Off-Shell Higgs Measurements

Hugues BRUN,

Université Libre de Bruxelles

on behalf of the ATLAS and CMS collaborations

Higgs Couplings 2016

November 10th, 2016

Interest of the Higgs Off-Shell measurement

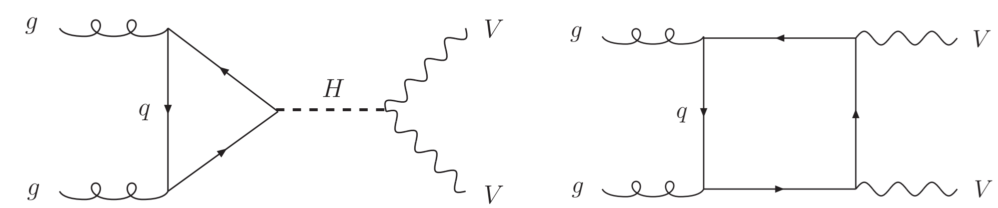
- Off-Shell production of the Higgs boson in VV gives interesting extra information about the coupling structure of the Higgs boson
  - Also sensitive to possible new physics that changes the interaction between the Higgs and the SM particles in this region

- Off-shell cross section does not depend on total width (Γ_H) as $\sigma_{\text{On-shell}}$ does:

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

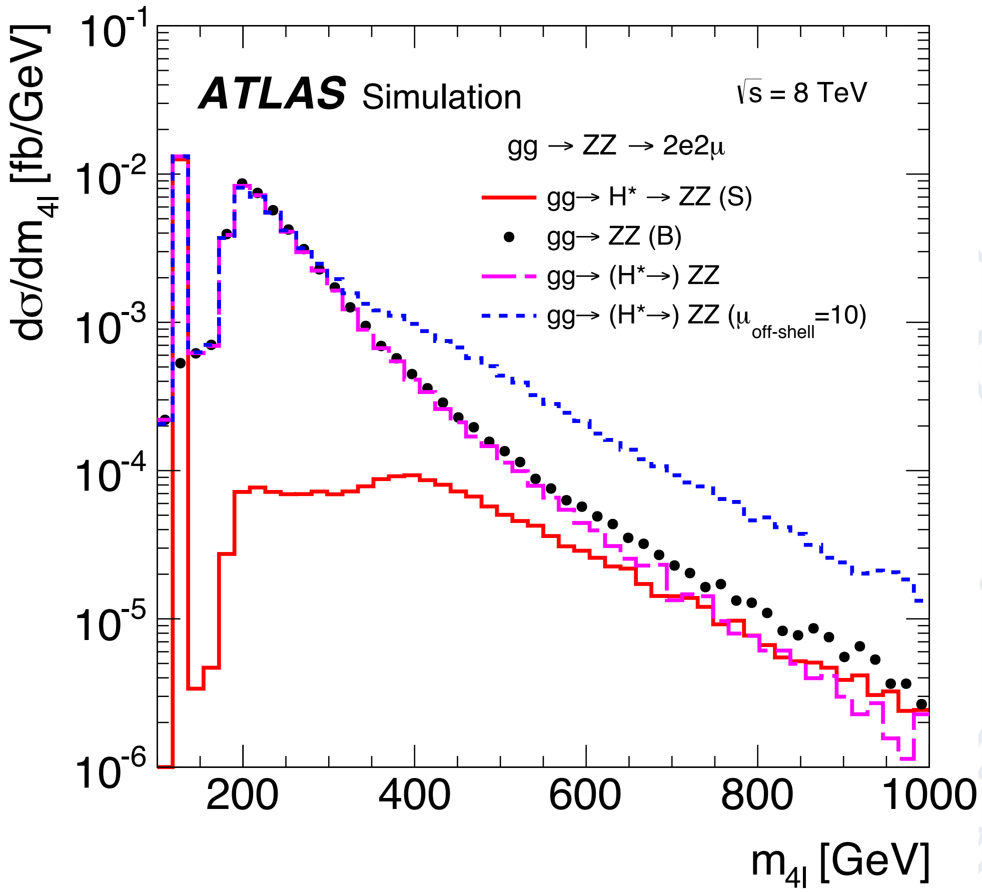
$$\frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell, SM}}} = \mu_{\text{on-shell}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

  - In the SM, assuming that the on peak and the off peak couplings are scaling the same, combined measurement of $\mu_{\text{on-shell}}$ and $\mu_{\text{off-shell}}$, can be interpreted as a limit on Γ_H



➡ In the high mass region, interference between gg→H*→VV and gg→VV is sizeable and negative in SM

➡ Similar for qq →VV + 2 jet and VBF production

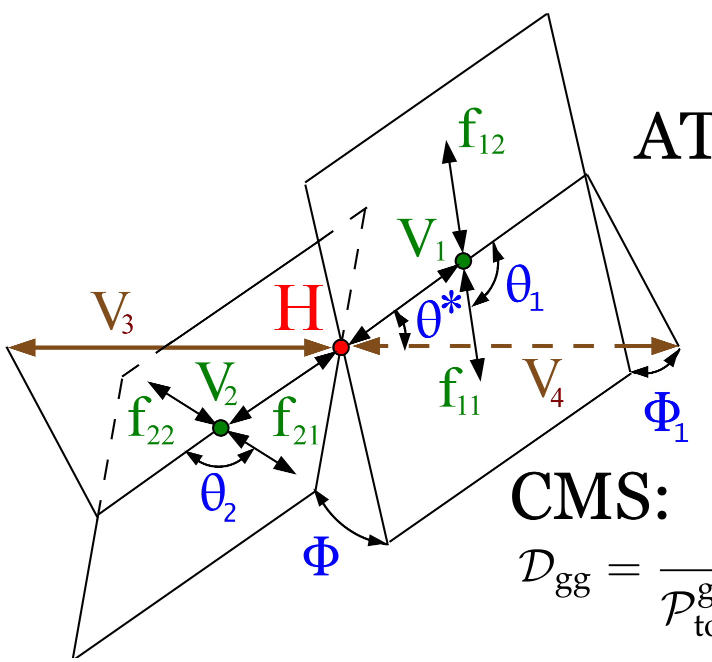


Combination of Off-Shell measurements in Run I data

ATLAS: Eur. Phys. C(2015) 75:335
CMS : Phys. Lett B 736 (2014), 64
JHEP09(2016)051,
CMS PAS HIG-16-033

H→ZZ→4l final state

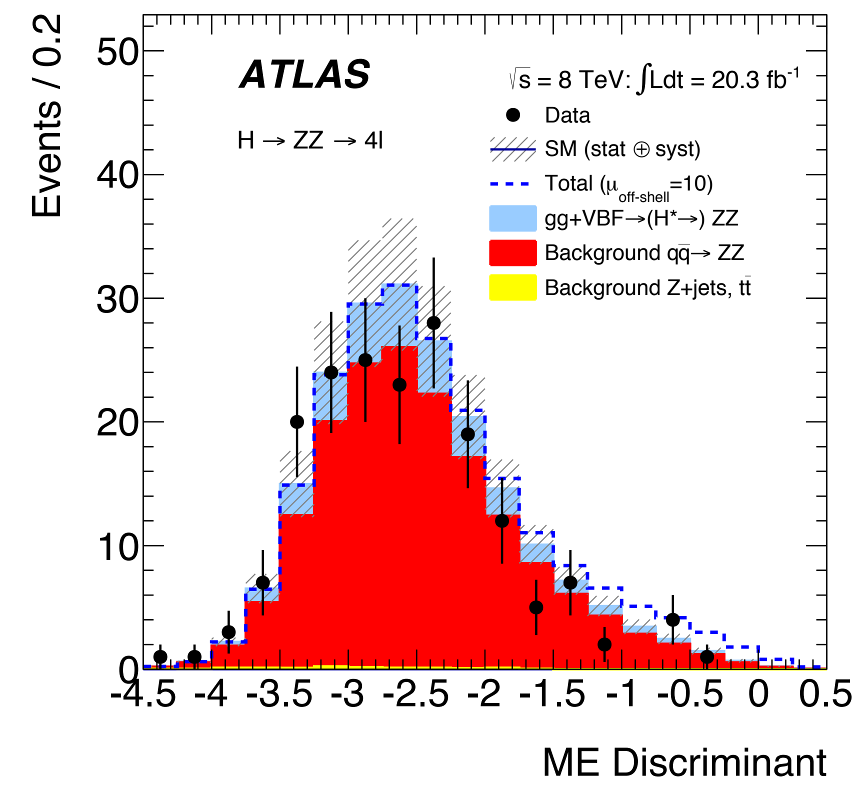
- **Final states:** 2μ2e, 2e2μ, 4μ,4e
- **Selection:**
  - 2 pairs of same flavour lepton in a mass window around the m_Z
- Exploit the kinematic of the decay to construct a likelihood discriminant:
  - matrix discriminant used to enhance the sensitivity to the gg→(H*→)ZZ (in CMS) or to gg→H*→ZZ (in ATLAS)
  - m_{4l} m_{Z1} m_{Z2} and 5 production/decay angles used as input of the discriminant

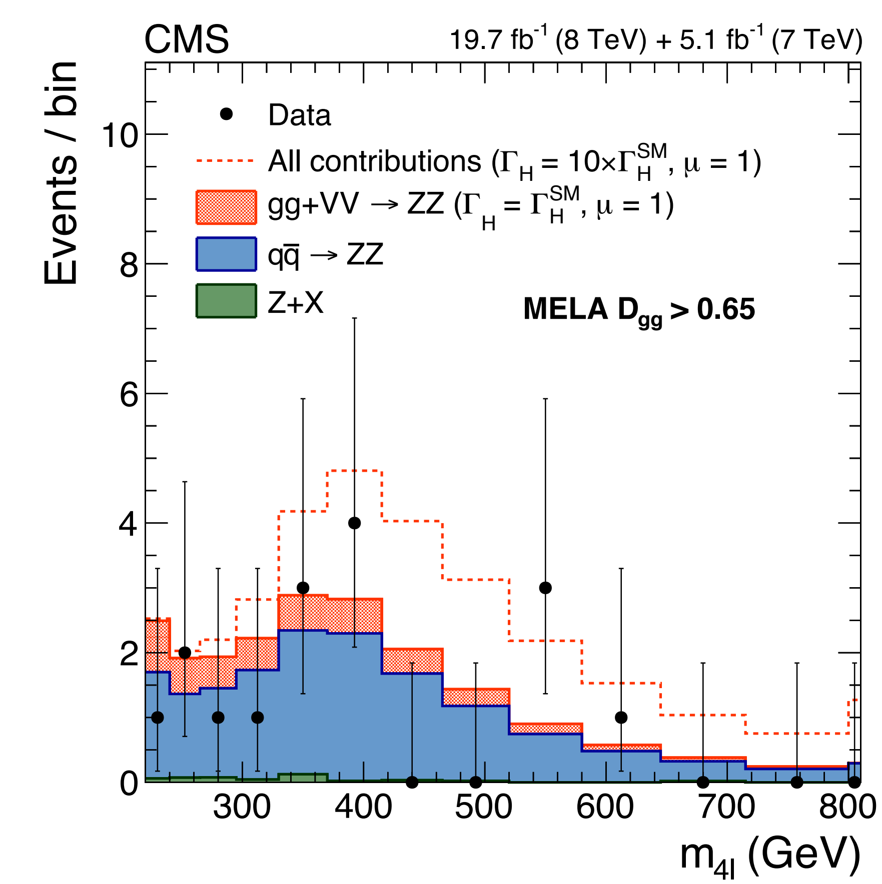


ATLAS: $$\mathrm{ME} = \log_{10}\left(\frac{P_H}{P_{gg} + c \cdot P_{q\bar{q}}}\right)$$

CMS: $$\mathcal{D}_{gg} = \frac{\mathcal{P}^{gg}_{\mathrm{tot}}}{\mathcal{P}^{gg}_{\mathrm{tot}} + \mathcal{P}^{q\bar{q}}_{\mathrm{bkg}}} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{\mathrm{bkg}}}{a \times \mathcal{P}^{gg}_{\mathrm{sig}} + \sqrt{a} \times \mathcal{P}^{gg}_{\mathrm{int}} + \mathcal{P}^{gg}_{\mathrm{bkg}}}\right]^{-1}$$

- **Selection: Off-Shell enriched region:** m_{4l} > 220 GeV

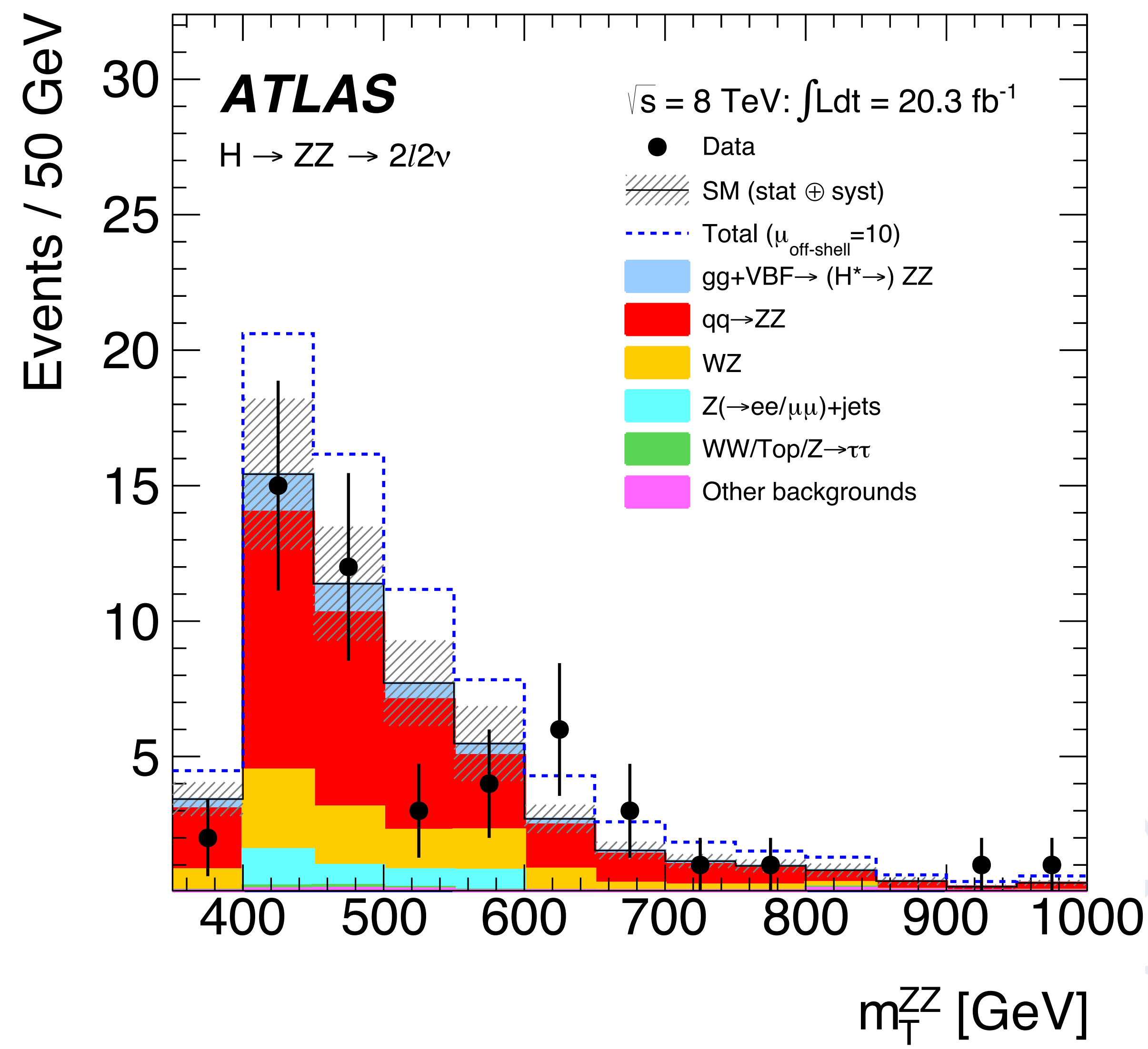




H→ZZ→2l2v final state

- **Selection:**
  - ll pair in a mass window around Z mass
  - cut on E_T^{miss}
  - + additional kinematic requirement such as $\Delta\Phi\left(p_T^{ll}, E_T^{miss}\right)$

$$m_T^{ZZ} \equiv \sqrt{\left(\sqrt{m_Z^2 + \left|\boldsymbol{p}_T^{\ell\ell}\right|^2} + \sqrt{m_Z^2 + \left|\boldsymbol{E}_T^{\text{miss}}\right|^2}\right)^2 - \left|\boldsymbol{p}_T^{\ell\ell} + \boldsymbol{E}_T^{\text{miss}}\right|^2}$$



- **Backgrounds:**
  - qq→ZZ, WZ ⟶ estimated from MC
  - Z → ee (μμ) with a genuine lepton
  - WW, top, Z → ττ

  } data-driven estimations

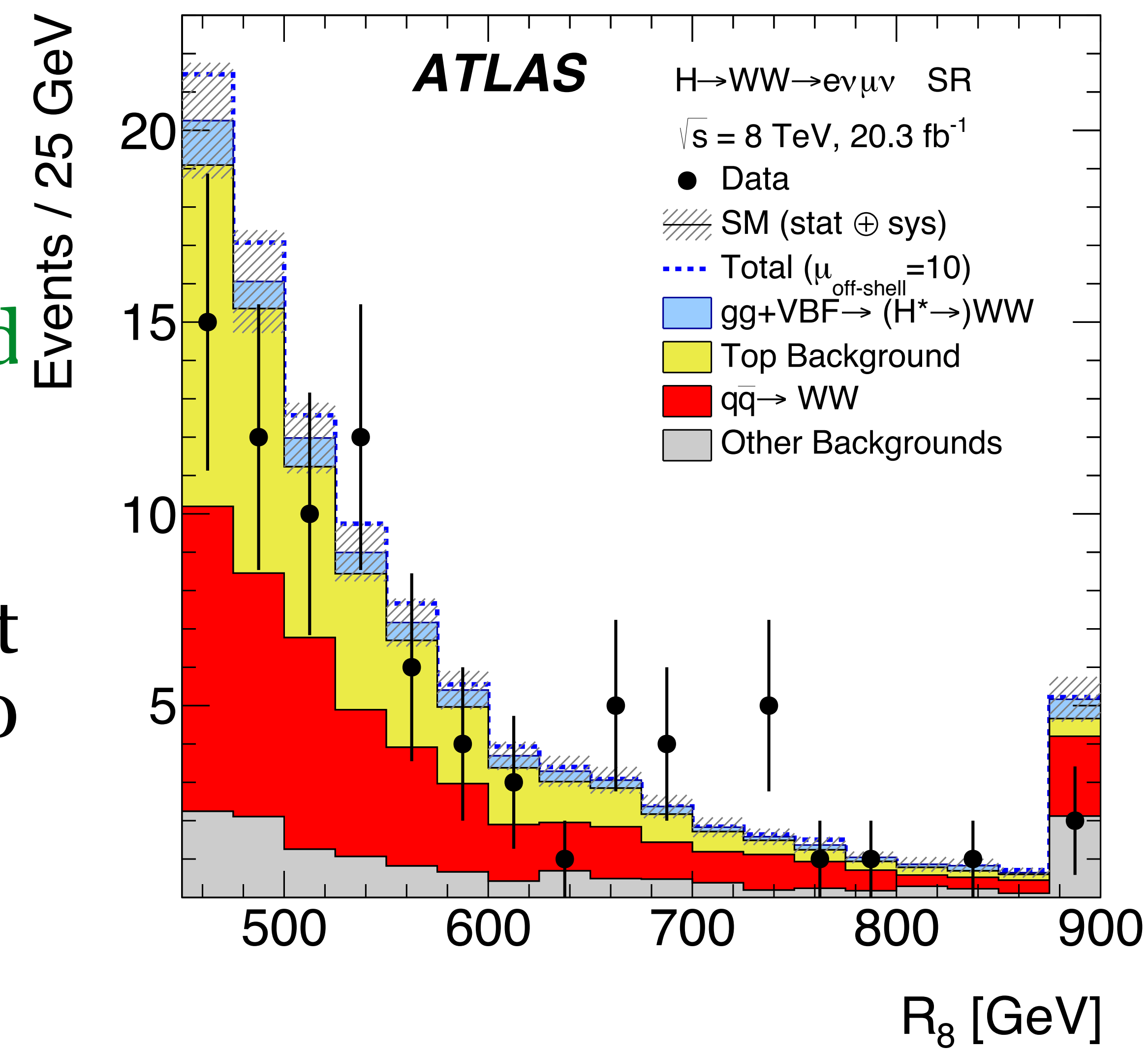
Off-Shell enriched region:

- ATLAS : 350GeV<m_T<1TeV
- CMS : 180GeV<mT<1TeV

H→WW→eνμν final state

2 different approaches:

- <u>in CMS:</u>
  - Off-Shell region defined with $m_{ll}>70$ GeV+ higher cut on $p_T ll$ (45 GeV) and on the p_T^{l2} (20 GeV)
  - signal extracted using a MVA or the 2D (m_T, m_{ll}) depending of the dataset (7 TeV/8 TeV) and the jet category (0 1, 2 jets)



- <u>in ATLAS:</u>
  - introduced a new variable

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

  - off-shell signal sensitive region defined with $R_8 > 450$ GeV and a = 0.8

- main backgrounds estimated using data-driven methods and control regions

Simulation of the main processes:

- **gg→H*→VV, gg→VV**
  - interferences computed at LO using gg2VV and MCFM (dynamic normalisation and factorisation scales: $m_{VV}/2$)
  - gg→H*→VV obtained at NNLO QCD using NNLO/LO K-factors (including NLO EWK corrections)
  - signal K-factor found to provide a reliable K-factor for gg→VV:
    - <u>2 approaches:</u>
      - CMS: use of signal K-factor on gg→VV with a 10% systematic
      - ATLAS: introduction of the parameter $R^B_{H*} = \dfrac{K(gg \to VV)}{K(gg \to H* \to VV)}$
- **VBF VV production + interference:**
  - simulated with PHANTOM in CMS, with MadGraph5 (cross checked by PHANTOM) in ATLAS
  - normalised to NNLO QCD and NLO EWK
- **qq→VV:**
  - simulated with POWHEG-BOX + PYTHIA at NLO QCD
  - NLO EW correction
  - m_{ZZ} k-factor NNLO/NLO applied in ATLAS

Systematics :

- Systematic uncertainties dominated by theoretical uncertainties
  - QCD scale uncertainty for gg→H*→VV and qq→VV
  - PDF for qq→VV and gg→VV processes
  - Uncertainty due to unknown k-factor for the gg→VV
    - ATLAS: result as a function of $R^B_{H*} = \frac{K(gg \to VV)}{K(gg \to H* \to VV)}$
    - 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:
  - Main are lepton efficiency and luminosity in the 4l channel
  - JES and data-driven background estimate are dominating for ZZ→2l2ν and WW→2l2ν

ATLAS

Systematic uncertainty	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 (CMS):

- Off-shell signal extraction:
  - H→ZZ→4l: binned maximum-likelihood using (m_{4l}, kinematic discriminent)
  - H→ZZ→2l2υ: binned maximum-likelihood fit to transverse mass m_T
  - H→WW→eυμυ: MVA or (m_T, m_{ll}) depending of the dataset and jet category

- Scanning off-shell cross-section with signal strength:

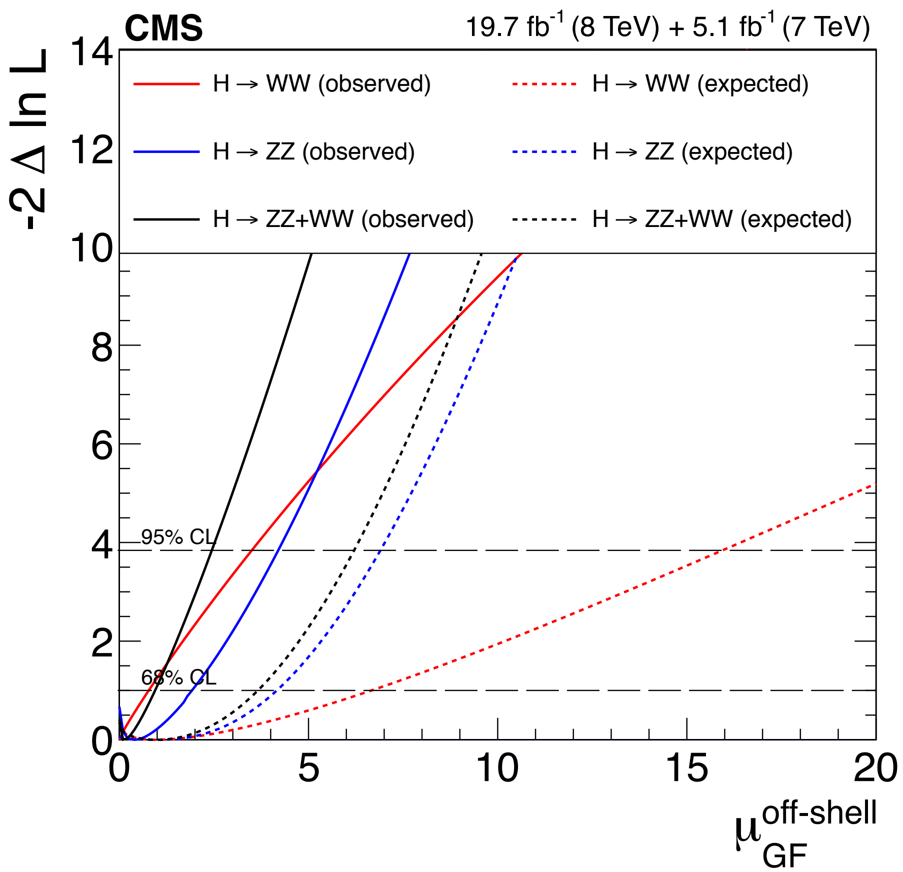
$$MC_{gg\to(H*\to)ZZ} = \mu \times MC_{gg\to H*\to ZZ} + \sqrt{\mu} \times MC_I + MC_{gg\to ZZ}$$

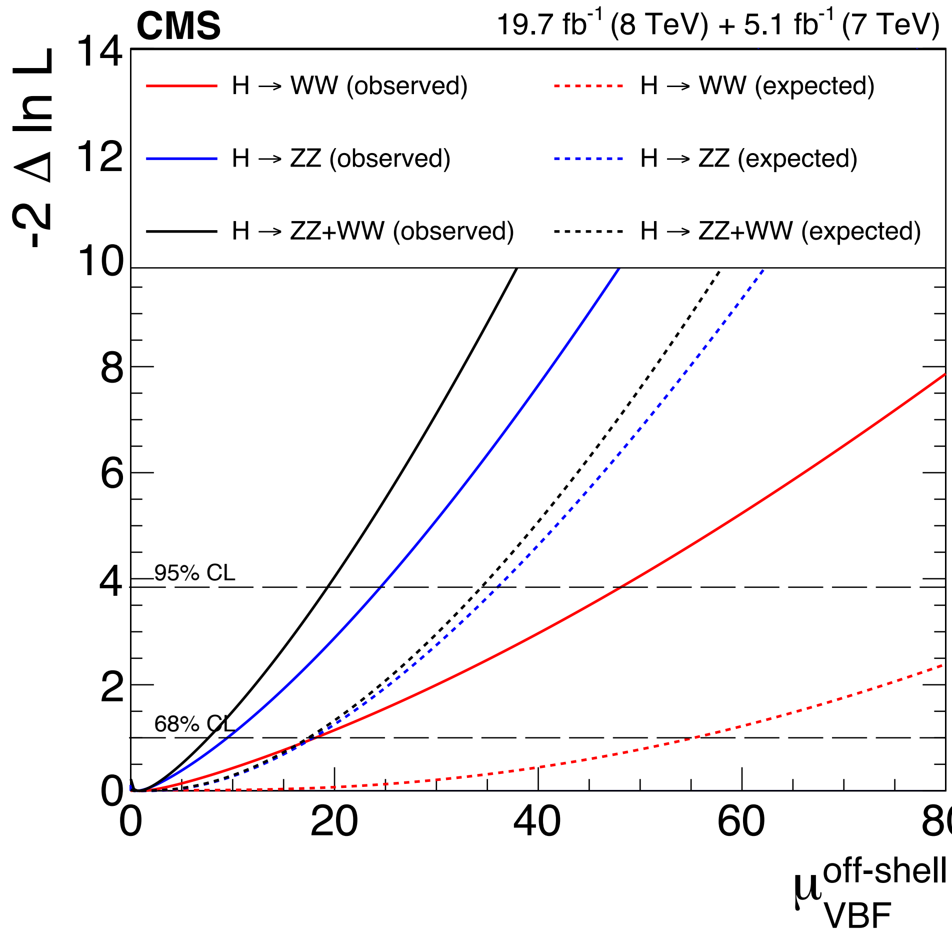
- Limits on $\mu_{ggH}^{\text{off-shell}}$ and $\mu_{VBF}^{\text{off-shell}}$ obtained separately :
  - while scanning one, the other is treated at a nuisance parameter
  - assuming SU2 custodial symmetry $\mu_{gg}^{ZZ}/\mu_{gg}^{WW} = \mu_{VBF}^{ZZ}/\mu_{VBF}^{WW}$

Results: Limit on $\mu_{offshell}$ (CMS)

$$\text{Expected event rate} = \mu_{GF}^{\text{off-shell}} \mathcal{P}^{gg}_{H,\text{off-shell}} + \sqrt{\mu_{GF}^{\text{off-shell}}}\, \mathcal{P}^{gg}_{\text{int}} + \mathcal{P}^{gg}_{\text{bkg}} + \mu_{VBF}^{\text{off-shell}} \mathcal{P}^{VBF}_{H,\text{off-shell}} + \sqrt{\mu_{VBF}^{\text{off-shell}}}\, \mathcal{P}^{VBF}_{\text{int}} + \mathcal{P}^{VBF}_{\text{bkg}} + \mu_{GF} \mathcal{P}^{gg}_{H,\text{on-shell}} + \mu_{VBF} \mathcal{P}^{VBF}_{H,\text{on-shell}} + \mathcal{P}^{q\bar{q}}_{\text{bkg}} + \mathcal{P}_{\text{other bkg}}.$$

under the assumption that $\mu_{gg}^{ZZ}/\mu_{gg}^{WW} = \mu_{VBF}^{ZZ}/\mu_{VBF}^{WW} = 1$





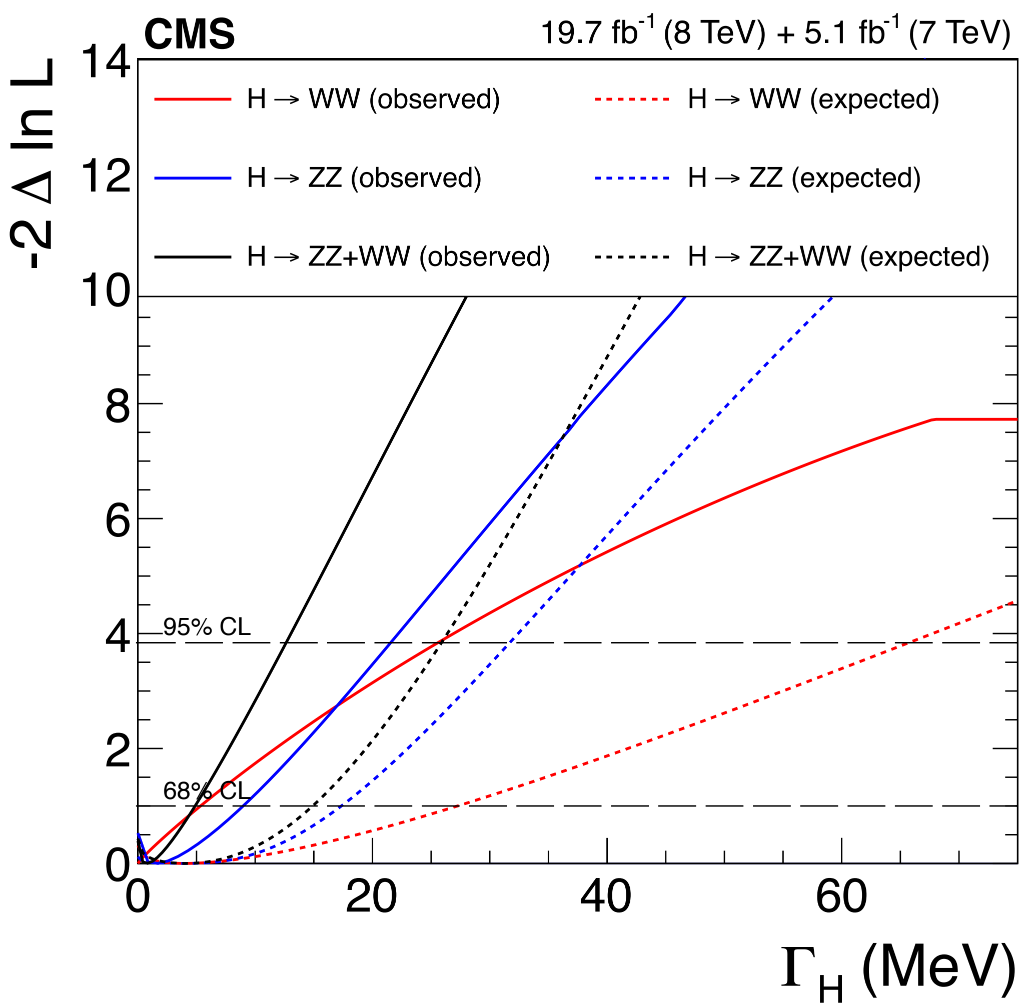
$\boxed{\mu_{gg}^{\text{off-shell}} < 2.4 \text{ @ 95\% CL (expected } \mu_{gg}^{\text{off-shell}} < 6.2)}$

$\boxed{\mu_{VBF}^{\text{off-shell}} < 19.3 \text{ @ 95\% CL (expected } \mu_{VBF}^{\text{off-shell}} < 34.4)}$

Results: Limit on Higgs Width (CMS)

$$\text{Expected event rate} = \mu_{\mathrm{GF}}\, r\, \mathcal{P}^{\mathrm{gg}}_{\mathrm{H,\,off\text{-}shell}} + \sqrt{\mu_{\mathrm{GF}}\, r}\, \mathcal{P}^{\mathrm{gg}}_{\mathrm{int}} + \mathcal{P}^{\mathrm{gg}}_{\mathrm{bkg}} + \mu_{\mathrm{VBF}}\, r\, \mathcal{P}^{\mathrm{VBF}}_{\mathrm{H,\,off\text{-}shell}} + \sqrt{\mu_{\mathrm{VBF}}\, r}\, \mathcal{P}^{\mathrm{VBF}}_{\mathrm{int}} + \mathcal{P}^{\mathrm{VBF}}_{\mathrm{bkg}} + \mu_{\mathrm{GF}}\, \mathcal{P}^{\mathrm{gg}}_{\mathrm{H,\,on\text{-}shell}} + \mu_{\mathrm{VBF}}\, \mathcal{P}^{\mathrm{VBF}}_{\mathrm{H,\,on\text{-}shell}} + \mathcal{P}^{\mathrm{q\bar{q}}}_{\mathrm{bkg}} + \mathcal{P}_{\mathrm{other\,bkg}},$$

$$r = \Gamma_{\mathrm{H}}/\Gamma^{\mathrm{SM}}_{\mathrm{H}}$$



$\boxed{\Gamma_{\mathrm{H}} < 13 \text{ MeV @ 95\% CL (expected } \Gamma_{\mathrm{H}} < 26 \text{ MeV)}}$

- limit obtained under the assumption $\mu_{gg}^{ZZ}/\mu_{gg}^{WW} = \mu_{VBF}^{ZZ}/\mu_{VBF}^{WW}$
  - relaxing it brings the limit @95% CL to $\Gamma_H < 15$ MeV
- WW decay channel alone: $\Gamma_H < 26$ MeV (expected 66 MeV)
  ZZ decay channel alone:
  $\Gamma_H < 22$ MeV
  (expected 33 MeV)
- p-value of the observed limit = 7.4 %

Results (ATLAS)

- Off-shell signal extraction:
  - $H \to ZZ \to 4l$: binned maximum-likelihood fit to the matrix element discriminant
  - $H \to ZZ \to 2l2\nu$: binned maximum-likelihood fit to transverse mass m_T
  - $H \to WW \to e\nu\mu\nu$: maximum-likelihood fit is performed using the event yields in the signal region and the two control regions

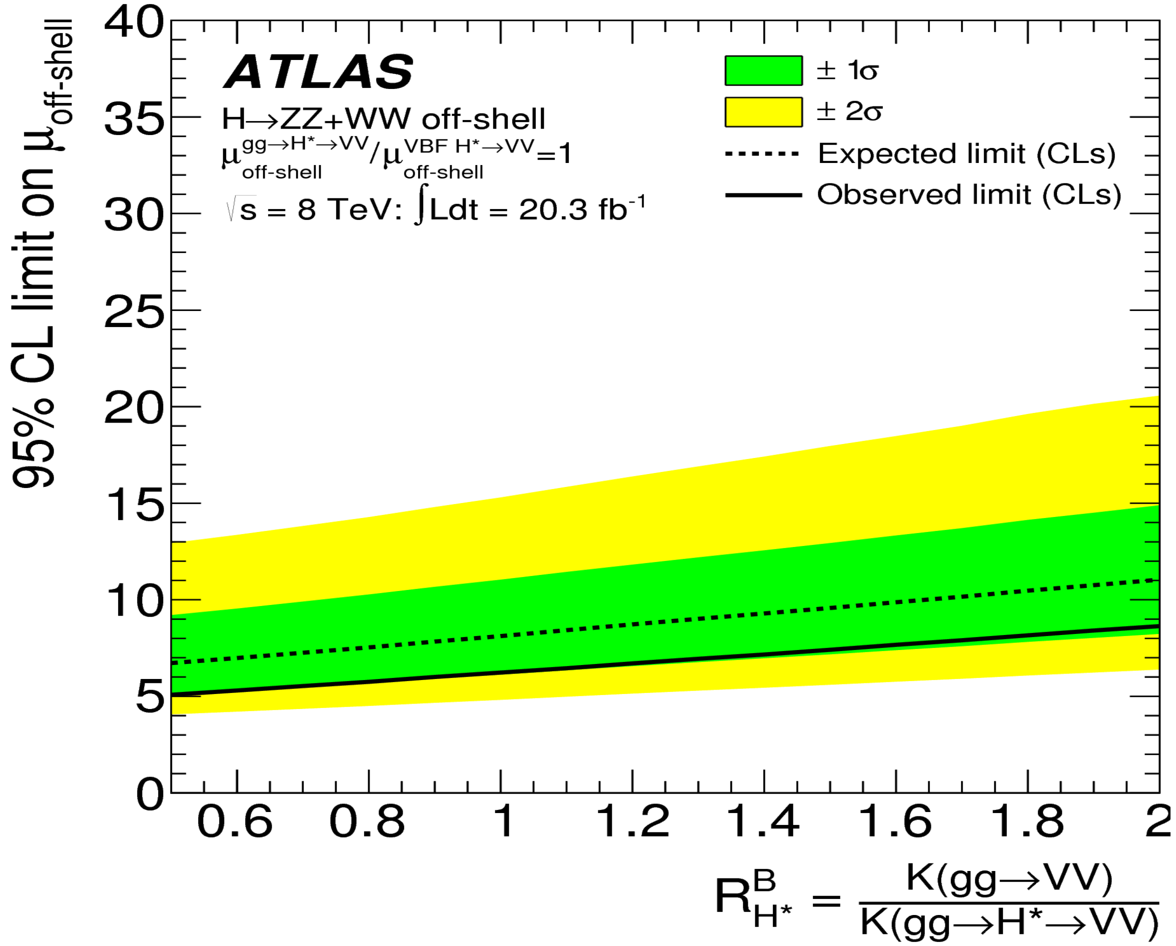
- Scanning off-shell cross-section with signal strength:

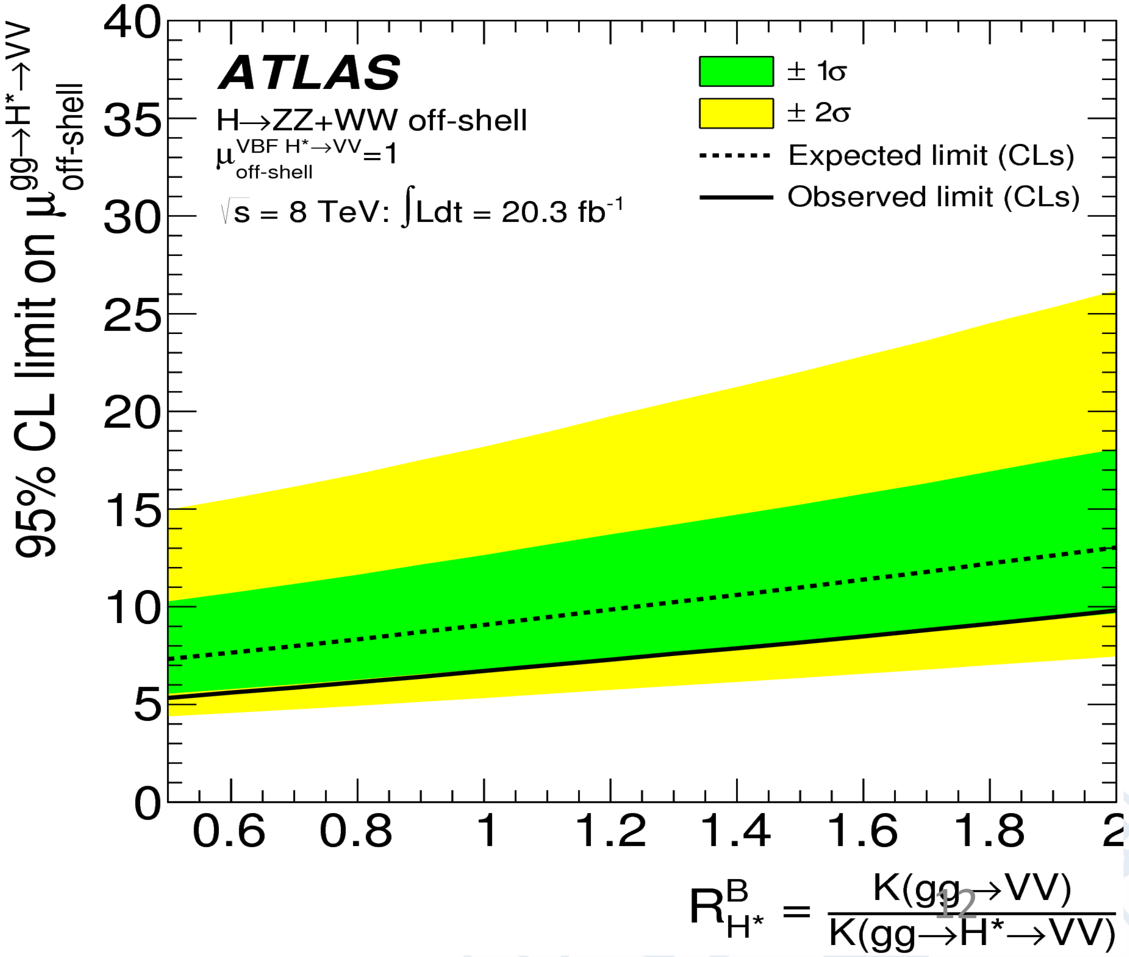
$$MC_{gg\to(H*\to)ZZ} = \mu \times MC_{gg\to H*\to ZZ} + \sqrt{\mu} \times MC_I + MC_{gg\to ZZ}$$

- Limits on $\mu_{\text{off-shell}}$ obtained under 2 alternative assumption:
  - fixing the ratio between the gg→H* and the VBF one $\mu^{VBF}_{off-shell} = 1$
  - fixing the VBF signal strength to the SM prediction $\mu^{gg\to H*}_{off-shell}/\mu^{VBF}_{off-shell} = 1$

Results: Limit on $\mu_{offshell}$ (ATLAS)

- Limits computed versus $R^B_{H*} = \frac{K(gg \to VV)}{K(gg \to H* \to VV)}$





$\mu_{off\text{-}shell} < 6.2$ @ 95% CL for
$R_{H*}{}^B = 1$
(expected $\mu_{off\text{-}shell} < 8.1$)

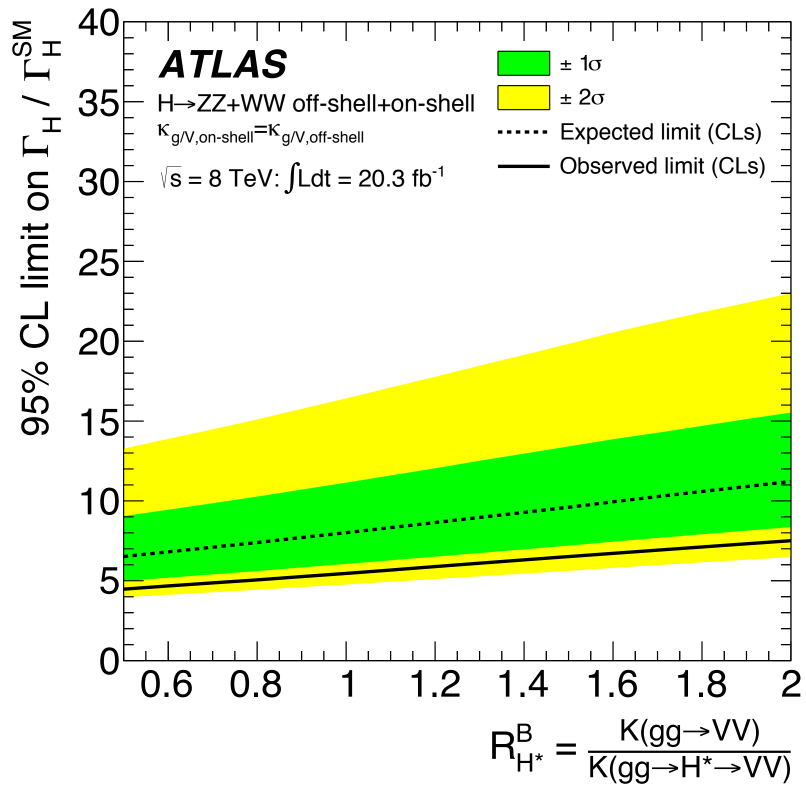
$\mu^{gg\to H*\to VV}_{off-shell} < 6.7$ @ 95% CL for
$R_{H*}{}^B = 1$
(expected $\mu^{gg\to H*\to VV}_{off-shell} < 9.1$)

No large dependance on R

Results: Limit on Higgs Width (ATLAS)

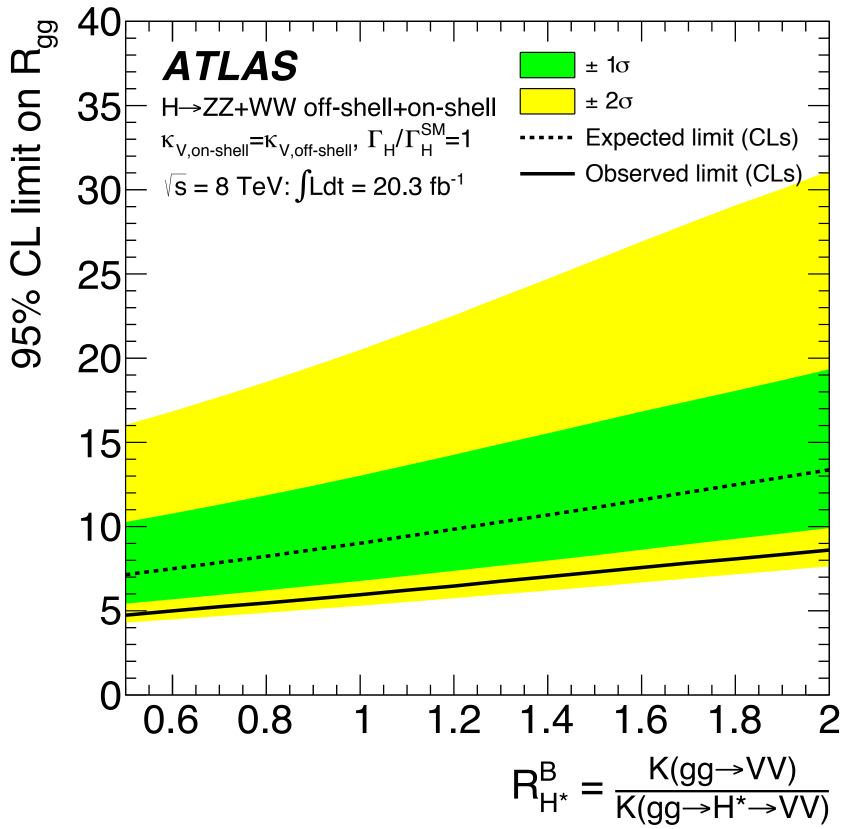
- Limit on Γ_H can be obtained by combining the on-shell with the off-shell signal strength measurement
  - μ_{ggH} and μ_{VBF} profiled on the data
  - assume same on-shell and off-shell couplings ($\kappa_{g/V,\text{ on-shell}} = \kappa_{g/V,\text{ off-shell}}$)

$\Gamma_H < 22.7$ MeV @ 95% CL for $R_{H^*}{}^{B} = 1$
(expected $\Gamma_H < 33$ MeV)



- Assuming $\Gamma_H = \Gamma_H^{SM}$ and $\kappa_{V,\text{ on-shell}} = \kappa_{V,\text{ off-shell}}$, can interpret result as a limit on $R_{gg} = \kappa_{g,\text{ on-shell}}/\kappa_{g,\text{ off-shell}}$

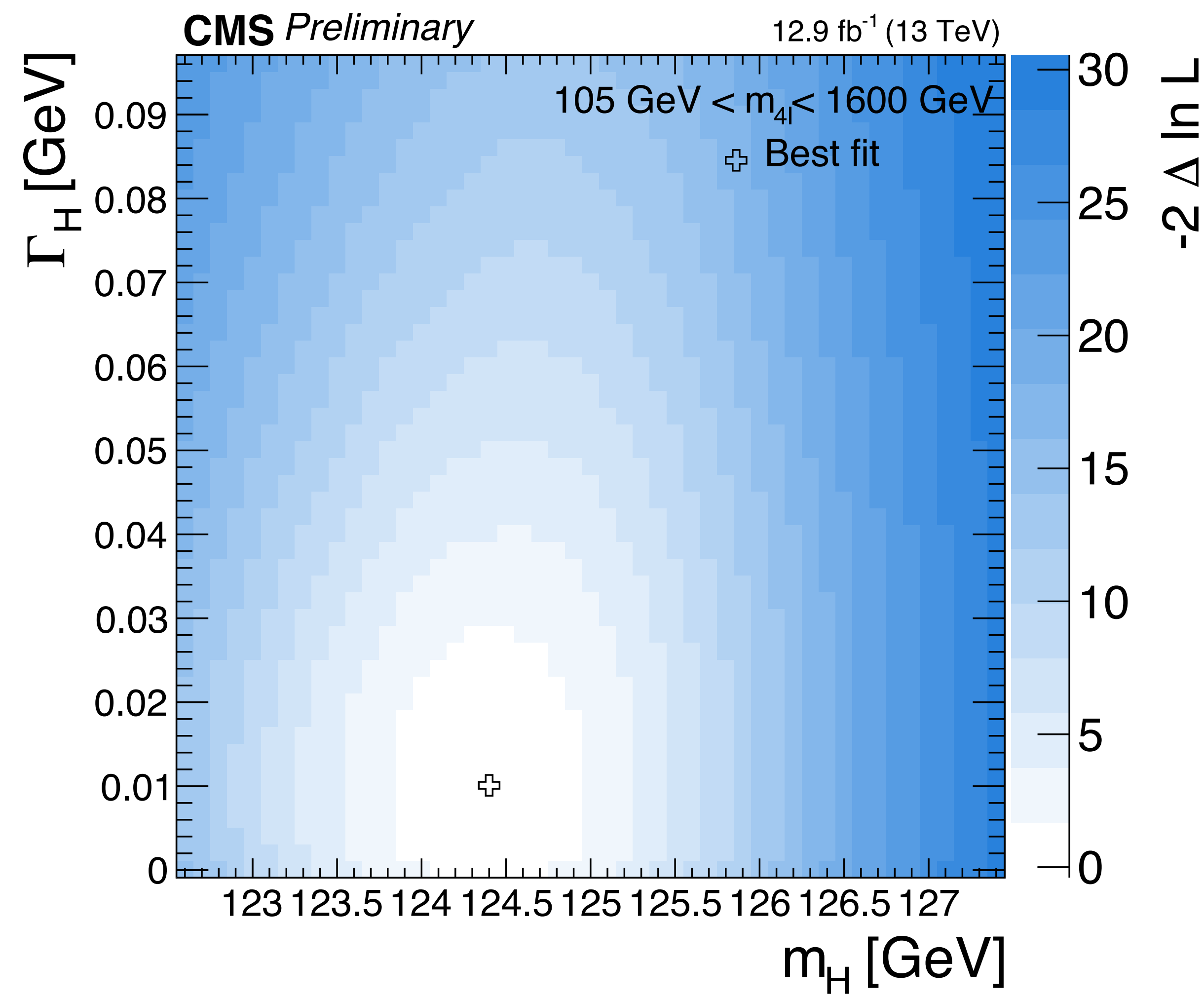
$R_{gg} < 6.0$ @ 95% CL for $R_{H^*}{}^{B} = 1$
(expected $R_{gg} < 9.0$)



First Results with 2016 data

CMS PAS HIG-16-033

- In $H^* \rightarrow ZZ \rightarrow 4l$ channel:
  - Measurement of the Higgs properties already performed by CMS in 2015 data + the first 12.9 fb-1 of 2016 data analysed
  - Addition in the high mass region of a 2 jet category, sensitive to VBF



$\Gamma_H < 41$ MeV @ 95% CL (expected $\Gamma_H < 32$ MeV)
best-fit = $0.01^{+0.014}_{-0.01}$ GeV

Constraints on anomalous couplings

CMS: Phys. Rev. D **92**, 072010

Limit allowing anomalous coupling:

- CMS H*→ZZ→4l also performed to constrain possible anomalous couplings

$$A(\mathrm{HVV}) \propto \left[a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_{V1}+q_{V2})^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}} \frac{(q_{V1}^2+q_{V2}^2)}{(\Lambda_1)^2}\right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

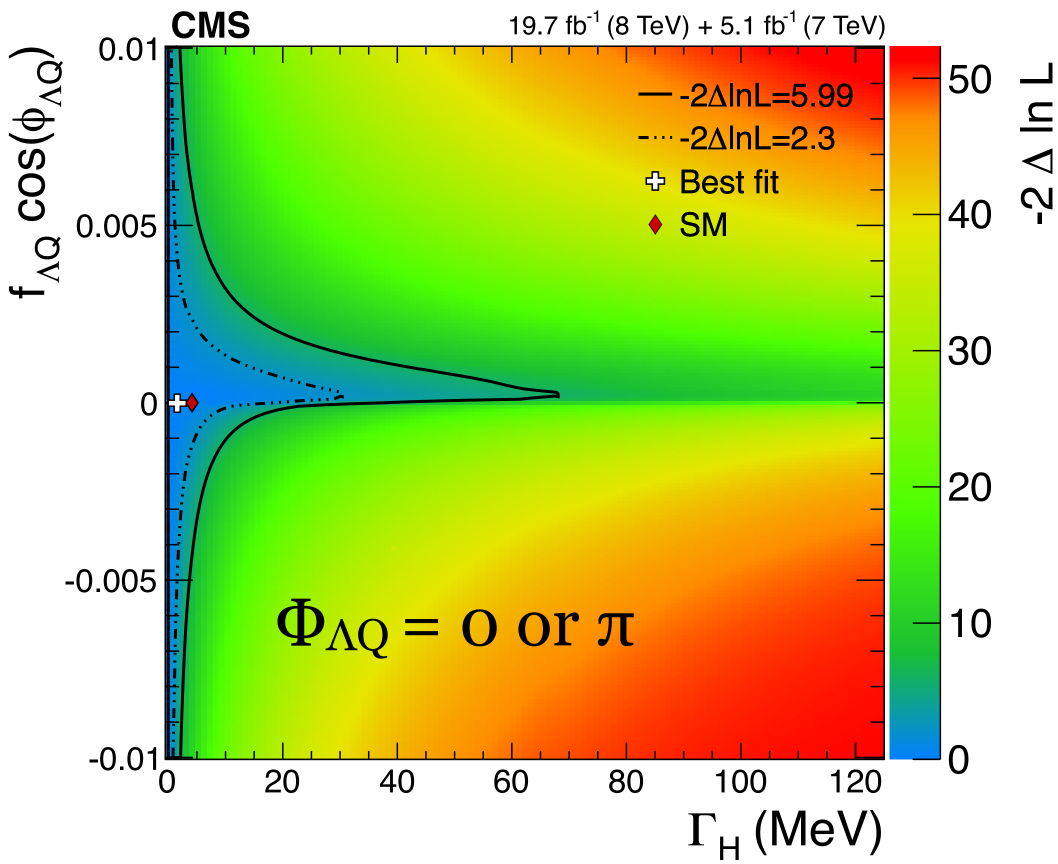
$$f^{(i)\mu\nu} = \epsilon_{Vi}^{\mu} q_{Vi}^{\nu} - \epsilon_{Vi}^{\nu} q_{Vi}^{\mu}$$

Additional term depending of the invariant mass can be probed by the off-shell region

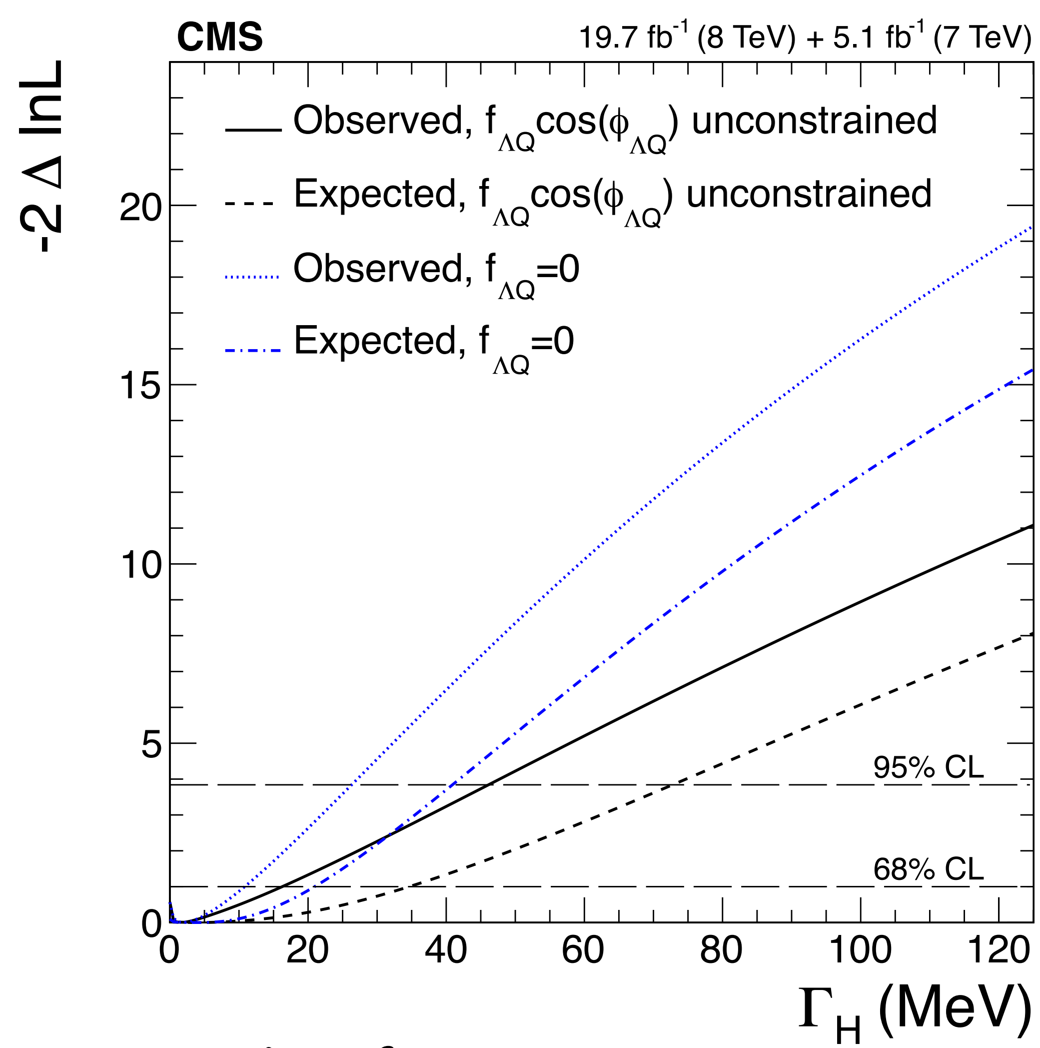
- Limit of the off-shell effective fraction $f_{\Lambda Q}$ due to Λ_Q as a function of Γ_H can be obtained.

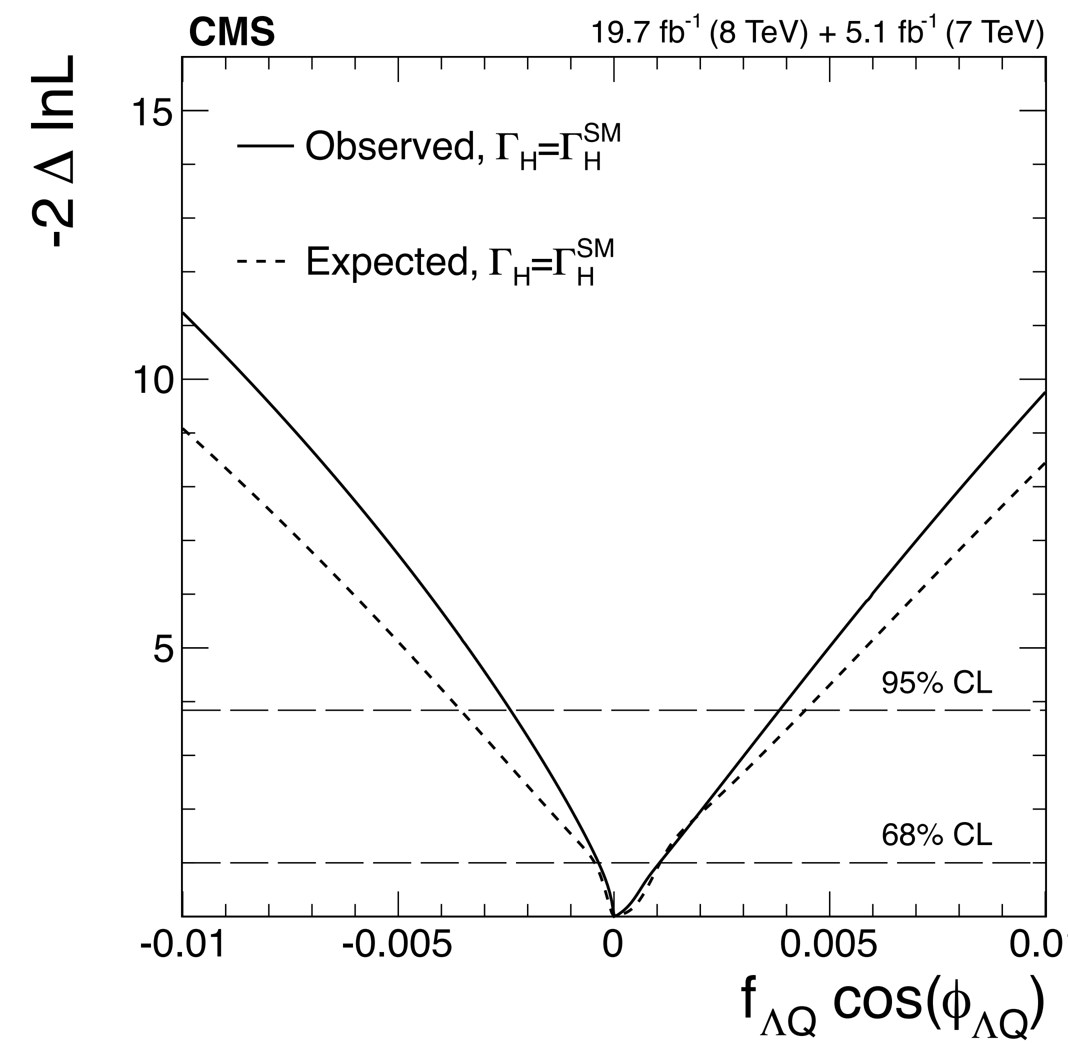
$$f_{\Lambda Q} = \frac{m_H^4/\Lambda_Q^4}{|a_1|^2 + m_H^4/\Lambda_Q^4}.$$

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



Limits on Γ_H and $f_{\Lambda Q}$:





- Assuming $f_{\Lambda Q} = 0$
  $\Gamma_H < 26$ MeV @ 95% CL
  (expected $\Gamma_H < 41$ MeV)

- $f_{\Lambda Q}$ unconstrained (but $\Phi_{\Lambda Q} = 0$ or π)
  $\Gamma_H < 46$ MeV @ 95% CL
  (expected $\Gamma_H < 73$ MeV)

- Allowed region assuming Γ_H^{SM}:
  $2.4 \times 10^{-3} < f_{\Lambda Q} < 3.8 \times 10^{-3}$
  (expected $-3.6 \times 10^{-3} < f_{\Lambda Q} < 4.4 \times 10^{-3}$)

Conclusion

ATLAS:ATL-PHYS-PUB-2015-024

- With run 1 data, limit on the off-shell Higgs cross-section better than ~ 10 time the cross section predicted by the Standard Model (scale of direct limit is 3 GeV in the 4l decay channel)

- Very interesting measurement to perform with RUN2 data (and HL-LHC)
  - measurement sensitivity @ 20% level with 3000fb^{-1} (if no theoretical uncertainties)

- Theoretical knowledge of the gg→H*→VV process and the backgrounds at higher orders in QCD will be a key point