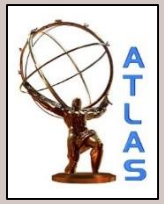
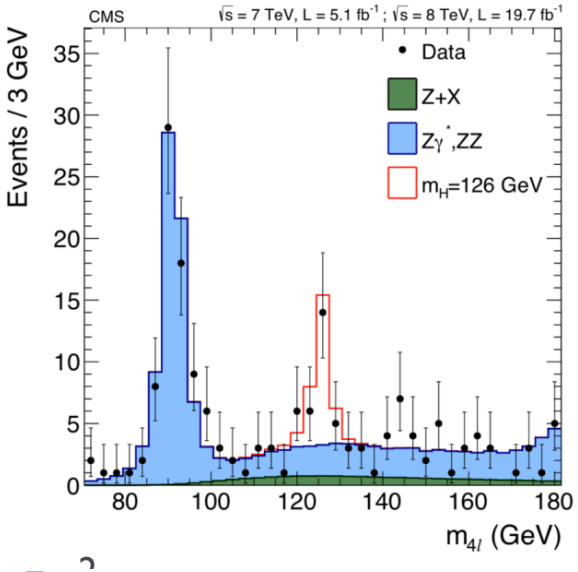


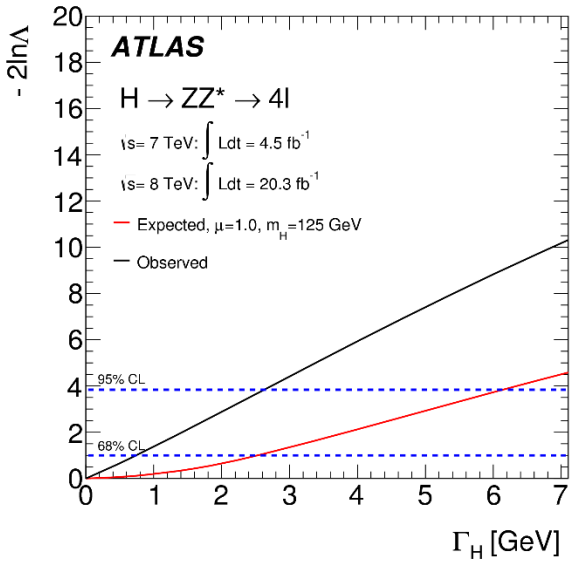

Perspective on width measurements

Roberto Covarelli (*University / INFN of Torino*)

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 $\Gamma << \sigma$, 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 $H \rightarrow ZZ^* \rightarrow 4l$ and $\gamma\gamma$





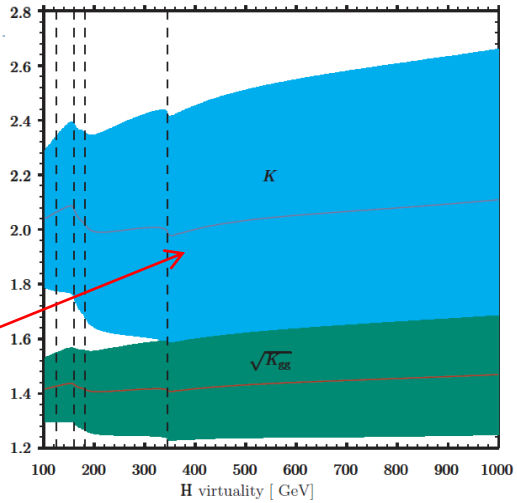
$\Gamma_H < 3.4$ GeV @ 95% CL (CMS)
$\Gamma_H < 2.6$ GeV @ 95% CL (ATLAS)
Similar results from $\gamma\gamma$
WILL NOT IMPROVE MUCH IN Run2

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

Off-shell: MC 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
  - ATLAS uses Sherpa+OpenLoops to correct acceptance as a function of $p_T(VV)$



$q\bar{q} \rightarrow ZZ$ / 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 $\sigma_{VBF}(m_{ZZ}) \sim 10\%$
  - Higher order effects very small (~6%)

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

Analysis of ZZ → 4l

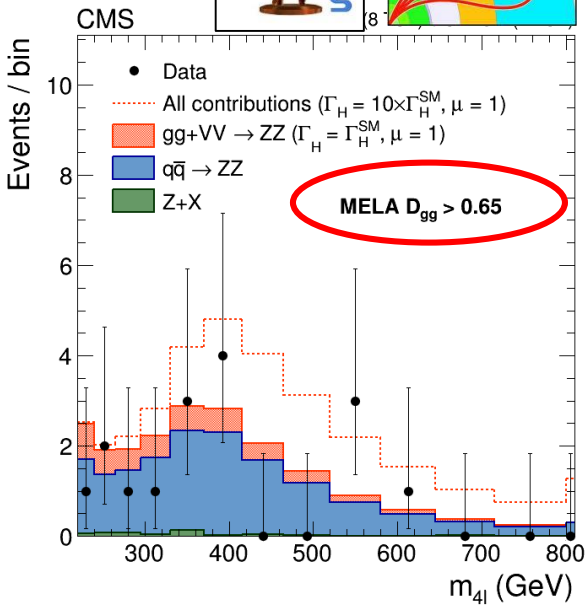
- Event selection:
  - As in main Higgs analysis
  - Off-shell analysis region: $m_{4l} > 220$ GeV
- Kinematic discriminants:
  - Use 7 variables completely describing decay kinematics (m_{Z1}, m_{Z2}, five lepton angles)
  - Build joint probabilities for various contributing processes ($gg \to 4l$ signal, $gg \to 4l$ total, $q\bar{q} \to 4l$ etc.) from MCFM matrix elements

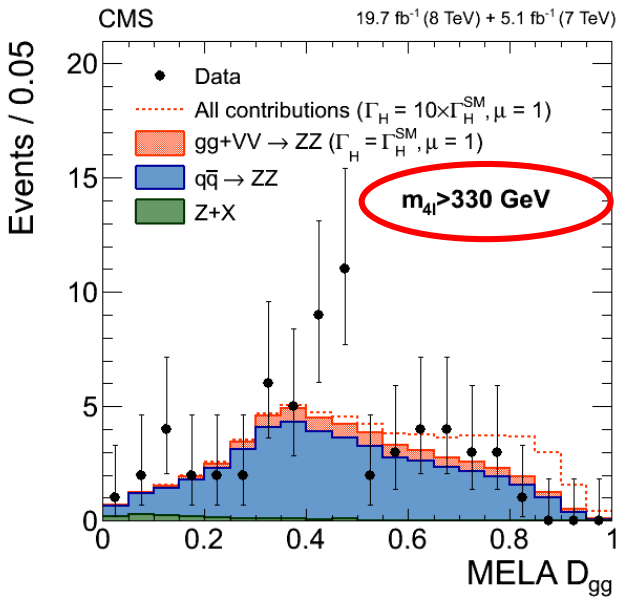
ATLAS

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

CMS

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



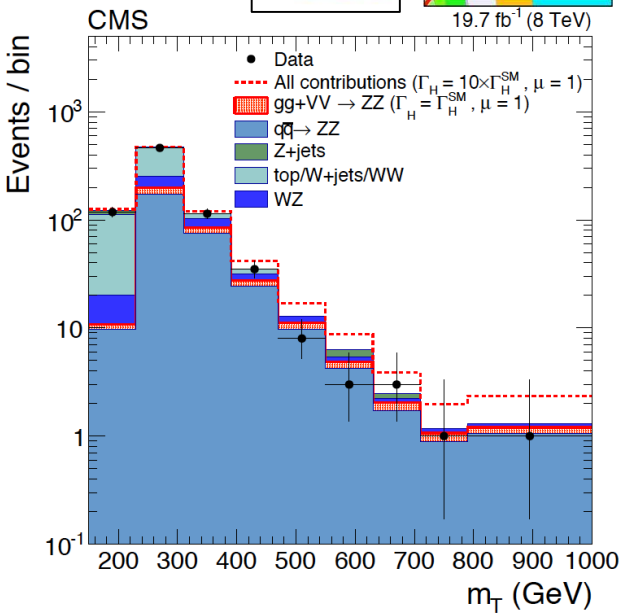


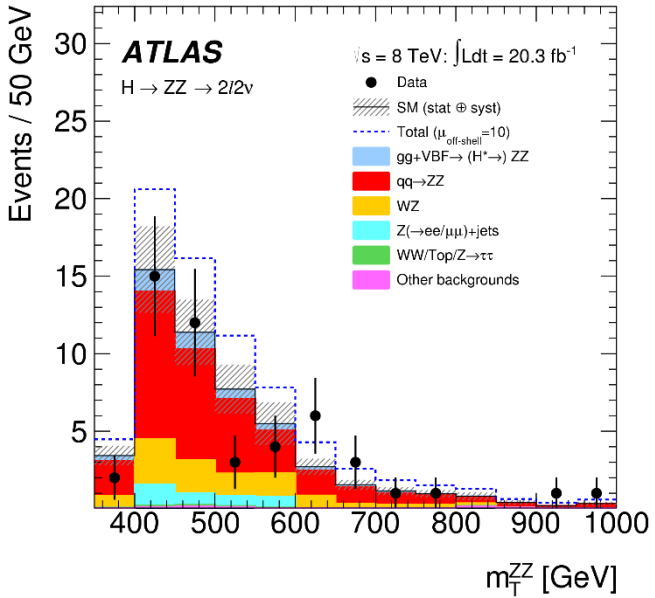
Analysis of ZZ → 2l2ν

- Event selections:
  - As in main Higgs analysis
  - 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
  - tt: 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





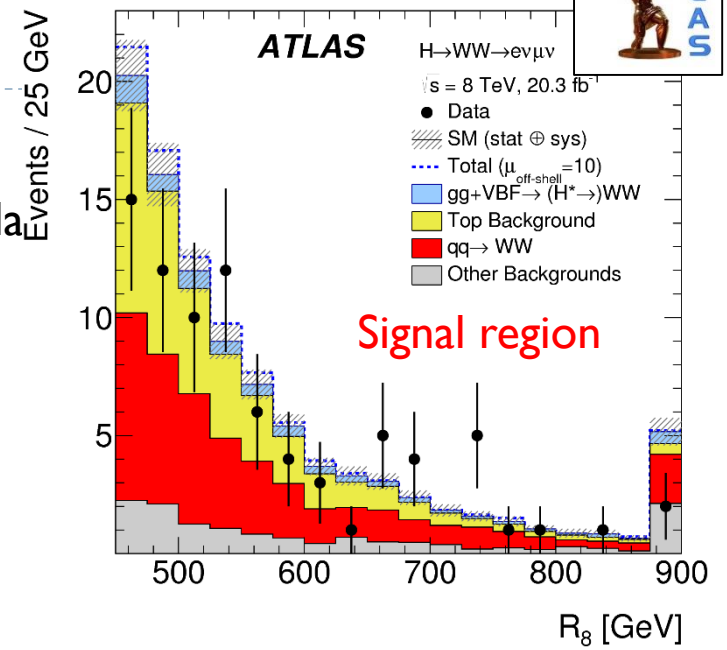
Analysis of WW → eμ2ν

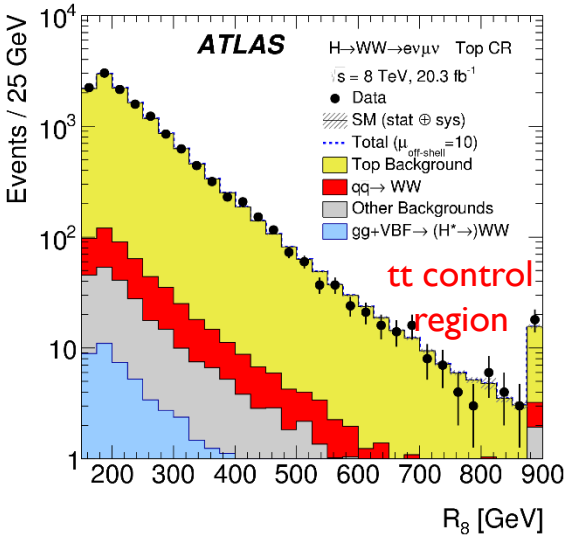
- Event selections:
  - Two leptons of different flavors only, rest is similar to main Higgs analysis
  - Analysis variable is a combination of dilepton mass and transverse mass

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

  - 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 $q\bar{q} \rightarrow WW$: normalization from data using suitable control regions





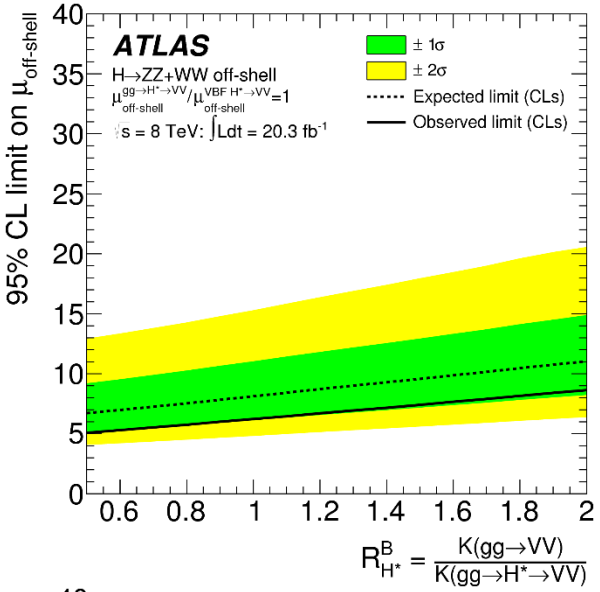
Analysis procedure

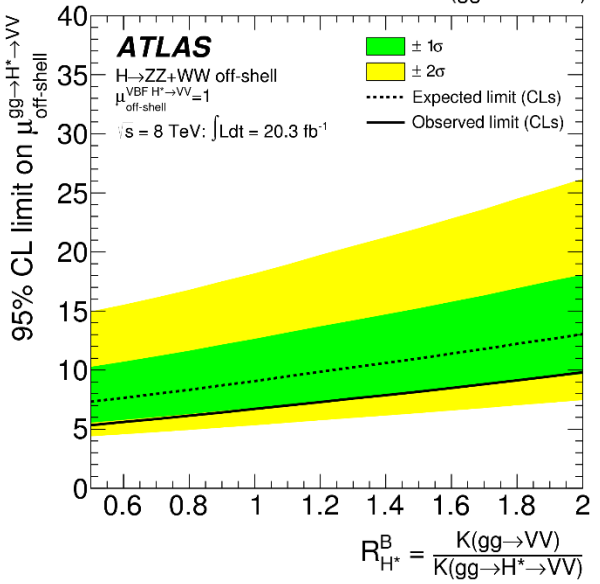
- For a given production mode (ggF or VBF):
  - Off-shell production; $\mathcal{P}_{\text{tot}} = \mu_{\text{off}} \mathcal{P}_{\text{sig}} + \sqrt{\mu_{\text{off}}} \mathcal{P}_{\text{int}} + \mathcal{P}_{\text{bkg}}$
  - $\mathcal{P}$ are MC- or data-derived templates for variables in each analysis
  - Sum of all terms (also including other backgrounds) gives final likelihood
- Analysis variables:
  - $ZZ \rightarrow 4l$: mass and ME discriminant (CMS) or ME discriminant only (ATLAS)
  - $ZZ \rightarrow 2l2\nu$: transverse mass
  - $WW \rightarrow e\mu 2\nu$: 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 $\mu_{off} = \mu r = \mu\,(\Gamma/\Gamma_{SM})$ and fit simultaneously with:
  - On shell-production (4l and WW only!): $\mathcal{P}_{\text{tot}} = \mu\,\mathcal{P}_{\text{sig}} + \mathcal{P}_{\text{bkg}}$

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, 2l2ν, 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: $\mu_{off} < 6.2\ (8.1)$
    - Variations with gg → VV k-factor: $\mu_{off} < [5.1, 8.6]$
  - μ_{off} for VBF is 1 (NP only in gluon-Higgs effective couplings) and determine $\mu_{off,\,gg}$
    - Observed (expected) 95% CL limit: $\mu_{off,\,gg} < 6.7\ (9.1)$
    - Variations with gg → VV k-factor: $\mu_{off,gg} < [5.3, 9.8]$

Limits on Γ

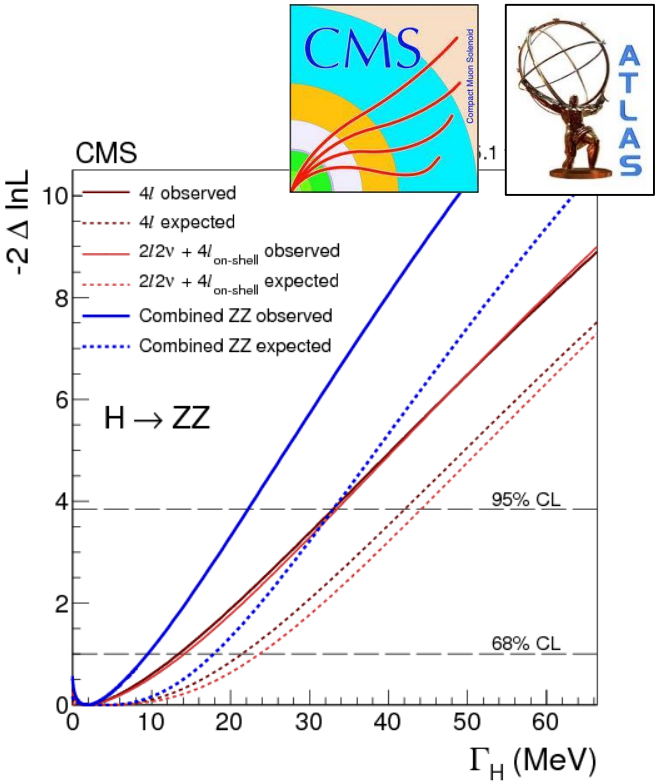
Assuming same on-shell and off-shell couplings

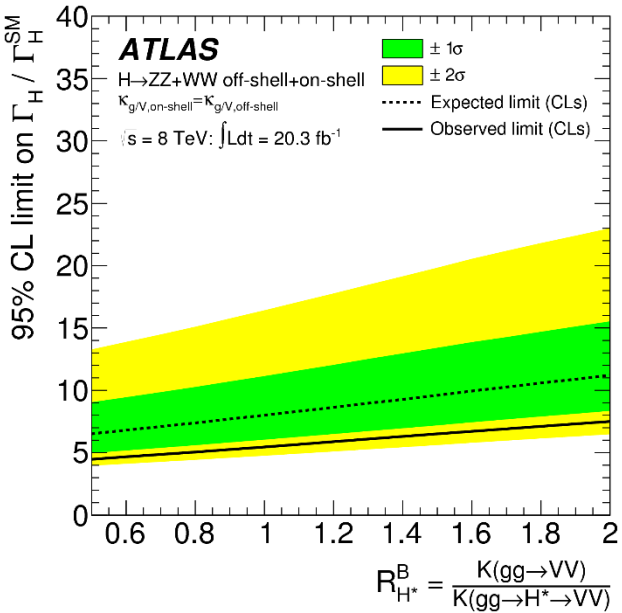
CMS: Observed (expected) 95% CL limit:
r < 5.4 (8.0) p-value = 0.25

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 ($\mu = 1$)

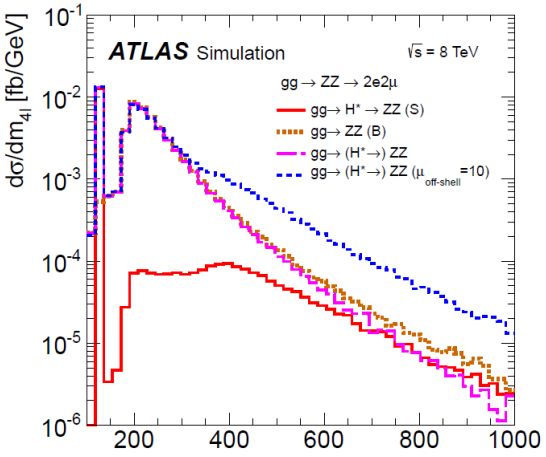
ATLAS: Almost identical central results
If assumption on couplings only valid for VBF and
r = 1 $R_{gg} = \kappa_{g,\text{off-shell}} / \kappa_{g,\text{on-shell}} < 6.0$

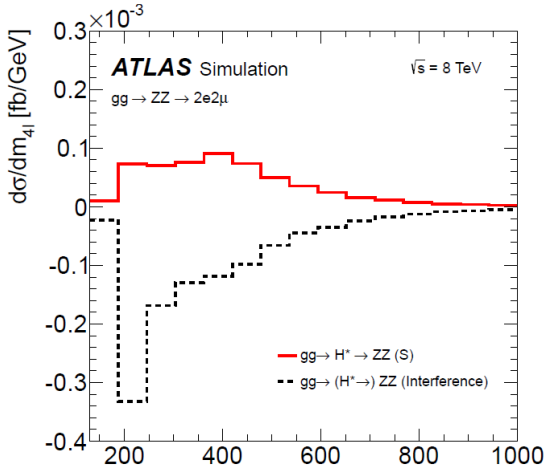


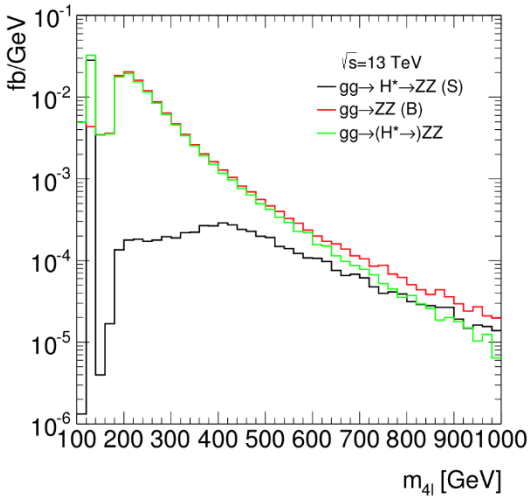


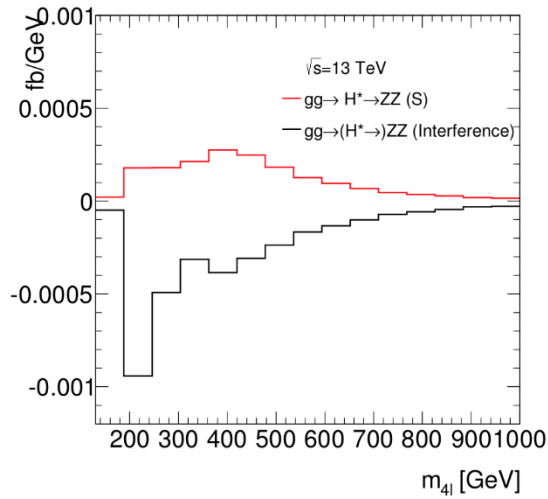
Perspectives for Run2 (I)

- σ(13 TeV)/σ(8TeV):
  - $q\bar{q} \rightarrow VV$ background ~ 2 (no cuts!)

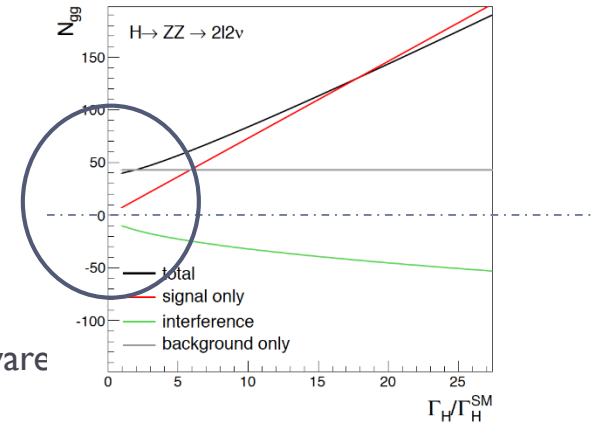








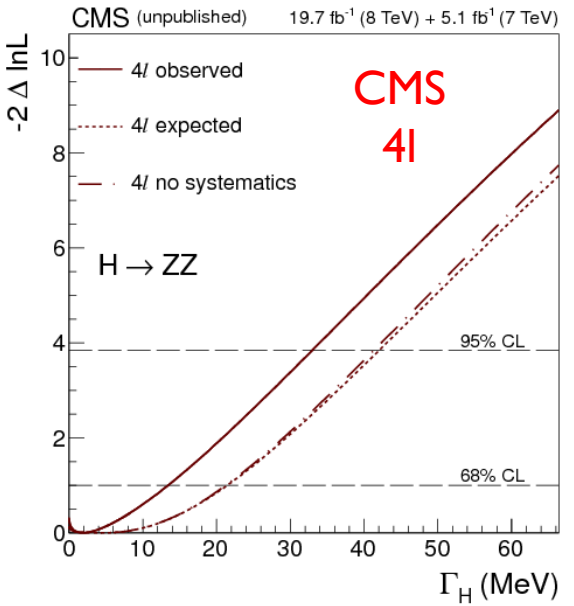
- Caveat:
  - When coming close to r = 1 interference plays a role → effective number of off-shell signal events S+I (at constant μ) does not scale anymore with r

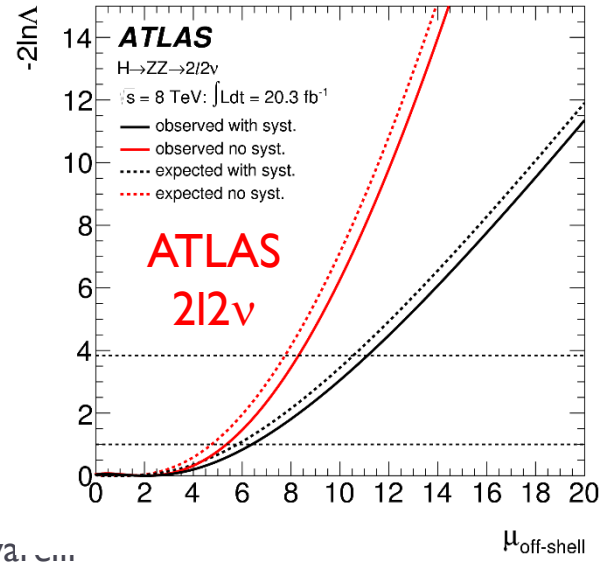


R. Covare

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
  - In partilcular calculation as a function of N_{jets} are needed to optimize analysis
  - 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





Back up