Evidence of off-shell Higgs, Higgs decay width and the EFT interpretation at ATLAS

SM@LHC 2023 - Fermilab

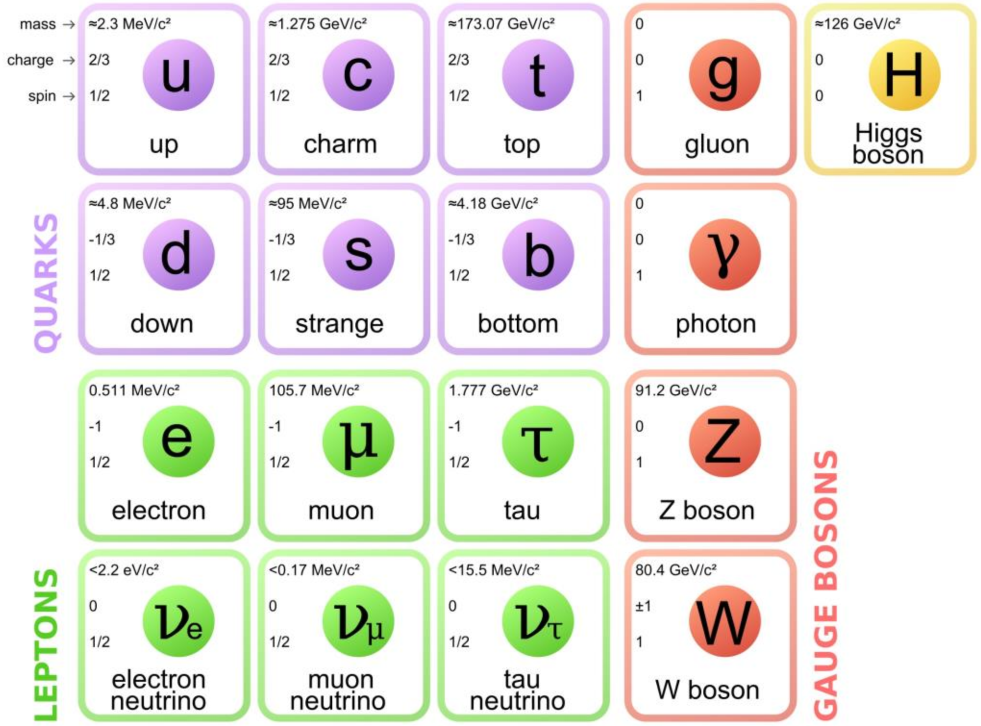
10-13 July 2023

Yingjie Wei

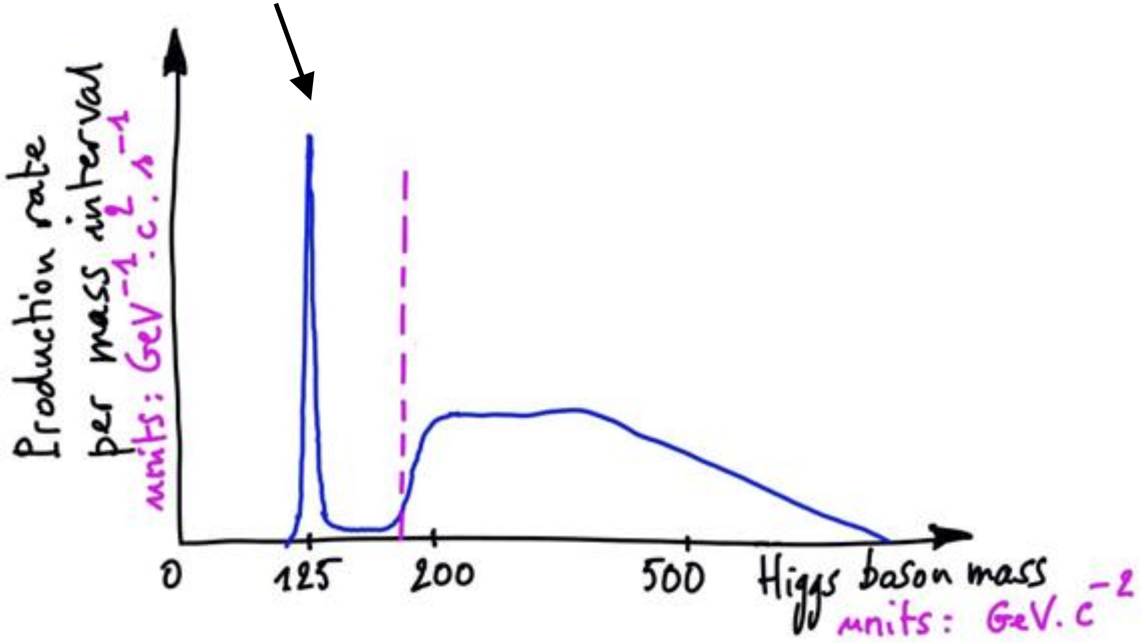
On behalf of the ATLAS collaboration

Introduction

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



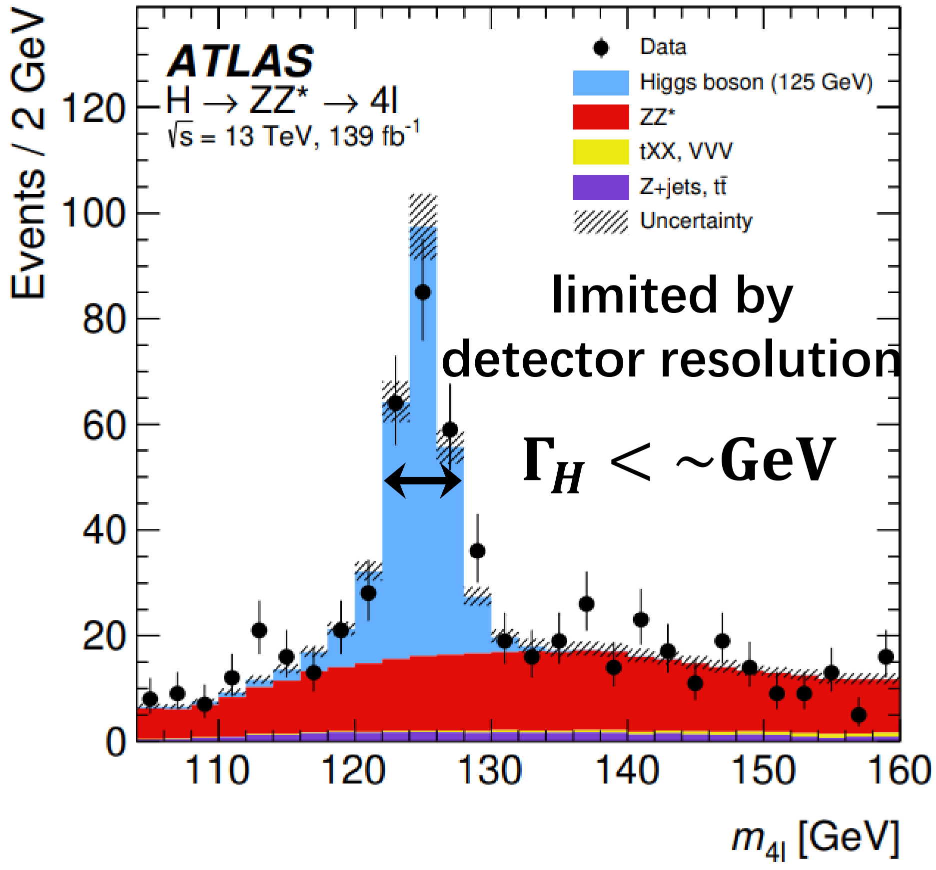
Year 2012



$$H \to ZZ \to 4l$$

Higgs width measurement

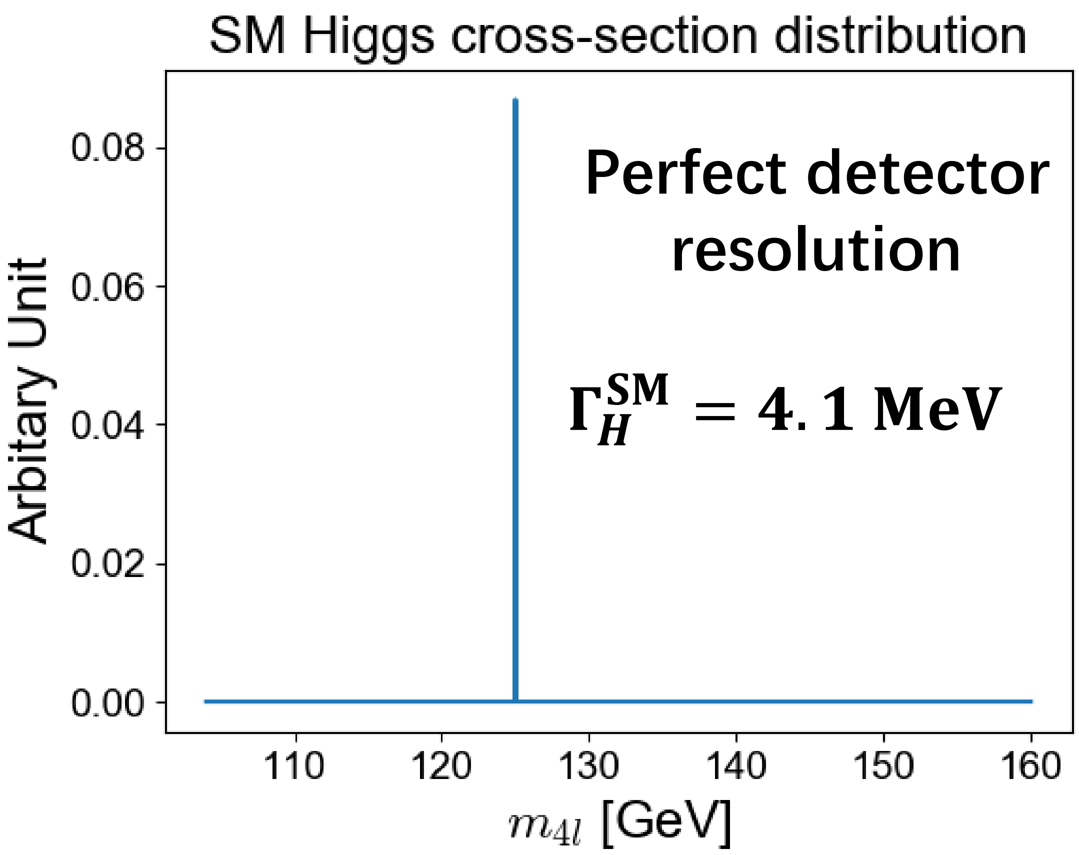
arXiv: 2207.00320



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

Higgs width measurement

The SM prediction



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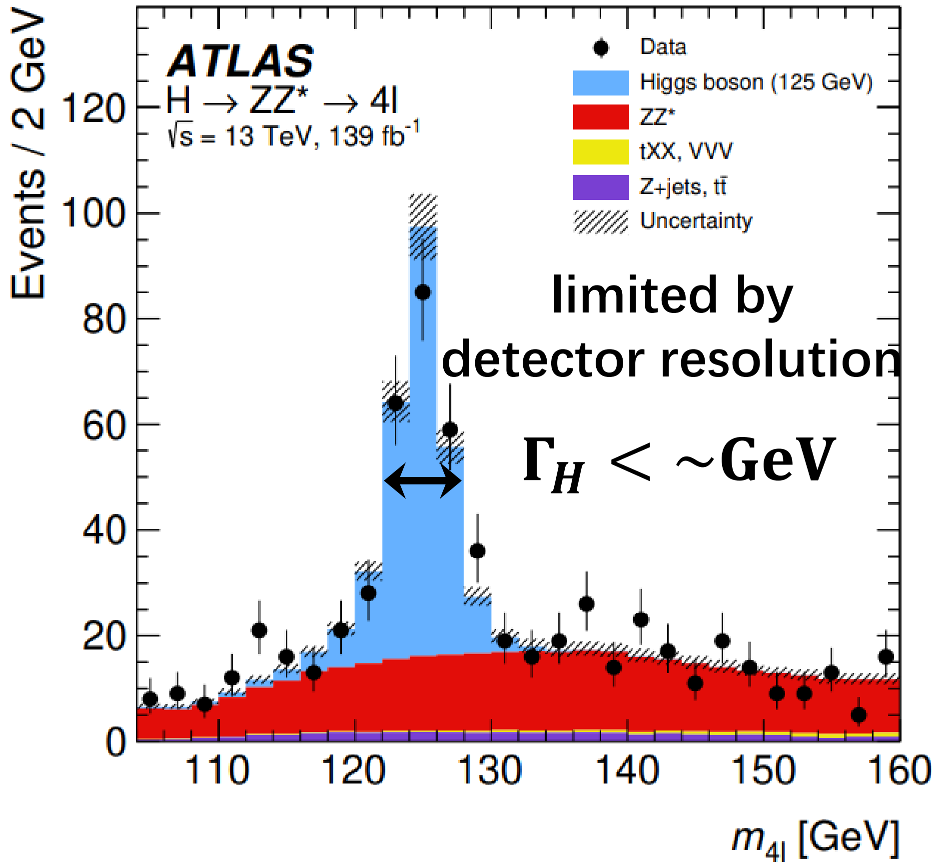

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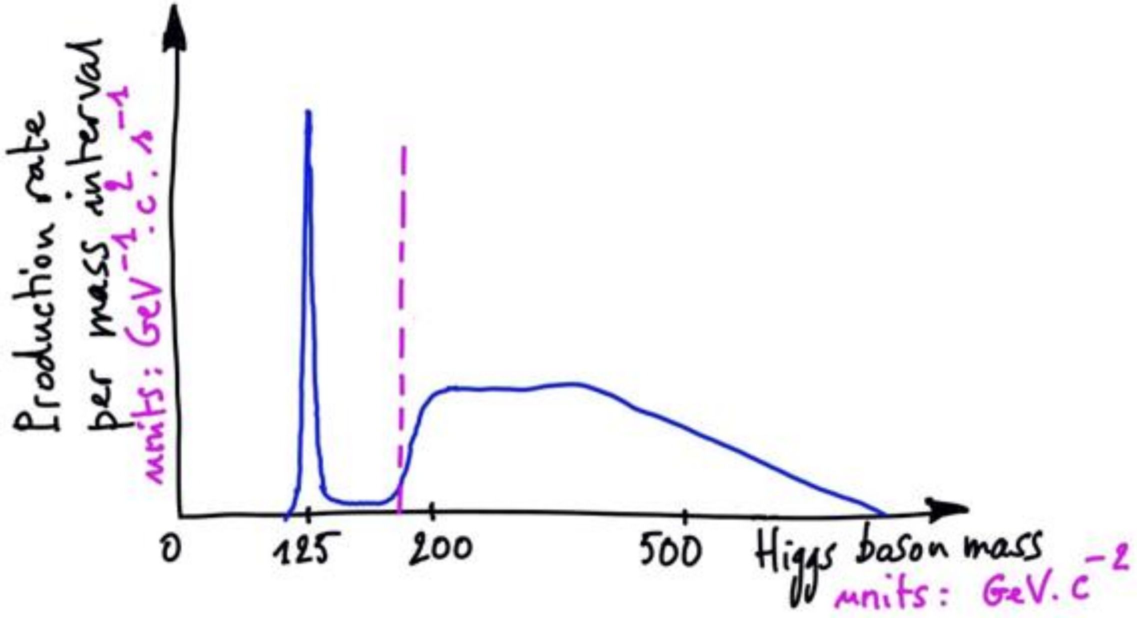
Higgs width measurement

- ❑ Indirect method



Higgs width measurement

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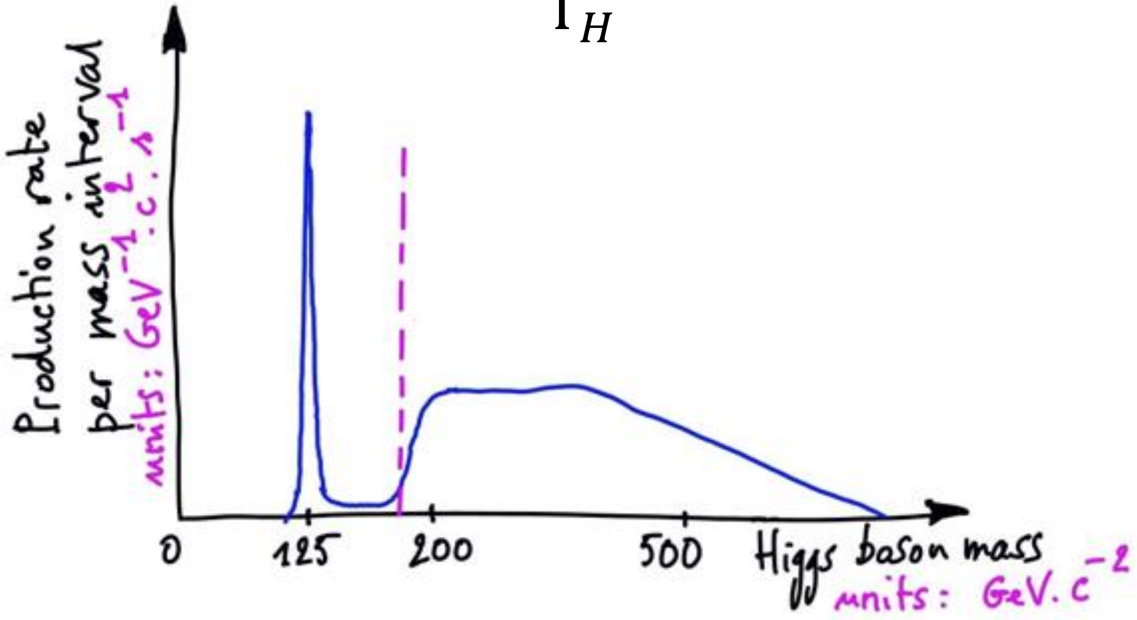
$$\sigma^{\text{onshell}} \propto \frac{g_{ggH}^2 g_{HZZ}^2}{\Gamma_H}$$



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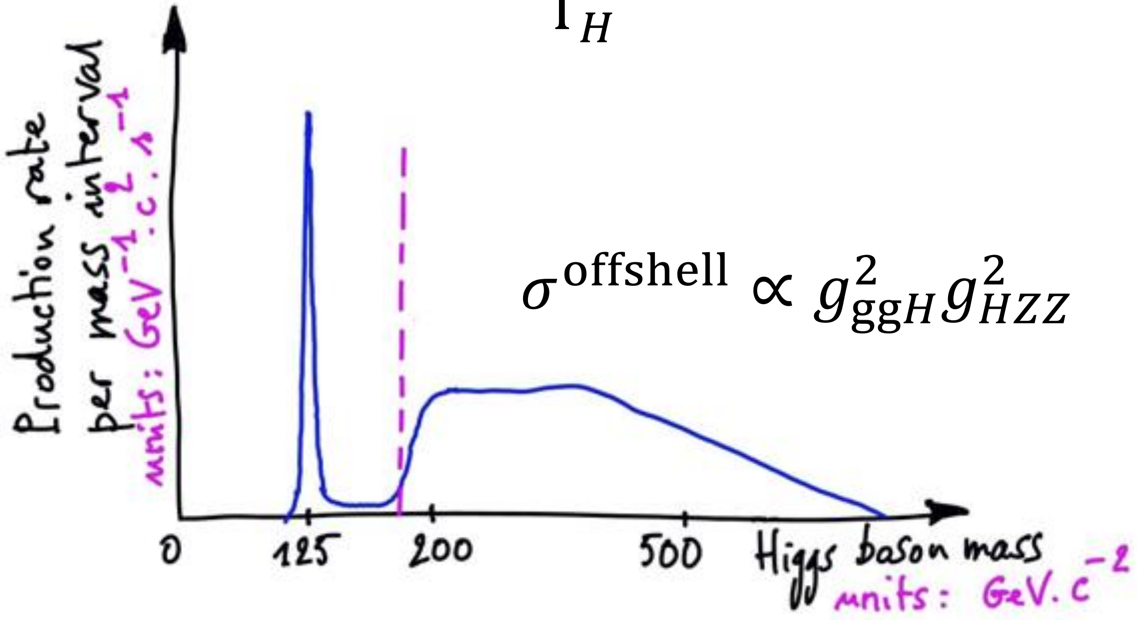

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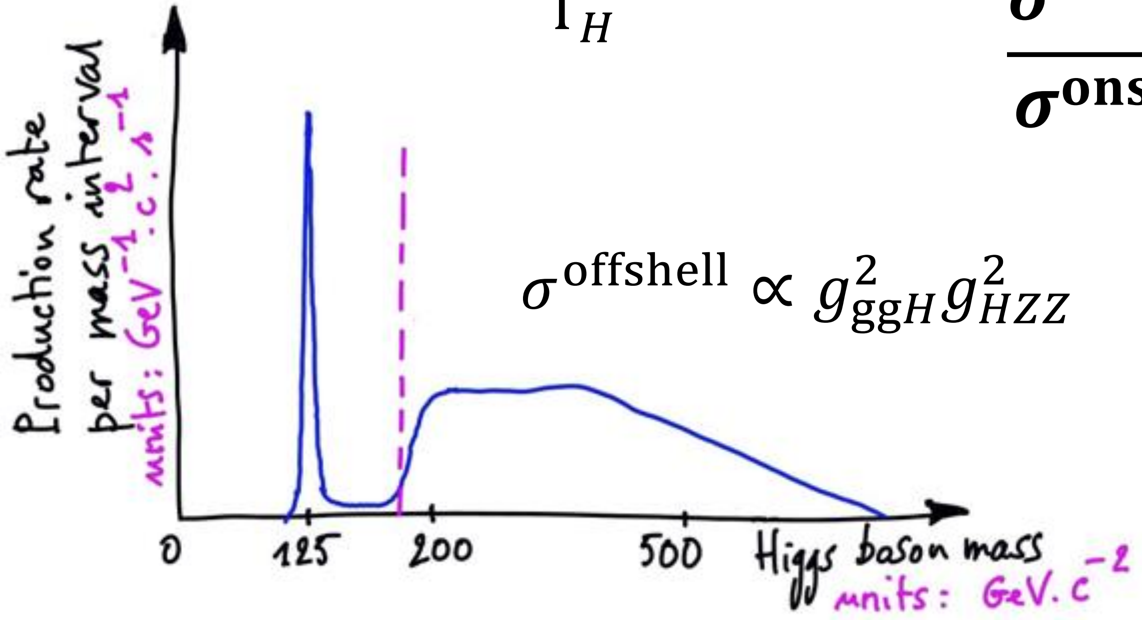

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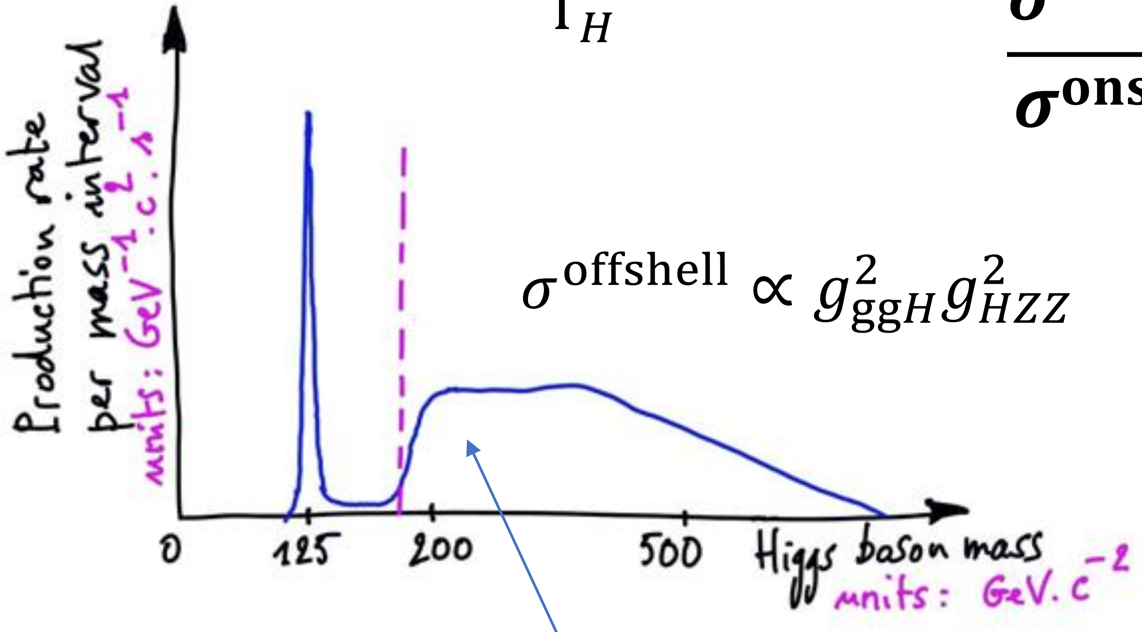

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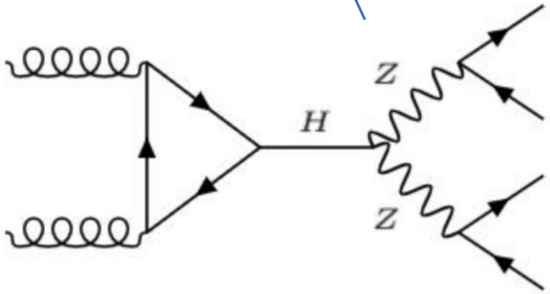

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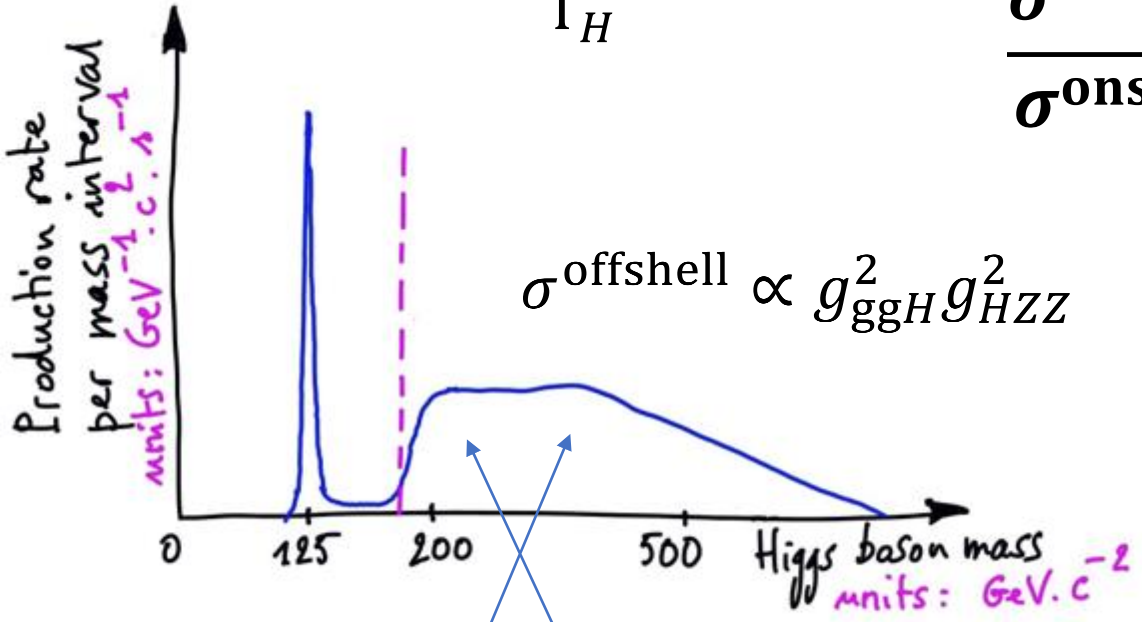

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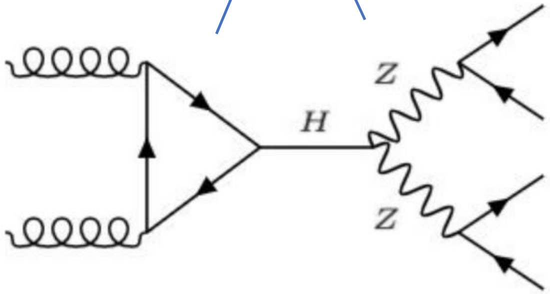

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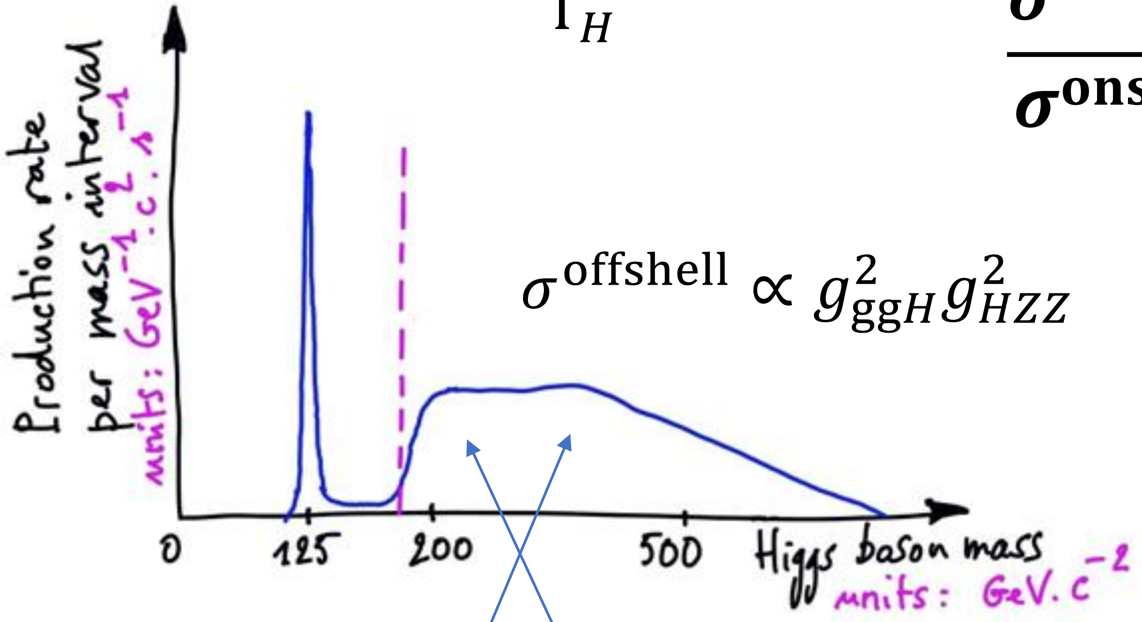

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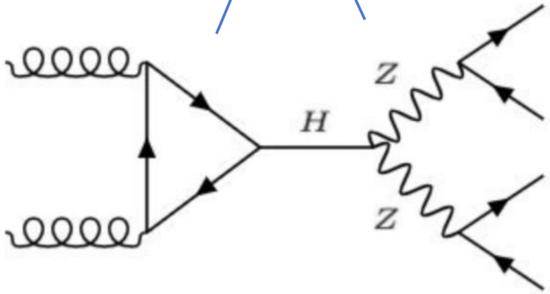

$\rightarrow \boldsymbol{4\ell}$ or $\boldsymbol{2\ell 2\nu}$

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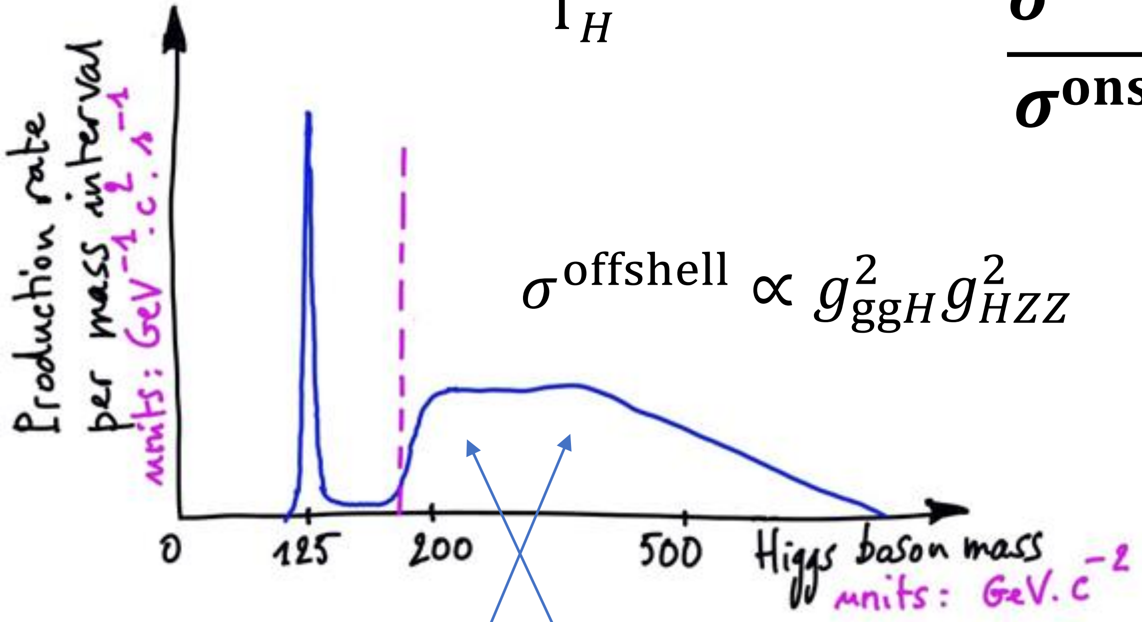

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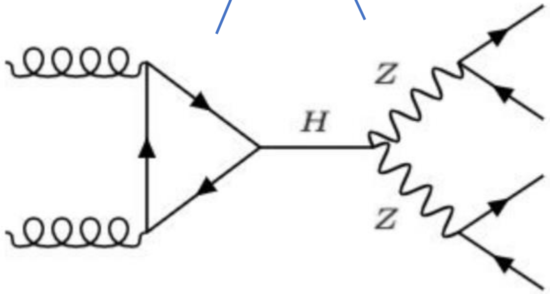

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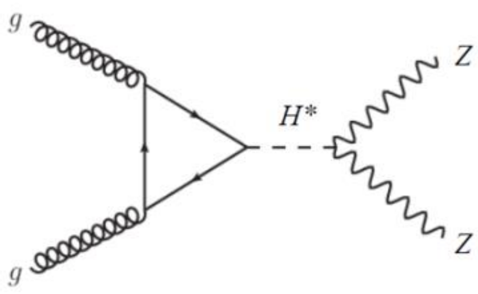
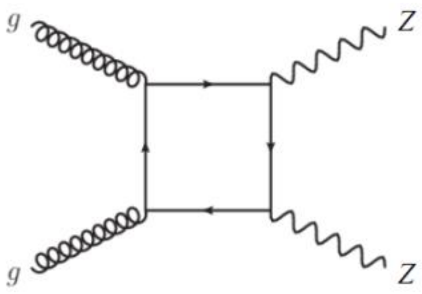
- ❑ Paper (April 2023):
  arXiv:2304.01532

Signal-background interference

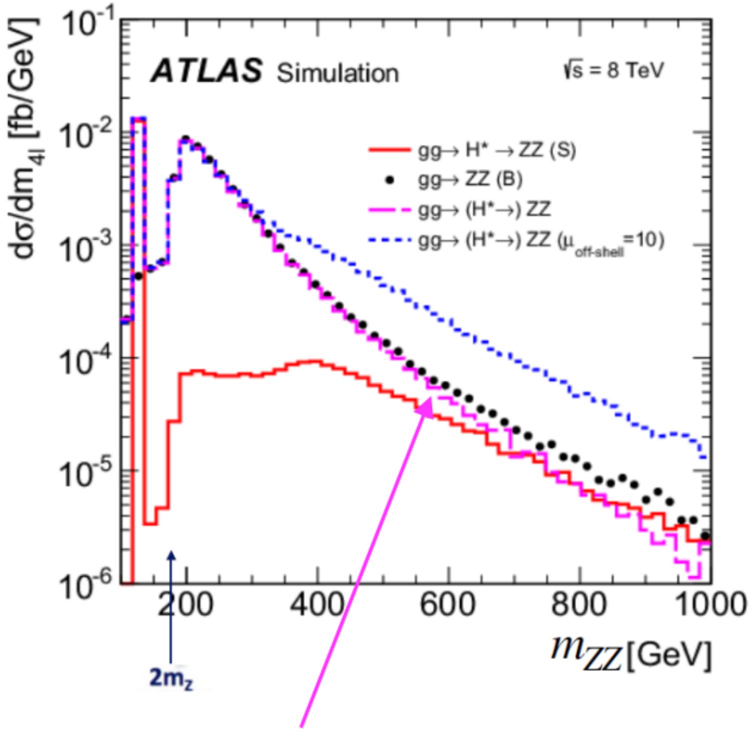
- The existence of the SM off-shell Higgs will reduce the yield due to a **large negative** interference (to preserve unitarity), i.e., Sig+Bkg+intf < Bkg only



signal (S)
$gg \to H^* \to ZZ$



background (B)
$gg \to ZZ$



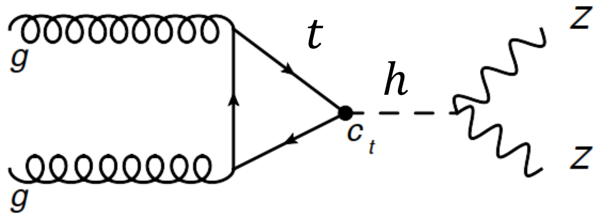
SBI = S + B + I

BSM/EFT analysis of the off-shell Higgs

❑ Motivations:

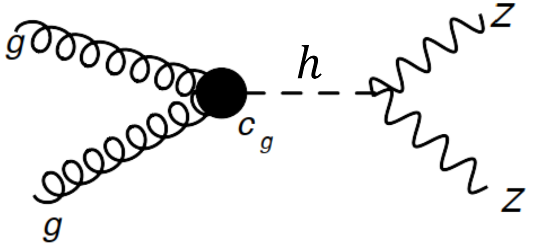
- ➢ Off-shell Higgs can be used to probe EFT operators at ~ TeV level.
- ➢ The degeneracy of Higgs-gluon and Higgs-top can break in the off-shell region.

SM

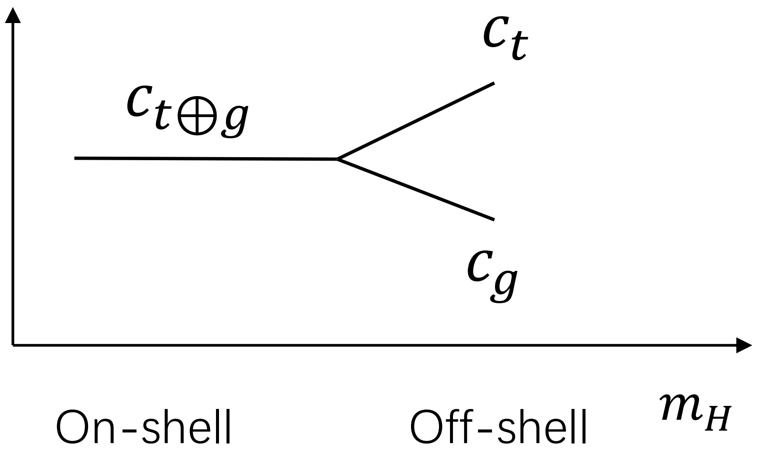


In SM, c_t = 1

BSM



In SM, c_g = 0

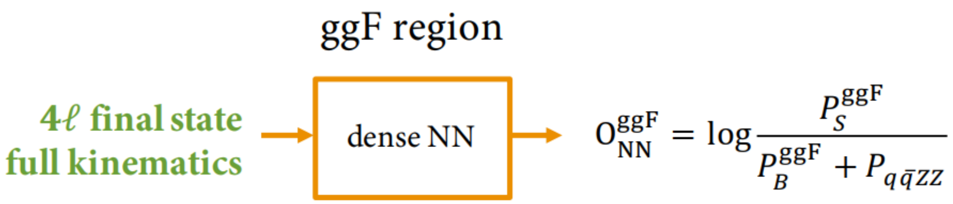


(Higgs Low-energy theorem)

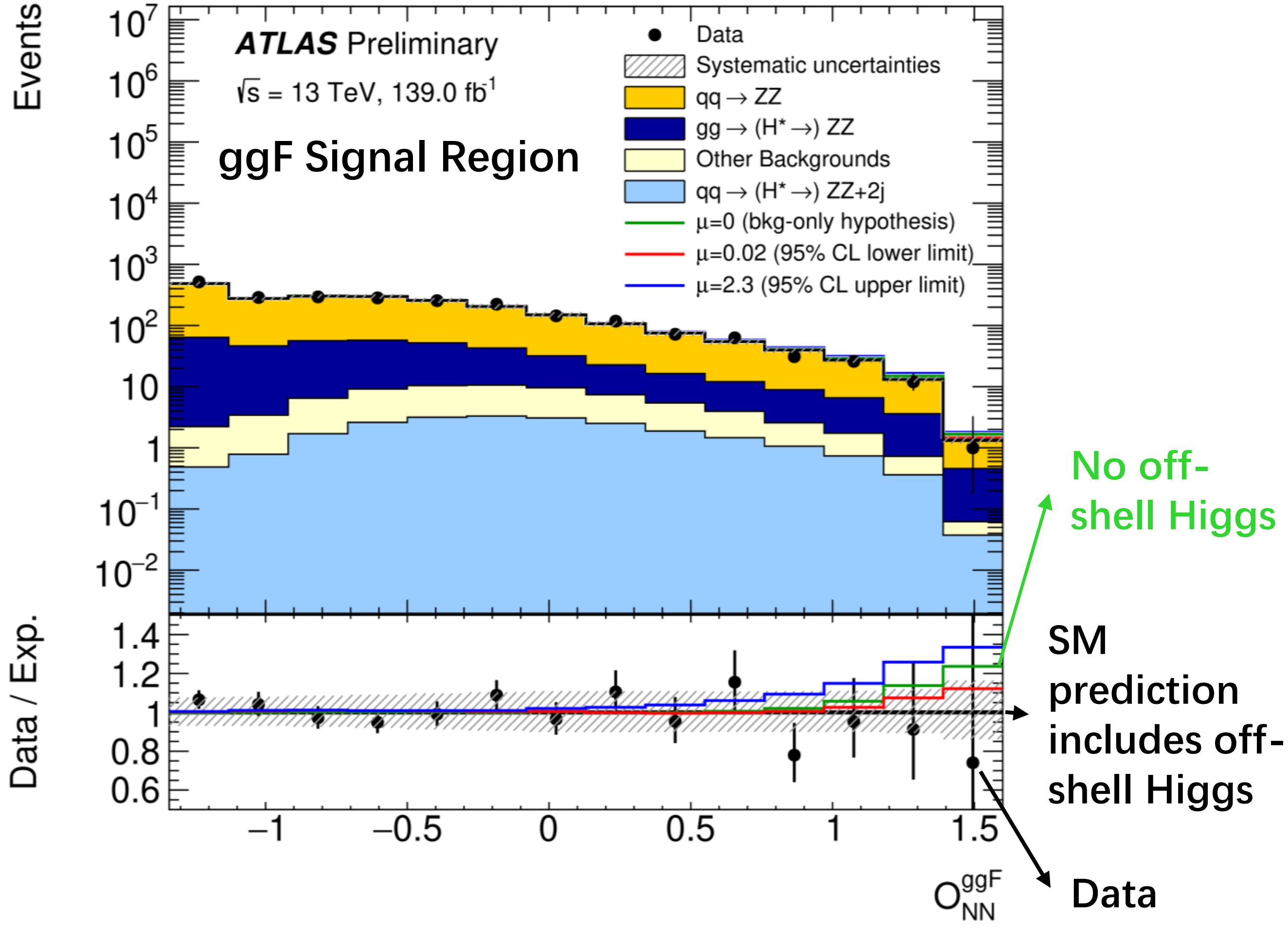
220 GeV- 2 TeV

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

- Final state decay objects (e and μ) can be fully reconstructed in the 4ℓ channel
- Signal regions (jet-binned SRs):
  - ggF, EW (VBF+VH) and Mixed
- Observables: neural network method (inputs: P_T, η, matrix-element, etc)



- Background: qqZZ (main), ggZZ

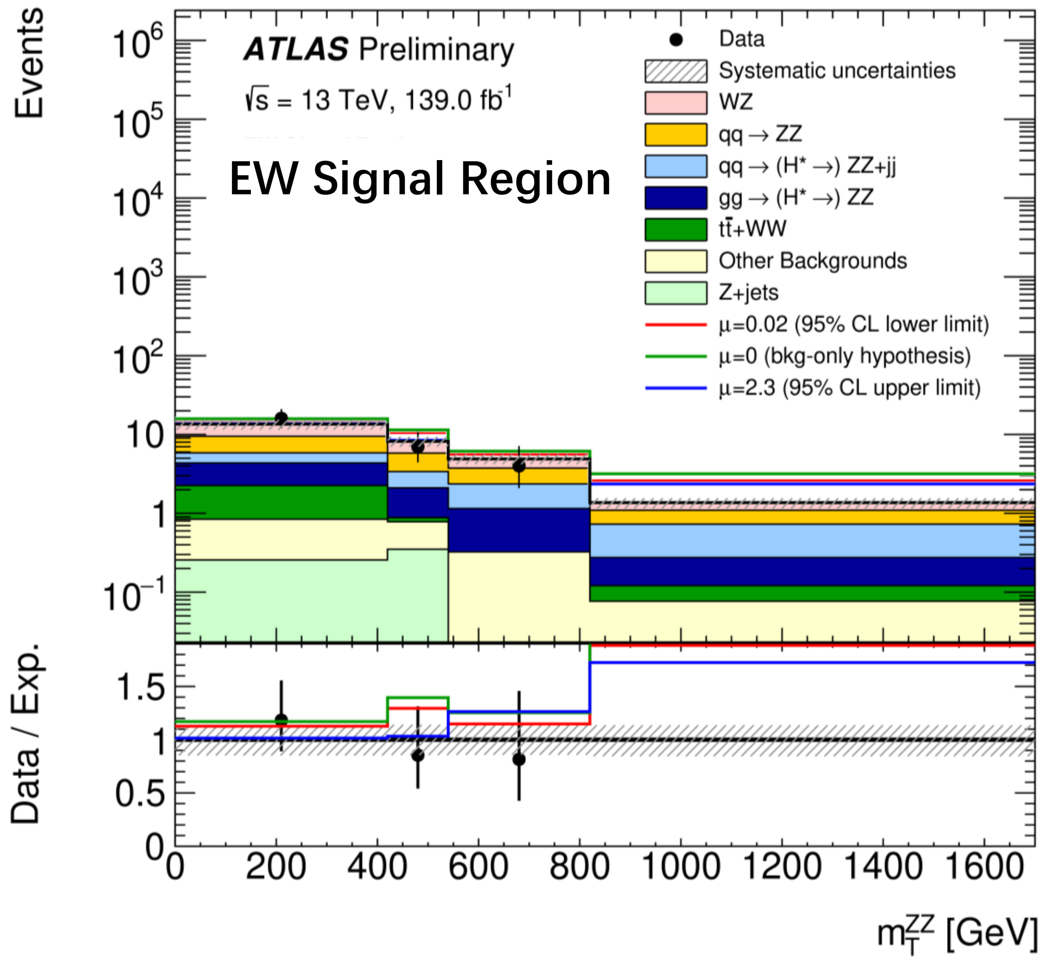


$\mathbf{H}^* \rightarrow \mathbf{ZZ} \rightarrow 2\ell 2\nu$ channel

- 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

$$m_{\mathrm{T}}^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_{\mathrm{T}}^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_{\mathrm{T}}^{\mathrm{miss}}\right)^2}\,\right]^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$

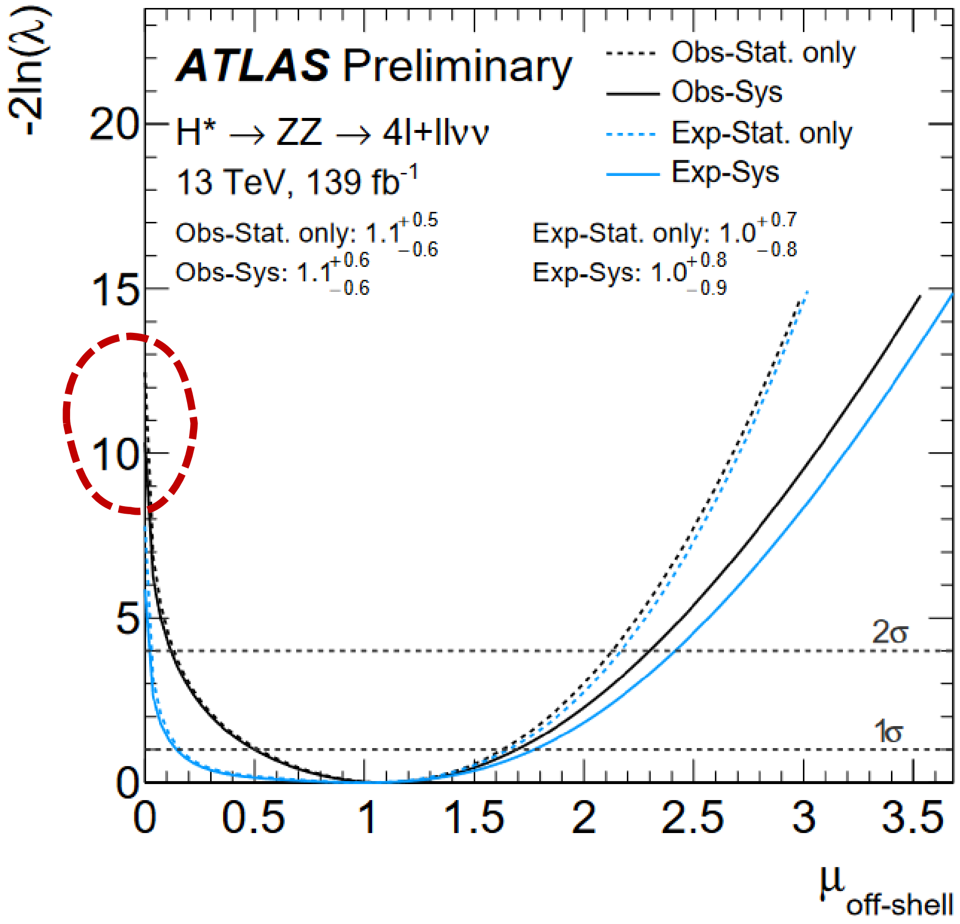
- More and complicated backgrounds:
  - qqZZ, ggZZ, WZ, tt, WW, Zjets, etc.



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

❑ Evidence of off-shell Higgs: 3.2σ

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



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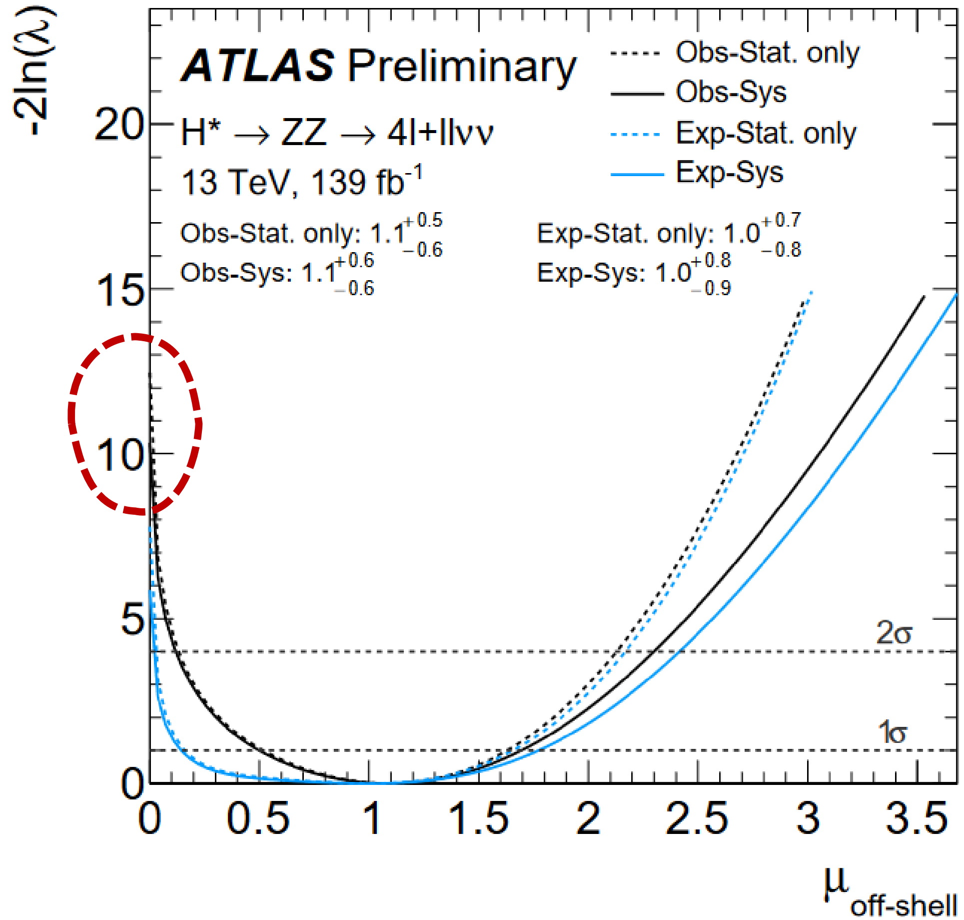

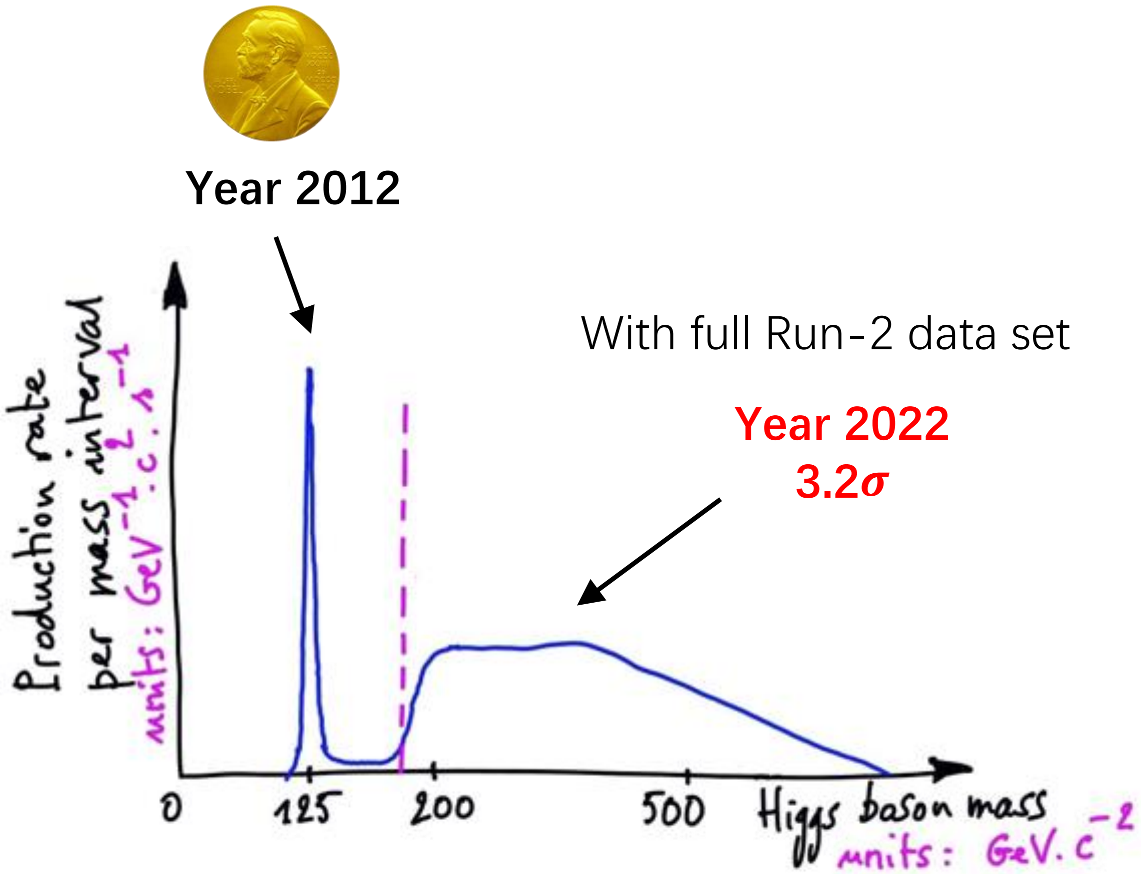

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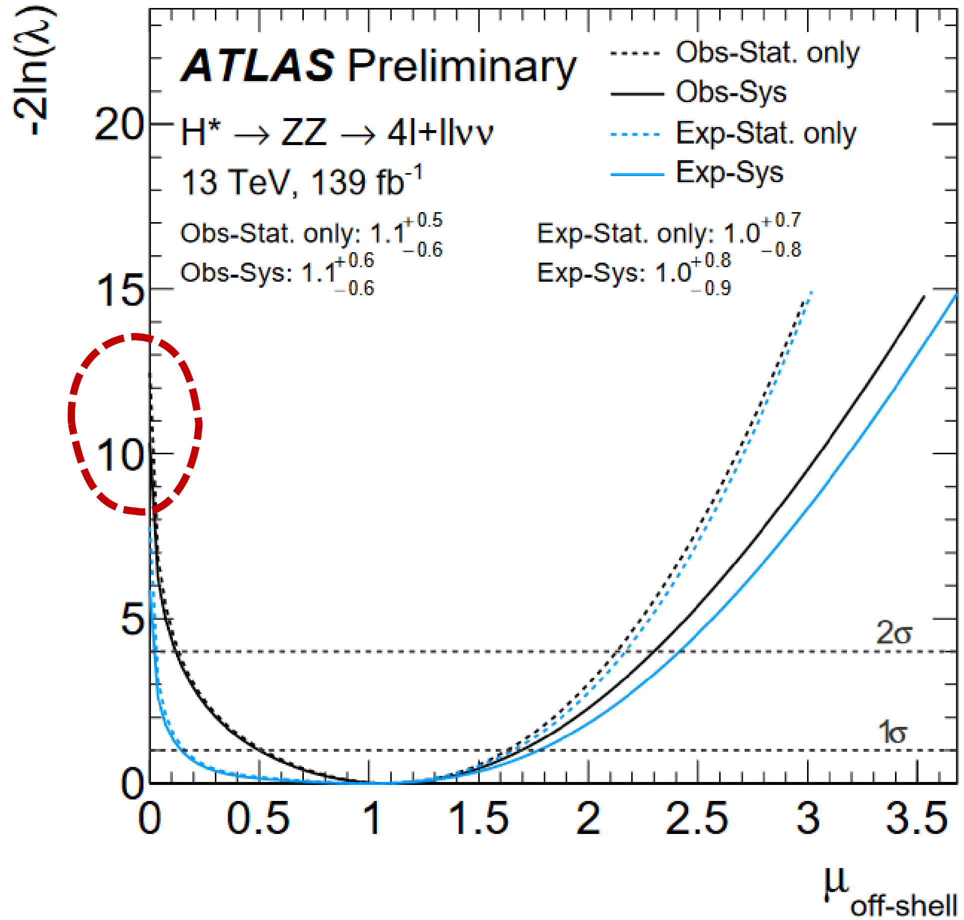


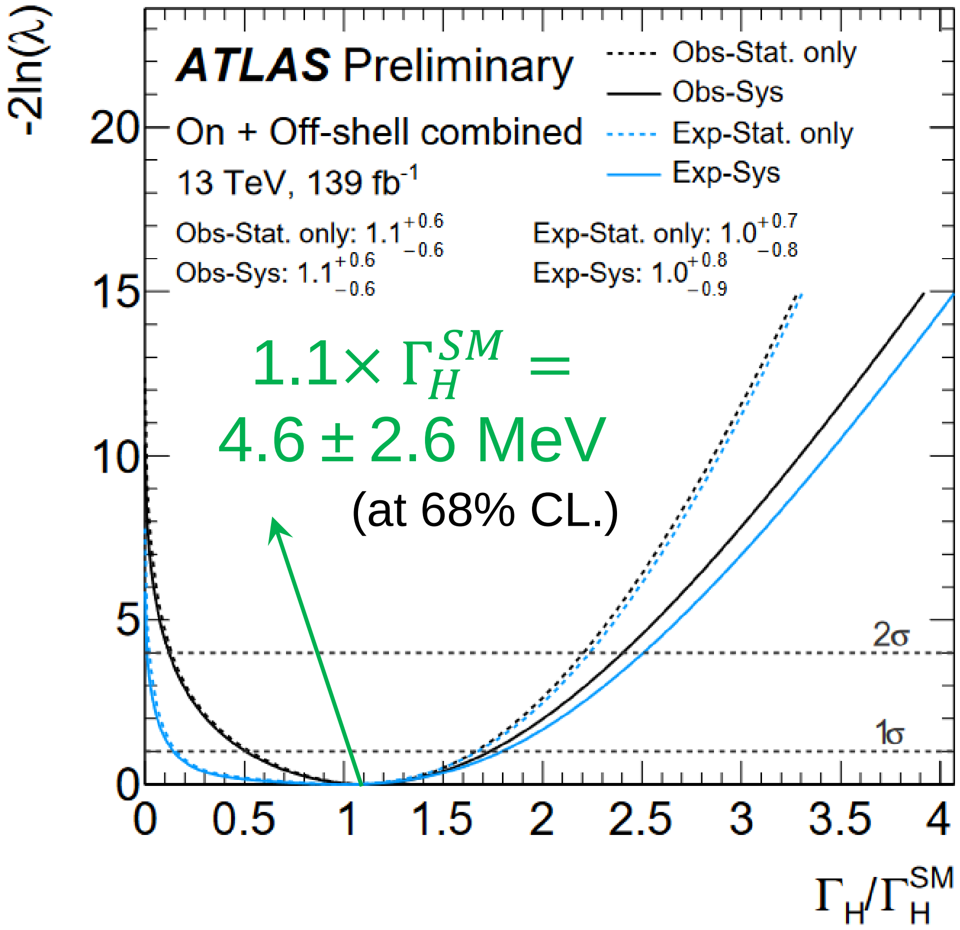
- ❑ Large systematic uncertainties include:
  - ➢ High-order QCD correction
  - ➢ Parton Shower (QSF, CKKW)
  - ➢ Jet energy and resolution uncertainties
- ❑ This analysis is statistically-limited.

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

❑ **Total Higgs decay width constraints:**

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

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

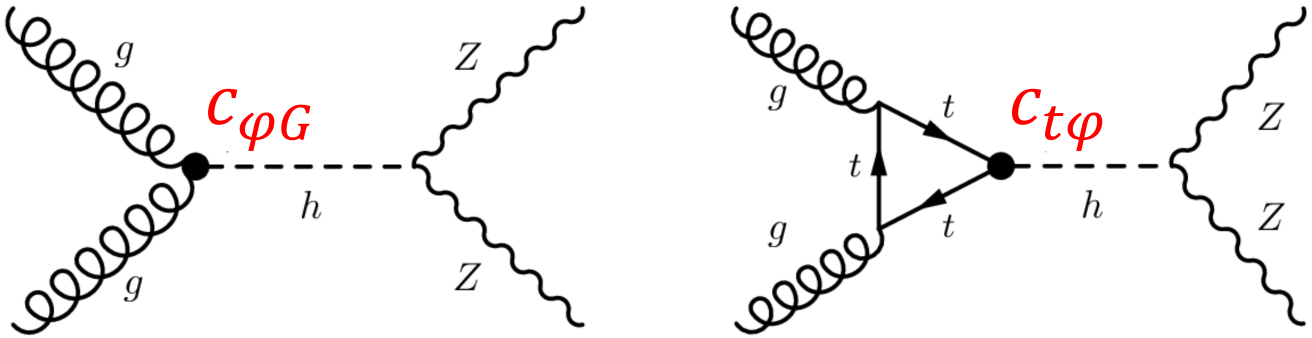


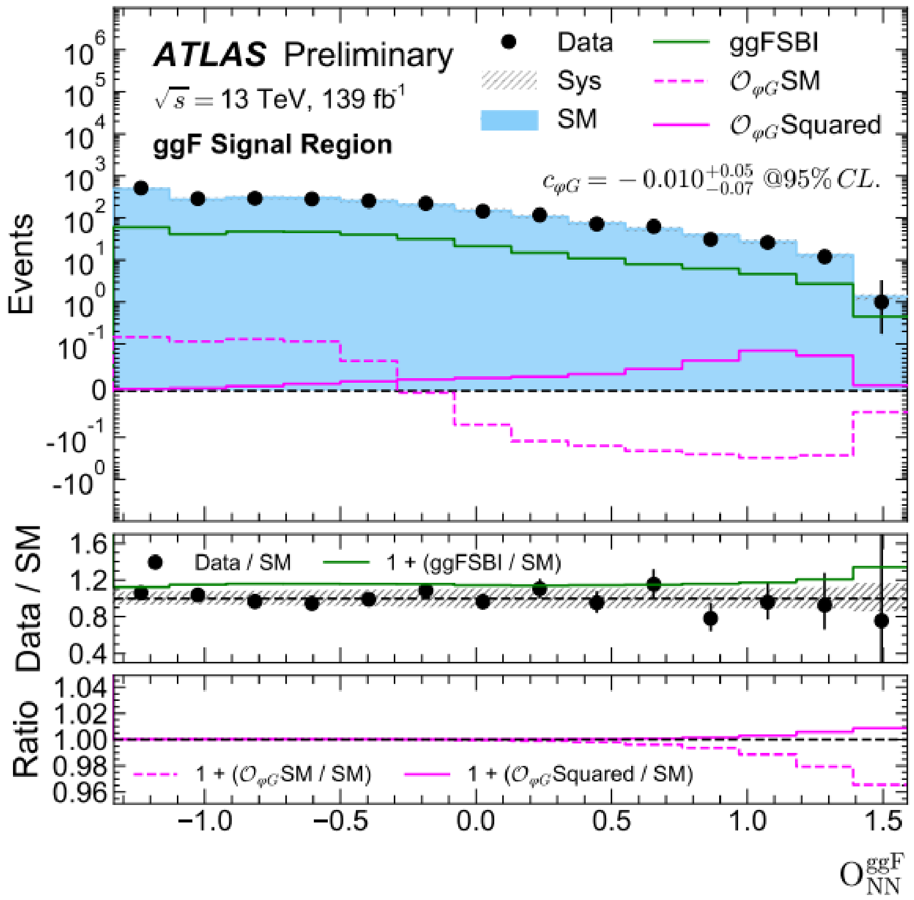
Off-shell $H^* \to ZZ$ EFT interpretation

- In the EFT interpretation:
  - The SM components are set as SM prediction:

$$\mu_{\text{off-shell}} = 1, \qquad \Gamma_H = \Gamma_H^{SM}$$

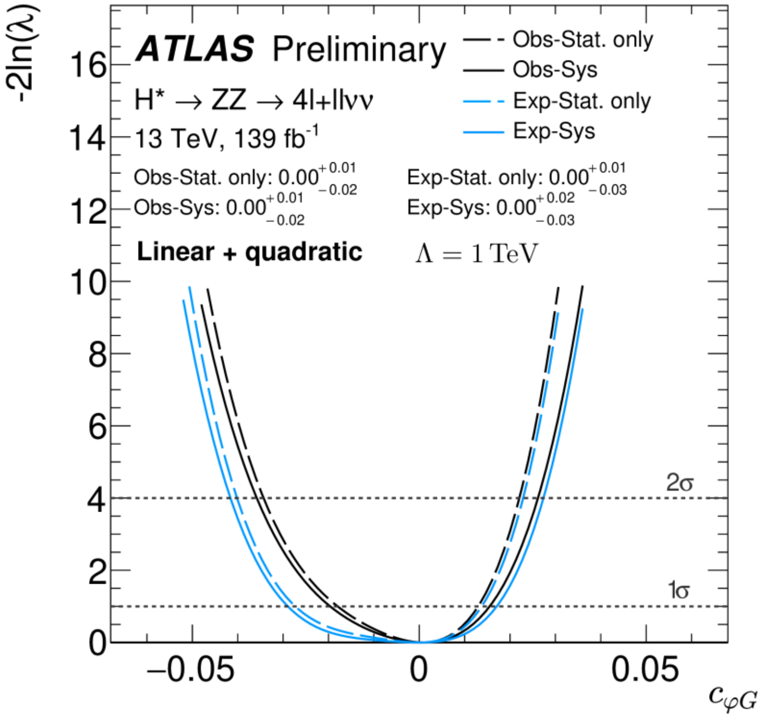
  - The EFT dim-6 coefficients are floating to fit.





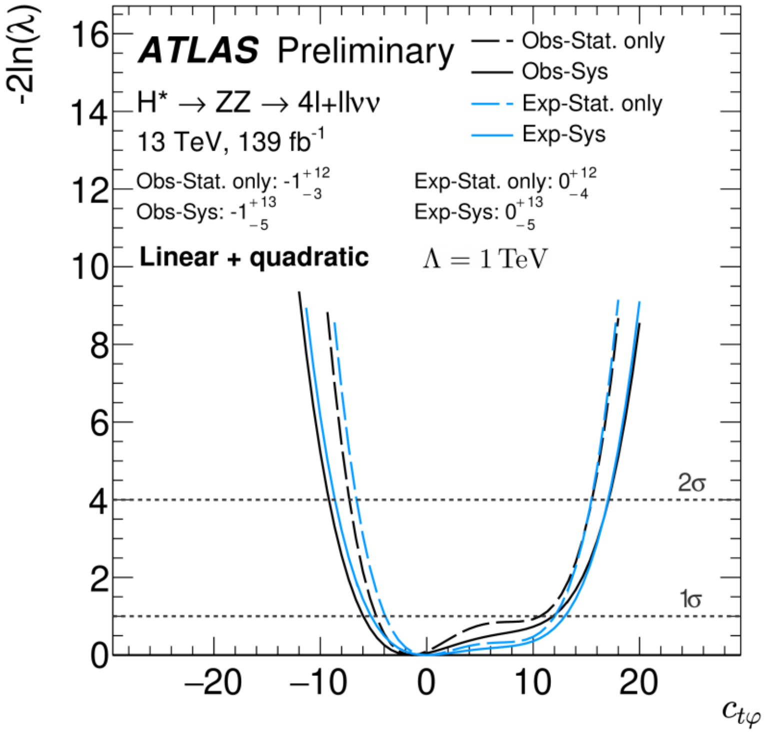
$H \to ZZ \to 4l$

Off-shell $H^* \to ZZ$ EFT interpretation



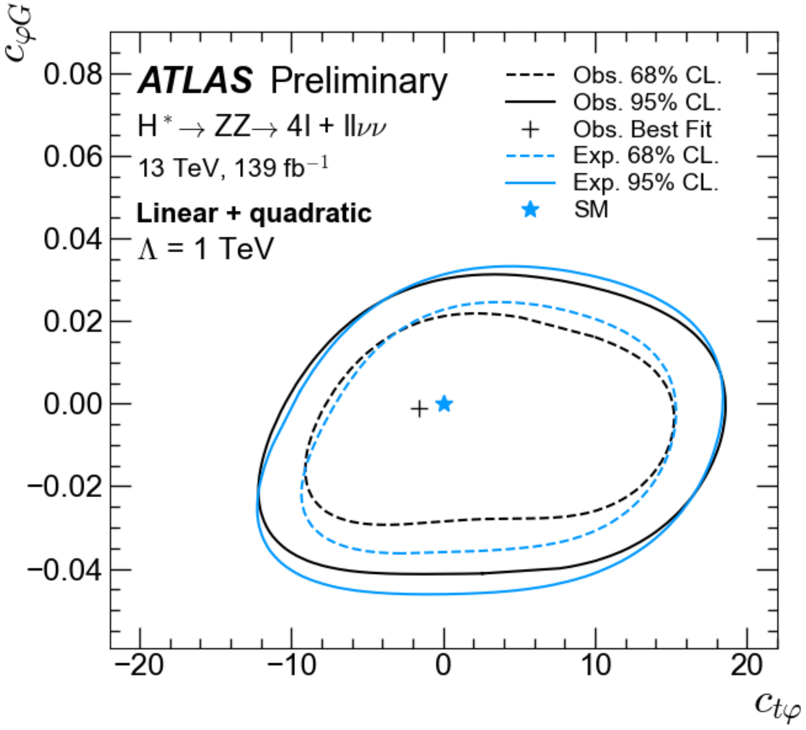
$0.00^{+0.03}_{-0.04}$ @95% $C.L.$

$c_{\varphi G}$: Higgs-gluon modifier



-1^{+13}_{-5} @95% $C.L.$

$c_{t\varphi}$: Higgs-top modifier



$c_{t\varphi}$ vs. $c_{\varphi G}$ 2D

Full results can be found: ATL-PHYS-PUB-2023-012

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. arXiv:2304.01532
- The measurement of the Higgs total decay width is

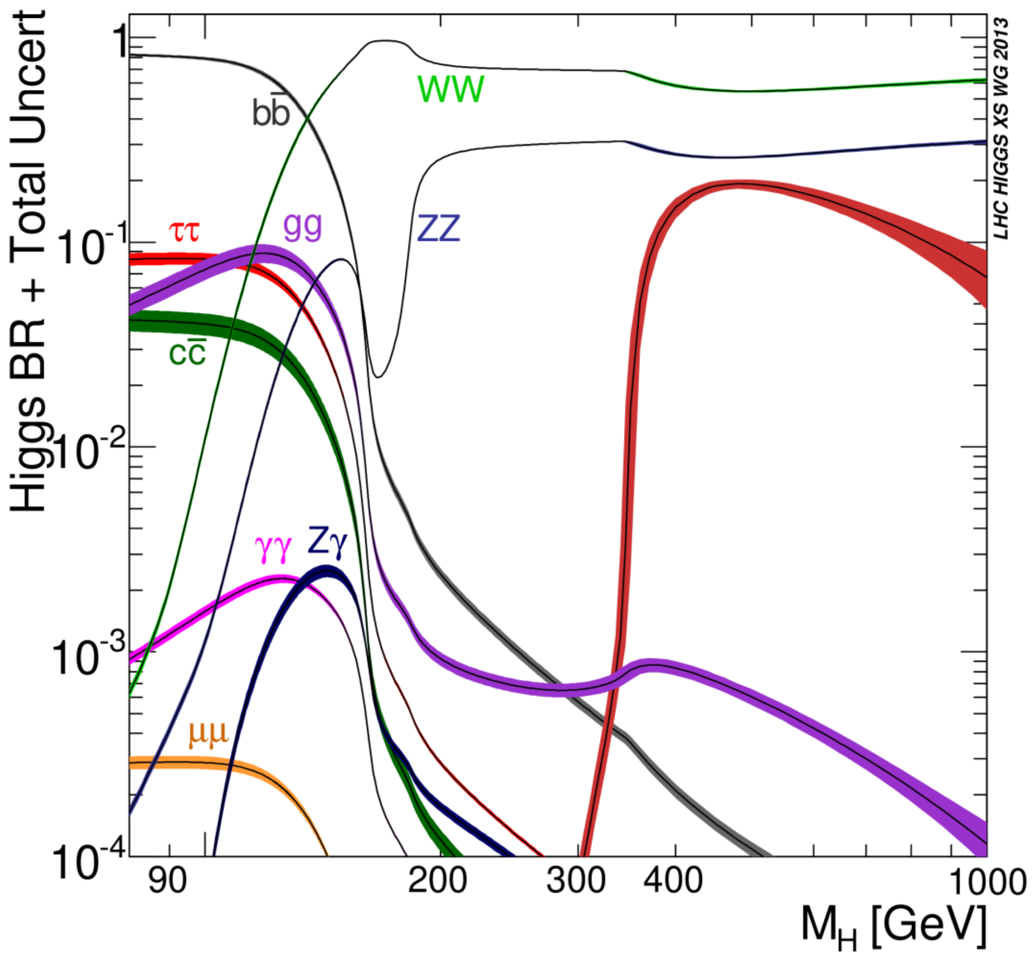
$$\Gamma_{\mathrm{H}} = 4.6^{+2.6}_{-2.5}\ \mathrm{MeV@68\%\ CL.}$$

- Consistent with CMS $\Gamma_{\mathrm{H}} = 3.2^{+2.4}_{-1.7}\ \mathrm{MeV@68\%\ CL.}$ Nature. Phys. 18 (2022) 1329
- The EFT interpretation is also provided. No significant derivation from SM is observed within uncertainties.

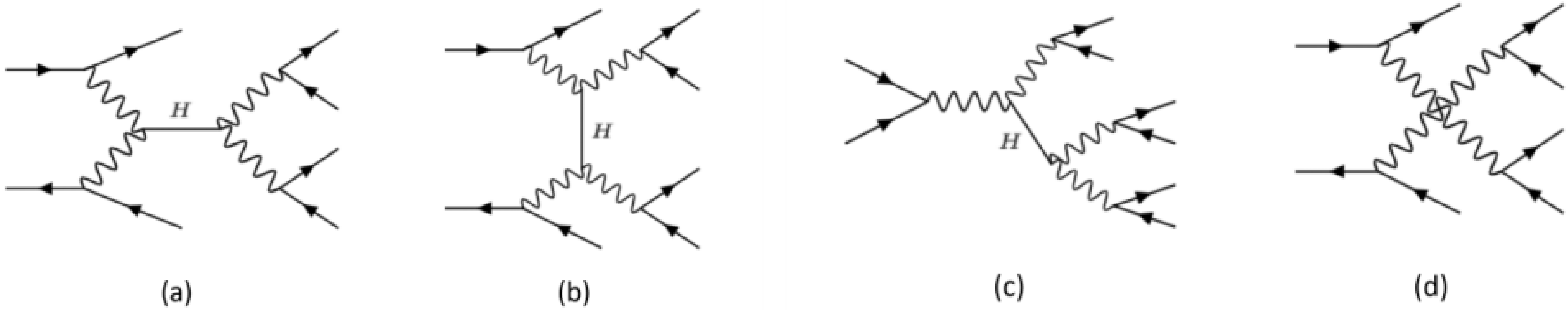
Backup

Higgs to ZZ and WW

- **Higgs** to **ZZ** and **WW** decay modes ideal to study Higgs properties!
  - H→ZZ: Large S/B ratio and high resolution (from e/μ), but small BR once Z → $ee/\mu\mu$ (6%), therefore stats limited.
  - H→WW: High sensitivity from large BR, but poor mass resolution due to undetectable ν's
- With the full Run 2 data (139 fb^{-1}) → window to precision measurements!
  - Higgs to ggF and VBF couplings
  - Higgs mass, Higgs decay width, Higgs XSec
  - EFT coupling measurements



EW signal, background and interference



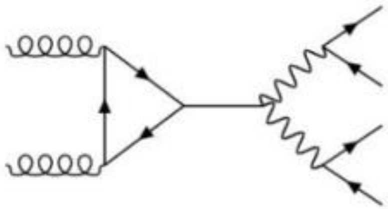
VBF s-channel | VBF t-channel | VH | VBS

Non-negligible interference among all the components

Event categories

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

ggF Signal region

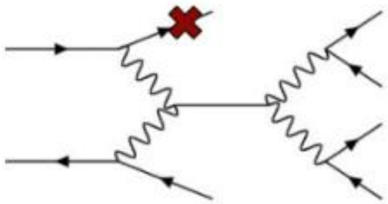


$n_{\text{jets}} = 0$

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

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

1 jet mixed signal region



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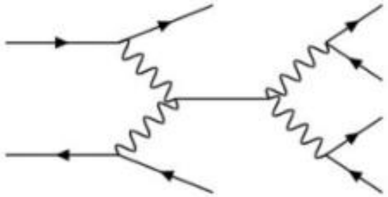

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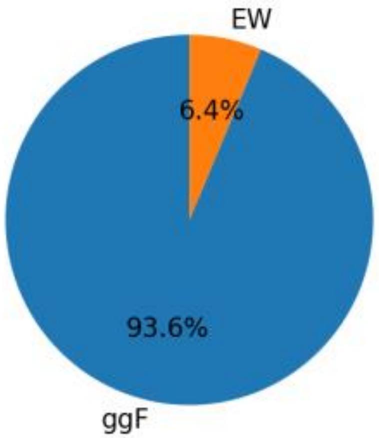
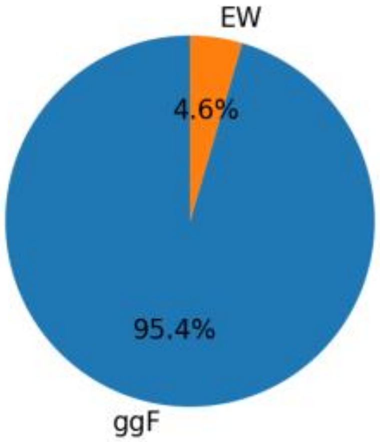
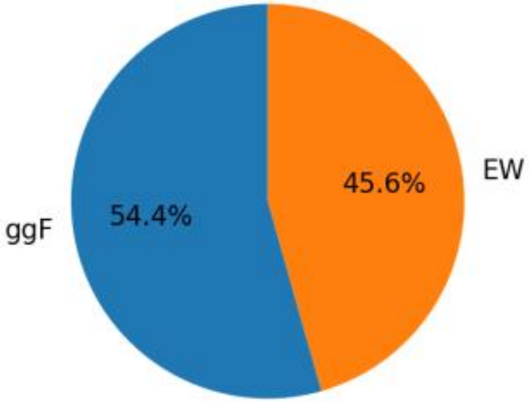
Fractions in 4ℓ channel







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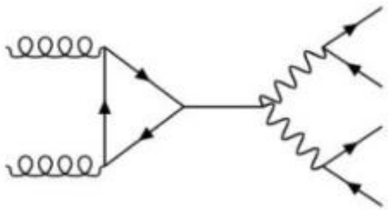

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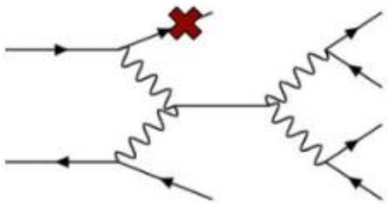

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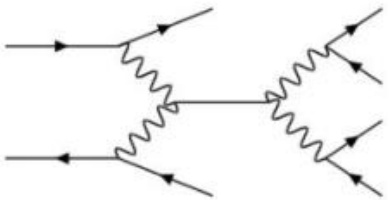
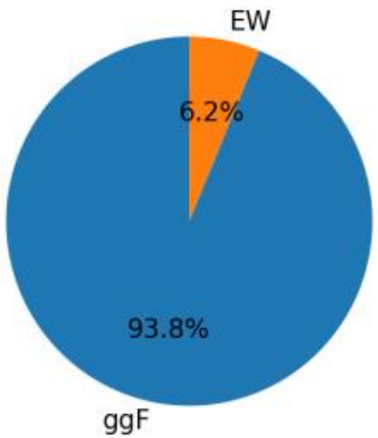
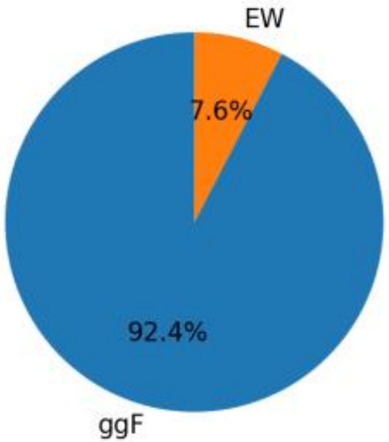
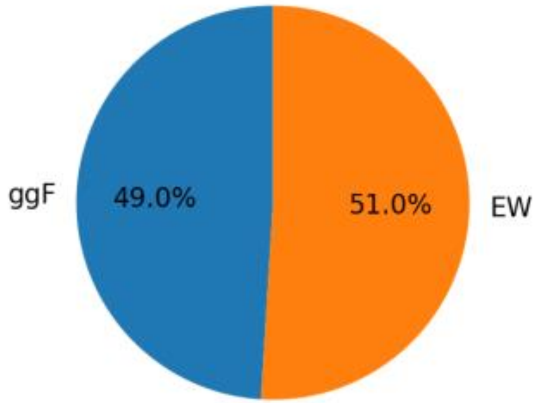


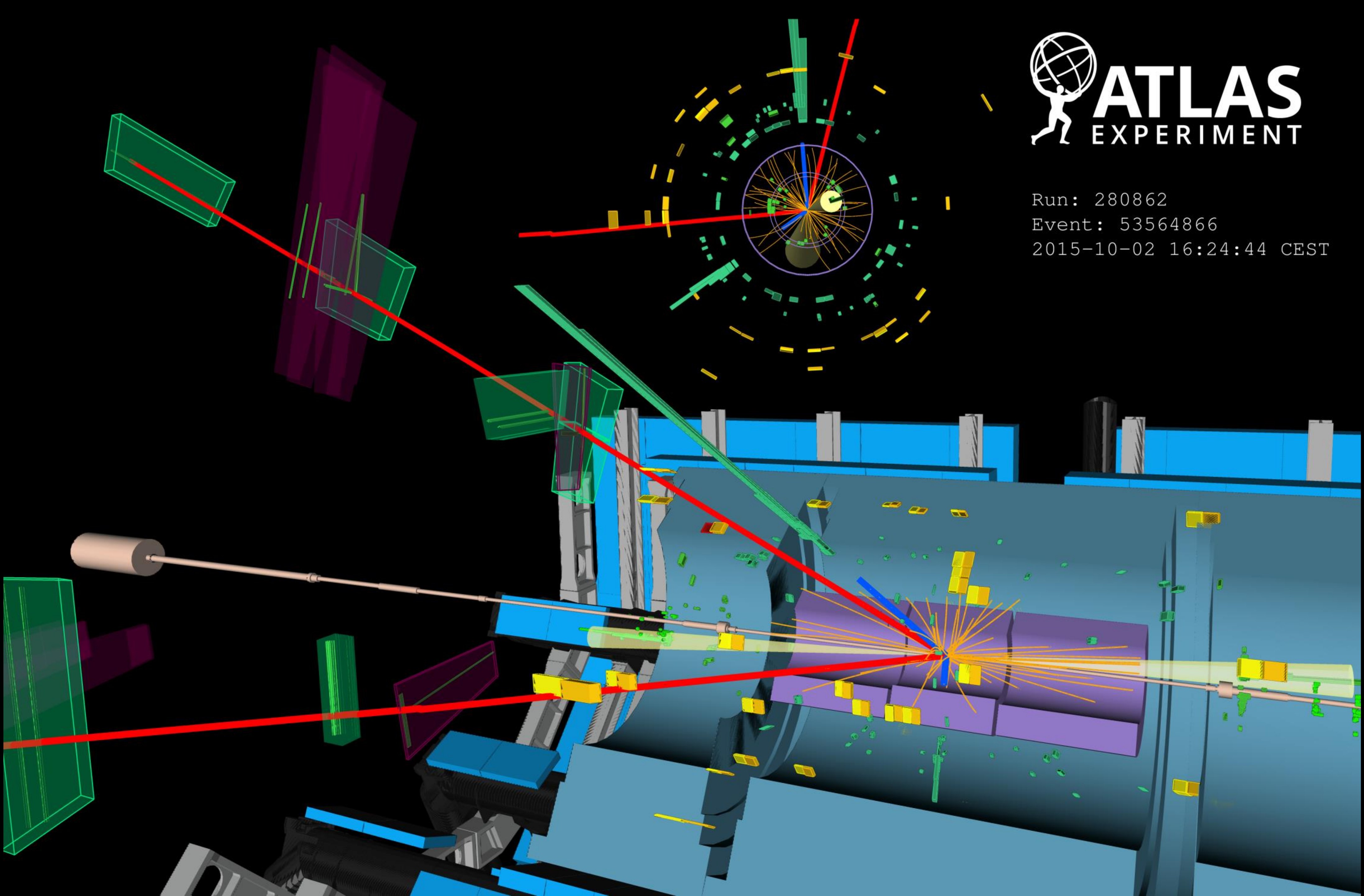
$n_{\text{jets}} \geq 2$ and $|\Delta\eta_{jj}| \geq 4.0$

Fractions in $2\ell 2\nu$ channel





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

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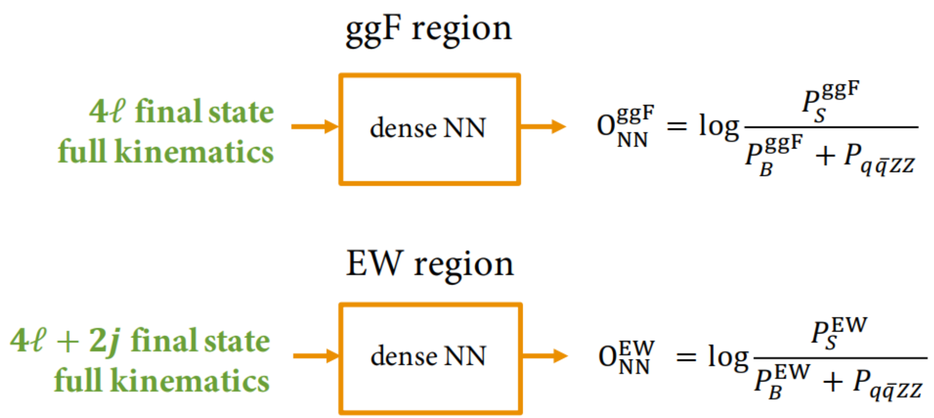
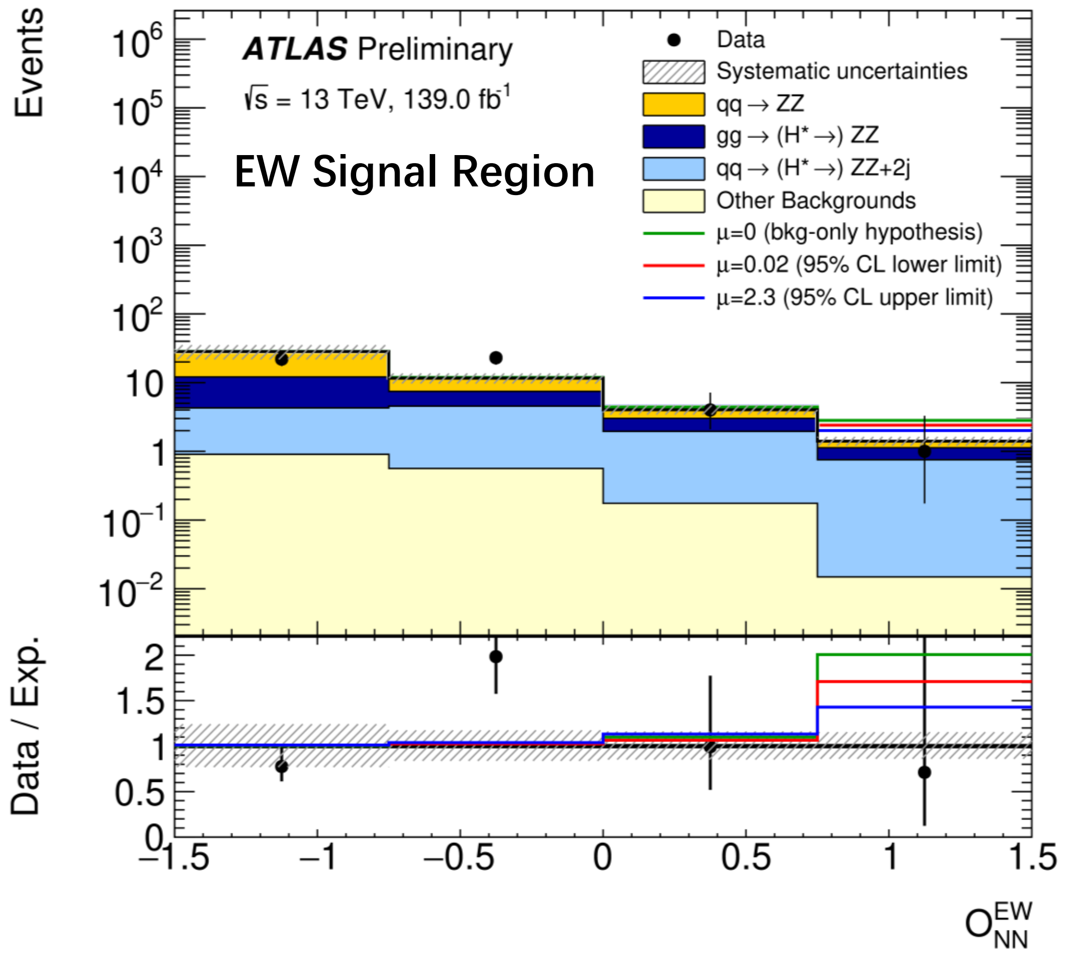
- Observables: neural network method (inputs: P_T, η, matrix-element, etc)





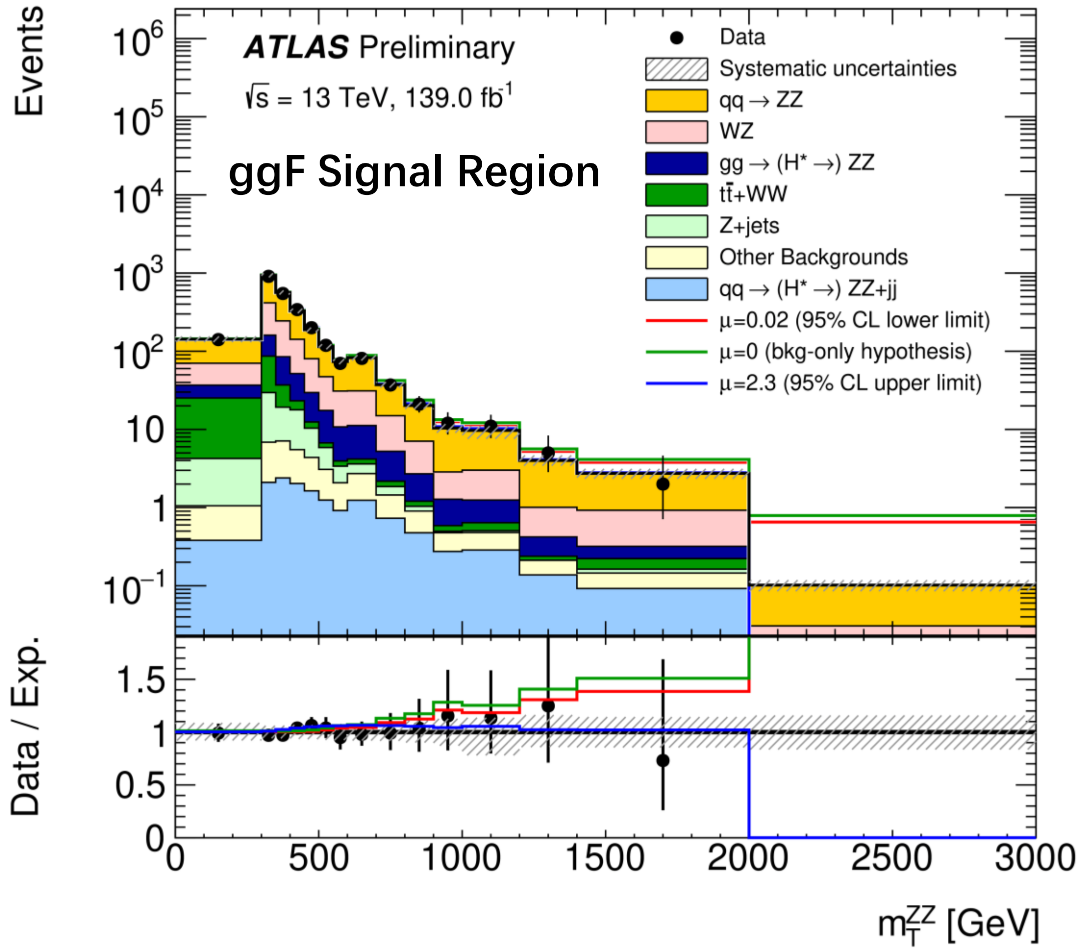
- Background: qqZZ (main), ggZZ

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

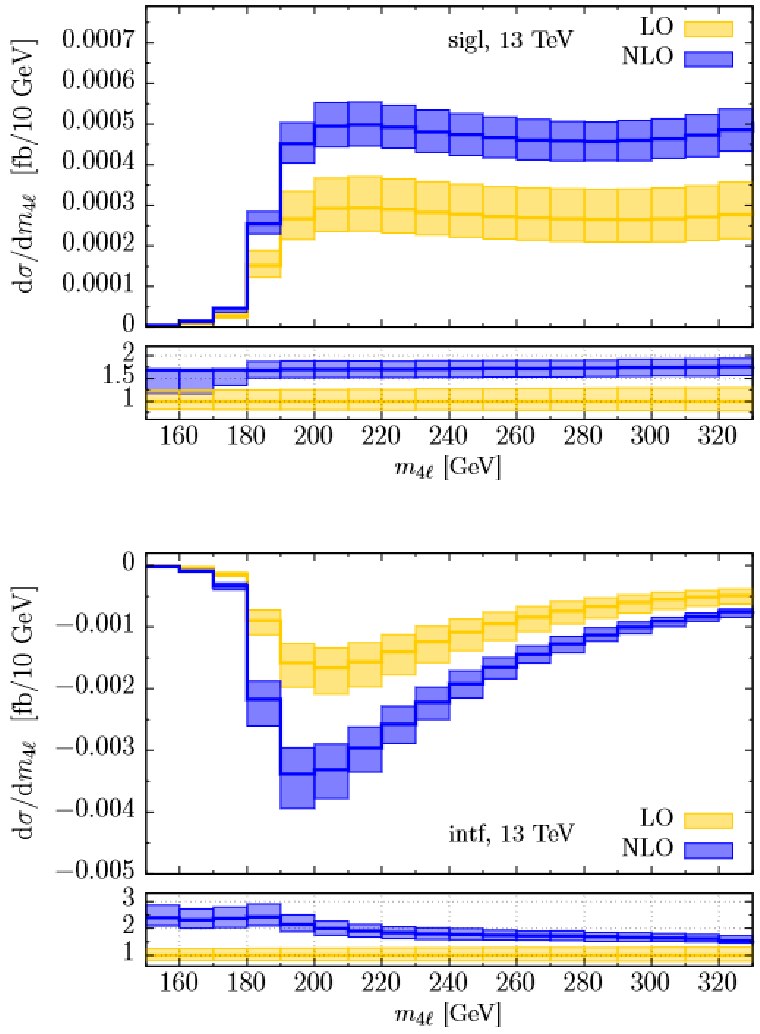
$$m_T^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_T^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_T^{\text{miss}}\right)^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right|^2}$$

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



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.



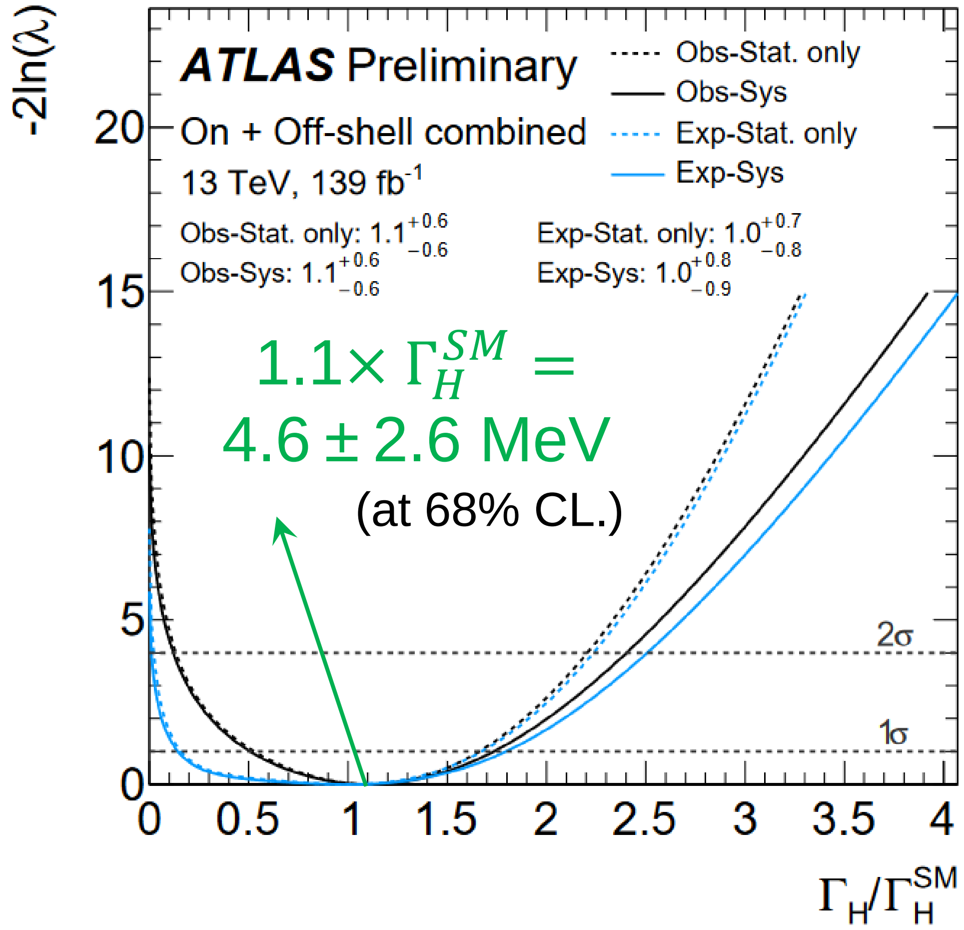
ggF: F.Caola et al. *JHEP* 07 (2016) 087

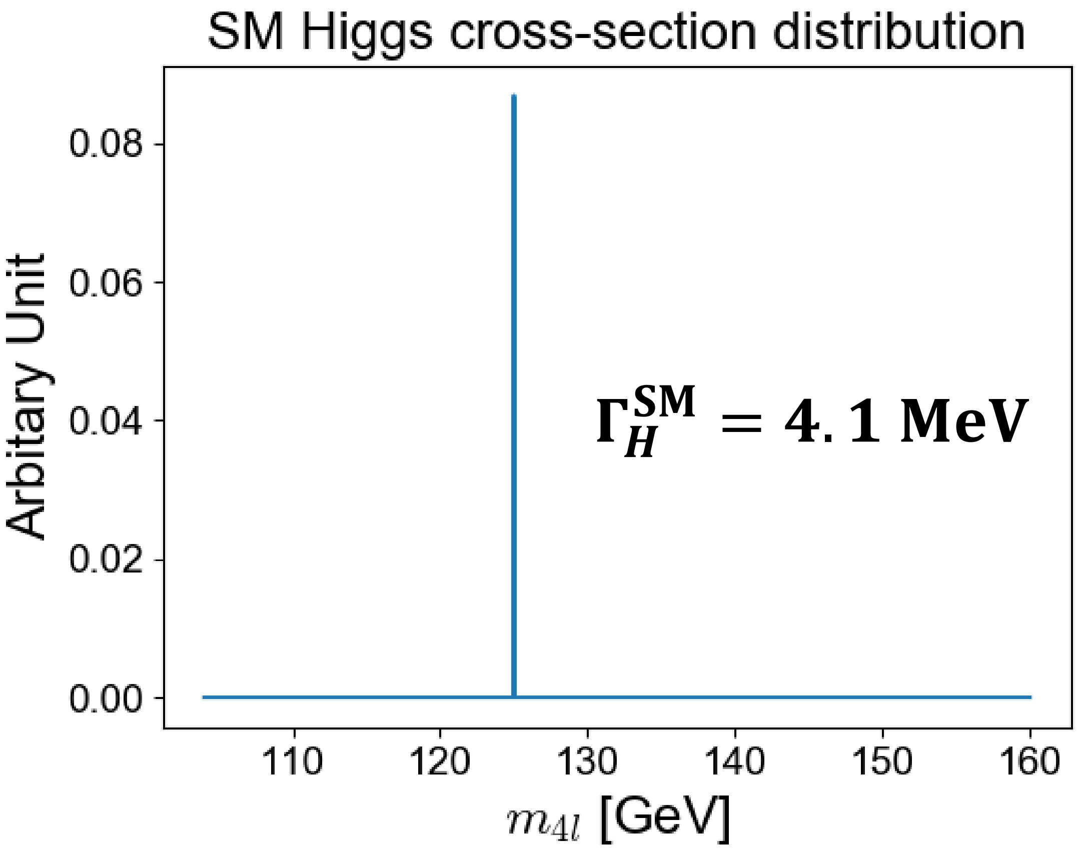
Off-shell $H^* \rightarrow ZZ$ analysis results

❑ Total Higgs decay width constraints:

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

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





Off-shell $\mathbf{H}^* \rightarrow$ ZZ EFT distribution