Evidence of the off-shell Higgs production and constraints on the total decay width of the Higgs boson in the $ZZ \to 4l$ and $ZZ \to 2l2v$ decay channels with the ATLAS detector

@La Thuile 2023 - Les Rencontres de Physique de la Vallée d'Aoste

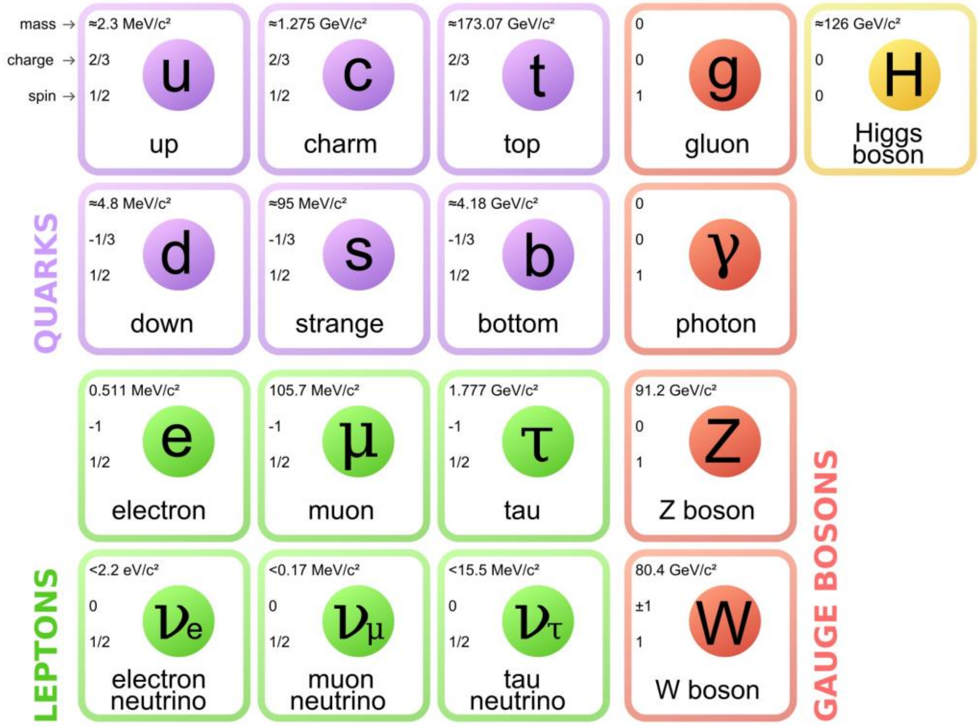
05-11 March 2023

Yingjie Wei

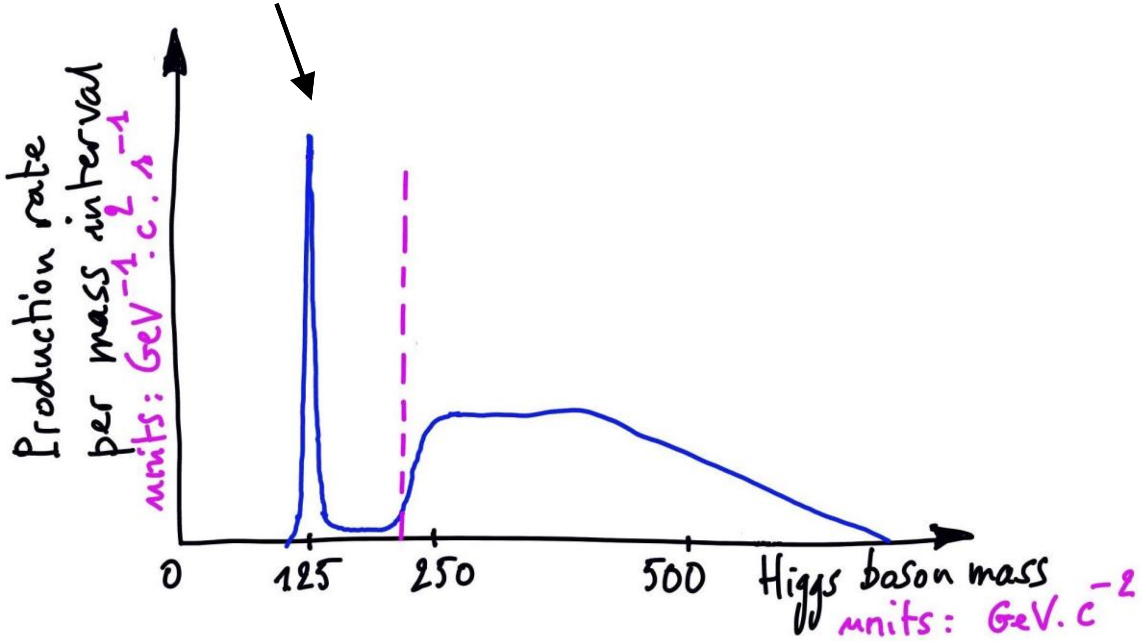
On behalf of the ATLAS collaboration

Introduction

In 2012, both ATLAS and CMS at LHC discovered the Higgs particle.



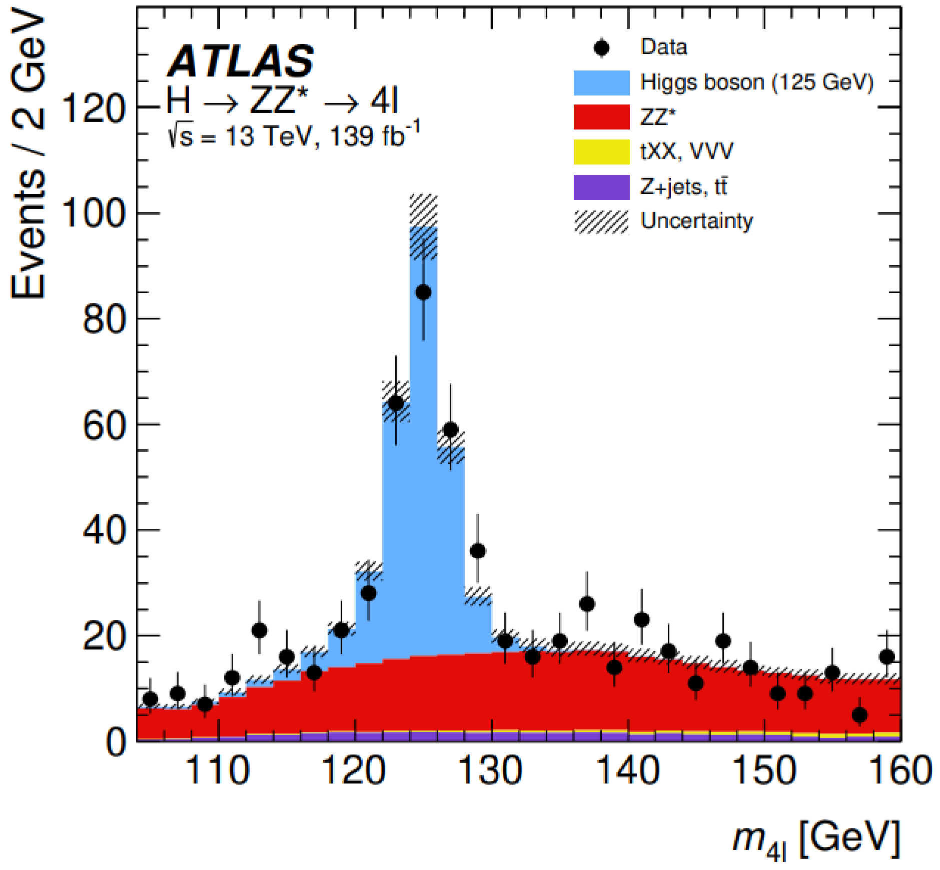
Year 2012



Higgs mass measurement

- The importance of having a precise Higgs mass:
  - Test the consistency of the SM
  - Predicted in some BSM
  - (plus top) Stability of the Universe [1, 2]

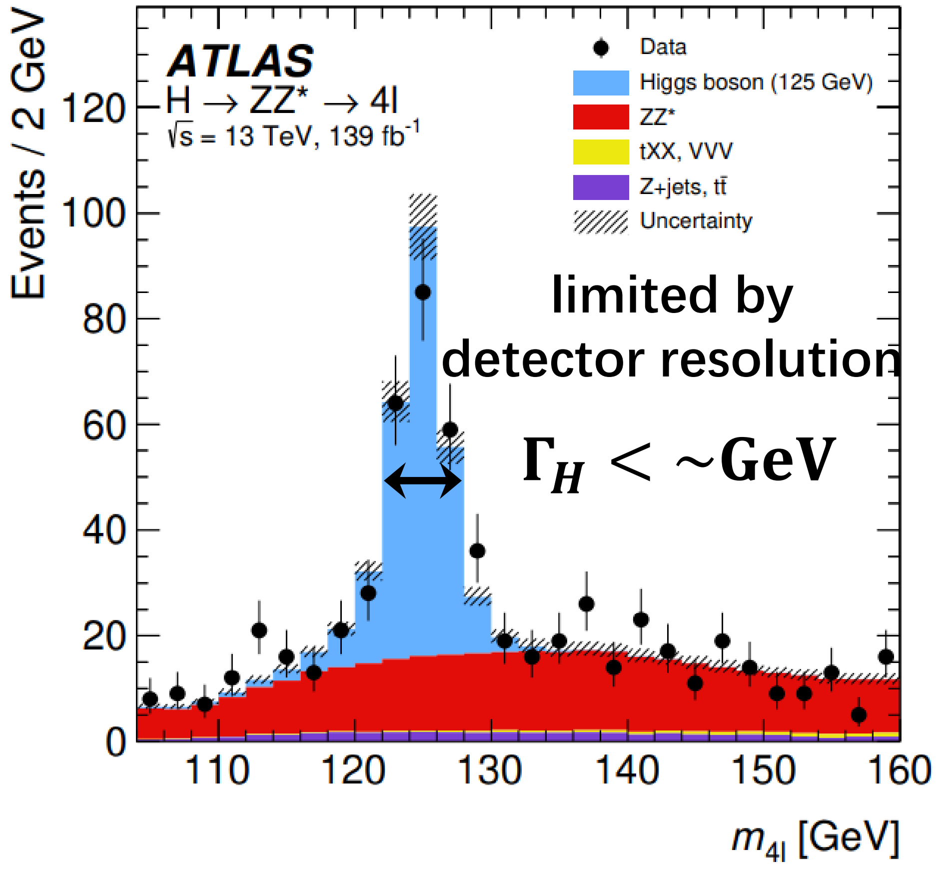
arXiv: 2207.00320



Run 1+2: 124.94 ± 0.17(stat.) ± 0.03(syst.) GeV

Higgs width measurement

arXiv: 2207.00320



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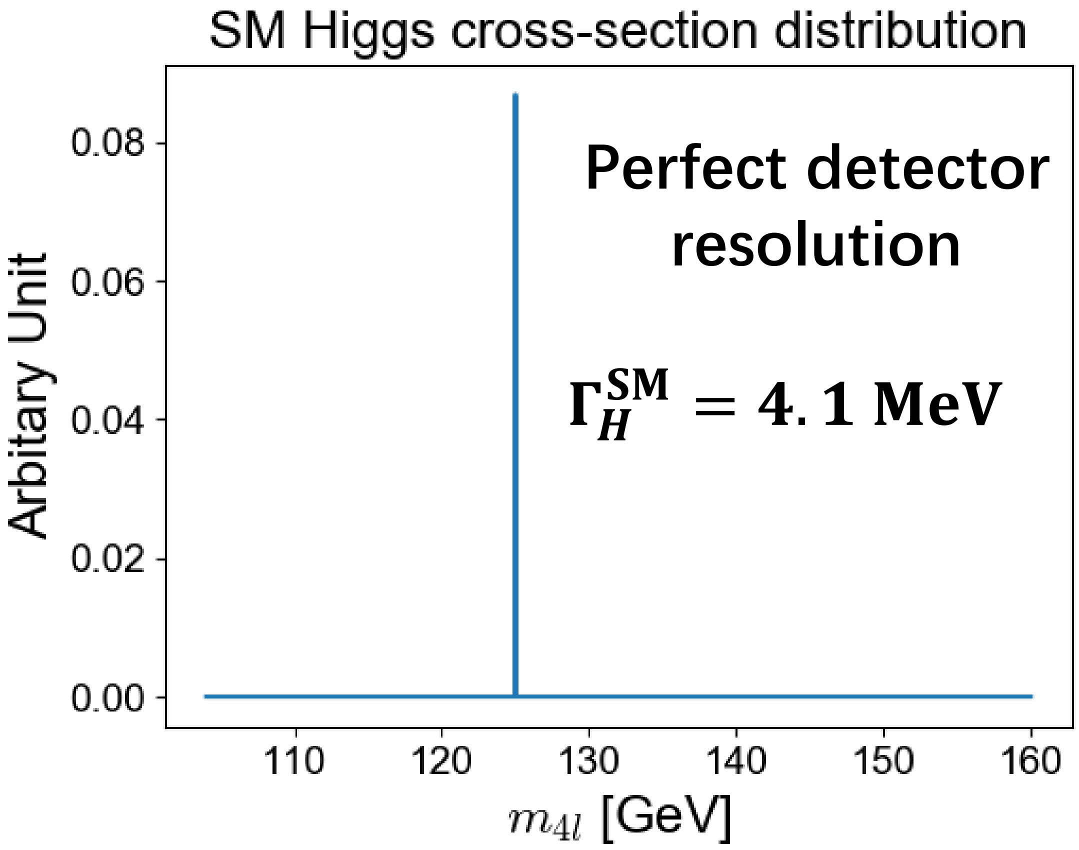
Higgs width measurement

The SM prediction



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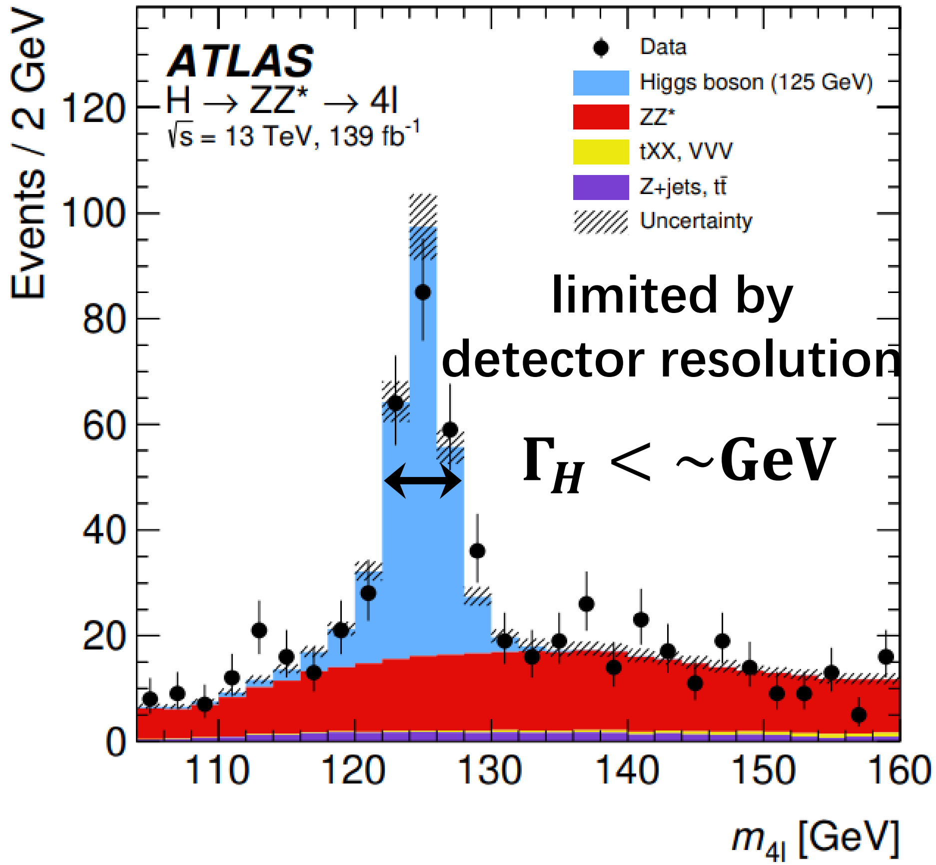

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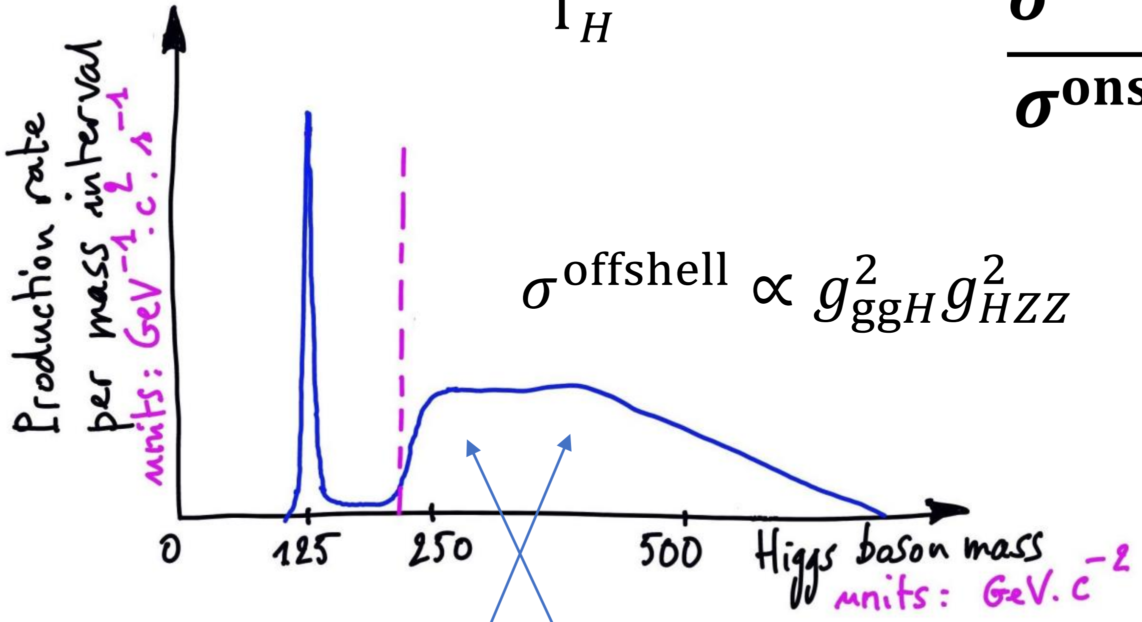
Higgs width measurement

- Indirect method

$$\sigma^{\text{onshell}} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}$$

$$\boldsymbol{\frac{\sigma^{\text{offshell}}}{\sigma^{\text{onshell}}} \propto \Gamma_H}$$



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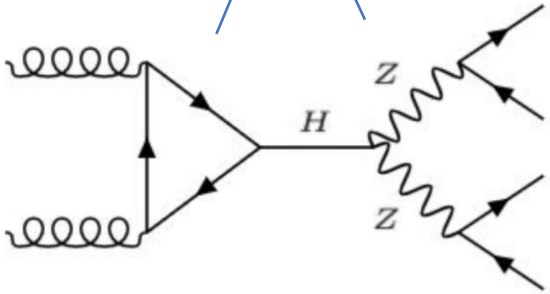
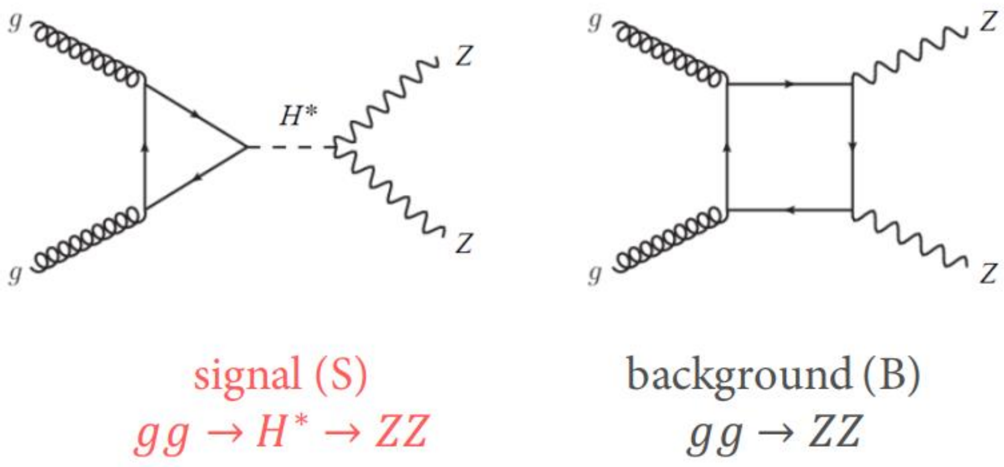


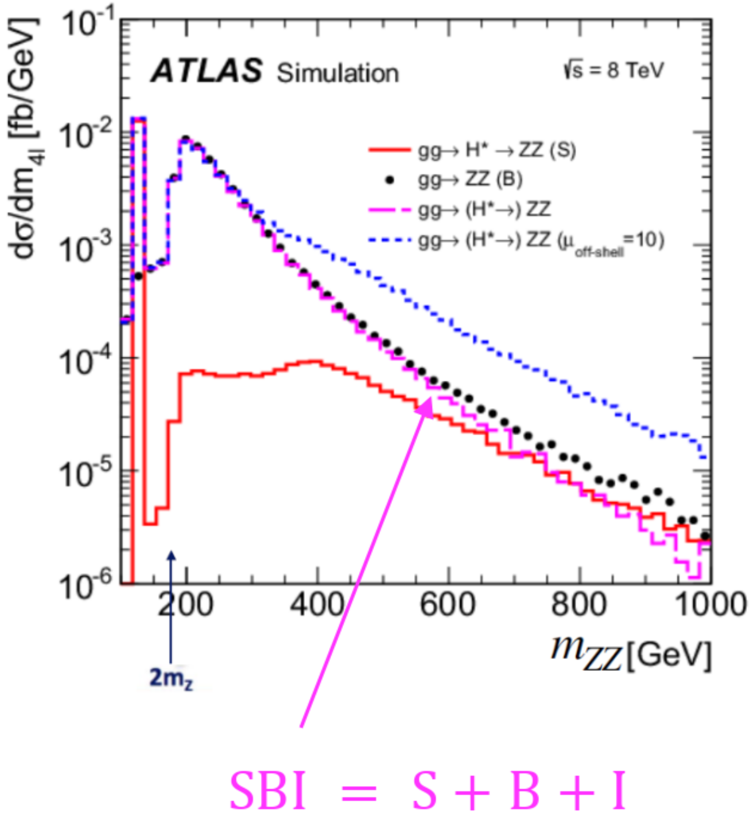
$\rightarrow \boldsymbol{4\ell}$ or $\boldsymbol{2\ell 2\nu}$

- Paper (Nov 2022):
  ATLAS-CONF-2022-068

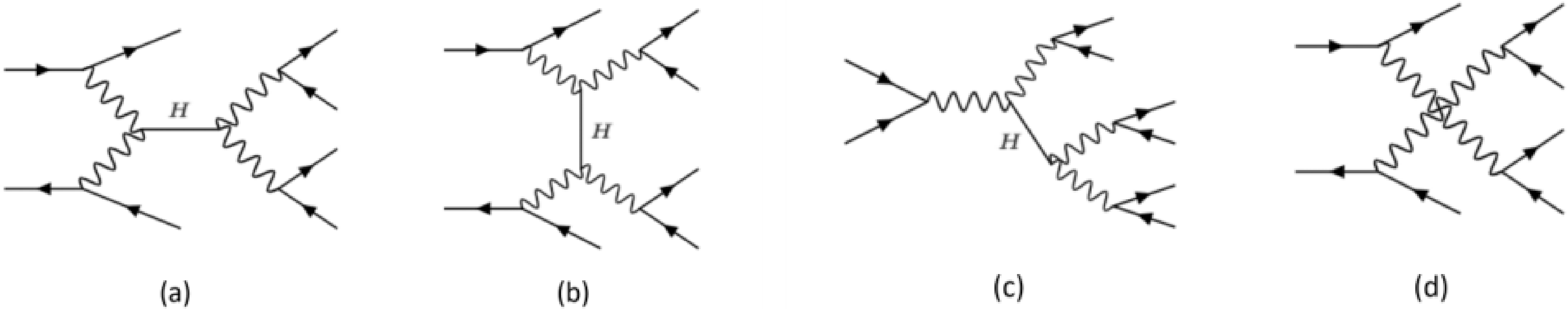
ggF Signal-background interference

- The existence of the SM off-shell Higgs will reduce the yield due to a large **negative** interference (to preserve unitarity), i.e. Sig+Bkg+intf < Bkg only





EW signal, background and interference



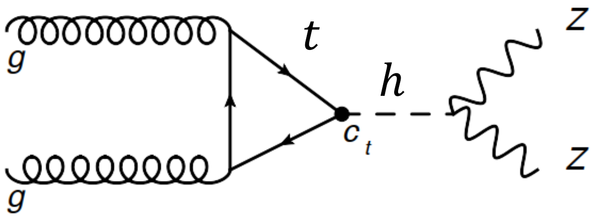
VBF s-channel VBF t-channel VH VBS

Non-negligible interference among all the components

BSM/EFT analysis of the off-shell Higgs

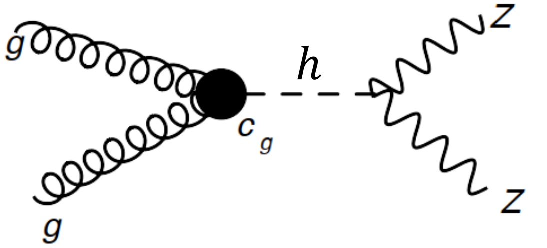
- ❑ Off-shell Higgs can be used to probe EFT operators at ~ TeV level.
- ❑ The degeneracy of Higgs-gluon and Higgs-top can break in the off-shell region.

SM

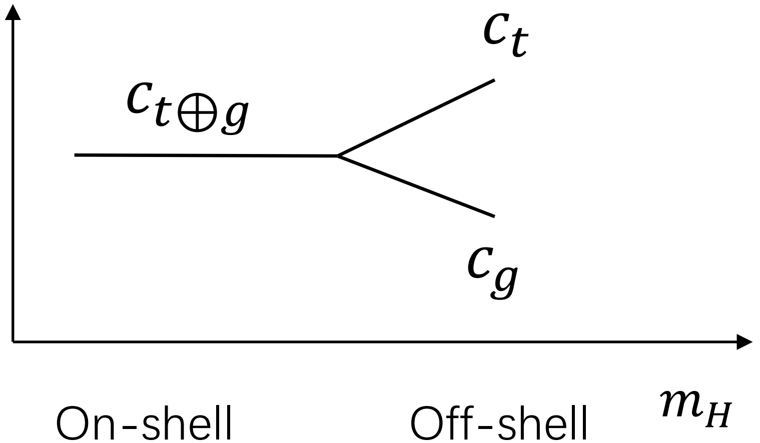


In SM, c_t = 1

BSM



In SM, c_g = 0

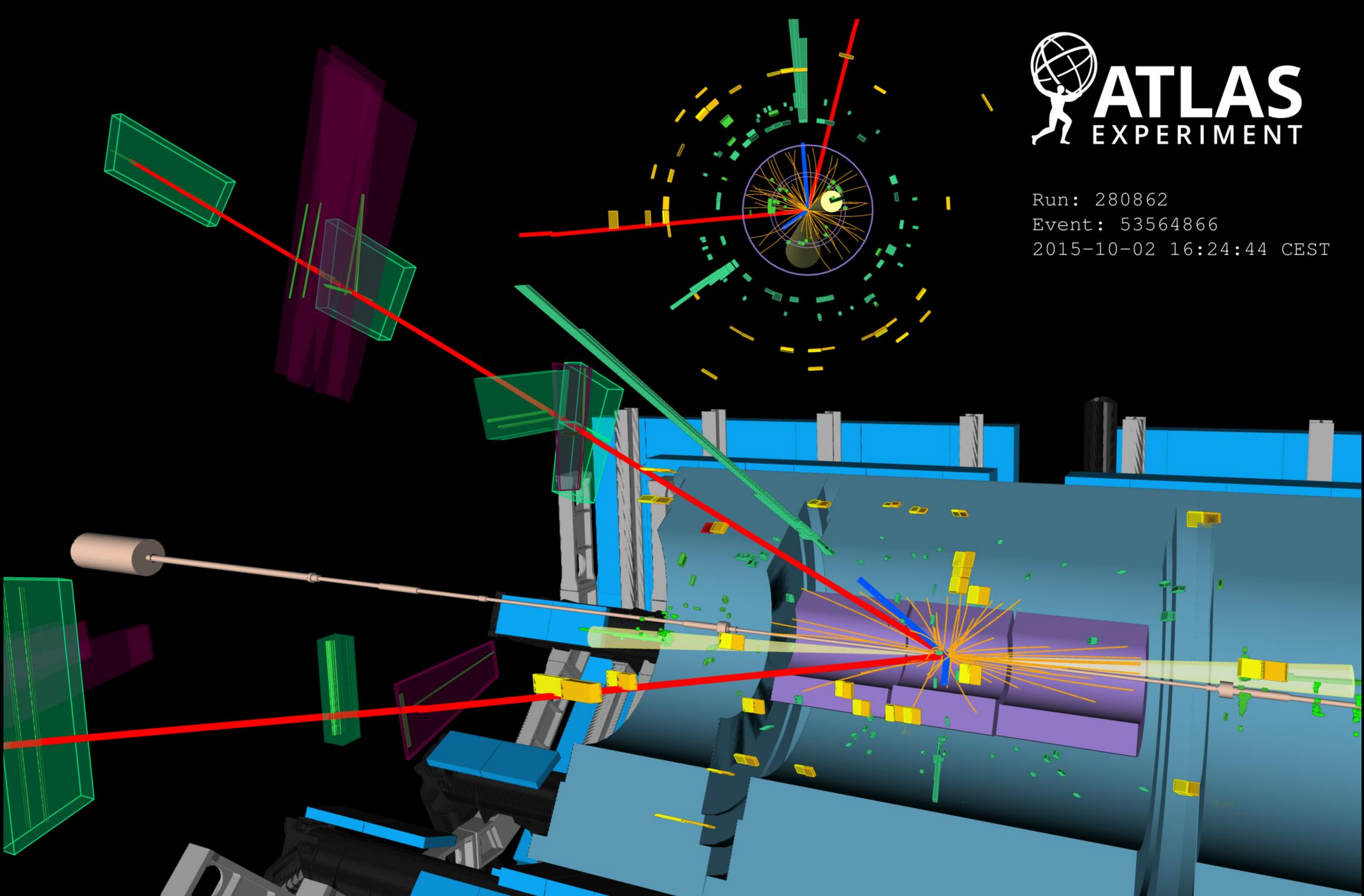


On-shell

(Higgs Low-energy theorem)

Off-shell

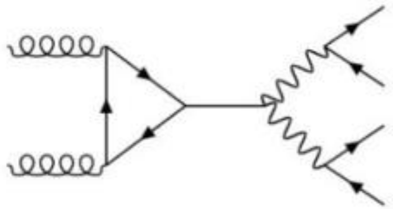
220GeV-2TeV


ATLAS
EXPERIMENT
Run: 280862
Event: 53564866
2015-10-02 16:24:44 CEST

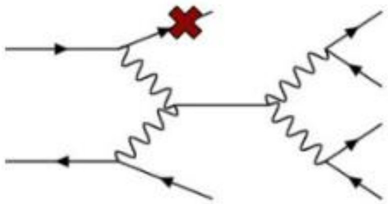
Event categories

Jets are selected with $p_T > 30$ GeV and $|\eta| < 4.5$

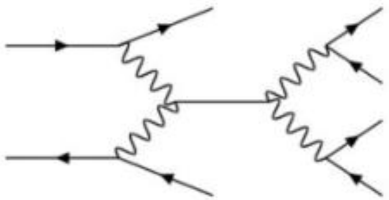
ggF Signal region



1 jet mixed signal region



EW signal region



$n_{\text{jets}} = 0$

$n_{\text{jets}} = 1$ and $\eta_j < 2.2$

$n_{\text{jets}} \geq 2$ and $|\Delta\eta_{jj}| < 4.0$

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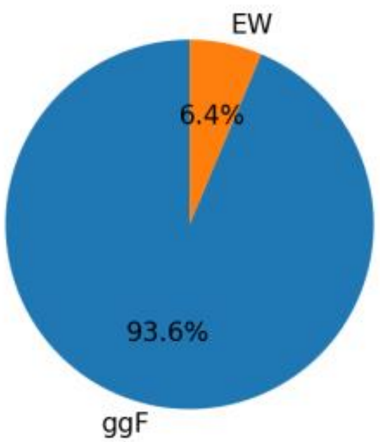
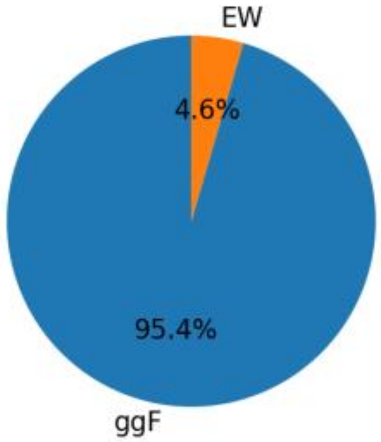
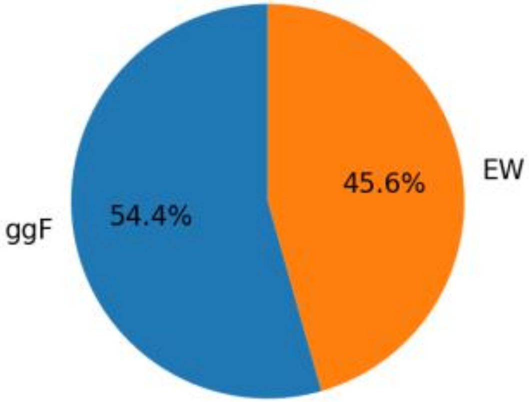
Fractions in 4ℓ channel







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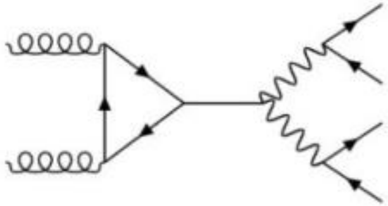

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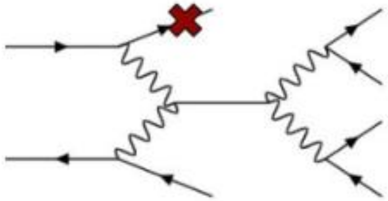
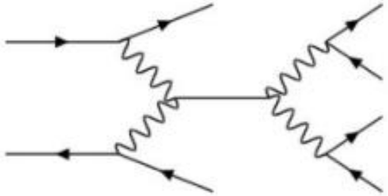


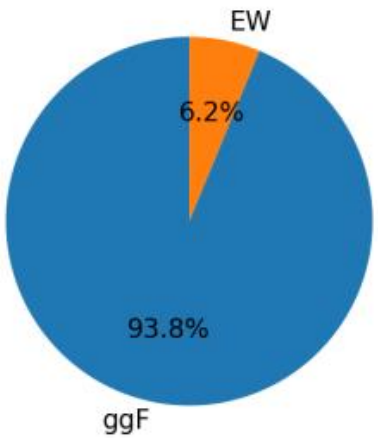
$n_{\text{jets}} = 1$ and $|\eta_j| \geq 2.2$

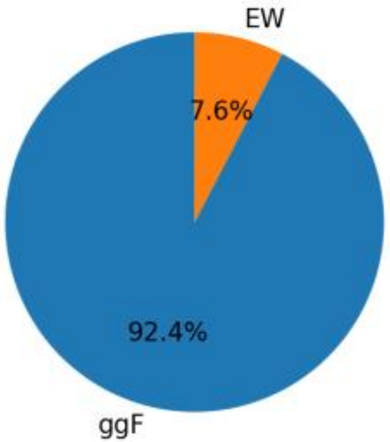
EW signal region

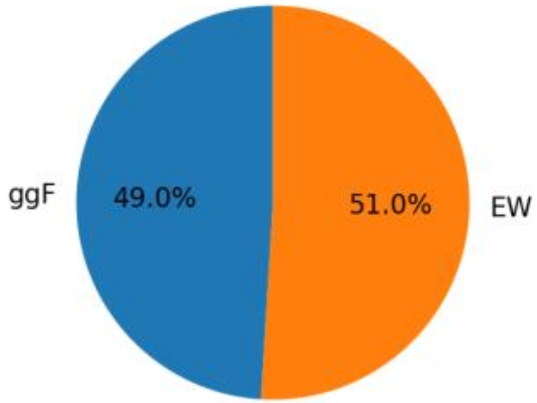


$n_{\text{jets}} \geq 2$ and $|\Delta\eta_{jj}| \geq 4.0$

Fractions in $2\ell 2\nu$ channel

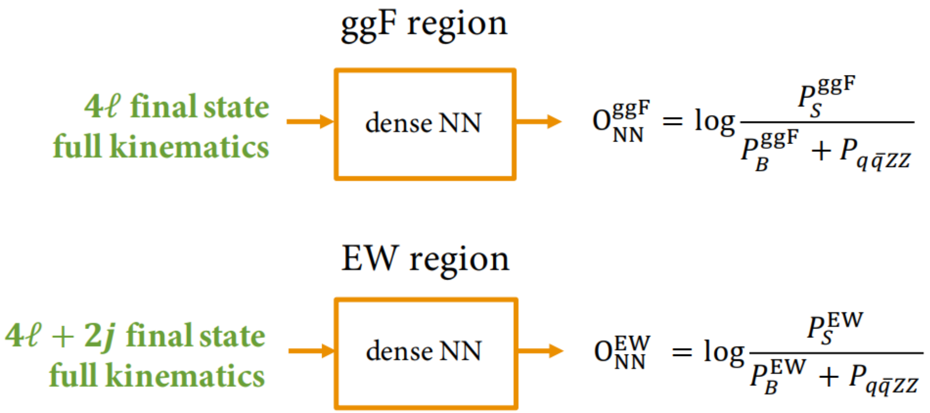


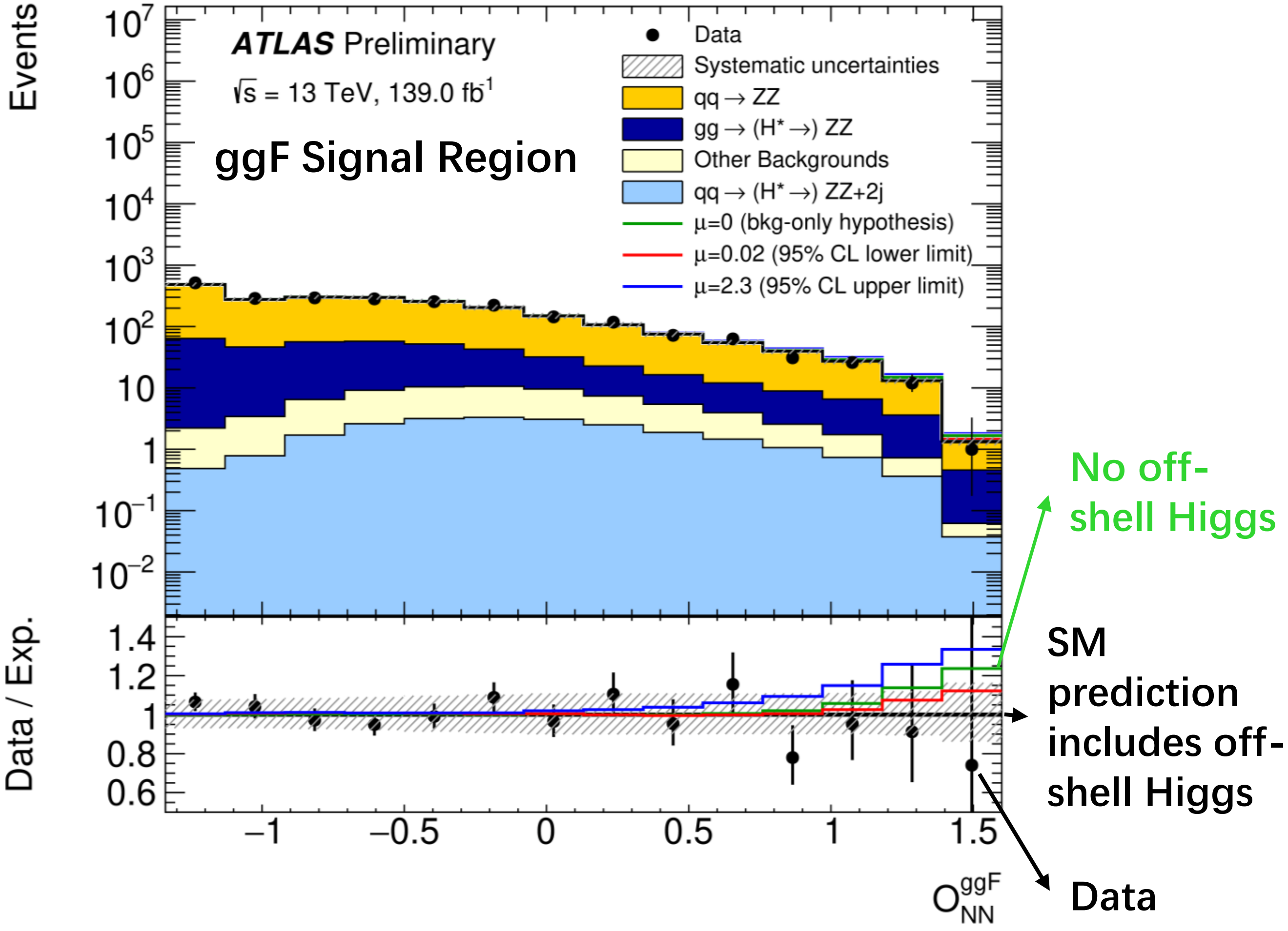




$H^* \to ZZ \to 4\ell$ channel

- Final state decay objects (e and μ) can be fully reconstructed in the 4ℓ channel
- Observables: neural network method (inputs: P_T, η, matrix-element, etc)





- Background: qqZZ (main), ggZZ

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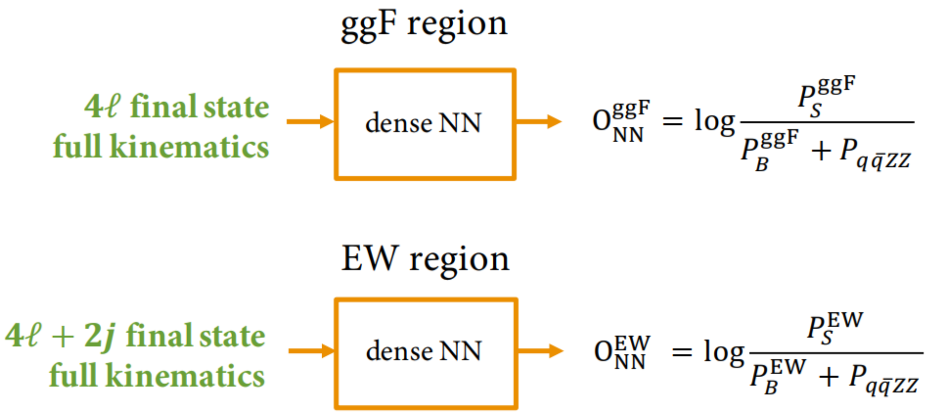

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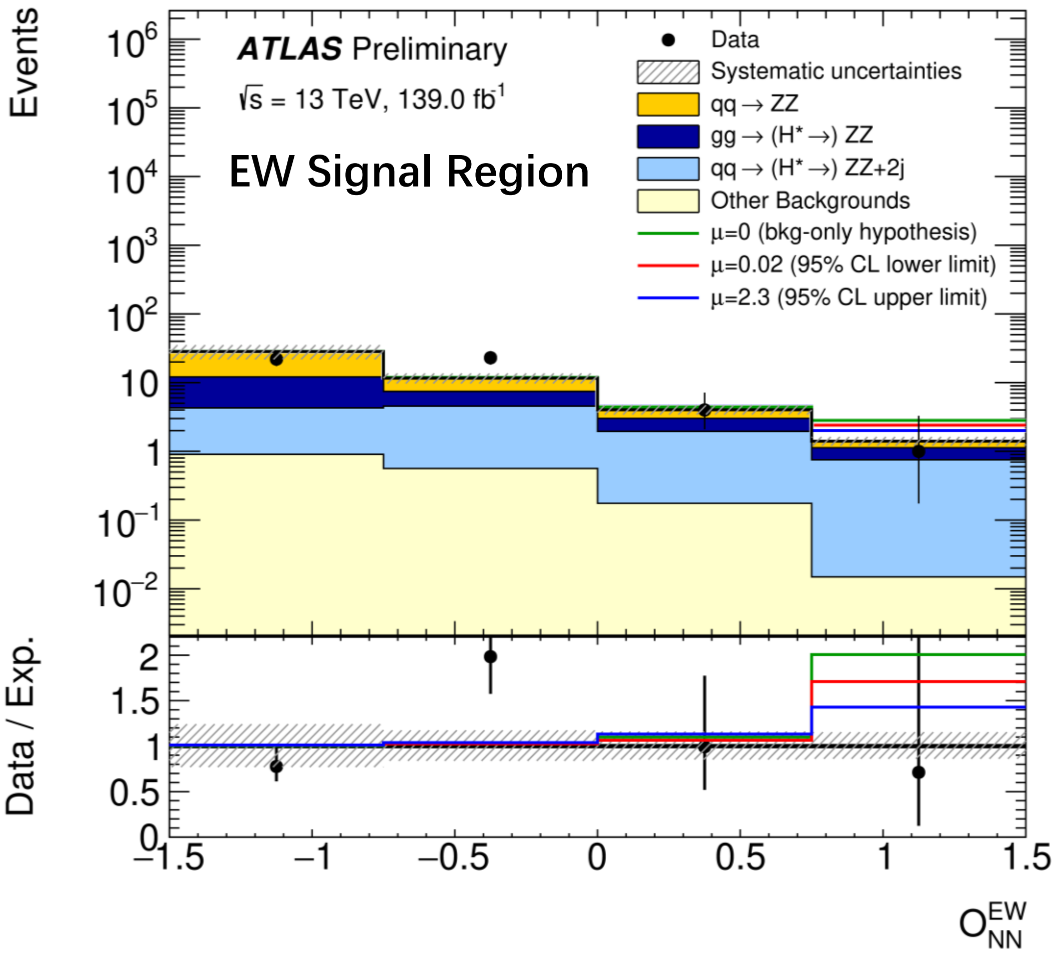
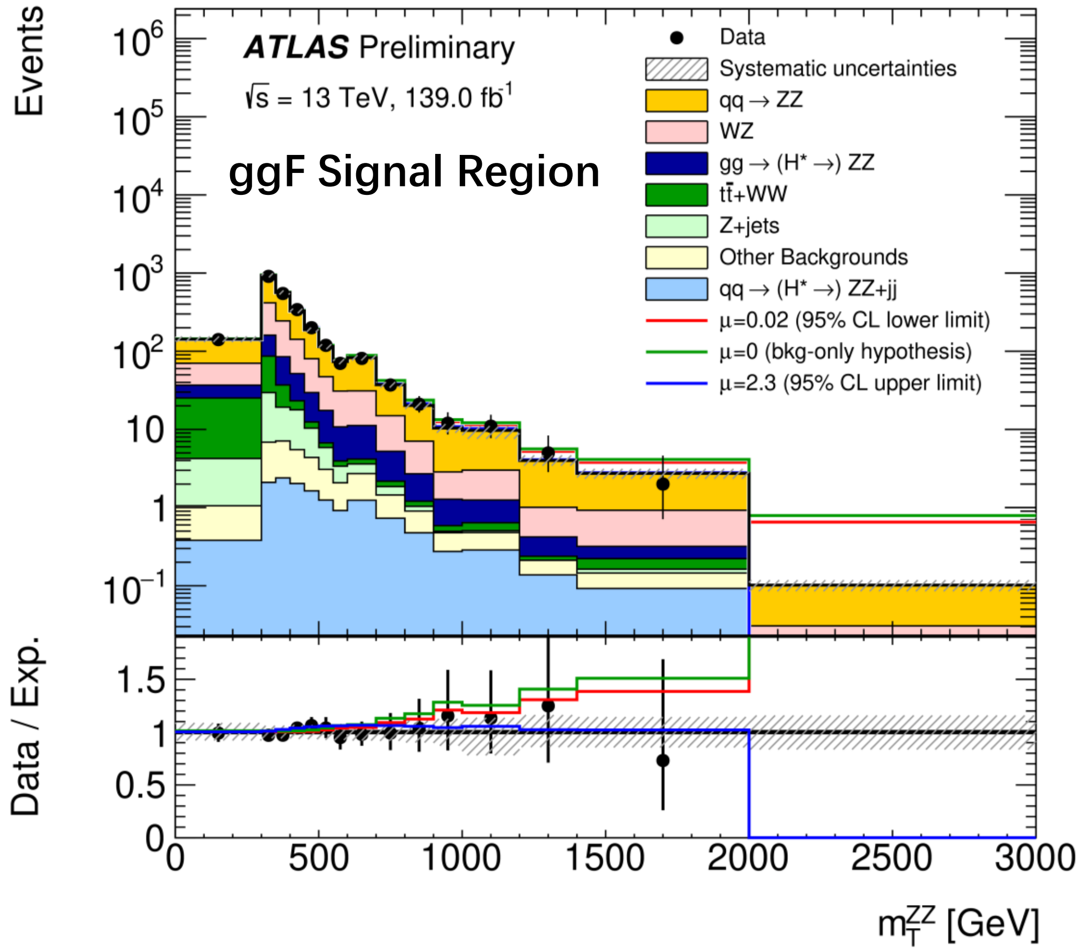


$H^* \to ZZ \to 2\ell 2\nu$ channel

- Six times larger branching ratio (compared with the 4ℓ decay channel)
- Signal regions (jet-binned SRs):
  - ggF, EW (VBF+VH) and Mixed
- Observable: transverse mass of ZZ

$$m_T^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_T^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_T^{miss}\right)^2}\right]^2 - \left|\vec{p_T}^{\ell\ell} + \vec{E}_T^{miss}\right|^2}$$

- More and complicated backgrounds:
  - qqZZ, ggZZ, WZ, tt, WW, Zjets, etc.



$\mathbf{H^* \to ZZ \to 2\ell 2\nu}$ channel

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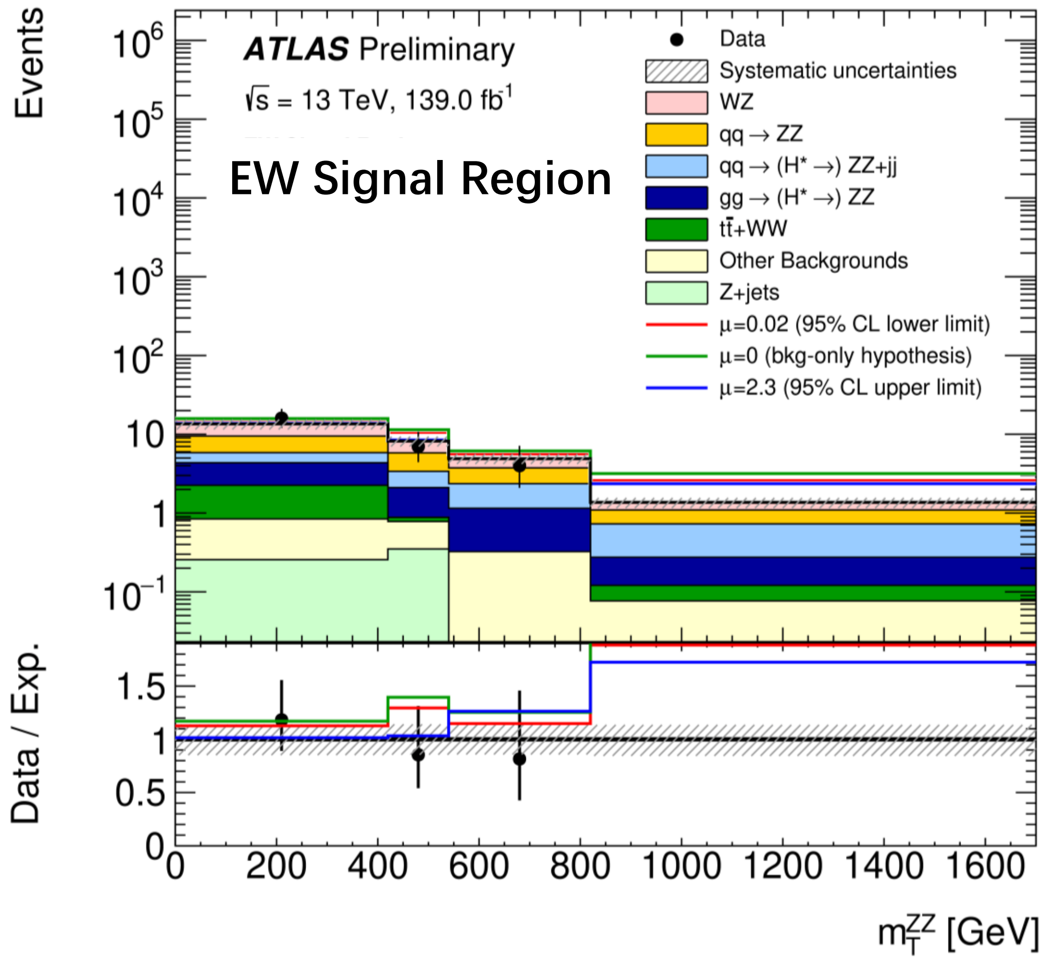
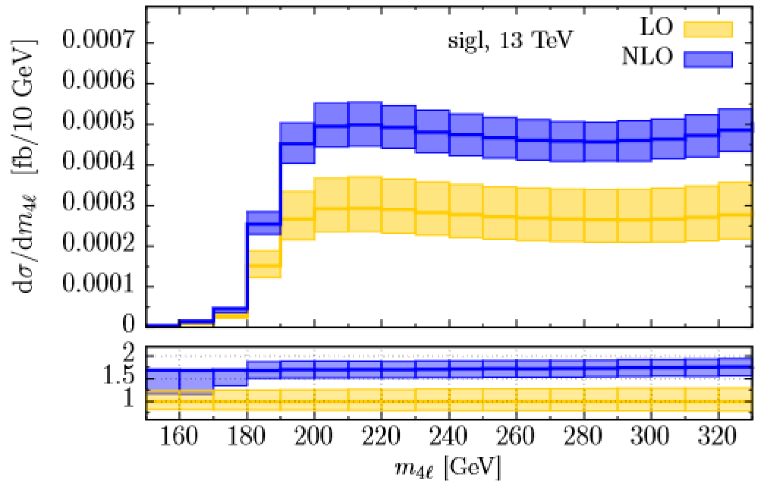
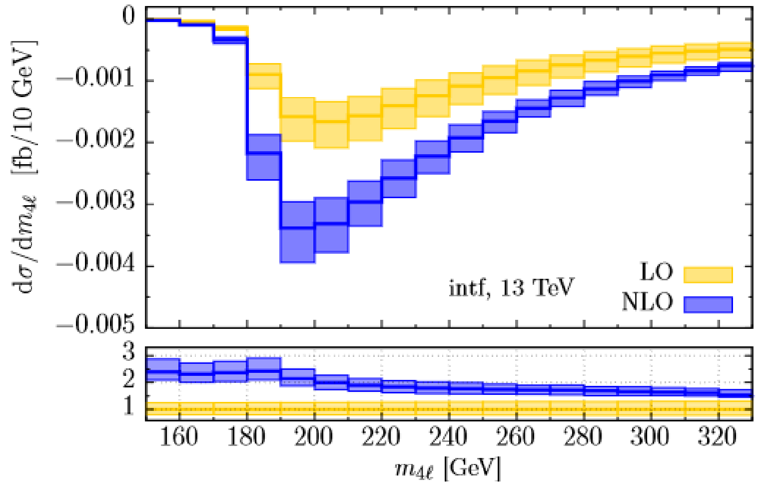


Systematic uncertainties

- ❑ Large uncertainties for signal ggF and VBF
  - ➢ VBF: High-order (HO) QCD
  - ➢ ggF: HOQCD and Parton Shower (PS)
- ❑ Large uncertainties for background
  - ➢ qq→ZZ: HOQCD, HOEW and PS
- ❑ Jet energy and resolution uncertainties for both signal and background are large.



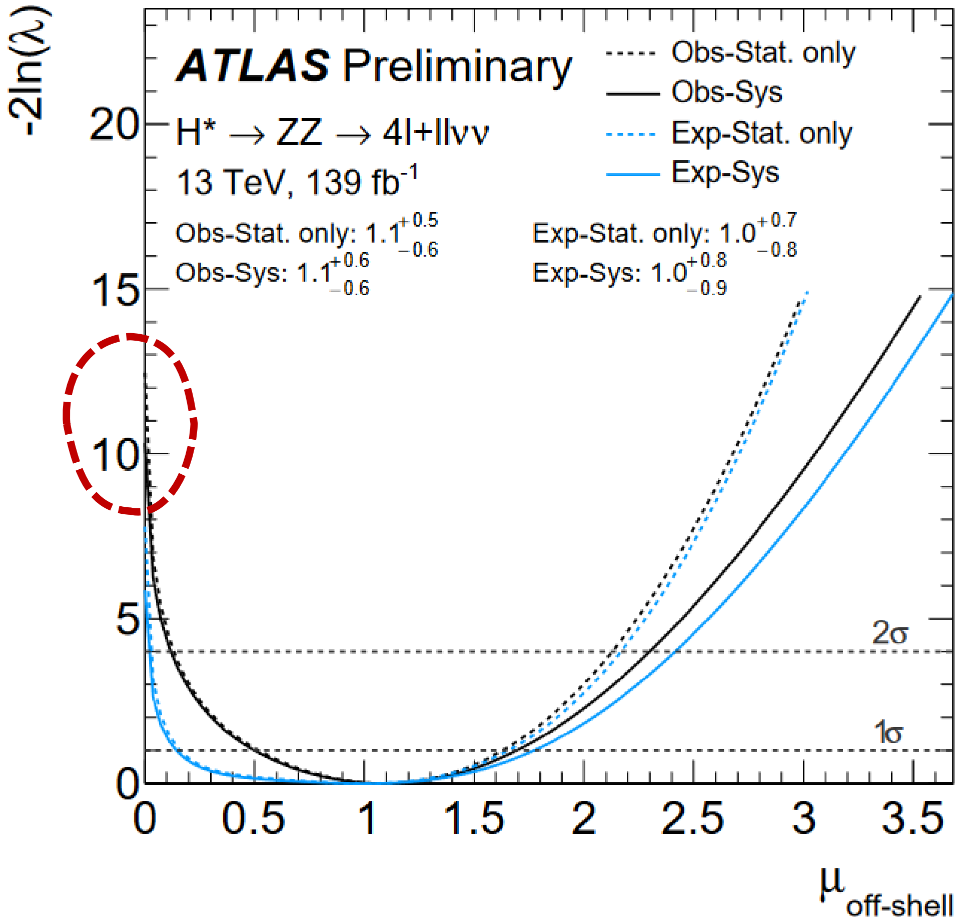


ggF: F.Caola et al. *JHEP* 07 (2016) 087

Off-shell $H^* \to ZZ$ analysis results

❑ Evidence of off-shell Higgs: 3.2σ

$$\sqrt{\mathrm{NLL}(\mu_{\mathrm{offshell}} = 0)} = 3.2$$



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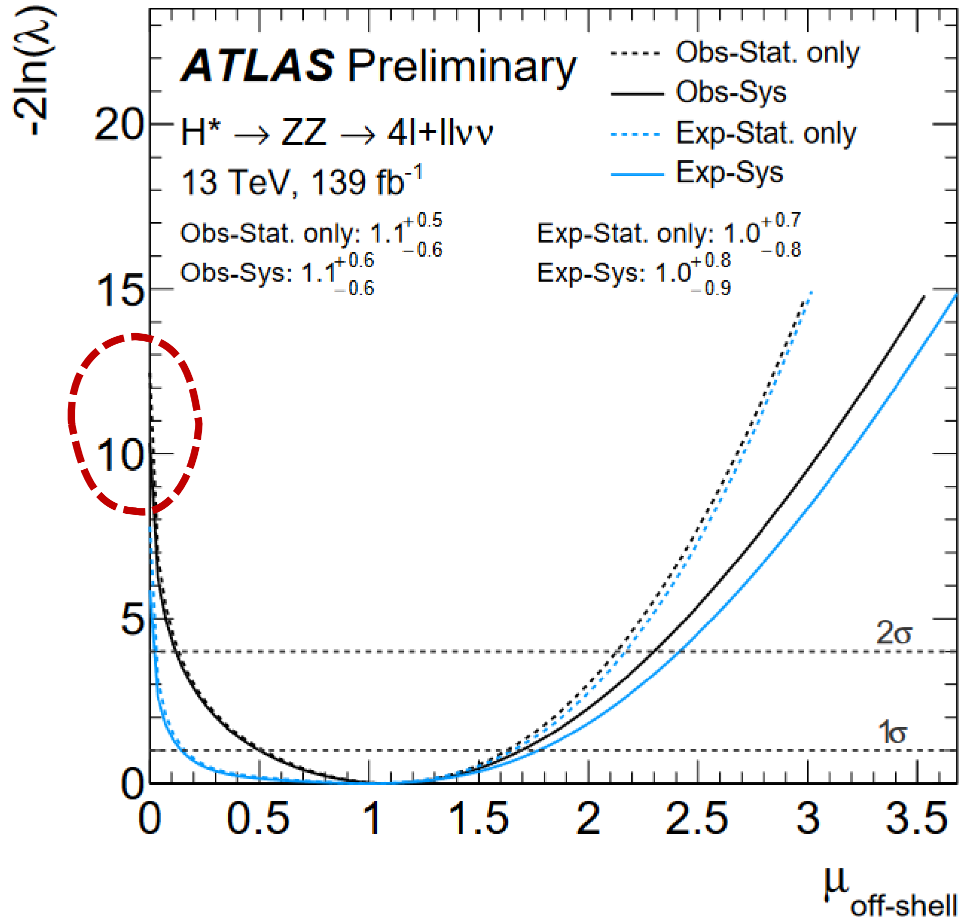
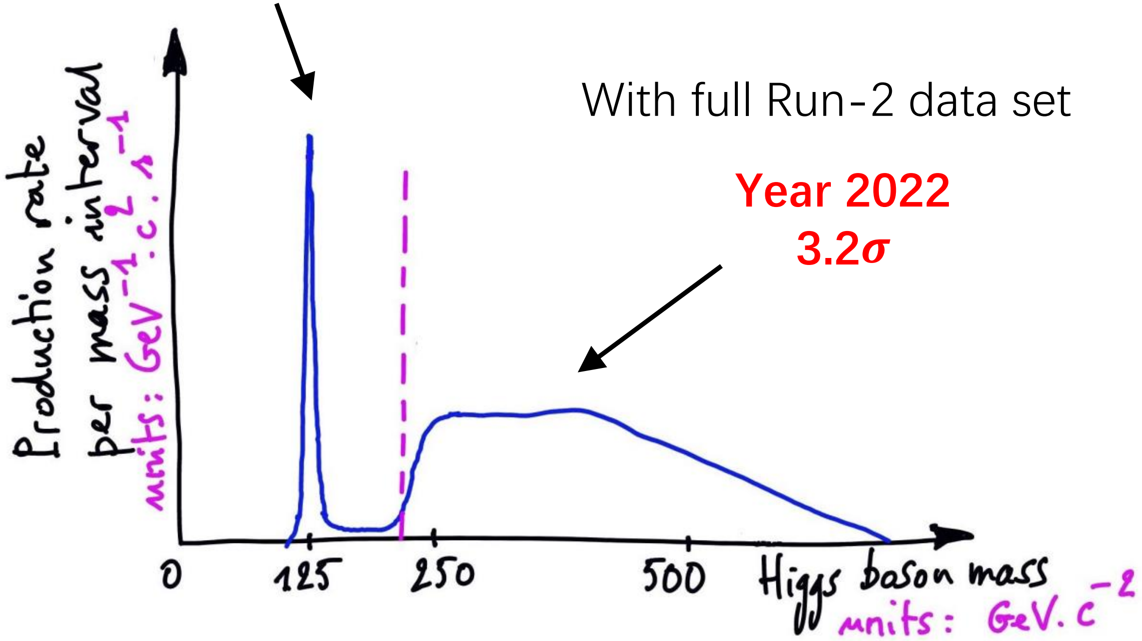


Year 2012

With full Run-2 data set

Year 2022
3.2σ

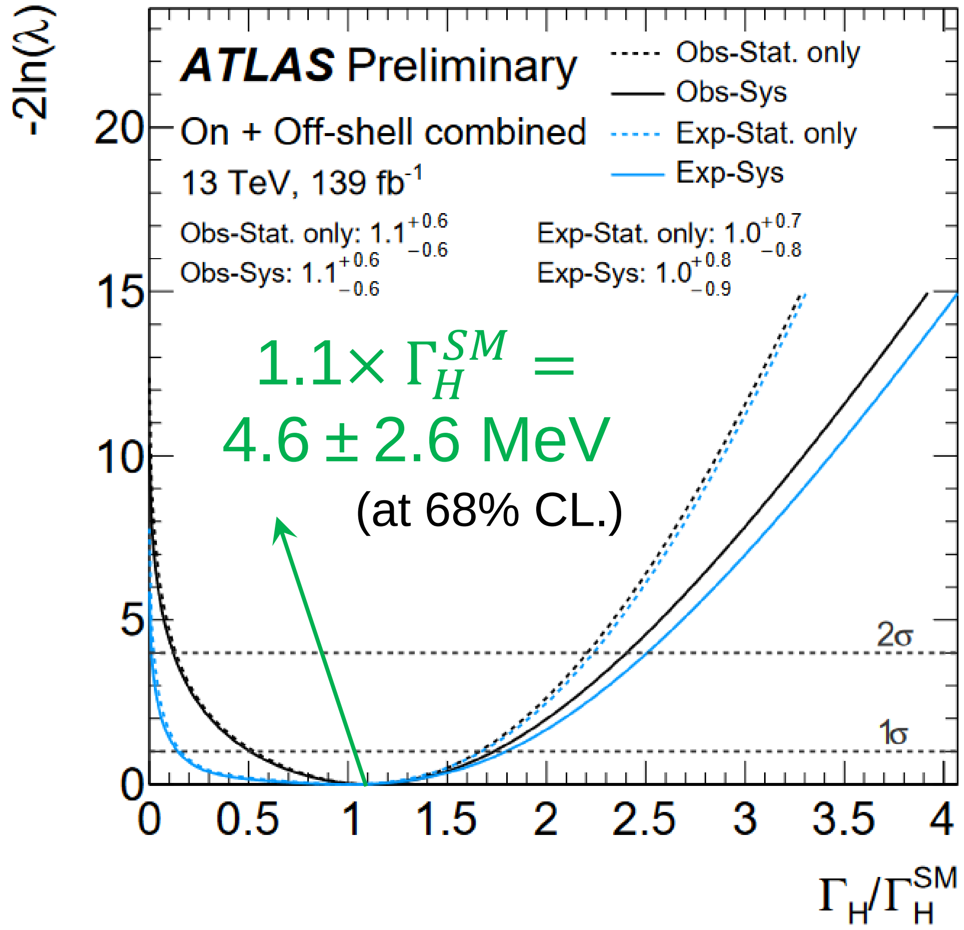


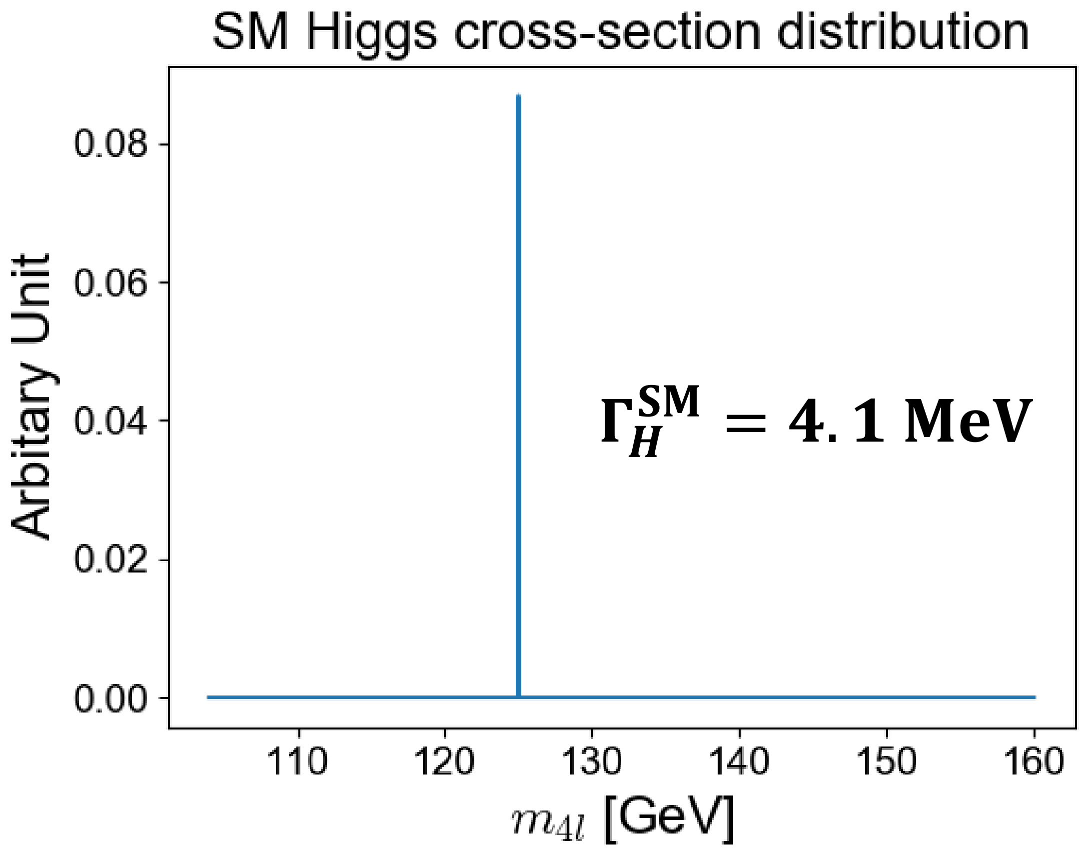
Off-shell $H^* \rightarrow ZZ$ analysis results

- **Total Higgs decay width constraints:**

$$\frac{\sigma^{\text{offshell}}}{\sigma^{\text{onshell}}} \propto \Gamma_H$$

$$0.53\ \text{MeV} < \Gamma_H(\text{at } 95\%\ \text{CL.}) < 9.7\ \text{MeV}$$





Summary

- We present measurements on off-shell Higgs to ZZ and Higgs decay width.
- We find evidence of the off-shell Higgs at 3.2σ. ATLAS-CONF-2022-068
- The measurement of the Higgs total decay width is

$$\Gamma_{\mathrm{H}} = 4.6^{+2.6}_{-2.5}\ \mathrm{MeV@68\%\ CL.}$$

- Consistent with CMS $\Gamma_{\mathrm{H}} = 3.2^{+2.4}_{-1.7}\ \mathrm{MeV@68\%\ CL.}$ Nature. Phys. 18 (2022) 1329
- The BSM/EFT interpretation is almost done and will be provided soon. Stay tuned!