Offshell couplings and Higgs width in ATLAS and CMS

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Workshop on the physics of HL-LHC, and perspectives at HE-LHC

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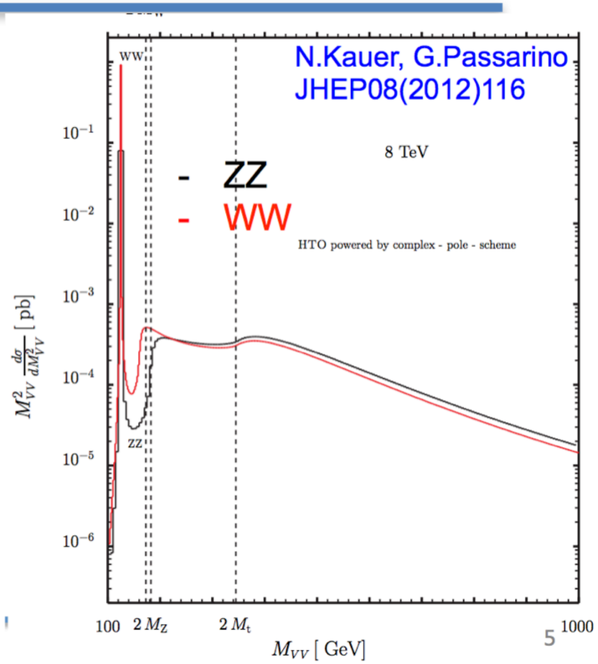
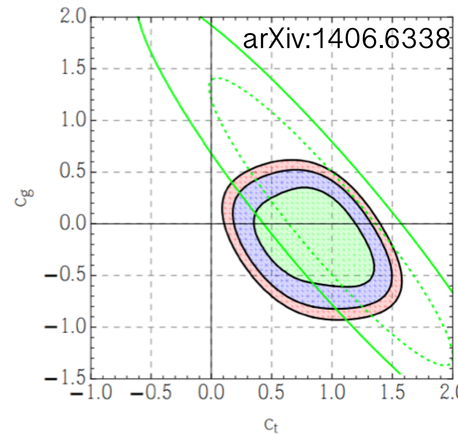
Why study the Higgs boson off-shell production?

- High mass region of H->VV above the 2m_V threshold sensitive to the Higgs boson production through off-shell and background interference effects
  - characterize the properties of the Higgs boson through off-shell signal strength and off-shell Higgs boson couplings
  - Sensitivity to new physics that change interaction between the Higgs and SM particles in this region
- Unique way to probe New Physics in the Higgs domain at large momenta



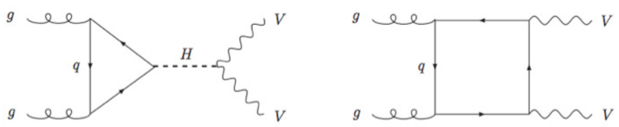


Why the width? ($\Gamma_{H,SM}$=4.2 MeV)

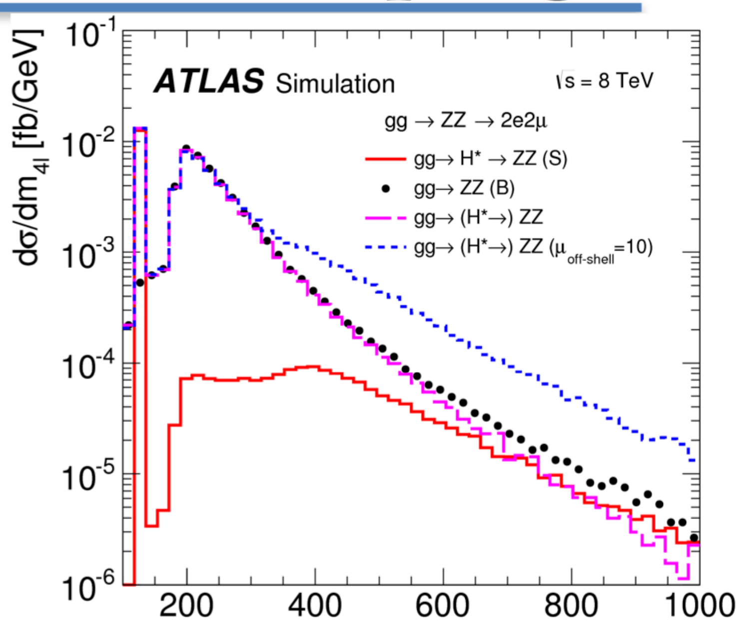
- @ LHC only σ*BR can be measured
  - Γ_H cannot be estimated from the Higgs boson rates
- Direct and indirect approaches to constrain the Higgs width are nevertheless available
  - Worth investigating the HL-LHC (and experiment upgrades) potential to exploit all of them!

Offshell couplings

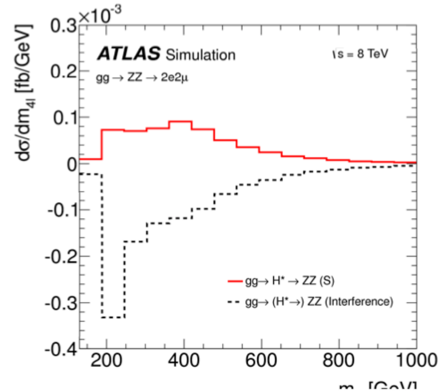
- Off-shell to on-shell cross section ratio ~ 8% in the SM
- In the high mass region off-shell Higgs production and non resonant gg→VV background (box diagram)

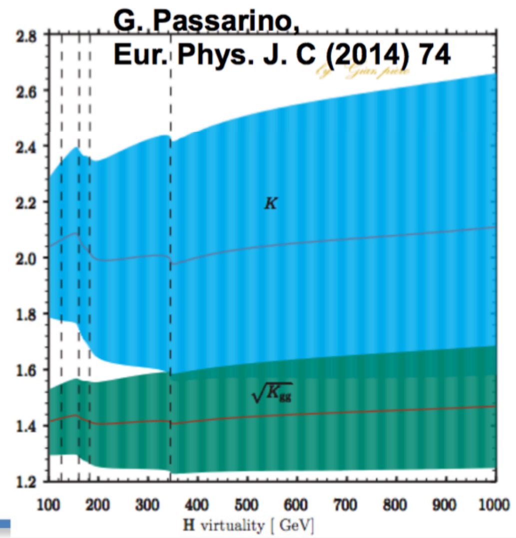


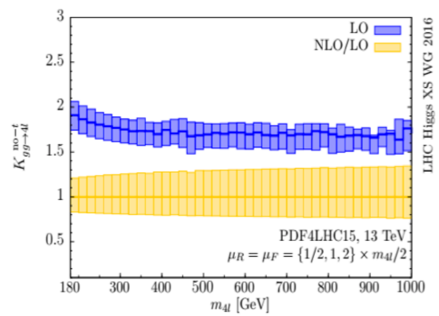
- Interference sizable and negative in SM
- Similar for qq→VV+2j and VBF production
- Possible to obtain a sample with an arbitrary value of $\mu_{offshell}$ combining the SM expectations for gg→(H*) →ZZ gg→H*→ZZ and gg→ZZ



$$MC_{gg\to(H^*\to)ZZ}(\mu_{\text{off-shell}}) = \left(K^{H^*}(m_{ZZ})\cdot\mu_{\text{off-shell}} - K^{H^*}_{gg}(m_{ZZ})\cdot\sqrt{R^{B}_{H^*}\cdot\mu_{\text{off-shell}}}\right)\cdot MC^{SM}_{gg\to H^*\to ZZ} + K^{H^*}_{gg}(m_{ZZ})\cdot\sqrt{R^{B}_{H^*}\cdot\mu_{\text{off-shell}}}\cdot MC^{SM}_{gg\to(H^*\to)ZZ} + K^{H^*}_{gg}(m_{ZZ})\cdot\left(R^{B}_{H^*} - \sqrt{R^{B}_{H^*}\cdot\mu_{\text{off-shell}}}\right)\cdot MC^{cont}_{gg\to ZZ},$$



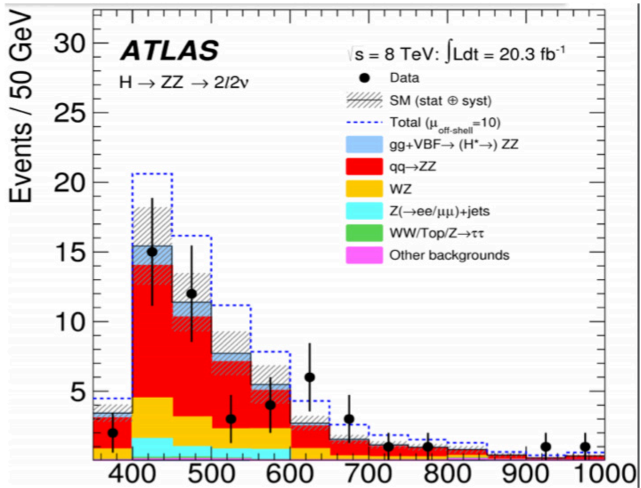




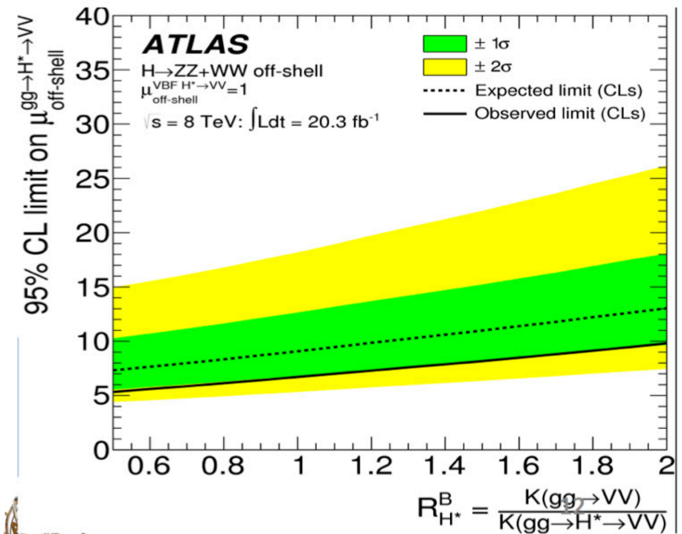
- LO (gg2VV/MCFM) generator used for run1 results
- Large k-factors (when known) at NNLO

Offshell couplings

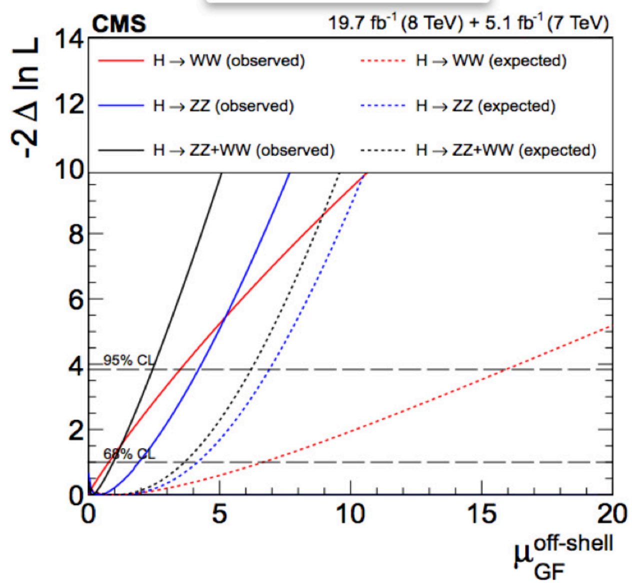
- Run1 results: combination of **WW→lνlν** and **ZZ→4l/llνν**
  - Similar sensitivity for 4l and llνν
  - Matrix Element discriminant exploited in the 4l, m_T used for llνν/lνlν
  - Channels with MET might be more challenging in HL environment
- qq→ZZ dominant bkg for driving channels
  - High precision needed for its prediction
- Systematics dominated by the theoretical uncertainties
  - QCD scales and PDF for qq→ZZ and gg→(H)→ZZ
  - experimental uncertainty subdominant
- Limits also on anomalous off-shell coupling



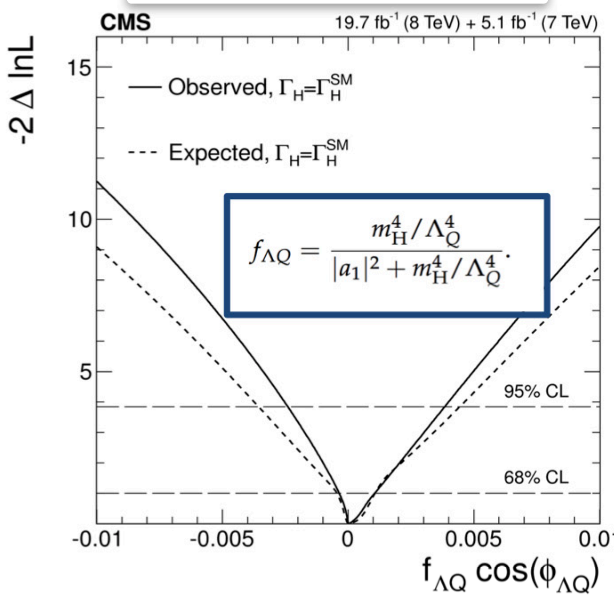
Eur.Phys.J.C (2015) 75:335



JHEP 09 (2016) 051



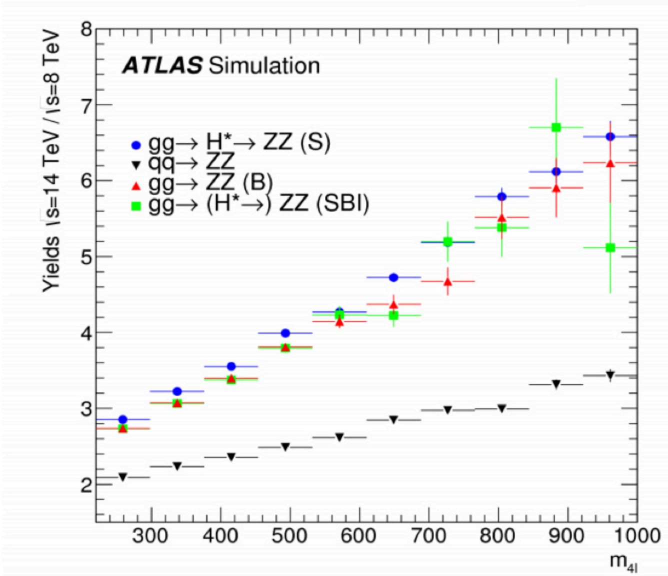
Phys. Rev. D 92 (2015) 072010



$$f_{\Lambda Q} = \frac{m_H^4/\Lambda_Q^4}{|a_1|^2 + m_H^4/\Lambda_Q^4}.$$

Offshell couplings – HL-LHC projection

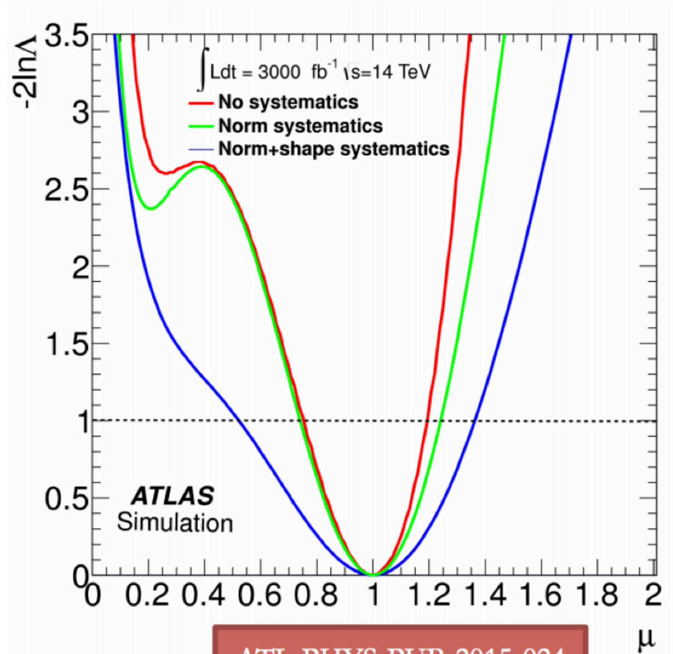
- With the increase in statistics, it will be crucial to have the most accurate possible theoretical predictions
  - To reduce the dominant theoretical uncertainties on cross sections and shapes of the different components
  - Essential to move from LO to NLO MC development for gg→(H*)→VV and gg→VV processes (for less "QCDinclusive" analysis)
    - gg→VV exact NLO available <2m_t, above approximate



- Equally important is to improve precision of MC generators (and predictions) for the main qq->VV background
  - pp->WW/ZZ at NNLO cross sections and NNLO MC development (+EW corrections)

- At HL-LHC $\mu_{offshell}$ measurement sensitivity @ 20% without theoretical systematic uncertainties (ATLAS)

- HE-LHC will increase even more the relative contribution of the gg compared to qq at high m4l

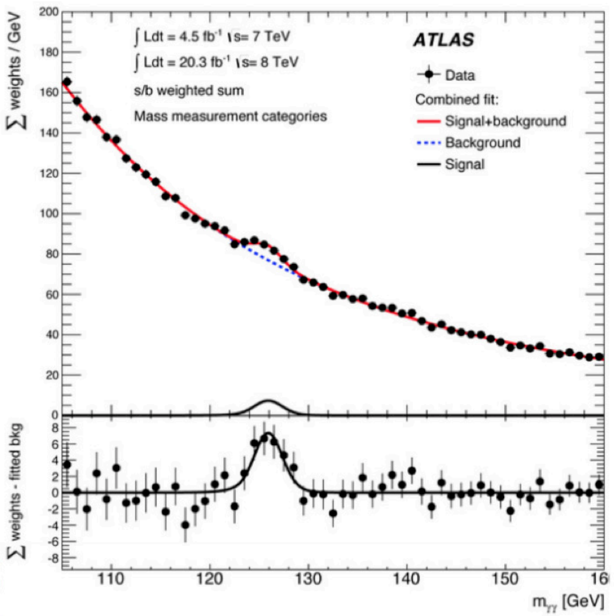


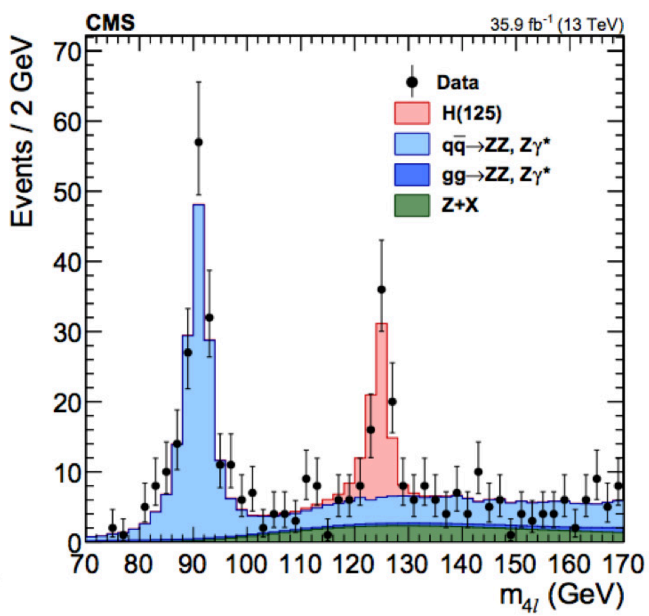
ATL-PHYS-PUB-2015-024

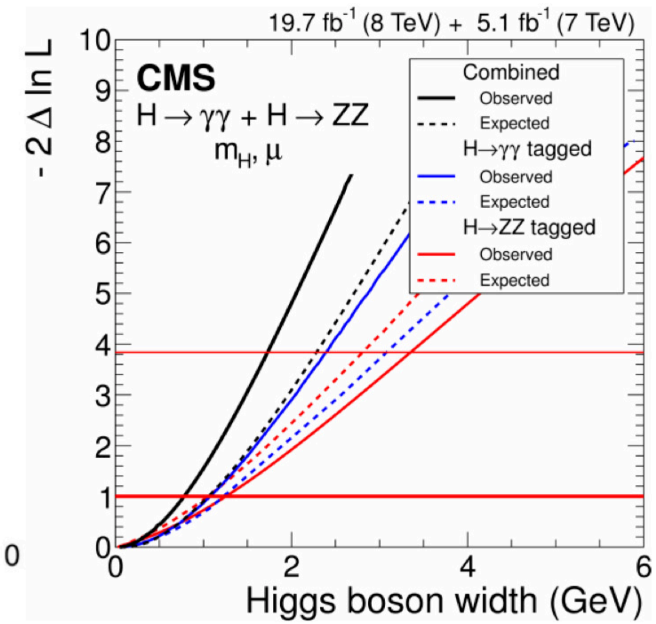
Higgs boson width: direct constraint

- Direct measurement using m_{4l} and $m_{\gamma\gamma}$ spectra
  - Very few assumptions, lower precision, limited by experimental resolution (~1-2%)
- Exploited using Run1 and Run2 data to obtain upper limit on Γ_H
  - **CMS**:
    - upper limit on Γ_H combining H->ZZ->4l and H->γγ : **Γ_H< 1.7 GeV** at 95% CL (exp. 2.3 GeV)
    - Run2 (35.9/fb) using 4l : **Γ_H< 1.1 GeV** at 95% CL (exp. 1.6 GeV)
  - **ATLAS**
    - Run1 H->ZZ->4l : **Γ_H< 2.6 GeV** at 95% CL (exp. 3.5 GeV for $\mu=\hat{\mu}$), similar limits using H->γγ
- **>250** times larger wrt SM prediction
  - At HL-LHC a limiting factor will be the uncertainties on the resolution
  - Some caveats for γγ due to interference with the bkg

arXiv:1706.09936v1
EPJ C 75 (2015) 212
Phys. Rev. D 90(2014) 052004







Lower bound on Γ_H

- Possible to set a direct lower bound on the Higgs width using its **lifetime**
- In the SM the $\tau_H c \sim 4.8\ 10^{-8}\ \mu m$ (far from experimental sensitivity)

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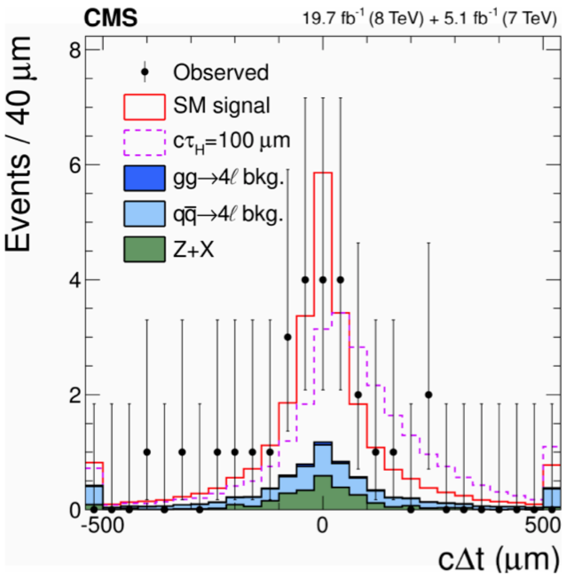
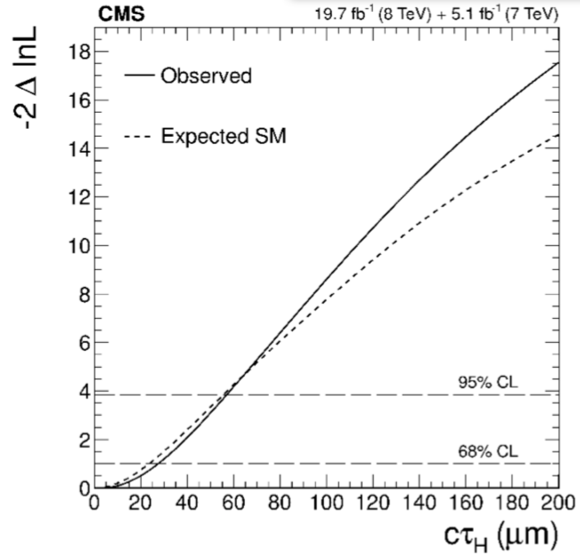
- $H \to ZZ \to 4l$ suitable channel to extract the lifetime from the flight distance
  - Displacement between production (PV) and decay (4l) vertex

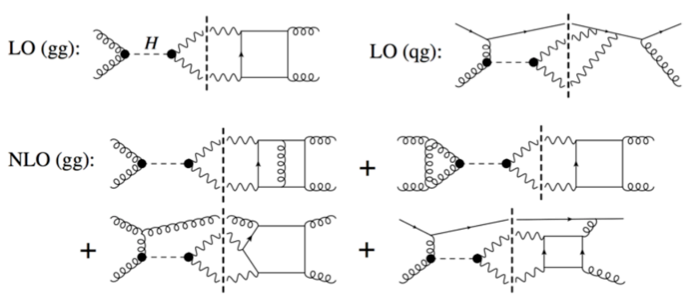


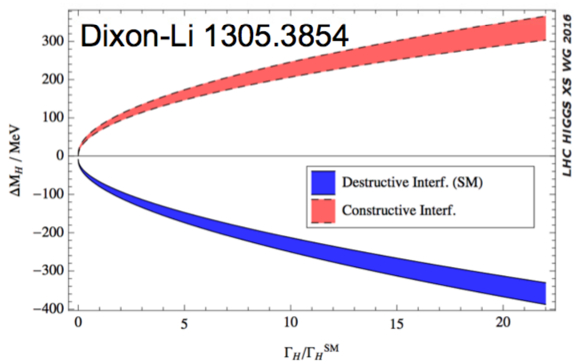


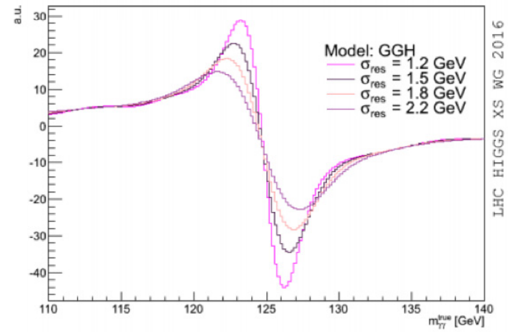
- Current Run1 limit (CMS)
  - **$c\tau_H < 57\ \mu m$** at the 95% CL $\Rightarrow$ **$\Gamma_H > 3.5\times10^{-3}$ eV** at 95% CL
- No extrapolation study available at the moment
  - Impossible to measure SM value also with 3/ab , nevertheless possible to improve sensitivity from highly boosted Higgs
  - Precise identification of the PV despite the high-pileup expected

Probing the Higgs width with Hγγ

- $gg \to H \to \gamma\gamma$ and the continuum irreducible background $gg \to \gamma\gamma$ interfere
  - The imaginary component reduces the total yield by 2-3%
  - The real part is responsible for a non negligible mass shift, depending on Γ_H $\delta m_H \propto \sqrt{\Gamma_H/\Gamma_{H,SM}}$
- Measuring this shift allows to indirectly constraint the total Higgs width
  - Estimation of $\Delta m_H = -35 \pm 9$ MeV for Run1 ATLAS measurement (Γ_H=4MeV) - ATL-PHYS-PUB-2016-009
  - same categorization and detector response as used in the Run1 mass measurement



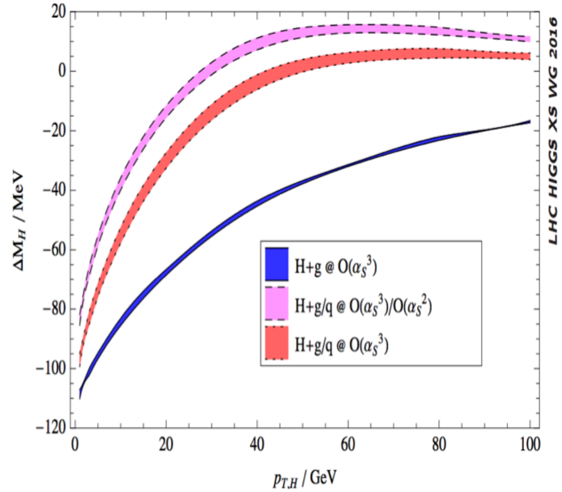


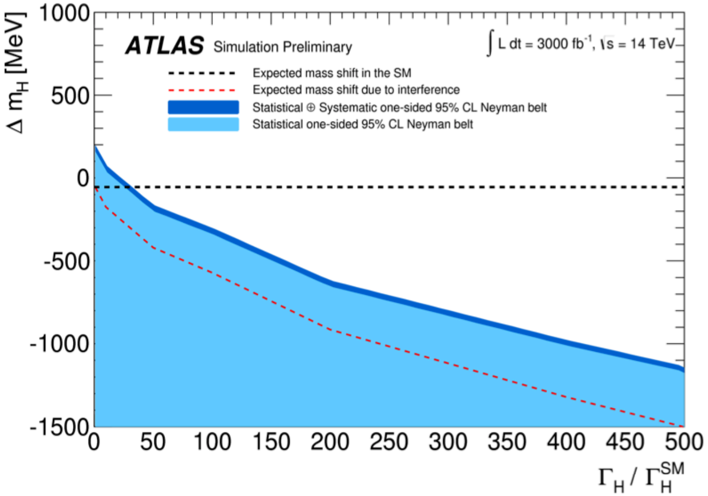


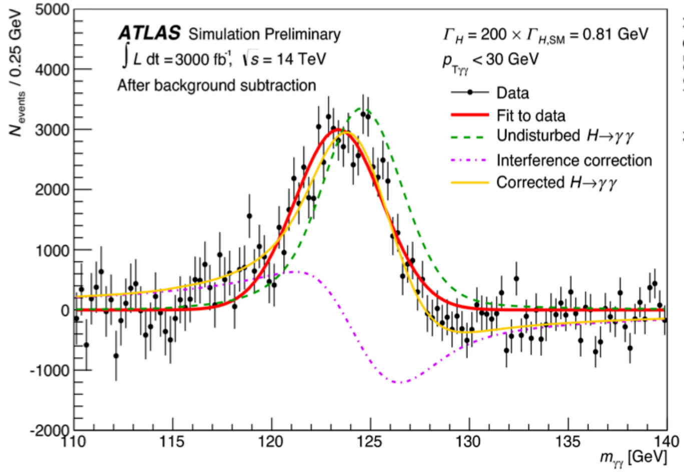
- 2 Possible way to approach the measurement (linked to the reference mass)
- Use $m_{H,ZZ}$ as reference value
  - Shift in this channel negligible (ggZZ small)
  - Drawback is detector calibration uncertainty from ZZ as well
  - Needed sensitivity down to ~70MeV
    - Strong reduction of photon scale uncertainty needed
    - Stat sensitivity to Δm_H~40 MeV at HL-LHC

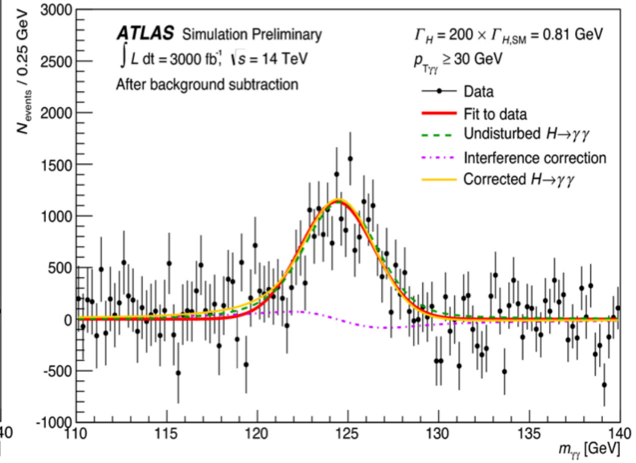
Probing the Higgs width with H->γγ

- Use the p_{TH} dependency of the shift
  - Constrained within the yy channel alone
  - Partial cancellation of calibration systematic uncertainties (energy scale)
- ATL-PHYS-PUB-2013-014
  - Evaluate the mass difference between p_{TH}<>30 GeV
  - Systematics on the difference roughly estimated to be <100 MeV
  - Stat dominated , if in presence of SM width, limit on Γ_H~<40-50 Γ_{SM}









- An alternative could be the usage of the mass difference wrt pp->H+2j
- Presented in Phys. Rev. D 92, 013004 , no projection study performed at the moment
  - H(->yy)+2jet provide good reference mass since cancellation between GGF and VBF

Indirect constraint on Γ_H from offshell production

- $\sigma_{offshell} \sim g_g^2 g_V^2$ does not depend on the total width Γ_H, $\sigma_{onshell}$ does
  - In terms of coupling modifiers

$$\frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell, SM}}} = \mu_{\text{off-shell}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{V,\text{off-shell}} \qquad \frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell, SM}}} = \mu_{\text{on-shell}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

- Under the assumption of equal on-peak and off-peak coupling modifiers, limit on $\mu_{offshell}$ can be reinterpreted, combined with $\mu_{onshell}$, as **limit on Γ_H**
  - Strong assumption, k_g(s) sensitive to possible new physics at higher mass scales
  - New physics which modify off-shell signal strength do not change bkg predictions

$$\kappa^2_{g,\,\text{on-shell}}\,\kappa^2_{V,\,\text{on-shell}} \leq \kappa^2_{g,\,\text{off-shell}}\,\kappa^2_{V,\,\text{off-shell}}$$

- Latest experimental results (WW+ZZ in Run1 for ATLAS and CMS, 4l Run2 CMS):

Γ_H < 22.7 MeV @ 95%CL (<33 MeV exp.) ATLAS Run1 Eur.Phys.J.C (2015) 75:335	Γ_H < 13MeV @ 95%CL (<26MeV exp.) CMS Run1 JHEP 09 (2016) 051	4l: Γ_H < 41 MeV @ 95%CL (<32 MeV exp.) CMS Run2, 12.9 fb^{-1} CMS PAS HIG-16-033

- For HL-LHC most of the consideration done for $\mu_{offshell}$ valid here as well
  - In this interpretation, the uncertainty on $\mu_{off\text{-}shell}$ dominates
    - ~5% precision achievable for $\mu_{onshell}$ ZZ
  - Estimate using 4l alone by ATLAS (10% syst on R^B_{H*})

$\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV ATL-PHYS-PUB-2015-024

Conclusions

- With Run1 data, both CMS and ATLAS set first limits on the Higgs boson width and offshell production
  - First results using Run2 data also available
- For the Higgs width exploited both direct and indirect methods
  - Direct measurement will be challenging also with RUN2 and HL-LHC statistics
  - Indirect methods (under well-defined assumptions) provide already today limits @ 3 times the SM width
  - For several of the presented measurements, also limitations from the detector performances
    - Key point is to keep the performances at the same level as today (or better) also in a high pileup environment
- Off-shell production of the Higgs boson gives interesting extra information about the coupling structure of the Higgs boson
  - Very interesting measurement to perform @ HL-LHC
  - $\mu_{offshell}$ measurement sensitivity @ 20% level with 3000fb^{-1} (no theoretical uncertainties)
  - Very important the theoretical knowledge of the gg->(H*)->VV process and the backgrounds at higher orders in QCD
  - m_{ZZ} differential cross section measurement might be used as well, at the price of reduced sensitivity
- Will be interesting to explore also the reach for HE-LHC

Backup