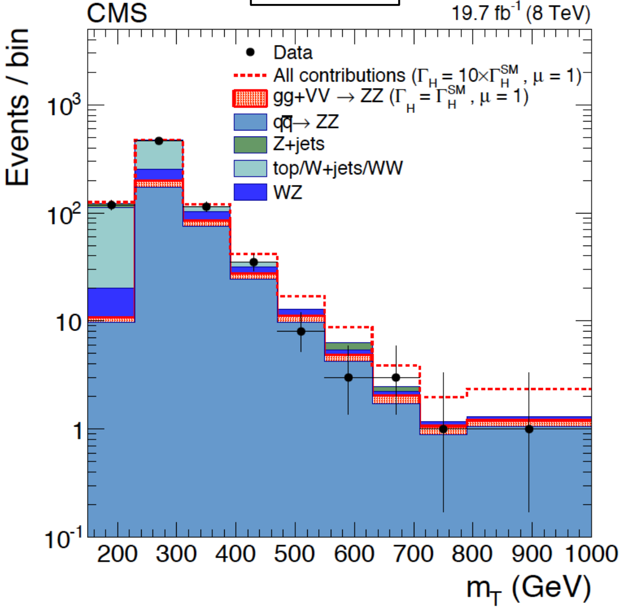
$$\mathcal{D}_{gg} = \frac{\mathcal{P}^{gg}_{\mathrm{tot}}}{\mathcal{P}^{gg}_{\mathrm{tot}} + \mathcal{P}^{q\bar{q}}_{\mathrm{bkg}}}$$

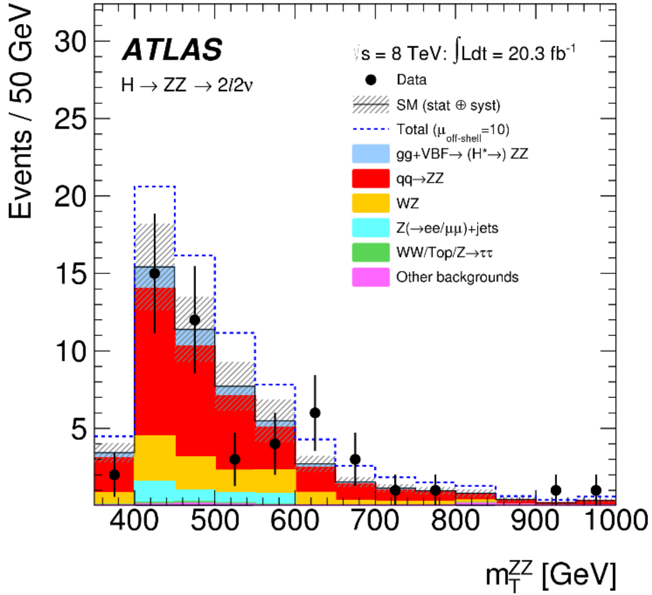
Analysis of ZZ → $2l2\nu$

- Event selections:
  - Two electrons or muons in on-shell Z region
  - Requirements on large $E_{T\text{miss}}$ and large $\Delta\phi$ between missing momentum and leptons/jets
  - Apply 3rd lepton and b-jet vetoes
  - Analysis variable is the transverse mass

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

- Background estimation:
  - True ZZ and WZ: from MC
  - $t\bar{t}$: use lepton flavor symmetry: compute the ee/eμ and μμ/eμ ratios in control regions, and apply the ratios to eμ events in signal region
  - Z+jets:
    - ATLAS: inverting cuts
    - CMS: Use γ+jets with modified kinematics



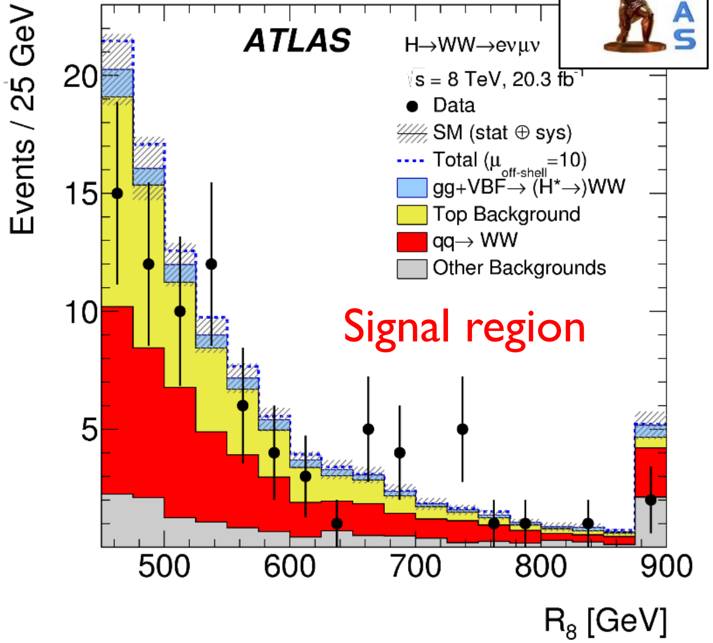


Analysis of WW → eμ2ν

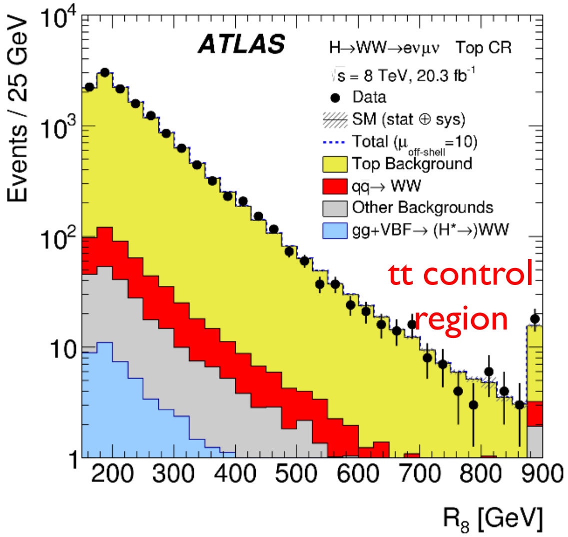
- Event selections:
  - Two leptons of different flavors (removing dominant Z+jets background)
  - Mild requirements on lepton p_T and E_{Tmiss}, require $\Delta\eta_{e\mu} > 1.2$, apply b-jet veto
  - Analysis variable is a combination of dilepton mass and transverse mass

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

  - $a = 0.8$ and $R_8 > 450$ GeV optimized to separate off-shell from on-shell contributions
- Background estimation:
  - Main background contributions from $t\bar{t}$ and $q\bar{q} \to WW$: normalization from data using suitable control regions



Signal region



tt control region

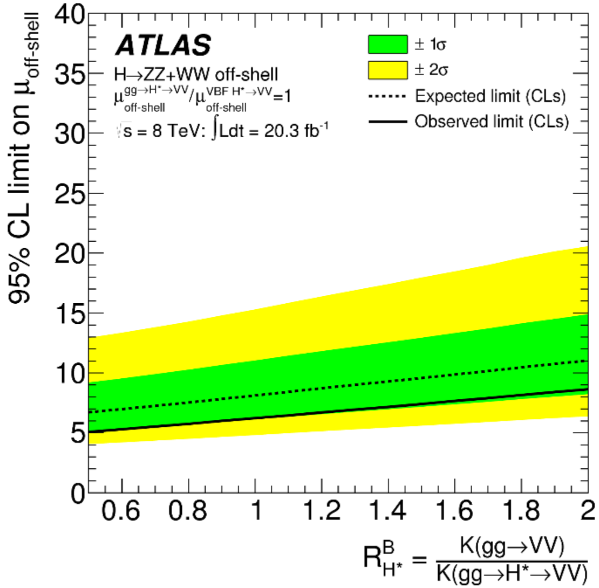
Analysis procedure

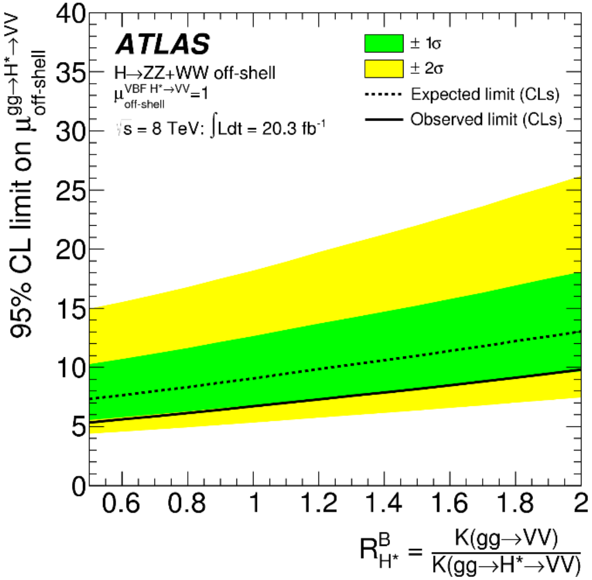
- For a given production mode (ggF or VBF):
  - Off-shell production; $\mathcal{P}_{\text{tot}} = \mu_{\text{off}} \mathcal{P}_{\text{sig}} + \sqrt{\mu_{\text{off}}} \mathcal{P}_{\text{int}} + \mathcal{P}_{\text{bkg}}$
  - $\mathcal{P}$ are MC- or data-derived templates for variables in each analysis
  - Sum of all terms (also including other backgrounds) gives final likelihood
- Analysis variables:
  - ZZ → 4l: mass and ME discriminant (CMS) or ME discriminant only (ATLAS)
  - ZZ → 2l2ν: transverse mass
  - WW → eμ2ν: only event count in R_8 off-shell region (ATLAS only)
  - All analysis yields evaluated inclusively in N_{jets} because most higher-order corrections from theory are only available in this form
- When combining with on-shell region, define $\mu_{\text{off}} = \mu r = \mu\ (\Gamma/\Gamma_{\text{SM}})$ and fit simultaneously with:
  - On shell-production: $\mathcal{P}_{\text{tot}} = \mu \mathcal{P}_{\text{sig}} + \mathcal{P}_{\text{bkg}}$

Systematic uncertainties

- Theoretical uncertainties (dominant)
  - gg and $q\bar{q} \rightarrow VV$ processes:
    - QCD scale variations by a factor of 2 up and down
    - Variation of Parton Distribution Functions (PDFs)
  - Unknown NNLO k-factor on continuum $gg \rightarrow VV$ background:
    - CMS: use 10% additional uncertainty on nominal hypothesis ($k_{continuum} = k_{signal}$)
    - ATLAS: give all results in a range of $k_{continuum} / k_{signal}$ between 0.5 and 2
  - Uncertainties on NLO EW correction as 100% of the NLO QCD x NLO EW corrections
- Experimental uncertainties (subdominant)
  - Lepton efficiencies
  - Jet energy scale effects on E_T^{miss} and b-tagging efficiency
  - Background estimations from data control regions … etc.

Limits on μ_{off} ($4l$, $2l2\nu$, WW)





- In the generic NP scenario, the off-shell signal strengths are not directly related to Γ
- Combined limits on μ_{off} derived under two assumptions:
  - μ_{off} for ggF and VBF are the same (i.e. couplings for the two processes scale by the same amount)
    - Observed (expected) 95% CL limit: $\mu_{\text{off}} < 6.2$ (8.1)
    - Variations with gg → VV k-factor: $\mu_{\text{off}} <$ [5.1, 8.6]
  - μ_{off} for VBF is 1 (NP only in gluon-Higgs effective couplings) and determine $\mu_{\text{off, gg}}$
    - Observed (expected) 95% CL limit: $\mu_{\text{off, gg}} < 6.7$ (9.1)
    - Variations with gg → VV k-factor: $\mu_{\text{off,gg}} <$ [5.3, 9.8]

Limits on Γ

Assuming same on-shell and off-shell couplings

Observed (expected) 95% CL limit: $r < 5.5\ (8.0)$

Variations with gg → VV k-factor: $r < [4.5, 7.5]$

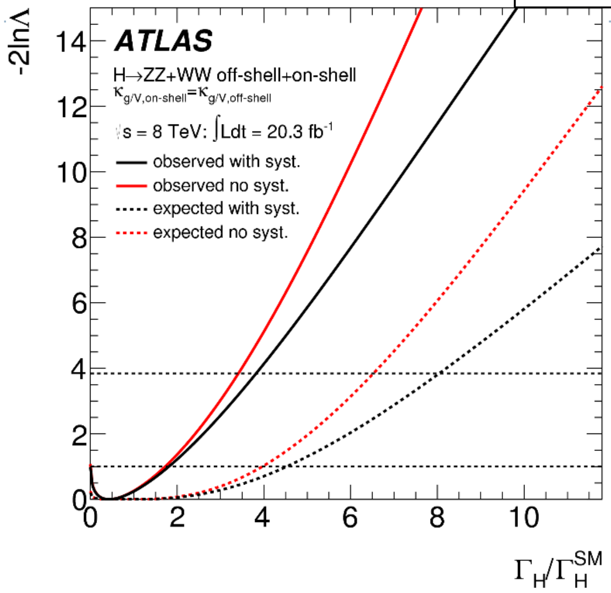
equivalent to

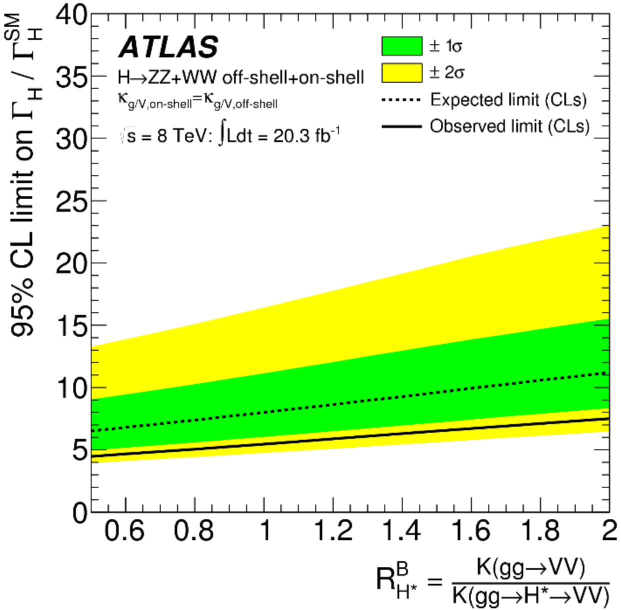
$$\boxed{\begin{array}{c} \Gamma < 23\ (33)\ \text{MeV} \\ \Gamma < [18, 31]\ \text{MeV} \end{array}}$$

μ_{ggF} and μ_{VBF} profiled on data

If assumption on couplings only valid for VBF and

$r = 1$ $R_{gg} = \kappa_{g,\ \text{off-shell}} / \kappa_{g,\ \text{on-shell}} \leq 6.0$





Limits on Γ

Observed (expected) 95% CL limit:

$r < 5.4\ (8.0)$

p-value = 0.25

Best fit value:

$r = 0.4^{+1.8}_{-0.4}$

equivalent to

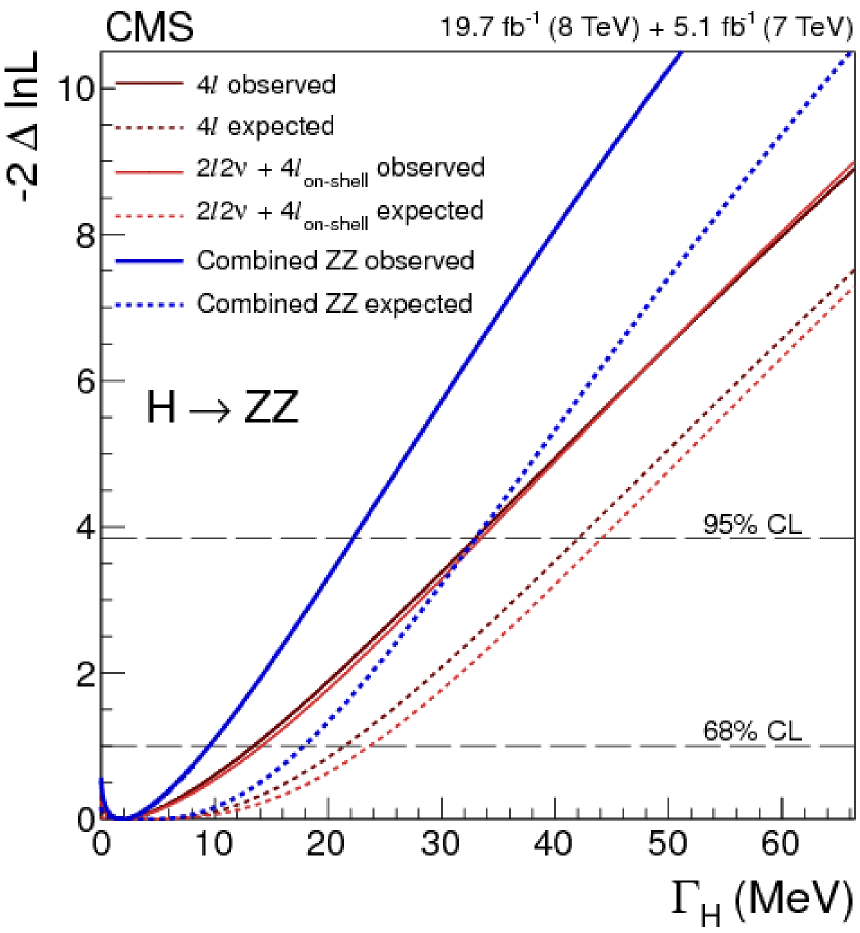
$\Gamma < 22\ (33)$ MeV

$\Gamma = 1.8^{+7.7}_{-1.8}$ MeV

$\mu_{ggF} = 0.81^{+0.47}_{-0.37}$

$\mu_{VBF} = 1.7^{+2.2}_{-1.7}$

both compatible with SM ($\mu = 1$)

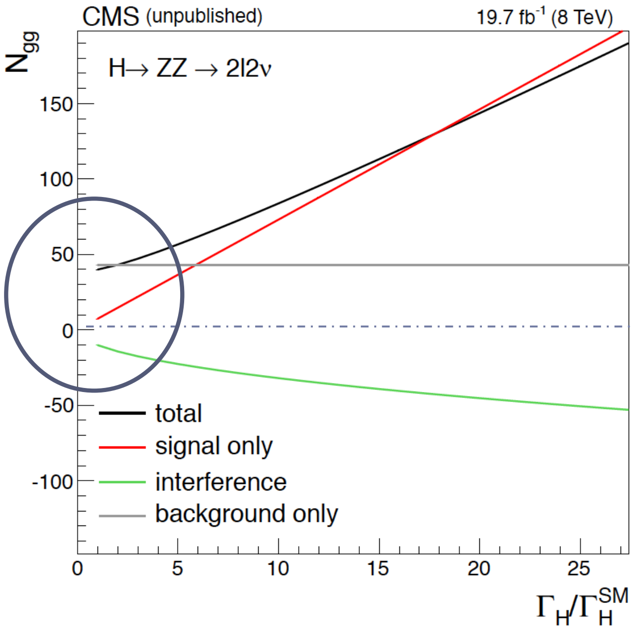


Perspectives for Run2 (I)

- σ(13 TeV)/σ(8TeV) from theory:
  - gg $\longrightarrow$ VV signal (S) ~ 3 at LO (~ 2.2 at NNLO)
  - gg $\longrightarrow$ VV continuum (C) ~ 2.5
  - gg $\longrightarrow$ VV S+C+interference ~ 2.7
  - qq $\longrightarrow$ VV background ~ 2

Significant increase of yield per fb^{-1} in Run2

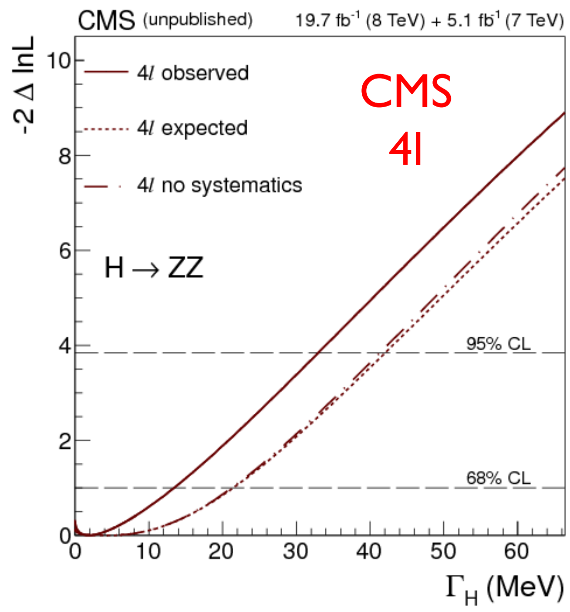
- Caveat:
  - When coming close to r = 1 interference plays a role → effective number of off-shell signal events S+I (at constant μ) does not scale anymore with r

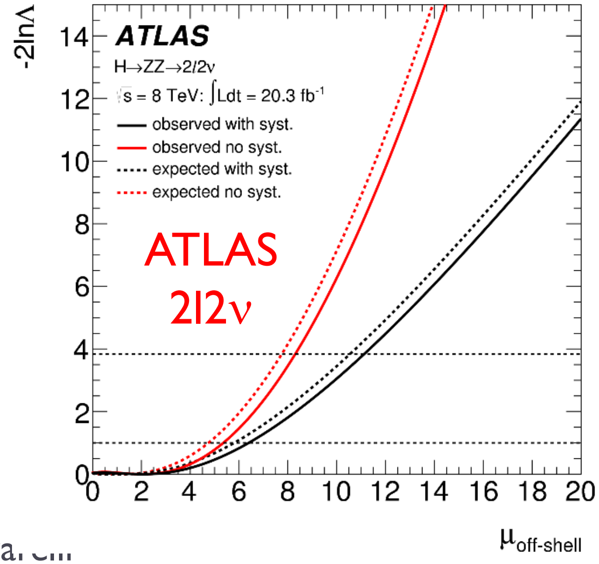


Perspectives for Run2 (II)

- Role of systematics is important
  - Calculations of $gg \rightarrow VV$ and $q\bar{q} \rightarrow VV$ processes at higher orders (both QCD and EW) would reduce dominant systematic uncertainties
  - Experimental uncertainties do not contribute equally in all final states
    - For 4l they are currently negligible w.r.t. statistical ones
    - For Γ their contribution is even smaller than for μ_{off}, as many of them cancel in the off-shell to on-shell ratio

Stay tuned for upcoming ATLAS and CMS Run2 results!





Back up