Higgs boson width measurements with different methods at LHC

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On behalf of the ATLAS and CMS collaborations

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Outline

- ATLAS and CMS used the full potential of RUN1 LHC data for an accurate Higgs boson characterization
  - Is the boson discovered the SM Higgs boson?
- Several properties studied (i.e. mass, signal strength, couplings, spin and parity…)
- This Talk: Higgs Boson Width
  - Direct limit on the Higgs boson width
  - Lower bound exploiting the Higgs boson lifetime
  - Indirect limit through Higgs boson offshell production
  - HL-LHC prospective
- Complementary to the direct searches for Higgs boson to invisible decays and constraints coming from the Higgs boson coupling tests

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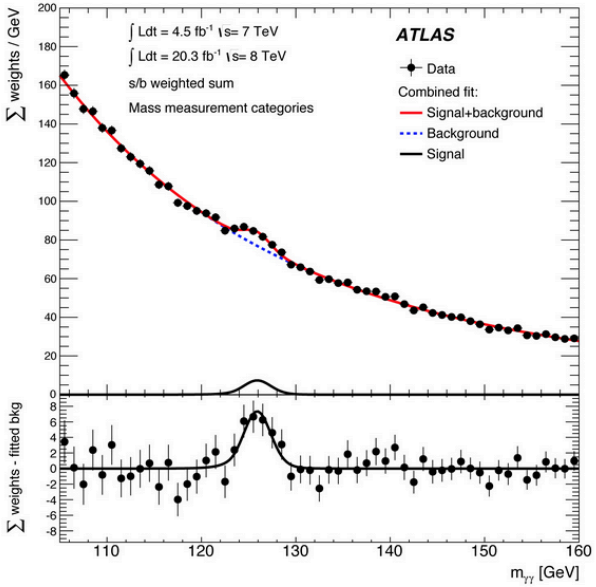
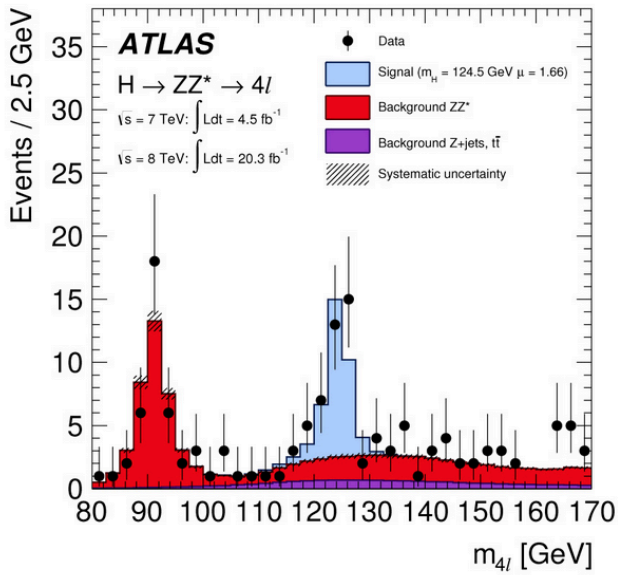
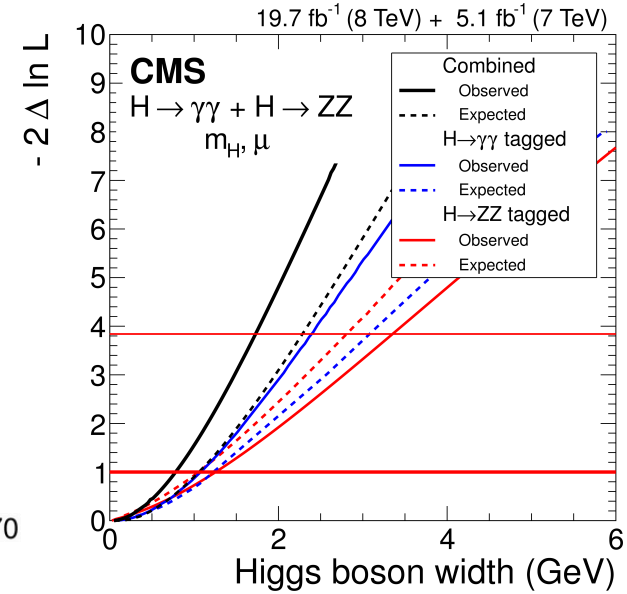
Direct width measurement: upper bound

- In the Standard Model the $\Gamma_{H,SM}$ prediction is ~4.1 MeV for m_H=125 GeV
- Direct measurement using m_{4l} and $m_{\gamma\gamma}$ spectra
  - Limited by experimental resolution (~1-2%)

EPJ C 75 (2015) 212
Phys. Rev. D 90(2014) 052004







- CMS upper limit on Γ_H combining **$H\to ZZ^*\to 4l$** and **$H\to\gamma\gamma$** :
  - **Γ_H< 1.7 GeV at 95% CL** (exp. 2.3 GeV), m_H and signal strength profiled (free to float in the fit)
- ATLAS **$H\to ZZ^*\to 4l$** : **Γ_H< 2.6 GeV at 95% CL** (exp. 3.5 GeV for the observed signal strength), similar direct limits using $H\to\gamma\gamma$
- **>400 times** larger wrt **SM prediction**

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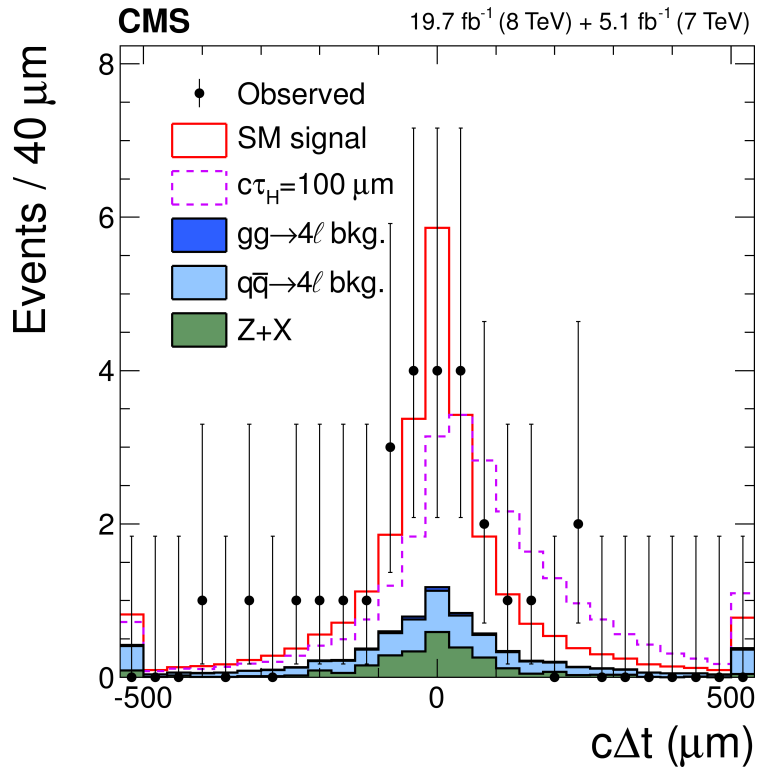
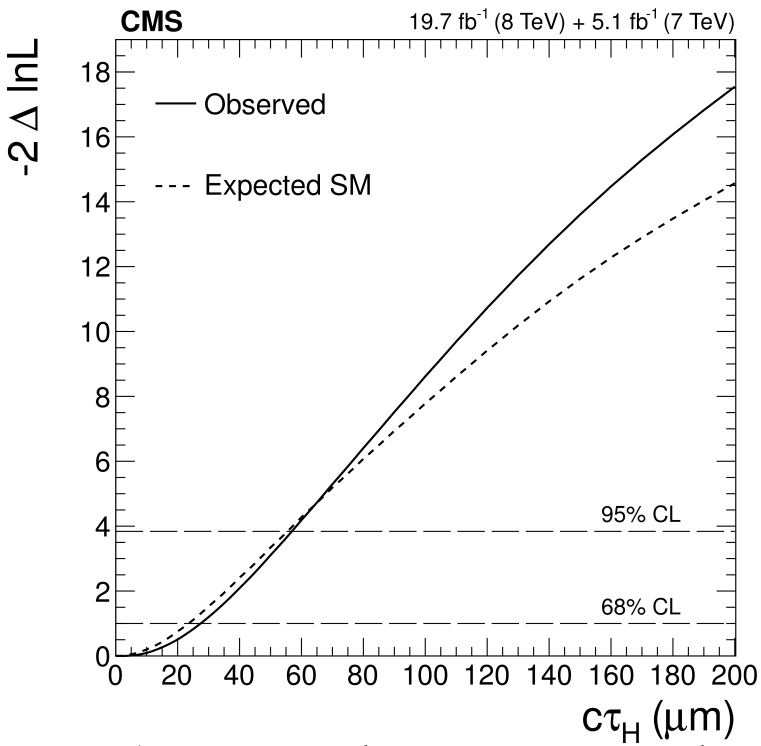
Lower bound: Higgs lifetime

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

arXiv:1507.06656





- Lifetime from flight distance in H→ZZ*→4l events

$$\Delta t = \frac{m_{4\ell}}{p_T}\left(\Delta\vec{r}_T.\hat{p}_T\right)$$

Displacement vertex between H production and decay

- D_{bkg} kinematic discriminant used
  - Fit to $P(\Delta t) x P(D_{bkg})$

$c\tau_H < 57\mu m$ at the 95% CL

$\Gamma_H > 3.5\times10^{-3}$ eV at 95% CL

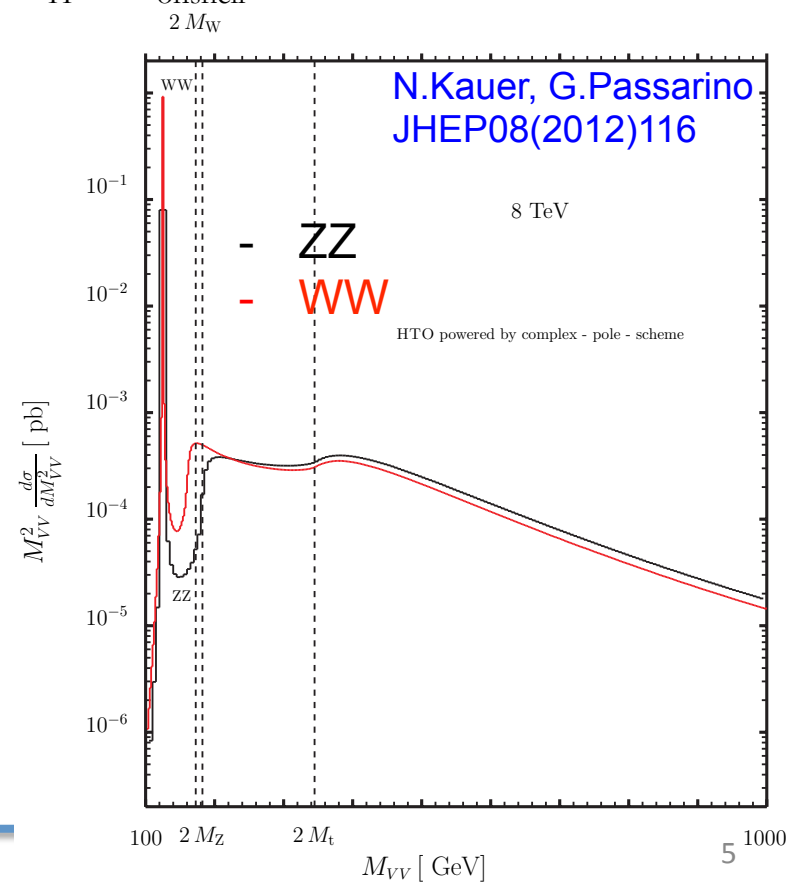
Limit on Γ_H through off-shell production

- 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 particle in this region
- $\sigma_{offshell} \sim g_g^2 g_V^2$ and doesn't depend on total width Γ_H as $\sigma_{onshell}$ does
  - In terms of couplings modifiers

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

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

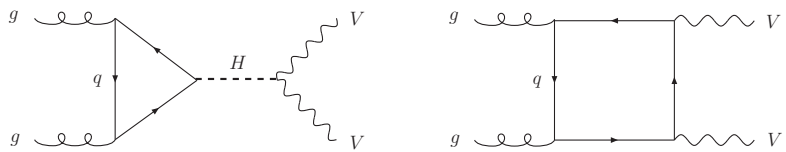
- Assuming the on-peak and off-peak couplings are the same, we can reinterpret the limit on $\mu_{offshell}$, combined with $\mu_{onshell}$ measurement, as a **limit on Γ_H**



ATLAS: Eur. Phys. J. C (2015) 75:335
CMS: Phys. Lett. B 736 (2014) 64

Interference effects and MC generators

- In the high mass region off-shell Higgs production and non resonant gg→ VV background (box diagram)



- Interference between the two processes sizable and negative in SM
- Similar for qq→VV+2j and VBF production

ggF production mechanism

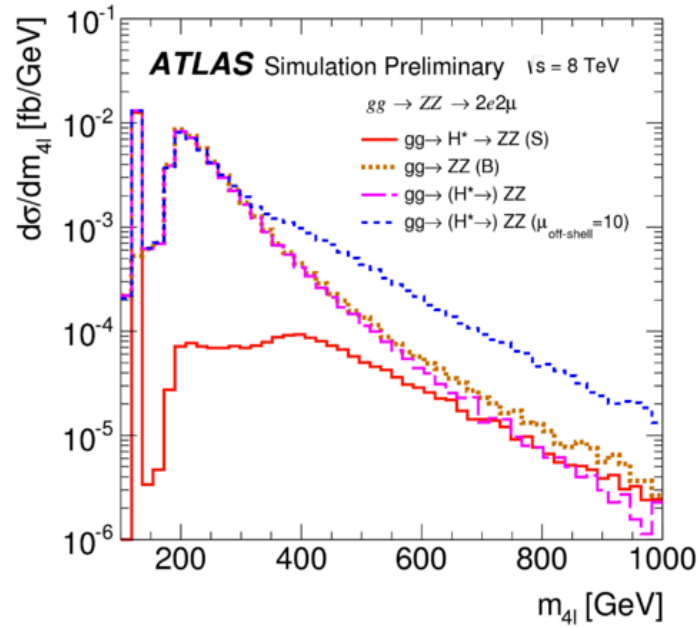
- MCFM and gg2VV (LO, $\mu_R=\mu_F=m_{ZZ}/2$)
  - gg→(H*)→ ZZ gg→H*→ ZZ , gg→ZZ
- Sherpa (0j+1j) for $p_{T(ZZ)}$ description (ATLAS)

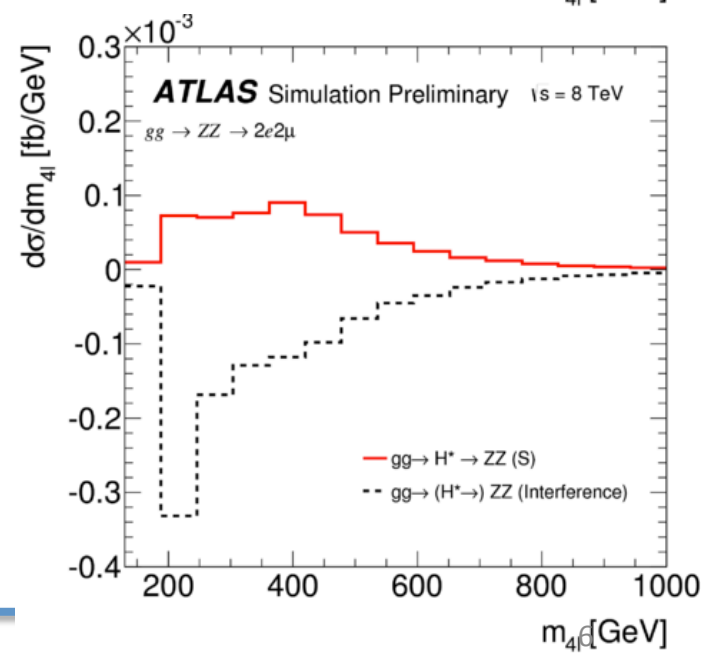
VBF production mechanism

- MadGraph and Phantom used
- Other production mechanisms (VH,ttH) negligible

qqZZ background

- Powheg NLO QCD + corrections NLO EW
  - also NNLO m_{ZZ} k-factor in ATLAS





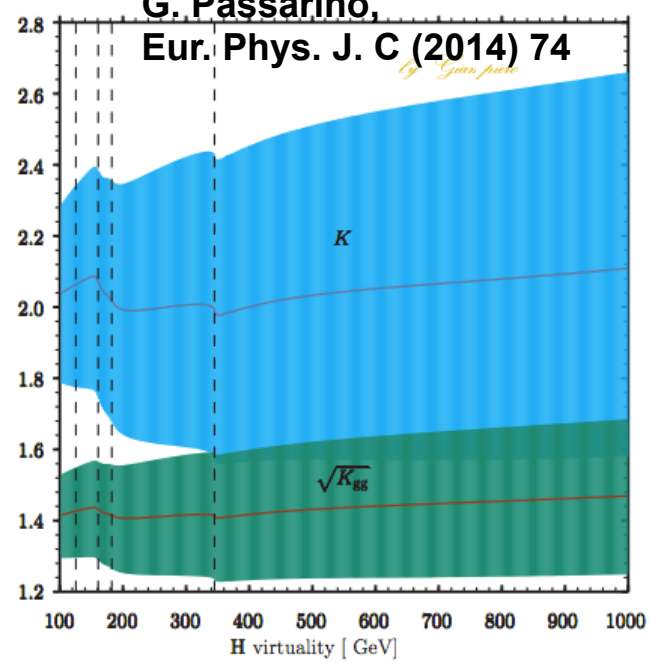
$\mu_{offshell}$ dependence and K-factors

- Possible to obtain a sample with an arbitrary value of $\mu_{offshell}$ combining the SM expectations for $gg \to H^* \to ZZ$, $gg \to (H^* \to) ZZ$ and $gg \to ZZ$: $\mu\, MC_{gg \to H^* \to ZZ} + \sqrt{\mu}\, MC_I + MC_{gg \to VV}$

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

- $K^{H^*}(m_{ZZ})$: NNLO/LO K factor for the signal
  - Includes contribution from qg qq initial states
  - Calculated inclusively (integrated over jet p_T and $p_T(ZZ)$ induced by higher order QCD corrections)
  - 20-30% QCD scale uncertainty
- $K^{H^*}_{gg}(m_{ZZ})$: NNLO/LO K factor for the gg initiated process
  - Only gg contribution and larger uncertainty wrt $K^{H^*}(m_{ZZ})$
- $R^B_{H^*}$: $K^B/K^{H^*}_{gg}(m_{ZZ})$
  - K-factor for $gg \to ZZ$ unknown

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



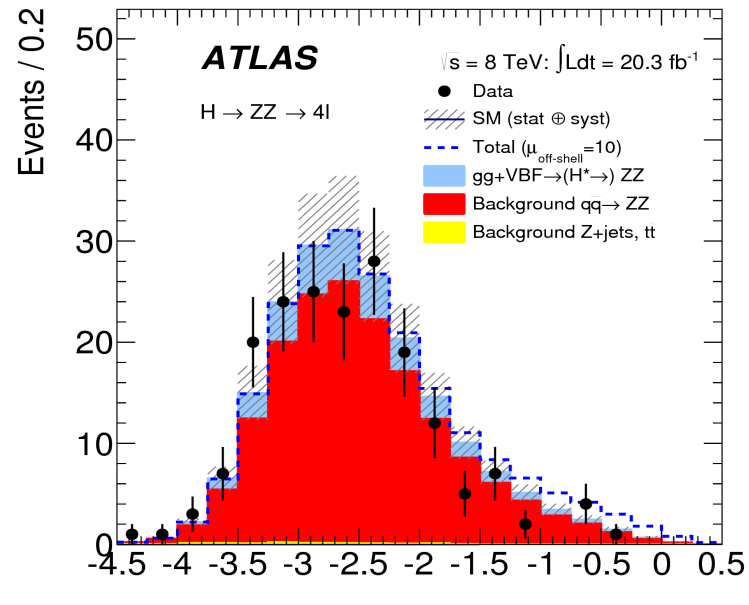
ZZ→4l analysis

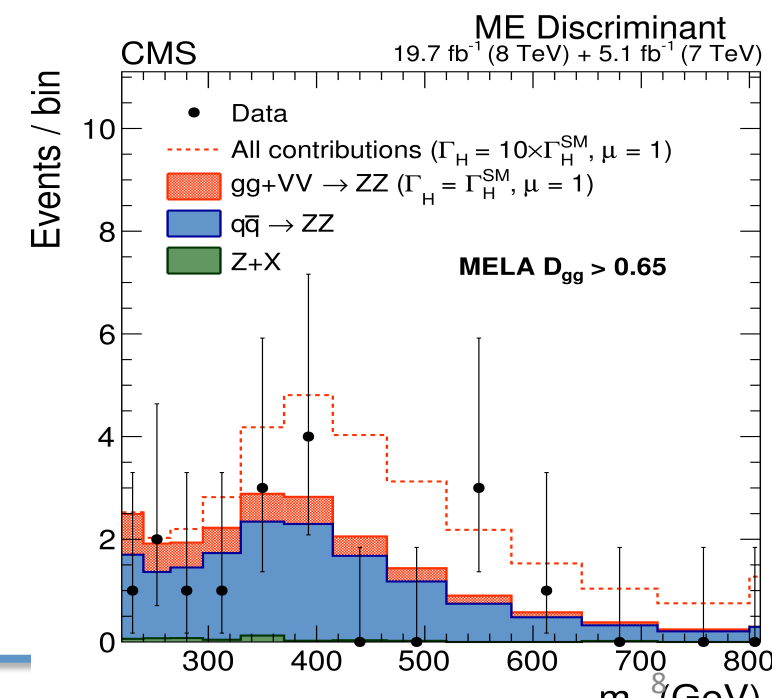
- 4l analysis designed to be mostly inclusive wrt additional QCD activity
- Selection similar to the one used for the on-shell coupling results both for ATLAS and CMS
  - 2 opposite-sign same-flavour pairs of isolated and prompt leptons
  - Signal region **m_{4l}>220GeV**
- A leading order matrix element based discriminant used to enhance the sensitivity to the $gg \to H^* \to ZZ$ (ATLAS) or $gg \to (H^* \to) ZZ$ (CMS)

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

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

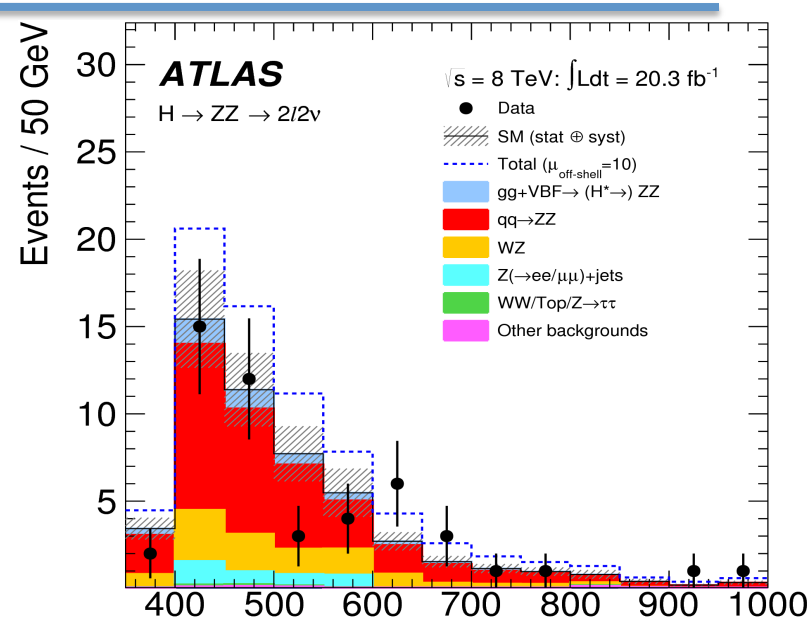
- m_{4l} m_{Z1} m_{Z2} and 5 production/decay angles used to calculate the ME for the different processes with MCFM
- Fit to the ME discriminant shape (ATLAS) or m_{4l}-ME (CMS) to extract the limit on $\mu_{offshell}$

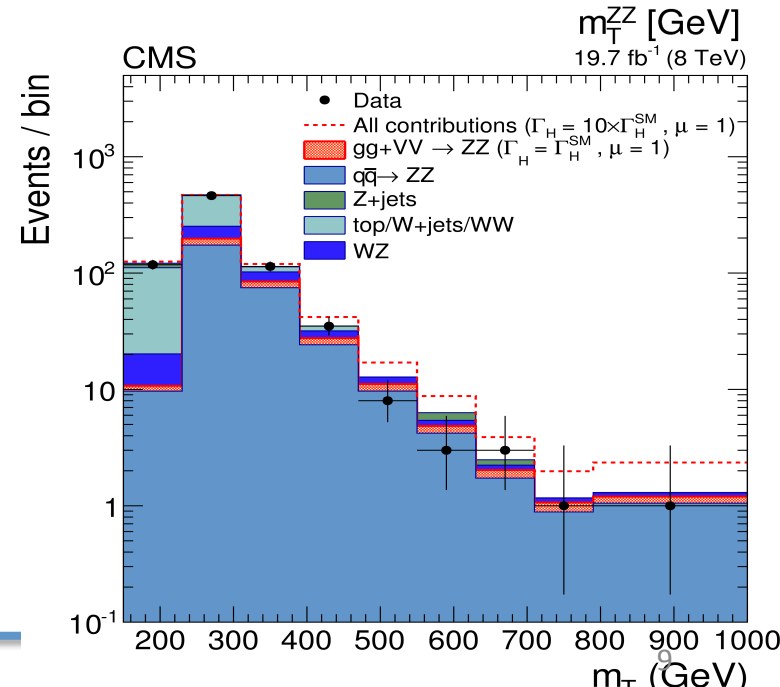




ZZ→llνν

- Similar sensitivity to the 4l analysis
  - Profit from factor 6 higher BR
- Selection cuts:
  - High E_T^{miss}, m_{ll} compatible with Zboson mass within ±15 GeV
- Signal region:
  - ATLAS: 350GeV<m_T<1TeV
  - CMS: 180GeV<m_T<1TeV
- Main backgrounds
  - qq→ZZ, WZ: MC based estimation
  - WW/tt/Zττ: estimated inclusively with eμ events assuming lepton flavour symmetry
  - Z+jets: data-driven with ABCD method (ATLAS),from γ+jet control sample (CMS)
- ML fit to m_T^{ZZ}



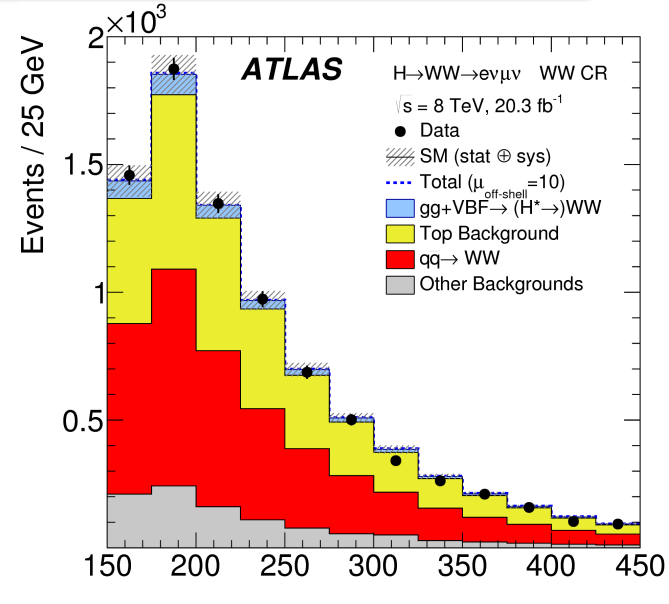


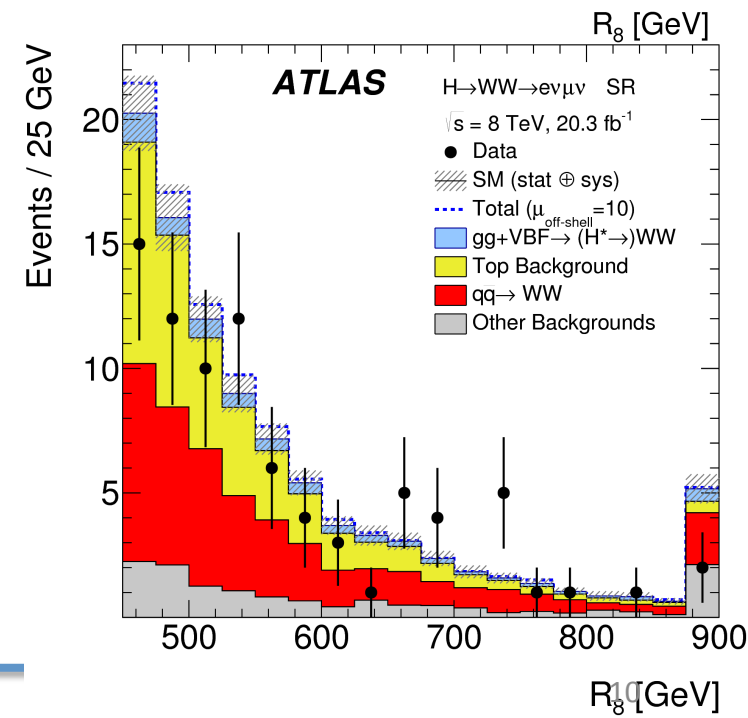
WW→eνμν

- Based on inclusive on-shell H→WW*→lνlν analysis but inclusive in jets
  - eμ final state is most sensitive and orthogonal with ZZ→2l2ν final state
- R_8 variable that combines the m_{ll} and m_T information is used in the analysis

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

- R_8 cut and a value optimized for off-shell signal sensitivity and rejecting on-shell H→WW*
- ML fit observable: yields in the signal region (R_8>450 GeV) and top, WW control regions





Systematic uncertainties

- Systematic uncertainties dominated by **theoretical uncertainties**
  - QCD scale uncertainty for gg→(H*→) VV and qq→VV
  - PDF for qq→VV and for gg→VV processes
  - Uncertainty due to unknown NNLO k-factor for the gg→VV
    - ATLAS: gives the result as function of the ratio between gg→VV and signal NNLO k-factors $R^{B}_{H^*}$ [0.5-2]
    - CMS: assumes same signal NNLO K-factor for the bkg and adds a 10% syst uncertainties.
  - Additional 30% uncertainty considered for the interference terms for ATLAS
- Experimental uncertainties are subdominant for both ATLAS and CMS
  - Luminosity, lepton efficiencies, JES
  - Data driven background estimates

Systematic uncertainty *ATLAS*	95% CL lim. (CL_s) on $\mu_{\text{off-shell}}$
Interference $gg \to (H^* \to)VV$	7.2
QCD scale $K^{H^*}(m_{VV})$ (correlated component)	7.1
PDF $q\bar{q} \to VV$ and $gg \to (H^* \to)VV$	6.7
QCD scale $q\bar{q} \to VV$	6.7
Luminosity	6.6
Drell–Yan background	6.6
QCD scale $K^{H^*}_{gg}(m_{VV})$ (uncorrelated component)	6.5
Remaining systematic uncertainties	6.5
All systematic uncertainties	8.1
No systematic uncertainties	6.5

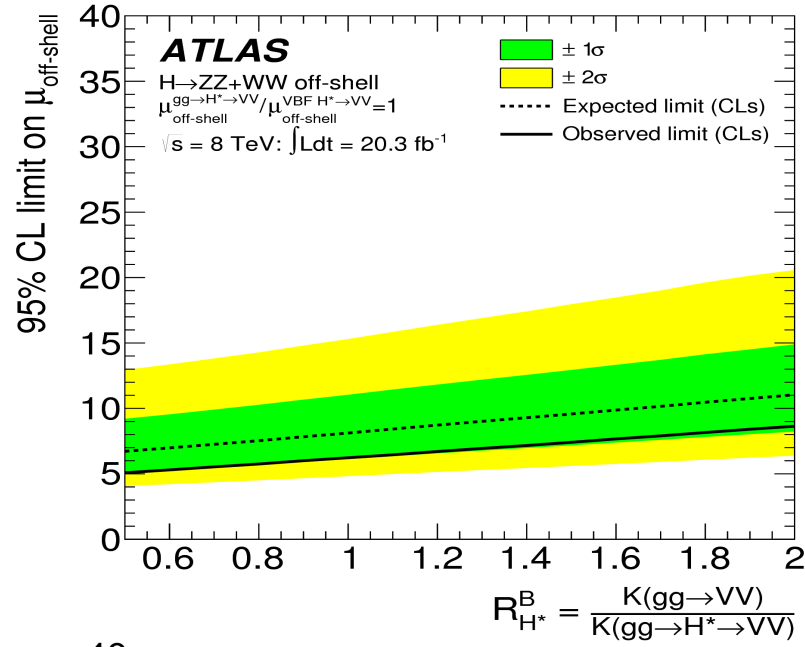
Results: limits on $\mu_{offshell}$

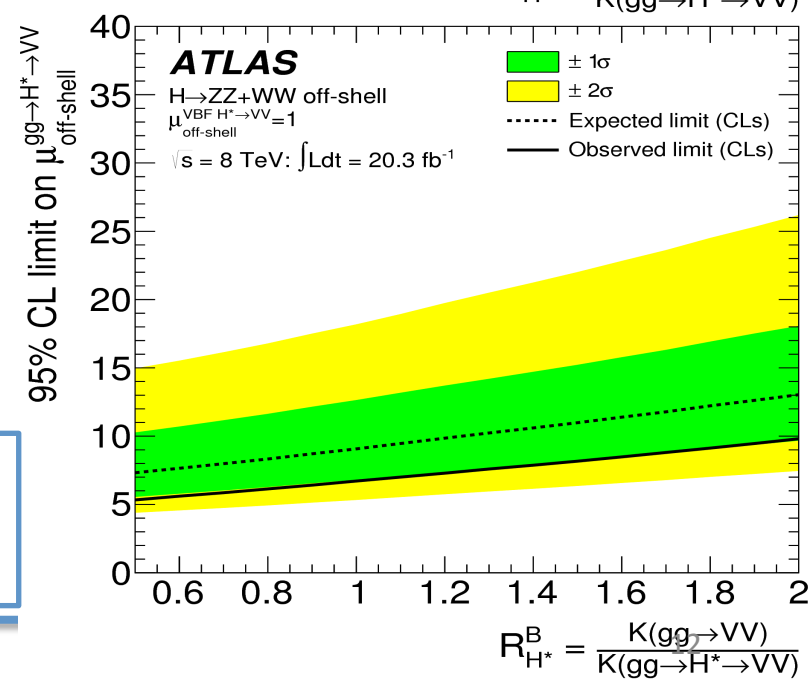
- Combination of $ZZ \to 4l$, $ZZ \to llvv$, $WW \to e\nu\mu\nu$
- Provided by ATLAS under different assumptions
- 1 single $\mu_{offshell}$, equivalent to assuming the $gg \to H$ to VBF production as predicted in the SM

$\mu_{offshell}$<6.2 @ 95% CL for R^B_{H*}=1
(expected: $\mu_{offshell}$<8.1 @ 95%CL)

- VBF production fixed to the SM prediction while just the $\mu_{offshell}$ of the $gg \to H^* \to VV$ process is considered.
  - interpreted as constraint on offshell coupling strength of the $gg \to H^*$ production mode.

$\mu_{offshell(gg \to H^* \to VV)}$<6.7 @ 95% CL for R^B_{H*}=1
(expected: $\mu_{offshell}$<9.1 @ 95%CL)





Results: limits on the Higgs width

- Limits on Γ_H obtained by combining the on-shell 4l(lvlv) and off-shell signal strength measurements
  - μ_{ggF} and μ_{VBF} profiled on data
  - assumes same on-shell and off-shell couplings

CMS

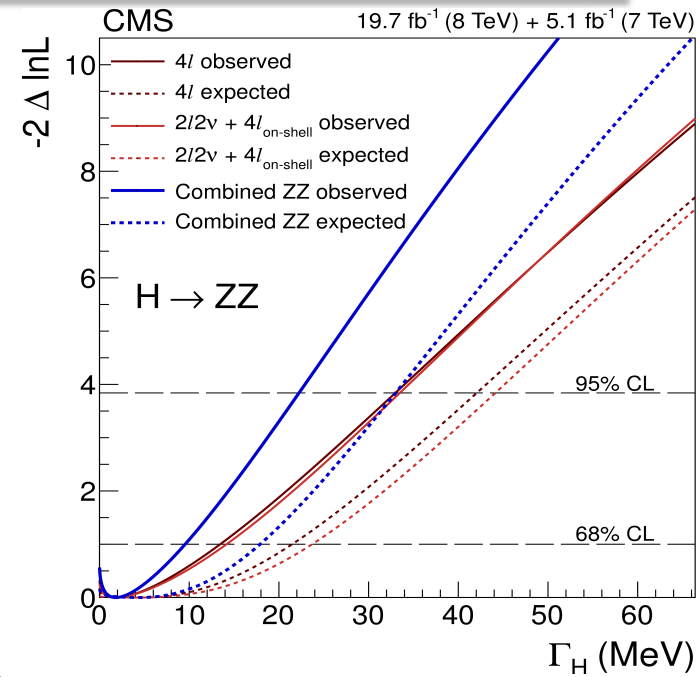
Γ_H < 22 MeV @ 95% CL

(expected: Γ_H < 33 MeV @ 95%CL)

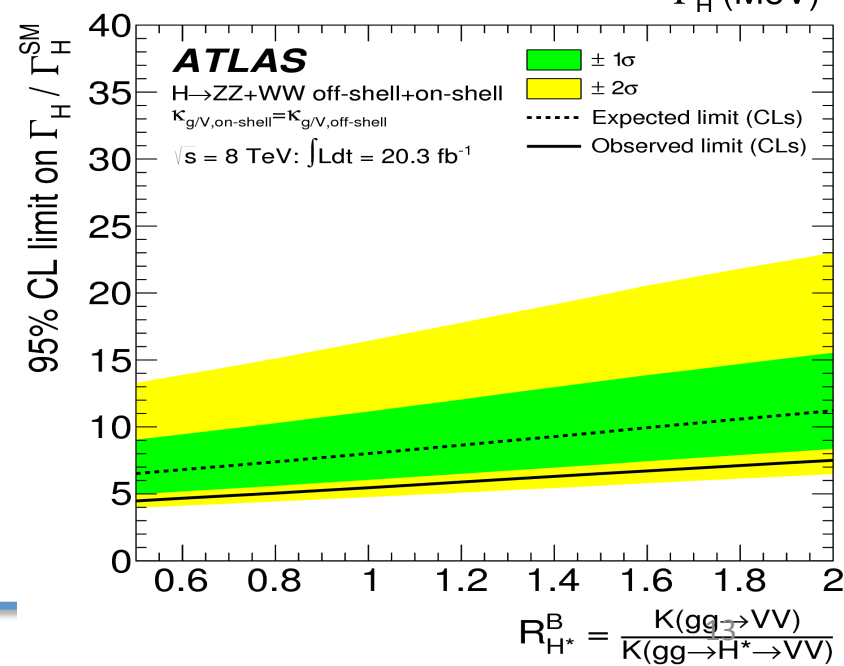
ATLAS

Γ_H < 22.7 MeV @ 95% CL for R^B_{H*}=1

(expected: Γ_H < 33 MeV @ 95%CL)



- **Assuming** $\Gamma_H/\Gamma_{H,SM}$=1, interpreted as limit on ratio of the off-shell to on-shell couplings to gluons (ATLAS)



R_{gg} < 6.0 @ 95% CL for R^B_{H*}=1

(expected: R_{gg} < 9.0 @ 95%CL)

Limits on Γ_H allowing anomalous couplings

- Updated analysis by CMS including the possible anomalous coupling in HVV
  - Additional term Λ_Q depending on the Higgs boson invariant mass can be probed with offshell analysis (cannot be distinguished in the on-shell region)

arXiv:1507.06656

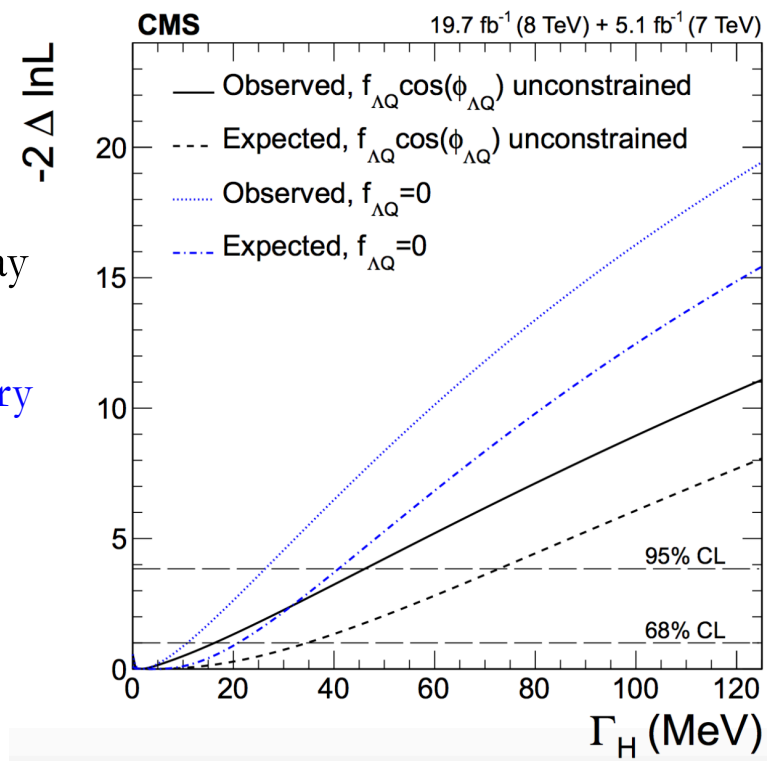
$$A(\mathrm{HVV}) \propto \left[a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_{V1}+q_{V2})^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}} \frac{(q_{V1}^2+q_{V2}^2)}{(\Lambda_1)^2} \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^*$$

$$+ a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

- Limits as function of effective cross-section fraction due to the Λ_Q term

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

- Anomalous coupling in both production and decay for VBF and VH
  - Sensitivity enhanced introducing a 2-jet tag category

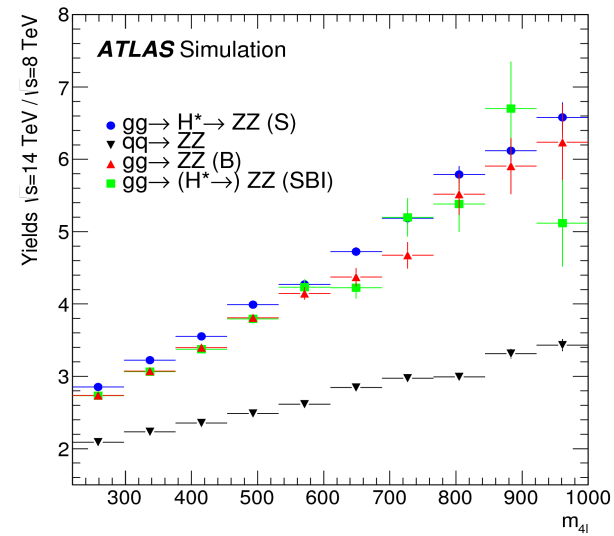


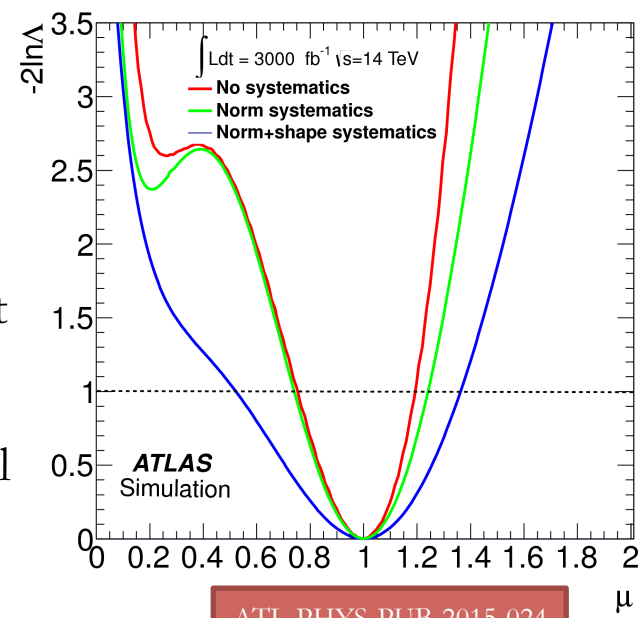
Γ_H < 46 MeV at the 95% CL
($f_{\Lambda Q}$ left unconstrained,
expected: Γ_H < 73 MeV @ 95%CL)

Γ_H < 26 MeV at the 95% CL
($f_{\Lambda Q}$ = 0, expected: Γ_H < 41 MeV @ 95%CL)

Prospects for run2 and HL-LHC

- With the increase in statistics, it will be crucial to have the most accurate possible theoretical prediction
  - 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 "QCD-inclusive" analysis)
- Equally important is the development of MC generators for the main qq→VV background
  - pp→WW/ZZ at NNLO cross sections and NNLO MC development
- At HL-LHC $\mu_{offshell}$ measurement sensitivity @ 20% without theoretical systematic uncertainties (ATLAS)
- Under well-defined assumption and combining with on-shell measurement → probe Γ_H
  - off-shell uncertainties dominate (on-shell ~5%)





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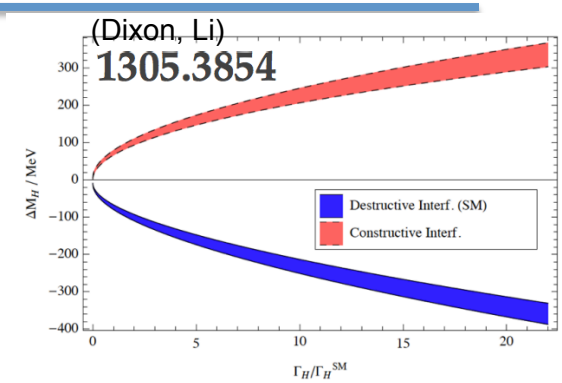
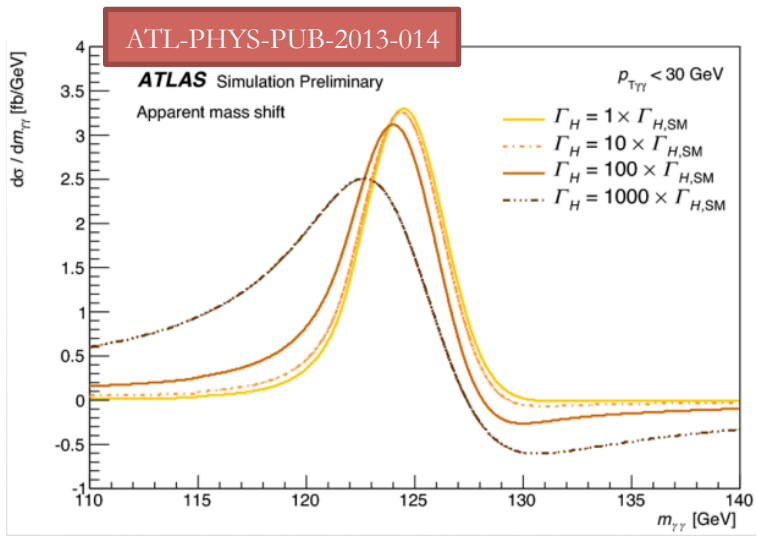
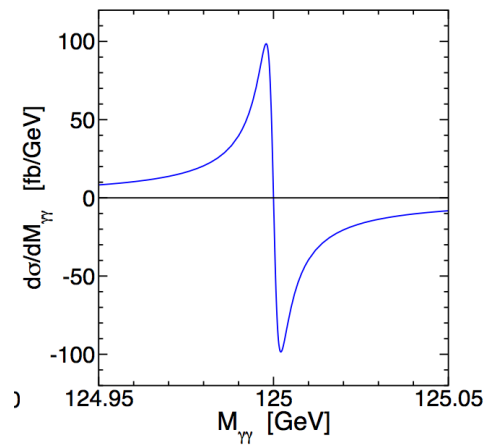
Prospects for run2 and HL-LHC

- For $gg \to H \to \gamma\gamma$ the interference with the $gg \to \gamma\gamma$ background induces a distortion in the $m_{\gamma\gamma}$ mass shape and depends on Γ_H
  - Needed to know the apparent mass shift induced



- Possible to extract an indirect limit on Γ_H
- In the SM the shift is ~ -60MeV





- Interference effects are different depending on the $p_T^{\gamma\gamma}$
  - Possible control mass with $m_{\gamma\gamma}$ for events with p_{TH}>30GeV or using $H \to ZZ^* \to 4l$
  - In the $H(\to\gamma\gamma)$+2j channel, VBF and ggF contributions generate shifts of opposite signs → good reference mass
- Expected limit by ATLAS at ~40 $\Gamma_{H,SM}$ for 3000fb^{-1}

Conclusions

- With RUN1 data, both CMS and ATLAS set first limits on the Higgs boson 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 @ 5 times the SM width
- Off-shell production of the Higgs boson gives interesting extra information about the coupling structure of the Higgs boson
  - Very interesting measurement to perform with RUN2 data (and HL-LHC)
  - $\mu_{offshell}$ measurement sensitivity @ 20% level with 3000fb^{-1} (no theoretical uncertainties)
  - Very important the theoretical knowledge of the $gg \rightarrow (H^*) \rightarrow VV$ process and the backgrounds at higher orders in QCD

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$R^B_{H^*}$	Observed			Median expected		
	0.5	**1.0**	2.0	0.5	**1.0**	2.0
$ZZ \to 4\ell$ analysis	6.1	**7.3**	10.0	9.1	**10.6**	14.8
$ZZ \to 2\ell 2\nu$ analysis	9.9	**11.0**	12.8	9.1	**10.6**	13.6
$WW \to e\nu\mu\nu$ analysis	15.6	**17.2**	20.3	19.6	**21.3**	24.7