Higgs Searches: A Status Report

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ATLAS EXPERIMENT

Evidence of off-shell Higgs boson production

Introduction

- It is essential to measure the Higgs boson properties precisely—think of its decay width.
- However, a direct measurement of the Higgs boson total width is probably inconceivable.

- Due to the following reasons:
  - The width predicted by the SM is 4.1 MeV—very small;
  - but the experimental resolution is ~ 0.2 GeV—experimental limitation.

- Why the $H^* \to ZZ$ off-shell is a good idea to measure the Higgs total width?

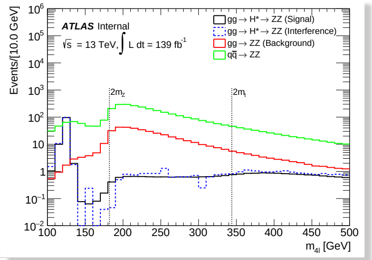
$$\frac{\mathrm{d}\sigma^{pp\to H\to ZZ}}{\mathrm{d}M_{ZZ}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{\left(M_{ZZ}^2 - m_H^2\right)^2 + m_H^2 \Gamma_H^2}$$

- Assuming the on-shell ($m_H \sim M_{ZZ}$) and off-shell case (m_H is an arbitrary)

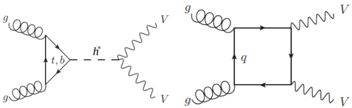
$$\frac{\mathrm{d}\sigma_{\text{on-shell}}^{pp\to H\to ZZ}}{\mathrm{d}M_{ZZ}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{m_H^2 \Gamma_H^2} \qquad \text{and} \qquad \frac{\mathrm{d}\sigma_{\text{off-shell}}^{pp\to H\to ZZ}}{\mathrm{d}M_{ZZ}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{\left(M_{ZZ}^2 - m_H^2\right)^2}$$

- Notice that the off-shell cross-section does not depend on the Higgs boson width.

- **Motivation**:
  - The ggF cross-section extends by O(15%);
  - due to two threshold effects on the off-shell.
  - The Higgs total width can indirectly measured.
  - Constrain the Higgs couplings in BSM scenarios.



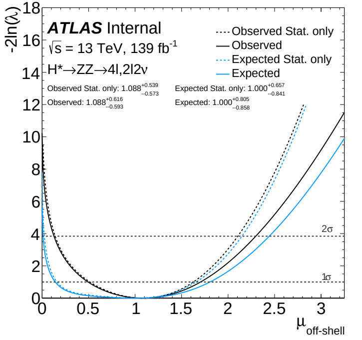
- **Off-shell Higgs measurements**:
  - $H^* \to ZZ \to 4\ell$
  - $H^* \to ZZ \to 2\ell 2\nu$
- *HZZ* combined results:
  - The $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$ off-shell results
  - Eur. Phys. J. C 80 (2020) 957 on-shell results
- Previous round was published using 36.1 fb^{-1} [1].
- This round uses the 139 fb^{-1} full Run-II datasets.



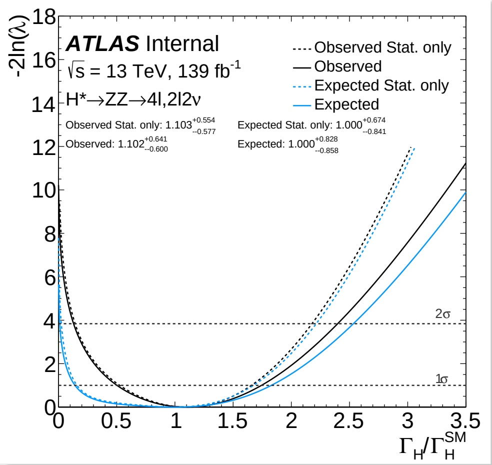
Evidence of off-shell Higgs boson production

Off-shell signal strength

- A simultaneous fit is performed on the Signal and Control regions:
  - Signal regions:
    ggF: 0-jet; 1-jet & $\eta_j < 2.2$; 2-jets& $\Delta\eta_{jj} < 4.0$
    VBF: 0-jet; 1-jet & $\eta_j < 2.2$; 2-jets& $\Delta\eta_{jj} < 4.0$
  - A control region to constrain the $q\bar{q} \to ZZ$ in $80 < m_{4\ell} < 220$ with 0-, 1-, 2-jets
- The $q\bar{q} \to ZZ$ normalisation is extracted from the data.
- The background-only hypothesis is rejected with an observed (expected) significance of 3.2 (2.4) σ
- The central observed value with 1 σ confidence:
  - $\mu = 1.09^{+0.60}_{-0.59}$



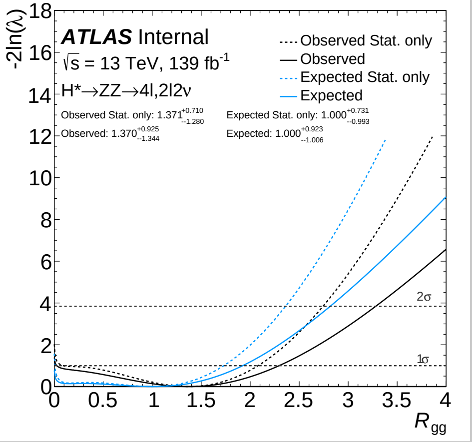
Evidence of off-shell Higgs boson production
Total Higgs width

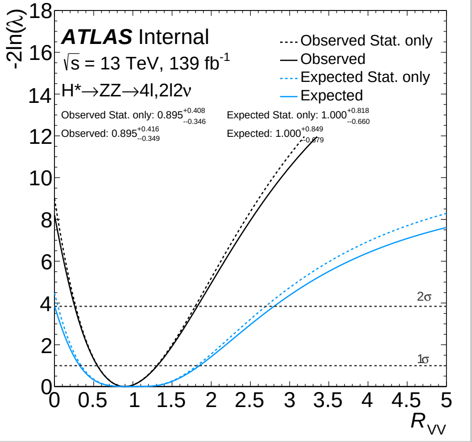


- The central observed value with 1 σ confidence:
  - $\Gamma_H/\Gamma_H^{\text{SM}} = 1.10^{+0.55}_{-0.60} \Rightarrow \Gamma_H = 4.6^{+2.6}_{-2.5}$ MeV

Evidence of off-shell Higgs boson production

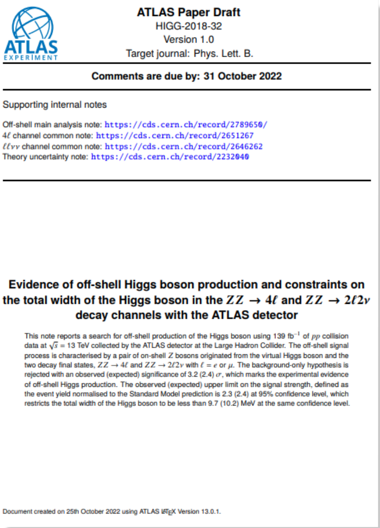
Couplings ratio





Summary

- Measure the Higgs boson total width by exploiting the ratio between on-shell and off-shell production.
- We measured the off-shell Higgs boson production in the ZZ to 4ℓ and ZZ to $2\ell 2\nu$ final states.
- The total Higgs width is measured to be:
  - $\Gamma_H = 4.6^{+2.6}_{-2.5}$ MeV
- Results will be shown in the HIGGS 2022 Pisa, November 9th, 2022



ATLAS Paper Draft
HIGG-2018-32
Version 1.0
Target journal: Phys. Lett. B.

Comments are due by: 31 October 2022

Supporting internal notes

Off-shell main analysis note: https://cds.cern.ch/record/2789650/
4ℓ channel common note: https://cds.cern.ch/record/2651267
$\ell\ell\nu\nu$ channel common note: https://cds.cern.ch/record/2646262
Theory uncertainty note: https://cds.cern.ch/record/2232040

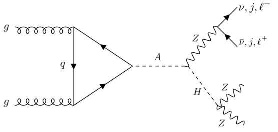
Evidence of off-shell Higgs boson production and constraints on the total width of the Higgs boson in the $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$ decay channels with the ATLAS detector

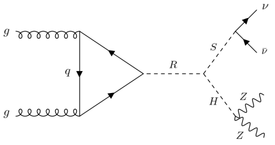
This note reports a search for off-shell production of the Higgs boson using 139 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV collected by the ATLAS detector at the Large Hadron Collider. The off-shell signal process is characterised by a pair of on-shell Z bosons originated from the virtual Higgs boson and the two decay final states, $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$ with $\ell = e$ or μ. The background-only hypothesis is rejected with an observed (expected) significance of 3.2 (2.4) σ, which marks the experimental evidence of off-shell Higgs production. The observed (expected) upper limit on the signal strength, defined as the event yield normalised to the Standard Model prediction is 2.3 (2.4) at 95% confidence level, which restricts the total width of the Higgs boson to be less than 9.7 (10.2) MeV at the same confidence level.

Document created on 25th October 2022 using ATLAS LaTeX Version 13.0.1.

$4\ell + E_T^{miss}$ analysis

- **4ℓ+MET analysis**:
  - Glance link
  - TWiki
  - Supporting note in the CDS ⇒
  - Recent communication through the CDS
- We had a pre-approval talk October 27, 2022.
- Expect to give a closure-talk in the HBSM asap.





ATLAS Note

ANA-HDBS-2019-08-INT1

27th October 2022

Draft version 1.0

Search for heavy resonances in final states with 4ℓ and missing transverse energy or jets in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

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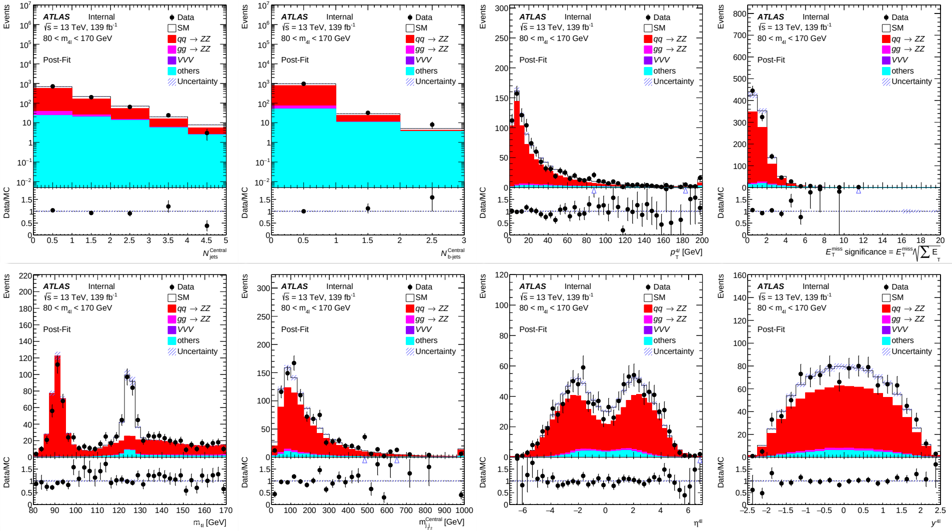
[d]University of the Witwatersrand

A search for a new heavy boson produced via gluon-fusion in the four-lepton channel with missing transverse energy or jets is presented. The search uses proton–proton collision data equivalent to an integrated luminosity of 139 fb^{-1} at a centre-of-mass energy of 13 TeV collected by the ATLAS detector between 2015 and 2018 at the Large Hadron Collider. The heavy boson, R (A), decays to an S (Z) boson and another lighter Higgs-like boson, H, which subsequently decays to 4ℓ. The S boson is supposed to decay to dark matter, and the Z boson can decay inclusively. The mass spectrum studied is 390 - 2160 (320 - 2090) GeV for the R (A) boson and 220 - 1000 GeV for the H boson. The S boson mass is fixed to 160 GeV. Upper limits on the $\sigma \times \text{BR}(R(A) \to SH(ZH)) \times \text{BR}(H \to ZZ) \times \text{B}(ZZ(ZZZ) \to 4\ell)$ at 95% confidence level are set. For the $R \to SH \to 4\ell + E_T^{miss}$ expected (observed) upper limits are in the range of 0.030 - 0.305 (xx - xx) fb for (m_R, m_H) = (390, 220) GeV to (m_R, m_H) = (1300, 1000) GeV. And expected (observed) upper limits for $A \to ZH \to 4\ell + X$ are in the range of 0.028 - 0.293 (xx - xx) fb for (m_A, m_H) = (320, 220) GeV to (m_A, m_H) = (1300, 1000) GeV. The results are interpreted in terms of the two-Higgs-doublet model scenarios where exclusion limits are performed.

$4\ell + E_T^{miss}$ analysis

Control region

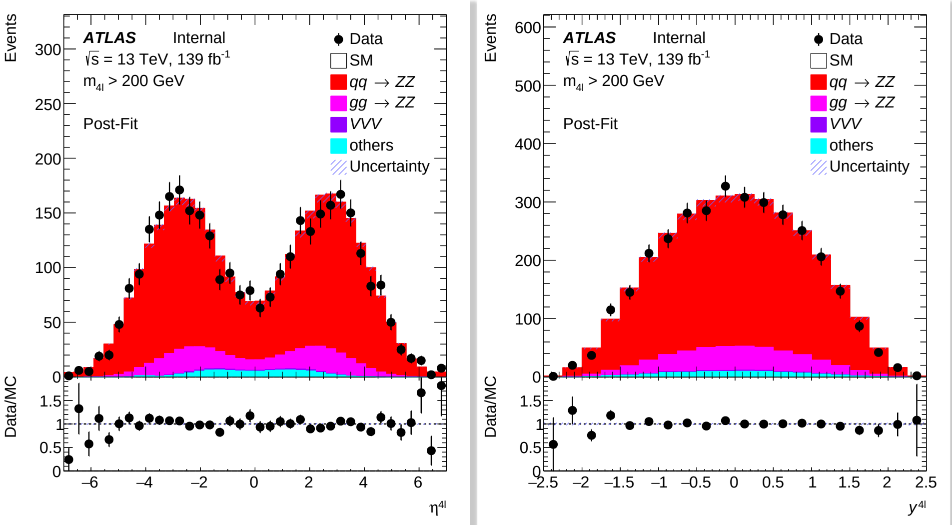
- **Control region definition:** $80 < m_{4\ell} < 170$ GeV
- Checking the compatibility of the data to the SM backgrounds on the control region.
- $\mu(q\bar{q} \to ZZ,\, gg \to ZZ) = 0.97 \pm 0.04$; similar method used in the $H \to ZZ \to 4\ell$ (High mass) note.



$4\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ analysis

Data/MC comparison for $m_{4\ell} > 200$ GeV

- Data/MC comparison for non-discriminative distributions at $m_{4\ell} > 200$ GeV—suggested by the EB.
- $\mu(q\bar{q} \to ZZ,\ gg \to ZZ) = 1.13 \pm 0.03$.



$4\ell + E_T^{miss}$ analysis

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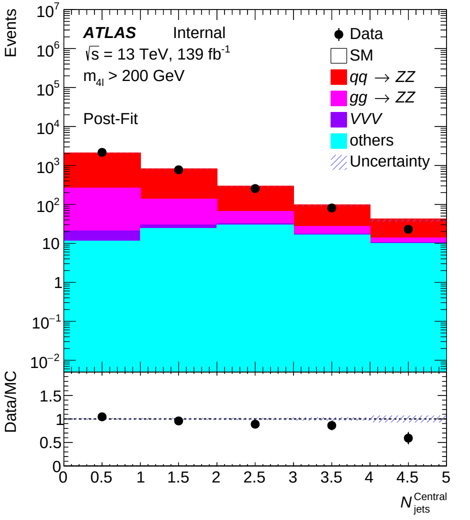
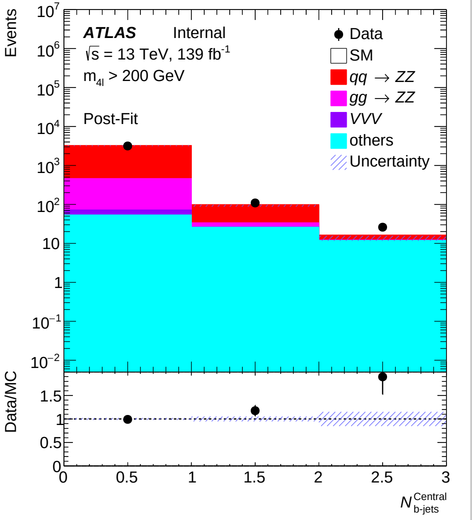
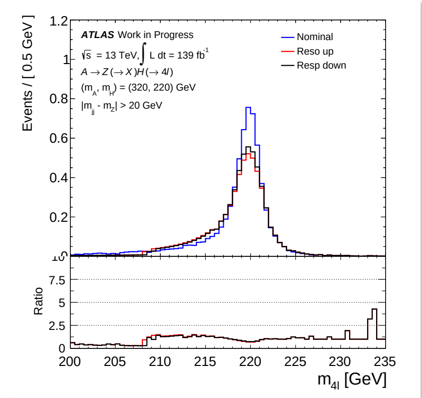
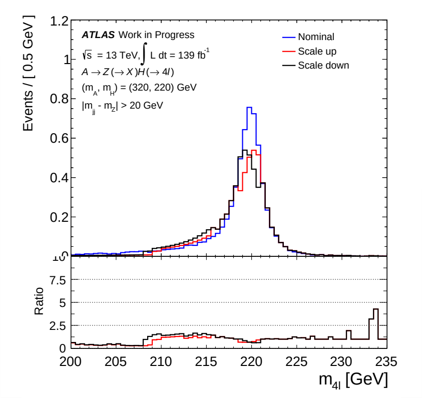




$4\ell + E_T^{miss}$ analysis
Systematic on the signal shape

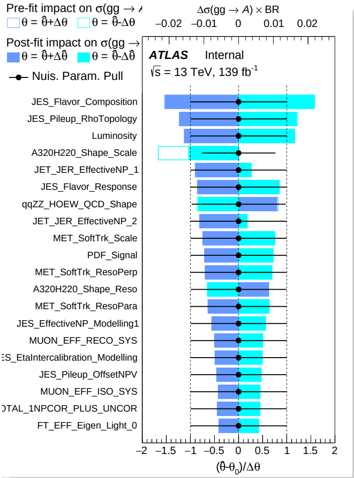




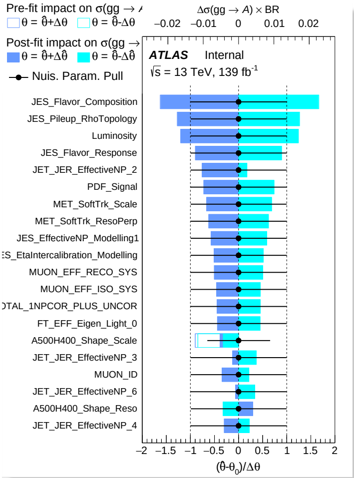
- ☐ Resolution: the σ is modified by 1.4% (up/down)
- ☐ Scale: the μ is modified by 0.23% (up/down)
- ☐ EG_RESOLUTION_ALL(RMS) & EG_SCALE_ALL(MEAN)

$4\ell + E_T^{miss}$ analysis

The impact of NPs parameter on the POI



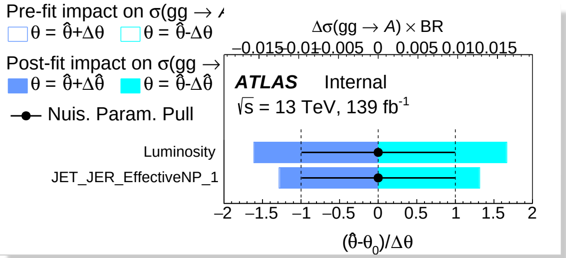
A320H220



A500H400

$4\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ analysis

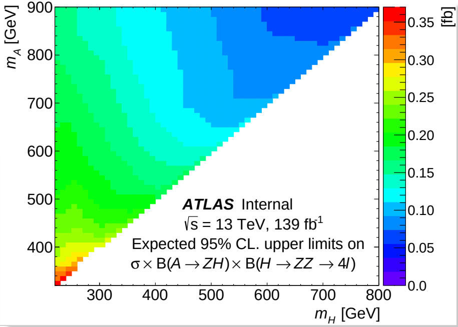
The impact of NPs parameter on the POI: the asymmetry behaviour

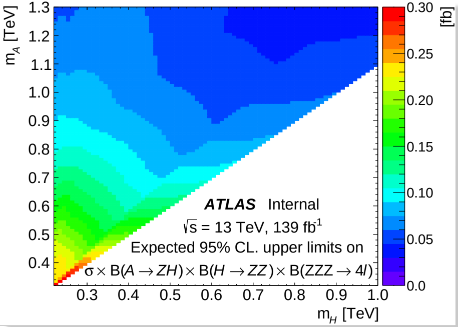


- ☐ The JET _ JER _ EffectiveNP _ 1 is estimated: +0.015364/-0.003235;
- ☐ This results on asymmetry behaviour seen in previous slides;
- ☐ When th NP is symmetrised this asymmetry effect disappeared.

$4\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ analysis

Upper limits on the $(m_H,\ m_A)$ plane for the $A \to ZH \to 4\ell + X$ model





- ☐ Upper limits at 95% CL between [0.028 - 0.293] fb on (320, 1300) - (220, 1000) GeV.
- ☐ The $A \to Z(\to X)H(\to 4\ell)$ signal only (left) and $A \to ZH \to 4\ell + X$ (right).

Summary

- ☐ Working on the questions asked during the approval meeting.

- ☐ However, the organisers preferred to be in-person.

“ Measurements of the Higgs boson properties and their interpretations with the ATLAS experiment PRE-ACCEPTED

status	PRE-ACCEPTED
duration	-
conference	Miami 2022 (Miami 2022)
website	https://cgc.physics.miami.edu/MiamiOriginal2022.html
start date	December 14th, 2022
end date	December 20th, 2022