Constraints on Off-shell Higgs Boson Production and the Higgs Boson Total Width in ZZ Final states with the ATLAS Detector

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on behalf of the ATLAS Collaboration

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Abstract

The off-shell production of SM Higgs boson, at the high-mass off-peak region beyond $2m_Z$, well above the measured resonance mass of m_H=125 GeV, has a substantial cross section at the LHC, due to the increased phase space as the Z bosons become on-shell with the increasing energy scale. This presents a novel way of characterizing the properties of the Higgs boson in terms of the off-shell event yields, normalized to the SM prediction (referred to as signal strength μ), and the associated off-shell Higgs boson couplings. Assuming the ratio of the Higgs boson couplings to the SM predictions is independent of the momentum transfer of the Higgs boson production mechanism, a combination with the on-shell signal-strength measurement was used to set indirect limits on the total Higgs boson width with the 36 fb^{-1} ATLAS Run-2 data collected in proton-proton collisions at the centre-of-mass energy of $\sqrt{s}$ = 13 TeV.

Introduction & Motivation

- Main Purpose is to study the off-shell Higgs boson production in ZZ events above the m_H peak (~15% of the overall ggF cross-section)
  - Further characterize the Higgs boson properties:
    - measure the off-shell signal strength
    - probe new physics which can play a role in modifying the couplings structure
  - The SM Higgs total width, $\Gamma_H \sim 4$ MeV, is not directly measurable at the LHC due to experimental limits
    - indirectly constrain the Higgs total width, assuming identical on-shell and off-shell couplings

Analysis Overview

- The study is based on two independent analyses ($ZZ \rightarrow 4\ell$, $ZZ \rightarrow 2\ell 2\nu$) that are combined to derive the final constraints
- The event selections are performed inclusively in the number of jets to reduce QCD-corrections dependence
- Use data collected by the ATLAS experiment in 2015 and 2016 at an integrated luminosity of 36.1 fb^{-1}
- On-shell region is defined between 118-129 GeV, while the off-shell is defined between 220-2000 GeV ($ZZ \rightarrow 4\ell$) and 250-2000 GeV ($ZZ \rightarrow 2\ell 2\nu$)

Analysis Strategy

Two-steps strategy:

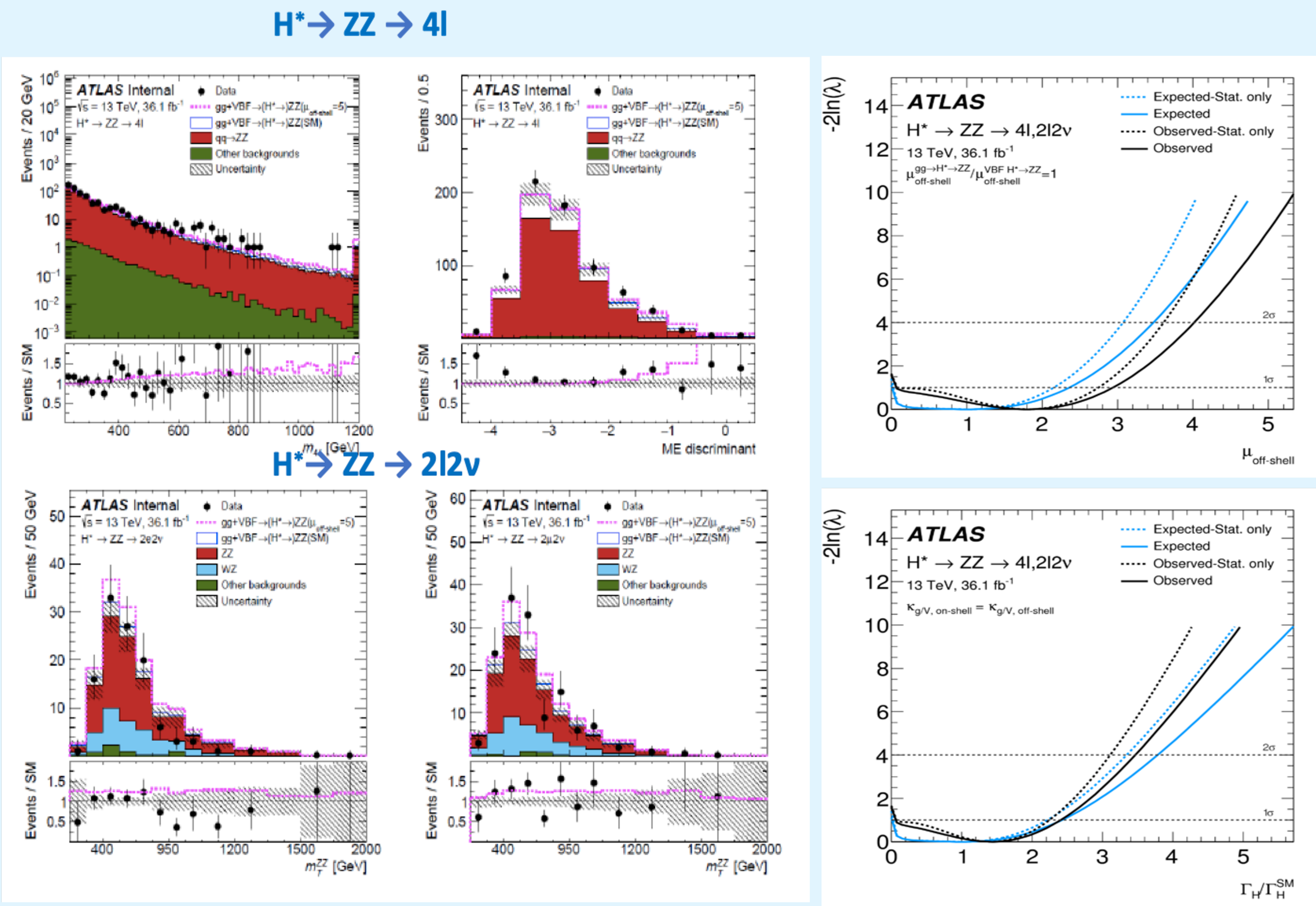
1. Off-shell signal strength measurement
   - Interpetation of off-shell when fixing the ratio of the signal strength in ggF and VBF to the SM prediction
2. Higgs total width measurenent
   - Interpretation of the Higgs total width when assuming the same on-shell and off-shell couplings $\frac{\mu_{off-shell}}{\mu_{on-shell}} = \frac{\Gamma_H}{\Gamma_H^{SM}}$

References:

1. Phys. Lett. B 786 (2018) 223
2. Eur. Phys. J. C (2015) 75:335

Analysis Results

- For the $ZZ \rightarrow 4\ell$ channel, the shape fits to a Matrix Element -based kinematic discriminant, while the $ZZ \rightarrow 2\ell 2\nu$ fits to the transverse mass ZZ distribution
- Main backgrounds: $qq \rightarrow ZZ$, $gg \rightarrow ZZ$
- Interference (negative) between signal and $gg \rightarrow ZZ$ continuum is considered
- The experimental systematics are almost negligible. The dominant systematic is the theory uncertainty on the high-order QCD corrections for ZZ background and signal



Conclusions

- Measurement of off-shell Higgs boson production in $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$ (ℓ = e or μ)
- Using LHC ATLAS Run-2 36.1 fb^{-1} data at $\sqrt{s}$=13 TeV
- Observed (expected) upper limit at 95% CL on **off-shell Higgs signal strength** of 3.8 (3.4)
  - Off-shell Higgs signal strength: event yield normalized to SM prediction
- Combination with the on-shell signal-strength measurements yields observed (expected) 95% CL upper limit on **Higgs boson total width** of 14.4 (15.2) MeV
  - Assuming ratio of Higgs boson couplings to SM predictions independent of momentum transfer of Higgs production mechanism

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CONSTRAINTS ON OFF-SHELL HIGGS BOSON PRODUCTION AND THE HIGGS BOSON TOTAL WIDTH IN ZZ FINAL STATES WITH THE ATLAS DETECTOR

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On behalf of the ATLAS Collaboration

INTRODUCTION& MOTIVATION

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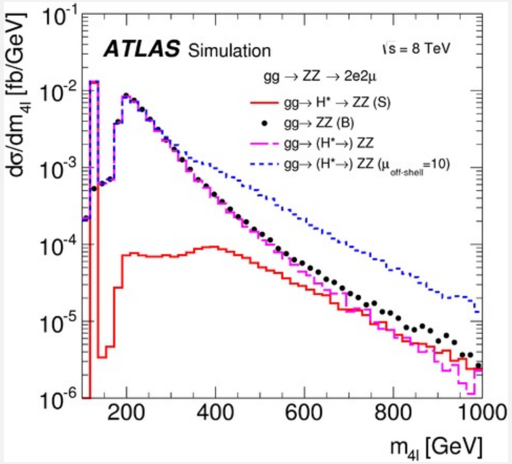
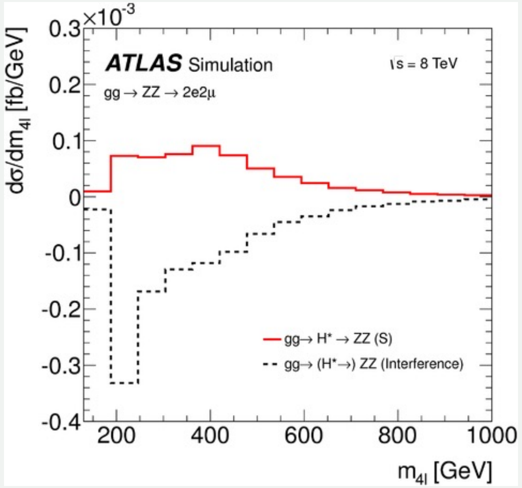
Differential cross-sections



INTERFERENCE

- <u>Interference</u> is significant between off-shell signal and continuum ggZZ background
- SBI=S+B+I, S : signal ($gg \rightarrow H^{\star} \rightarrow ZZ$), B : background ($gg \rightarrow ZZ$), I : interference term

Differential cross-sections



- Signal only, Background only, and SBI samples used
- Interference term "I" is derived with the samples "I = SBI-S-B"
- Signal related distribution ***(signal strength, μ): $\mu \cdot S + \sqrt{\mu} \cdot I + B$***

ANALYSIS STRATEGY

- The study is based on two independent analyses ($ZZ \to 4\ell$, $ZZ \to 2\ell 2\nu$) that are combined to derive the final constraints
- On-shell region is defined between 118-129 GeV, while the off-shell is defined between 220-2000 GeV ($ZZ \to 4\ell$) and 250-2000 GeV ($ZZ \to 2\ell 2\nu$)
- Interference (negative) between signal and $gg \to ZZ$ continuum background is considered

- $ZZ \to 4\ell$ channel, ME, Matrix Element based kinematic discriminant
- $ZZ \to 2\ell 2\nu$ channel, m_T^{ZZ}, transverse mass ZZ distribution

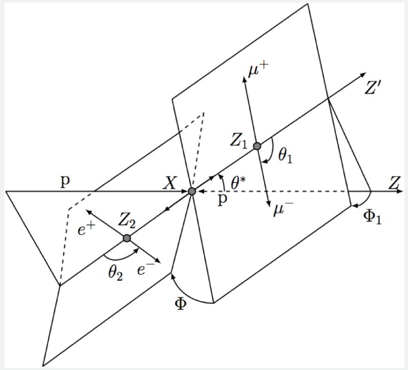
$$D_{\mathrm{ME}} = \log_{10}\left(\frac{P_H}{P_{gg} + c \cdot P_{q\bar{q}}}\right)$$

c=0.1

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

ANALYSIS OVERVIEW ($ZZ \rightarrow 4\ell$)

- On-shell high-mass★ event selection used as baseline in the off-shell region: 220 GeV < m_{4l} < 2000 GeV
- Four final states: 4e, 4μ, 2e2μ, 2μ2e
- Backgrounds:
  - ZZ continuum from MC, qq → ZZ and gg → ZZ, ~97%
  - Reducible estimated from data, ~3%
- Shape fit to Matrix Element (ME) based kinematic discriminant
  - ME is based on 8 observables defining the event kinematics in the center of mass frame of 4ℓ system



- $P_{q\bar{q}}$: the matrix element squared for the $q\bar{q} \rightarrow ZZ \rightarrow 4\ell$ process,
- P_{gg}: the matrix element squared for the $gg \rightarrow (H^* \rightarrow)ZZ \rightarrow 4\ell$ process which includes the Higgs boson with SM couplings, continuum background and their interference,
- P_H: the matrix element squared for the $gg \rightarrow H^* \rightarrow ZZ \rightarrow 4\ell$ process.

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

c=0.1

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ANALYSIS OVERVIEW($ZZ \to 2\ell 2\nu$)

- Gain in signal yield Br($ZZ \to 2\ell 2\nu$) ~ 6 Br($ZZ \to 4\ell$)
- Baseline selection same as high-mass★ $ZZ \to 2\ell 2\nu$ search reoptimized
  - Higher energy region: $E_T^{miss} > 175$ GeV, $E_T^{miss}/H_T > 0.33$
- Two final states: $2\mu 2\nu$, $2e2\nu$ (2 isolated leptons, large E_T^{miss})
- Backgrounds
  - Irreducible from MC, $qq \to ZZ$ and $gg \to ZZ$, ~63%
  - Reducible from data, ~37%
- Shape fit to transverse mass distribution m_T^{ZZ}

SYSTEMATICS

- The experimental systematic uncertainties for both channels are almost negligible
- The dominant systematic is the theory uncertainty on the high-order QCD corrections for qqZZ background and signal $gg(\to H^\star) \to ZZ$ (10-20%)

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ANALYSIS RESULTS (ZZ)

Expected and observed yields in the signal region for both final states

Process	$ZZ \to 4\ell$ $m_{4\ell} > 220$ GeV	$ZZ \to 4\ell$ $m_{4\ell} > 400$ GeV	$ZZ \to 2\ell 2\nu$ $m_T^{ZZ} > 250$ GeV
$gg \to (H^* \to)ZZ$	96 ± 15	10.6 ± 2.0	22 ± 4
($gg \to H^* \to ZZ$ (S)	9.8 ± 1.5	5.9 ± 1.0	20.1 ± 3.3)
($gg \to ZZ$ (B)	101 ± 16	11.8 ± 2.2	28 ± 6)
VBF $(H^* \to)ZZ$	8.29 ± 0.34	3.07 ± 0.13	2.83 ± 0.14
(VBF $H^* \to ZZ$ (S)	1.67 ± 0.08	1.14 ± 0.04	5.45 ± 0.30)
(VBF ZZ (B)	9.9 ± 0.4	4.17 ± 0.18	6.92 ± 0.35)
$q\bar{q} \to ZZ$	520 ± 42	77 ± 8	132 ± 15
$q\bar{q} \to WZ$	-	-	68 ± 4
$WW/t\bar{t}/Wt/Z \to \tau\tau$	-	-	2.6 ± 1.0
Z + jets	-	-	6.0 ± 2.8
Other backgrounds	14.6 ± 0.7	2.15 ± 0.15	1.14 ± 0.08
Total Expected (SM)	639 ± 60	93 ± 10	234 ± 16
Observed	704	114	261
Other signal hypothesis			
$gg \to (H^* \to)ZZ$ ($\mu_{\text{off-shell}} = 5$)	117 ± 18	26 ± 5	61 ± 12
VBF $(H^* \to)ZZ$ ($\mu_{\text{off-shell}} = 5$)	11.0 ± 0.5	4.85 ± 0.22	8.8 ± 0.4

Leading systematic uncertainties

Systematic uncertainty	95% CL upper limit on $\mu_{\text{off-shell}}$ $ZZ \to 4\ell$	$ZZ \to 2\ell 2\nu$	Combined
QCD scale $q\bar{q} \to ZZ$	4.2	3.9	3.2
QCD scale $gg \to (H^* \to)ZZ$	4.2	3.6	3.1
Luminosity	4.1	3.5	3.1
Remaining systematic uncertainties	4.1	3.5	3.0
All systematic uncertainties	4.3	4.4	3.4
No systematic uncertainties	4.0	3.4	3.0

ANALYSIS INTERPRETATION

- Derive the Higgs width based on the both on-shell and off-shell coupling measurement

$$\frac{d\sigma_{pp\to H\to ZZ}}{dM_{ZZ}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{ZZ}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

$$\sigma_{\text{off-shell}}^{pp\to H^*\to ZZ} \sim g_{Hgg}^2 g_{HZZ}^2$$

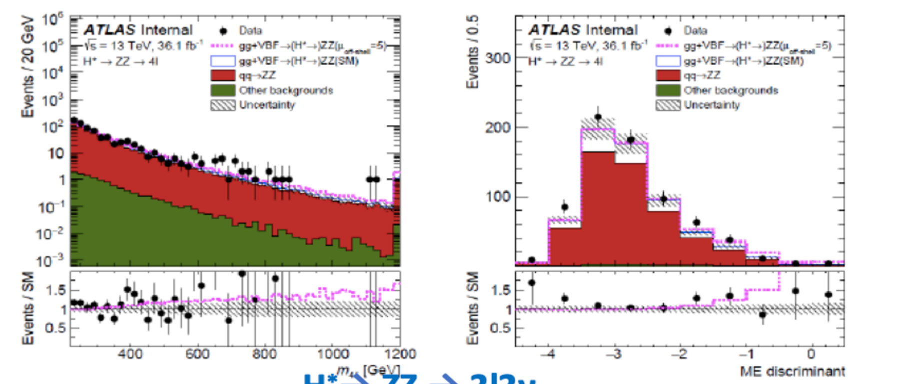
$$\sigma_{\text{on-shell}}^{pp\to H\to ZZ^*} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{m_H\Gamma_H}$$

$$\mu_{\text{off-shell}} = \frac{\sigma_{\text{off-shell}}^{gg\to H^*\to ZZ}}{\sigma_{\text{off-shell,SM}}^{gg\to H^*\to ZZ}} = \kappa_{g,\text{off-shell}}^2 \cdot \kappa_{Z,\text{off-shell}}^2 \qquad \mu_{\text{on-shell}} = \frac{\sigma_{\text{on-shell}}^{gg\to H\to ZZ}}{\sigma_{\text{on-shell,SM}}^{gg\to H\to ZZ}} = \frac{\kappa_{g,\text{on-shell}}^2 \cdot \kappa_{Z,\text{on-shell}}^2}{\Gamma_H/\Gamma_H^{SM}}$$

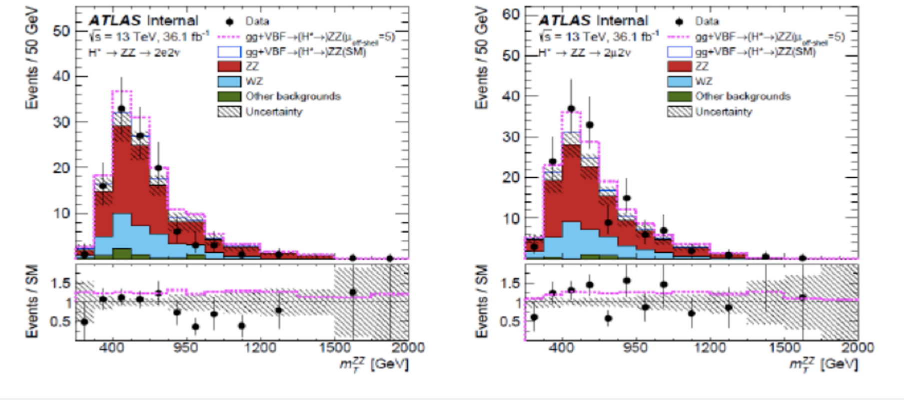
- Off-shell signal strength measurement:
  - Fix the ratio $\mu^{ggF}/\mu^{VBF} = 1$ as SM predicted, and derive the limit on inclusive $\boldsymbol{\mu_{off\text{-}shell}}$
- Higgs boson total width measurement: $\mu_{\text{off-shell}}/\mu_{\text{on-shell}} = \boldsymbol{\Gamma_H/\Gamma_{SM}}$
  - Assume identical on-shell and off-shell couplings ($\kappa_{g,\text{on-shell}} = \kappa_{g,\text{off-shell}} = \kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}}$)
- $\boldsymbol{R_{gg}} = \mu^{ggF}_{\text{off-shell}} / \mu^{ggF}_{\text{on-shell}}$, interpreted as ratio of off-shell to on-shell gluon couplings
  - Assume coupling scale factors $\kappa_V = \kappa_{V,\text{ on-shell}} = \kappa_{V,\text{ off-shell}}$ (profiled), and total width equal to SM prediction ($\Gamma/\Gamma_{SM}=1$)

ANALYSIS RESULTS-FITS

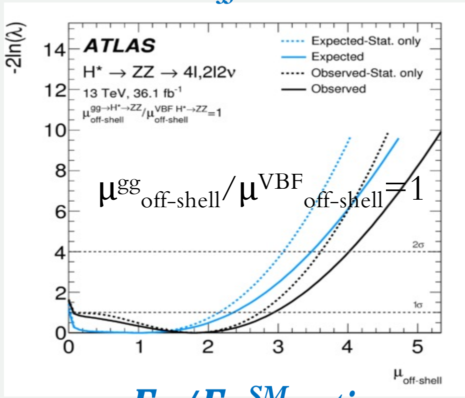
$H^* \rightarrow ZZ \rightarrow 4l$



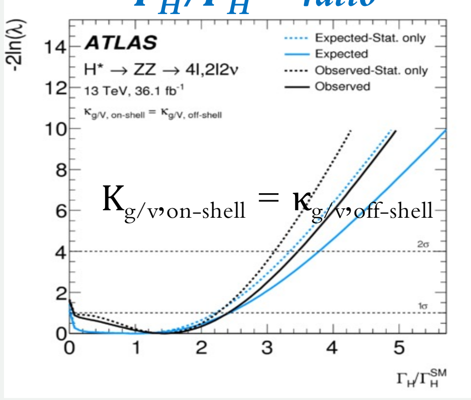
$H^* \rightarrow ZZ \rightarrow 2l2\nu$



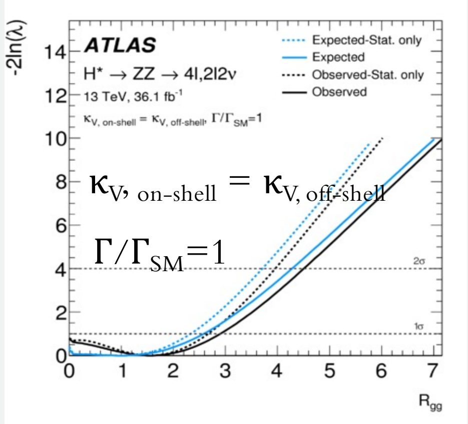
$\mu_{off\text{-}shell}$



Γ_H/Γ_H^{SM} ratio



$R_{gg}=\kappa_{g,off\text{-}shell}^2/\kappa_{g,on\text{-}shell}^2$



95% CL upper limits on $\mu_{\text{off-shell}}$, Γ_H/Γ_{SM} and R_{gg}

		Observed	Expected Median	Expected $\pm 1\sigma$	Expected $\pm 2\sigma$
$\mu_{\text{off-shell}}$	$ZZ \rightarrow 4\ell$ analysis	4.5	4.3	[3.3, 5.4]	[2.7, 7.1]
	$ZZ \rightarrow 2\ell 2\nu$ analysis	5.3	4.4	[3.4, 5.5]	[2.8, 7.0]
	Combined	3.8	3.4	[2.7, 4.2]	[2.3, 5.3]
Γ_H/Γ_H^{SM}	Combined	3.5	3.7	[2.9, 4.8]	[2.4, 6.5]
R_{gg}	Combined	4.3	4.1	[3.3, 5.6]	[2.7, 8.2]

CONCLUSIONS

- Measurement of off-shell Higgs boson production in $ZZ\rightarrow 4\ell$ and $ZZ\rightarrow 2\ell 2\nu$ (ℓ: e or μ),
- Using LHC-ATLAS Run-2 (2015+2016) data at $\sqrt{s}$=13 TeV with luminosity of 36.1 fb^{-1}
- Observed (expected) upper limit at 95% CL on ***off-shell Higgs signal strength*** of 3.8 (3.4)
  - Off-shell Higgs signal strength: event yield normalized to SM prediction
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