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

◆

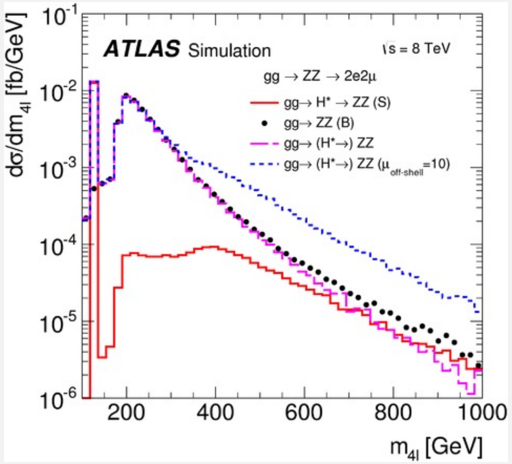
Theodota Lagouri (UTA)

On behalf of the ATLAS Collaboration

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

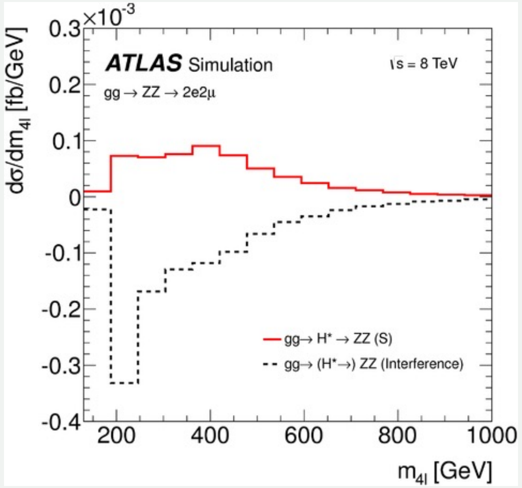
Differential cross-sections



INTERFERENCE

- Interference is significant between off-shell signal and continuum ggZZ background
- SBI=S+B+I, S : signal (gg → $H^{\star}$ → ZZ), B : background (gg → 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 → 4ℓ, ZZ → $2\ell2$v) 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 → 4ℓ) and 250-2000 GeV (ZZ → $2\ell2$v)
- Interference (negative) between signal and gg → ZZ continuum background is considered

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

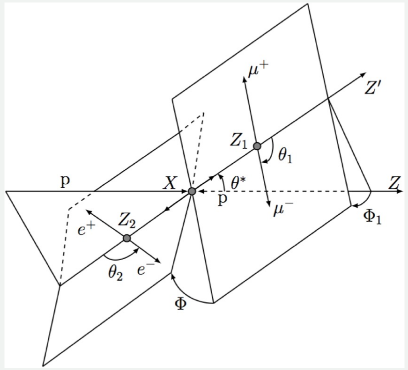
c=0.1

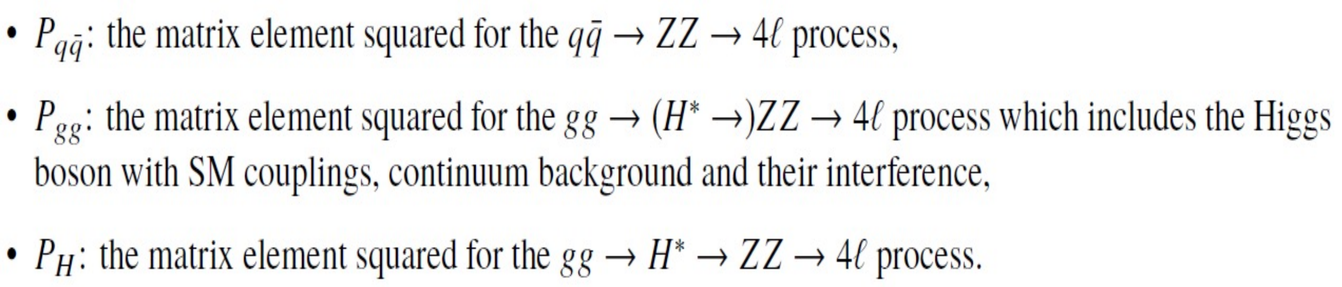
- ZZ → 4ℓ channel, ME, Matrix Element based kinematic discriminant
- ZZ → $2\ell2\nu$ channel, $\mathrm{m_T}^{\mathrm{ZZ}}$, transverse mass ZZ distribution

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

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

★Eur. Phys. J. C *78* (2018) 293

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

- Gain in signal yield Br($ZZ \rightarrow 2\ell 2\nu$) ~ 6 Br($ZZ \rightarrow 4\ell$)
- Baseline selection same as high-mass★ $ZZ \rightarrow 2\ell 2\nu$ 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 → ZZ and gg → ZZ, ~63%
  - Reducible from data, ~37%
- Shape fit to transverse mass distribution m_T^{ZZ}

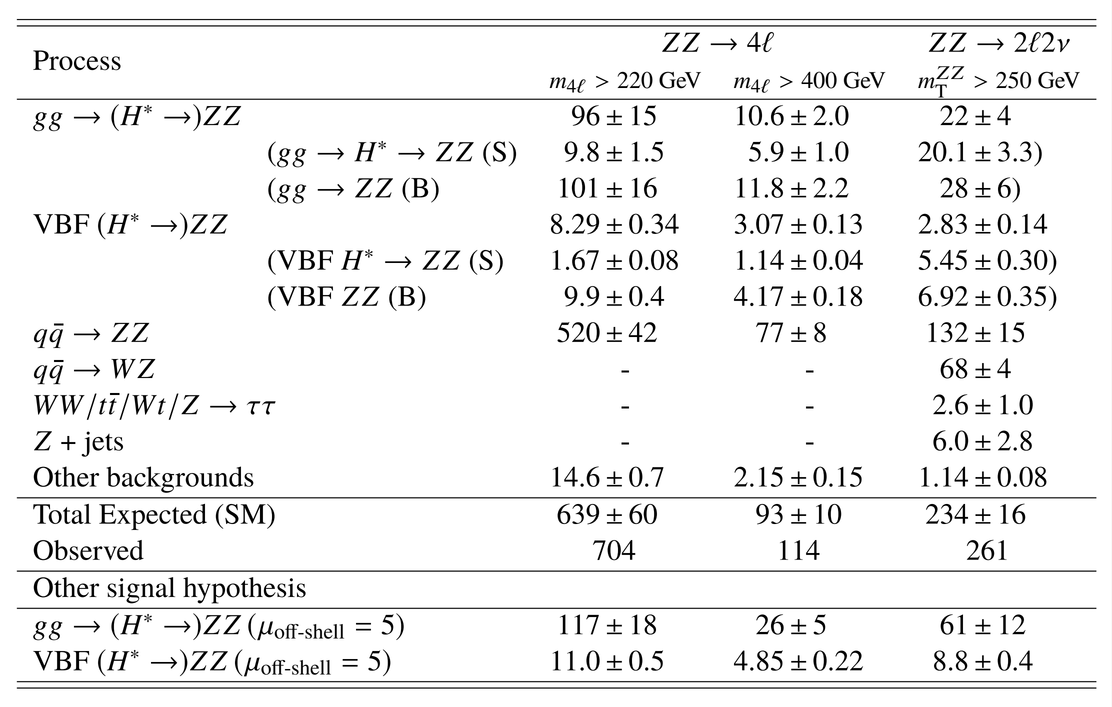
SYSTEMATICS

- 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(→ H★) → ZZ (10-20%)

★Eur. Phys. J. C *78* (2018) 293

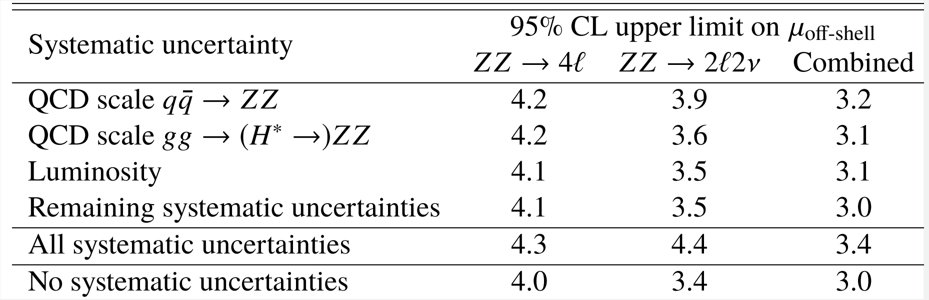
ANALYSIS RESULTS (ZZ)

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	$ZZ \to 2\ell 2\nu$ $m_{\mathrm{T}}^{ZZ} > 250$ 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	$20.1 \pm 3.3)$
$(gg \to ZZ$ (B)	101 ± 16	11.8 ± 2.2	$28 \pm 6)$
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	$5.45 \pm 0.30)$
(VBF ZZ (B)	9.9 ± 0.4	4.17 ± 0.18	$6.92 \pm 0.35)$
$q\bar{q} \to ZZ$	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

$$\frac{\mathrm{d}\sigma_{pp\to \mathrm{H}\to ZZ}}{\mathrm{d}M^2_{ZZ}} \sim \frac{g^2_{\mathrm{H}gg}\, g^2_{\mathrm{H}ZZ}}{(M^2_{ZZ}-m^2_{\mathrm{H}})^2+m^2_{\mathrm{H}}\Gamma^2_{\mathrm{H}}}$$

$$\sigma^{pp\to \mathrm{H}^*\to ZZ}_{\mathrm{off-shell}} \sim g^2_{\mathrm{H}gg}\, g^2_{\mathrm{H}ZZ}$$

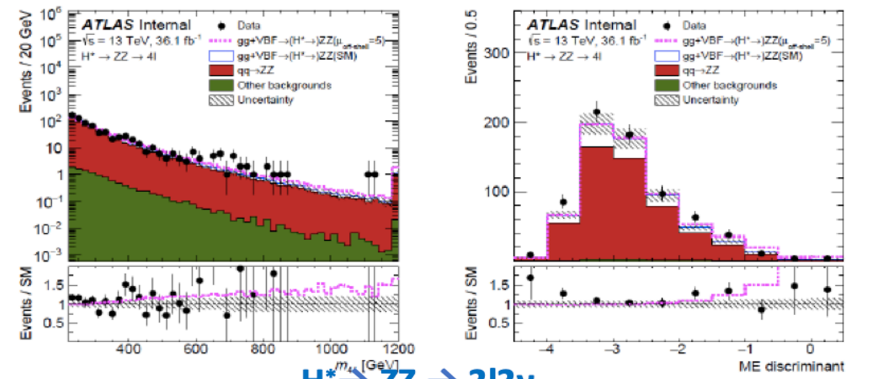
$$\sigma^{pp\to \mathrm{H}\to ZZ^*}_{\mathrm{on-shell}} \sim \frac{g^2_{\mathrm{H}gg}\, g^2_{\mathrm{H}ZZ}}{m_{\mathrm{H}}\Gamma_{\mathrm{H}}}$$

$$\mu_{\text{off-shell}} = \frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell,SM}}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{Z,\text{off-shell}} \qquad \mu_{\text{on-shell}} = \frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell,SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{Z,\text{on-shell}}}{\Gamma_H/\Gamma^{\text{SM}}_H}$$

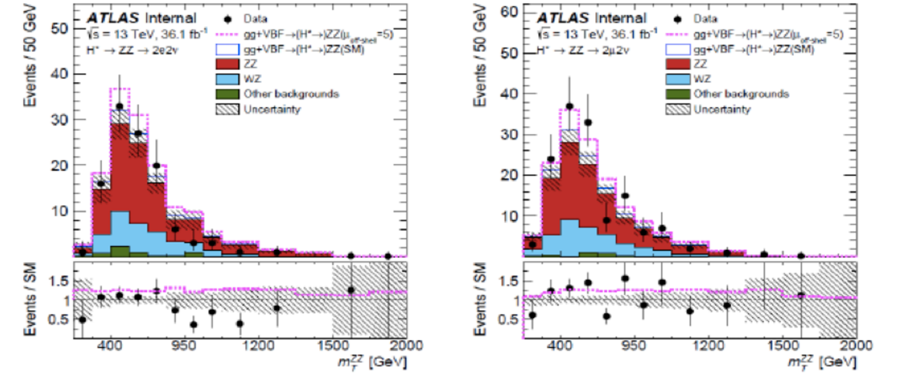
- Off-shell signal strength measurement:
  - Fix the ratio $\mu^{\mathrm{ggF}}/\mu^{\mathrm{VBF}} = 1$ as SM predicted, and derive the limit on inclusive $\boldsymbol{\mu_{\textit{off-shell}}}$
- Higgs boson total width measurement: $\mu_{\text{off-shell}}/\mu_{\text{on-shell}} = \boldsymbol{\Gamma_H/\Gamma_{SM}}$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

ANALYSIS RESULTS-FITS

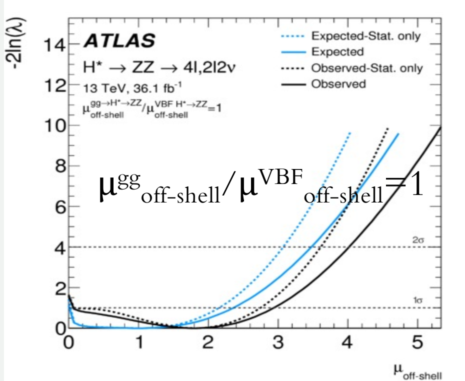
H*→ ZZ → 4l



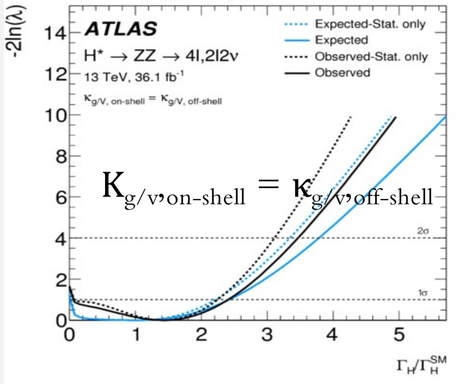
H*→ ZZ → 2l2v



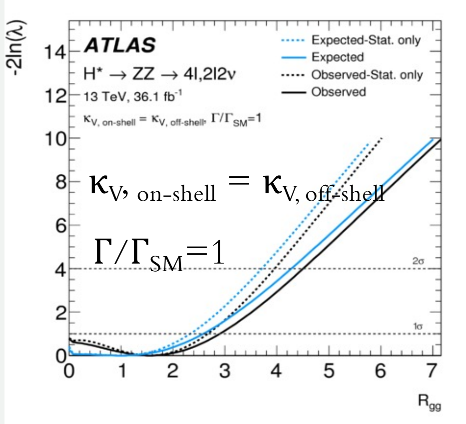
$\mu_{off\text{-}shell}$



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 $\mu_{off\text{-}shell}$, Γ_H/Γ_{SM} and R_{gg}

		Observed	Expected Median	 ±1 σ	 ±2 σ
$\mu_{off\text{-}shell}$	$ZZ\to 4\ell$ analysis	4.5	4.3	[3.3, 5.4]	[2.7, 7.1]
	$ZZ\to 2\ell 2\nu$ 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 $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$ (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
- 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

References:

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