The off-shell Higgs production and measurement of its decay width with the ATLAS experiment

Abdualazem Fadol

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中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

ATLAS EXPERIMENT

INSTITUTE FOR COLLIDER PARTICLE PHYSICS
UNIVERSITY OF THE WITWATERSRAND

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?

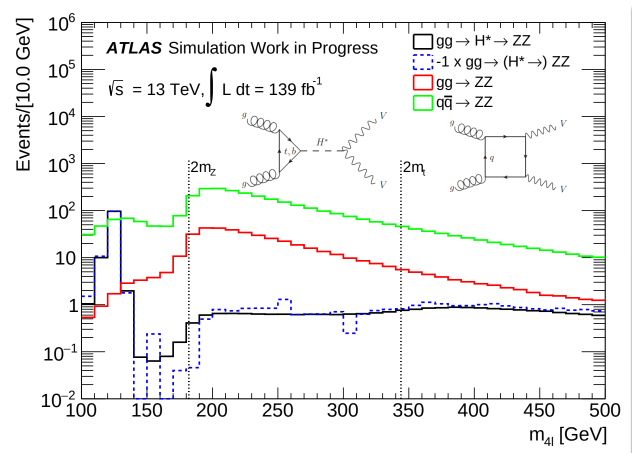
$$\frac{\mathrm{d}\sigma^{pp\to H\to ZZ}}{\mathrm{d}M_{ZZ}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{\left(M_{ZZ}^2 - m_H^2\right)^2 + m_H^2 \Gamma_H^2}$$

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

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

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

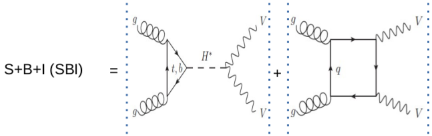
Introduction



- ☐ The ggF cross-section extends by O(15%) due to two threshold effects on the off-shell.
- ☐ The ability to constrain the Higgs couplings in BSM scenarios.

Analysis strategy

- The signal considers *ggF*, *VBF* & *VH* production modes
- Since the signal cannot be treated independently from the $gg \to ZZ$ background



$$gg\to(H^*\to)ZZ = gg \to H^* \to ZZ + gg \to ZZ$$

- Extracting the off-shell signal strength:

$$\sigma_{\mathrm{SM}}^{gg\to(H^*\to)ZZ}(\mu_{\text{off-shell}}) = \mu_{\text{off-shell}}\sigma_{\text{off-shell, SM}}^{gg\to H^*\to ZZ} + \sqrt{\mu_{\text{off-shell}}}\sigma_{\text{Int, SM}}^{gg\to ZZ} + \sigma_{\text{Cont, SM}}^{gg\to ZZ}$$

- Generate events with arbitrary values for $\mu_{\text{off-shell}}$, like 1 and 5.
- The off-shell Higgs production considered in two channels:
  - $H^* \to ZZ \to 4\ell$
  - $H^* \to ZZ \to 2\ell 2\nu$

Using neural network based observables, signal regions are defined to target *ggF* and *VBF&VH* production modes.

- ☐ **Signal regions:** $220 < m_{4\ell} < 2000$ GeV

ggF
- ∘ $n_{\text{jets}} = 0$
- ∘ $n_{\text{jets}} = 1$ & $\eta_j < 2.2$
- ∘ $n_{\text{jets}} \geq 2$ & $\Delta\eta_{jj} < 4.0$

VBF 1-jets
- ∘ $n_{\text{jets}} = 1$ & $\eta_j \geq 2.2$

VBF 2-jets
- ∘ $n_{\text{jets}} \geq 2$ & $\Delta\eta_{jj} \geq 4.0$

- ☐ **Control regions:**

- ∘ $180 < m_{4\ell} < 220$ GeV with 0-, 1- or 2-jets

Analysis strategy

$ZZ \to 2\ell 2\nu$ channel: signal and control regions

Signal regions are defined to target *ggF* and *VBF* & *VH* production modes.

- **Preselection:**
  - Common selection:
    - $76 < m_{\ell\ell} < 106$ GeV
    - $E_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV
  - Background rejection:
    - 3rd lepton veto
    - $\Delta R_{\ell\ell} < 1.8$
    - $\Delta\phi(Z, E_{\mathrm{T}}^{\mathrm{miss}}) > 2.5$
    - $\Delta\phi(\mathrm{jet}\ p_{\mathrm{T}} > 100\,\mathrm{GeV}, E_{\mathrm{T}}^{\mathrm{miss}}) > 2.5$
    - $E_{\mathrm{T}}^{\mathrm{miss}}$-significance > 9
    - b-jets veto

- **Signal regions:**
  - *ggF*
    - $n_{\mathrm{jets}} = 0$
    - $n_{\mathrm{jets}} = 1$
    - $n_{\mathrm{jets}} \geq 2$ & $\Delta\eta_{jj} < 4.0$
  - *VBF* 1-jets
    - $n_{\mathrm{jets}} = 1$ & $\eta_{jj} \geq 2.2$
  - *VBF* 2-jets
    - $n_{\mathrm{jets}} \geq 2$ & $\Delta\eta_{jj} \geq 4.0$

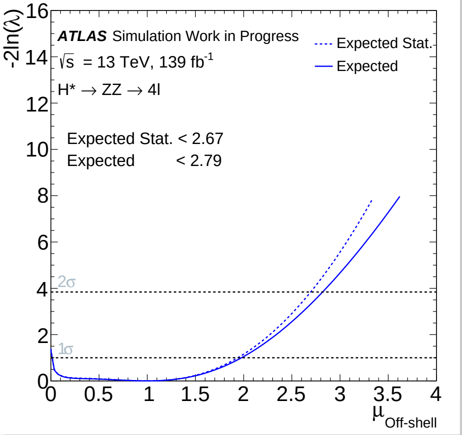
- **Control regions:**
  - Z CR (Z+jets): $E_{\mathrm{T}}^{\mathrm{miss}}$-significance < 9
  - $e\mu$ CR ($t\bar{t}$ & WW): 2 different flavour leptons
  - 3ℓ CR(WZ): $m_{\mathrm{T}}(\ell_3) > 60$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}}$-significance > 3

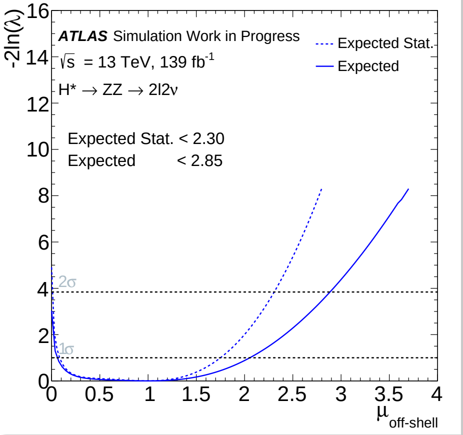
- Using the transverse mass as observable in the above three regions:

$$\left(m_T^{ZZ}\right)^2 = \left(\sqrt{m_Z^2 + |\vec{p}_T^{\,\ell\ell}|^2} + \sqrt{m_Z^2 + |\vec{E}_T^{miss}|^2}\right)^2 - \left(\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{miss}\right)^2$$

Expected results

The signal strength for $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$





- ☐ The scan was performed with the assumption that $\mu^{ggF}_{\text{off-shell}} = \mu^{VBF}_{\text{off-shell}} = 1$;
- ☐ The expected upper limit from 36.1 fb^{-1} was 4.36 (4.47) for 4ℓ ($2\ell 2\nu$).

HZZ combined results

- <u>Inputs:</u>
  - 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
- First, combining the $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$ off-shell results: where the CRs from the 4ℓ channel are used to constrain the $q\bar{q} \to ZZ$ background in the $2\ell 2\nu$ channel.
  - $\mu_{\text{off-shell}}$, $\mu^{ggF}_{\text{off-shell}}$ and $\mu^{VBF}_{\text{off-shell}}$
- The second step is to combine the off-shell to the on-shell results:
  - <u>$\Gamma_H/\Gamma_H^{\text{SM}}$ where $\Gamma_H^{\text{SM}} = 4.1$ MeV</u>

$$\begin{aligned}
\mu_{\text{off-shell}} &= k^2_{g,\,\text{off-shell}} \cdot k^2_{V,\,\text{off-shell}} \\
\mu_{\text{on-shell}} &= \frac{k^2_{g,\,\text{on-shell}} \cdot k^2_{V,\,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}} \\
\mu_{\text{off-shell}} &= \mu_{\text{on-shell}} \cdot \Gamma_H/\Gamma_H^{\text{SM}}
\end{aligned}$$

Assuming that $k^2_{g,\,\text{off-shell}} = k^2_{V,\,\text{on-shell}}$ & $k^2_{V,\,\text{off-shell}} = k^2_{V,\,\text{on-shell}}$

- Notice that $\mu_{\text{off-shell}} \equiv \dfrac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell, SM}}}$ & $\mu_{\text{off-shell}} \equiv \dfrac{\sigma^{gg\to H^*\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{on-shell, SM}}}$

HZZ combined results

- Similarly the couplings ratio

  - R_{gg} & R_{VV}

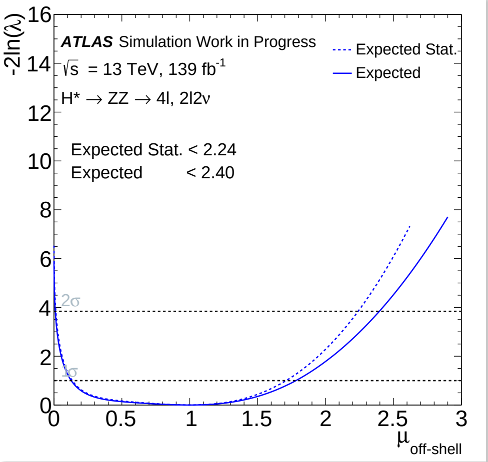
$$
\begin{aligned}
R_{gg} &\equiv k^2_{g,\text{off-shell}}/k^2_{g,\text{on-shell}} \\
R_{VV} &\equiv k^2_{V,\text{off-shell}}/k^2_{V,\text{on-shell}} \\
\mu^{ggF}_{\text{off-shell}} &= R_{gg} \cdot R_{VV} \cdot \mu^{ggF}_{\text{on-shell}} \cdot \Gamma_H/\Gamma_H^{\text{SM}} \\
\mu^{VBF}_{\text{off-shell}} &= R^2_{VV} \cdot \mu^{VBF}_{\text{on-shell}} \cdot \Gamma_H/\Gamma_H^{\text{SM}}
\end{aligned}
$$

  Assuming that $\Gamma_H/\Gamma_H^{\text{SM}} = 1.0$ & $R_{VV} = 1.0$; in case of the R_{gg}

- Nuisance parameters were properly correlated.

HZZ combined results

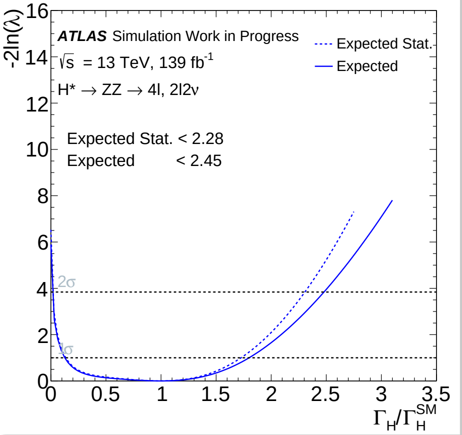
$ZZ \to 4\ell$, $2\ell2\nu$ combination: the off-shell signal strength ($\mu_{\text{off-shell}}$)

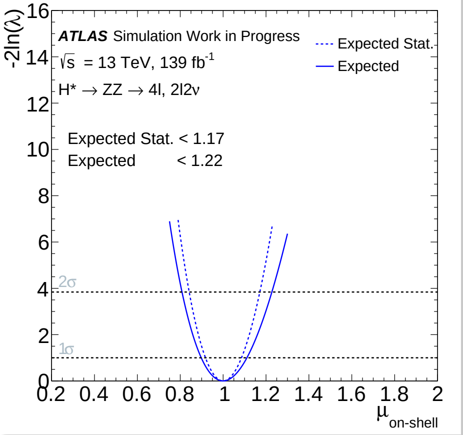


- ☐ The scan was performed with the assumption $\mu^{ggF}_{\text{off-shell}} = \mu^{VBF}_{\text{off-shell}} = 1$.
- ☐ The expected upper limit of the off-shell signal strength for 36.1 fb^{-1} was 3.48

HZZ combined results

The Higgs total width

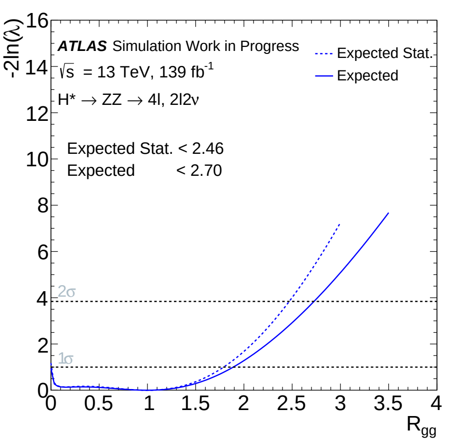


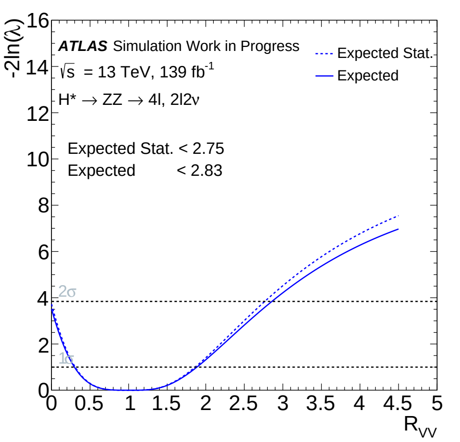


- Scanning $\Gamma_H/\Gamma_H^{\mathrm{SM}}$ while profiling $\mu_{\text{on-shell}}$
- The expected upper limit on the $\Gamma_H/\Gamma_H^{\mathrm{SM}}$ for 36.1 fb^{-1} was 3.78

HZZ combined results

Off-shell + on-shell combination: The R_{gg} & R_{VV} couplings ratio





- $\mu^{ggF}_{\text{off-shell}} = R_{gg} \cdot R_{VV} \cdot \mu^{ggF}_{\text{on-shell}} \cdot \Gamma_H/\Gamma_H^{\text{SM}}$ and $\mu^{VBF}_{\text{off-shell}} = R^2_{VV} \cdot \mu^{VBF}_{\text{on-shell}} \cdot \Gamma_H/\Gamma_H^{\text{SM}}$
- The expected upper limit on the R_{gg} for 36.1 fb^{-1} was 4.28.

Summary

Presented the off-shell Higgs production and measurement of its decay with with the ATLAS experiment in the $ZZ \to 4\ell$ and $ZZ \to 2\ell2\nu$ channels.

POI	Channel	Expected (NLL) 68% CL	Expected (NLL) 95% CL
$\mu_{\text{off-shell}}$	off-shell 4ℓ	1.98	2.79
	off-shell $2\ell2\nu$	2.25	2.85
	off-shell $4\ell + 2\ell2\nu$	1.80	2.40
$\mu^{ggF}_{\text{off-shell}}$	off-shell 4ℓ	2.25	3.01
	off-shell $2\ell2\nu$	2.30	3.41
	off-shell $4\ell + 2\ell2\nu$	1.82	2.61
$\mu^{VBF}_{\text{off-shell}}$	off-shell 4ℓ	4.10	6.57
	off-shell $2\ell2\nu$	2.45	4.28
	off-shell $4\ell + 2\ell2\nu$	2.90	4.14
$\Gamma_H/\Gamma_H^{\text{SM}}$	off-shell $4\ell + 2\ell2\nu$ + on-shell	1.80	2.45
R_{gg}	off-shell $4\ell + 2\ell2\nu$ + on-shell	1.80	2.70
R_{VV}	off-shell $4\ell + 2\ell2\nu$ + on-shell	1.90	2.83

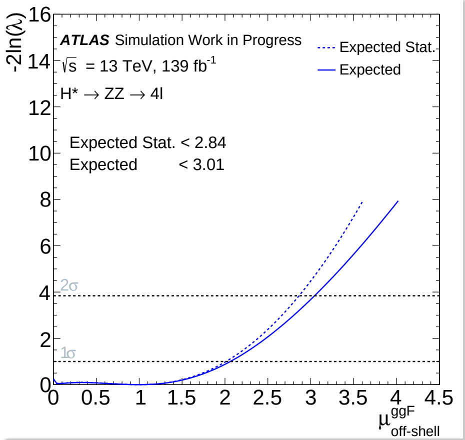
- First evidence for off-shell production of the Higgs boson reported by the CMS experiment (3.6σ).
- Where the expected Γ_H is found to be 11.3 MeV with $3.2^{+2.4}_{-1.7}$ MeV observed central value.
- Do you want to know how long it takes for the Higgs boson to vanish?
  Heisenberg uncertainty principle:

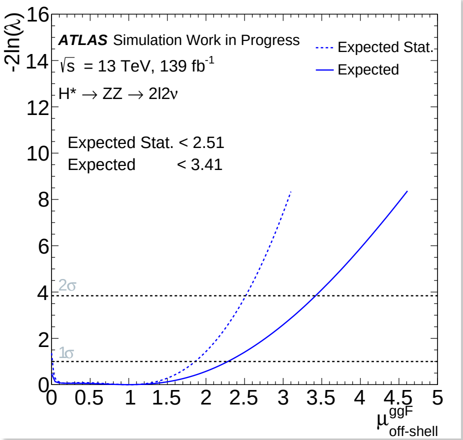
$$\tau = \hbar/\Gamma_H = 6.5821 \times 10^{-25}\,\text{GeV.s}/(2.45 \times 4.1 \times 10^{-3}\,\text{GeV}) = 6.5472637 \times 10^{-23}\,s$$

Additional slides

Additional slides

The *ggF* signal strength for $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$

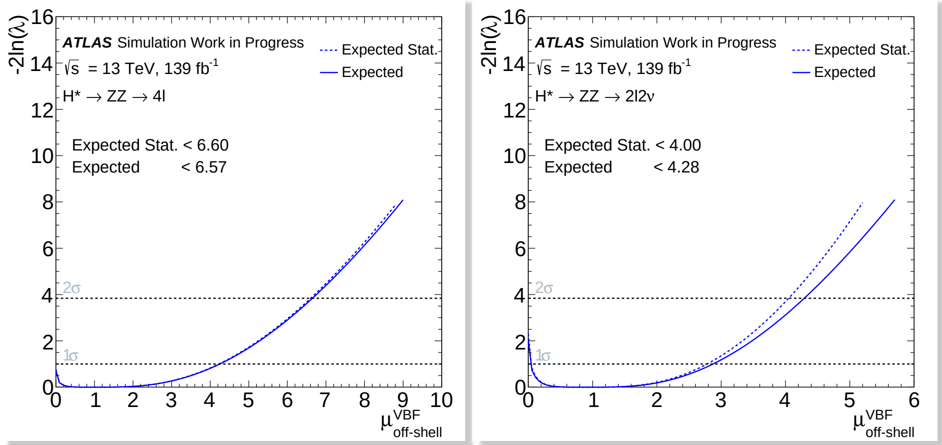




- ☐ Profiling $\mu^{VBF}_{\text{off-shell}}$ while scanning $\mu^{ggF}_{\text{off-shell}}$ and the other way round.

Additional slides

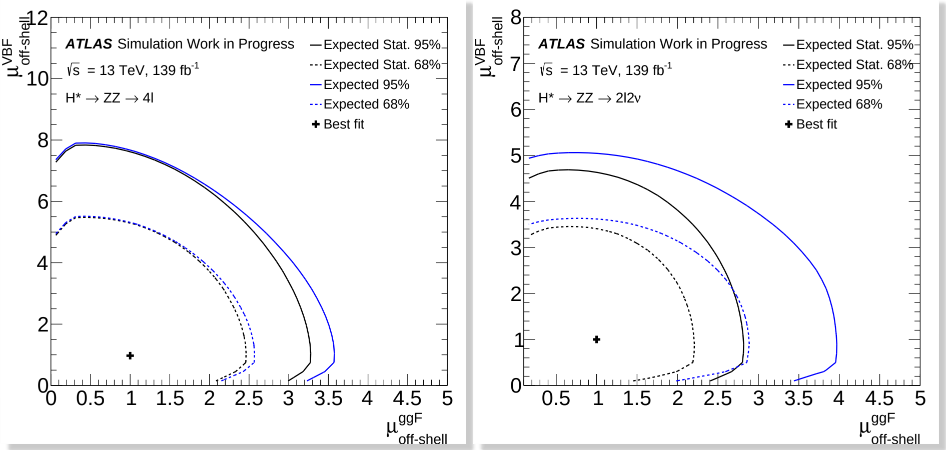
The *VBF* signal strength for $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell2\nu$



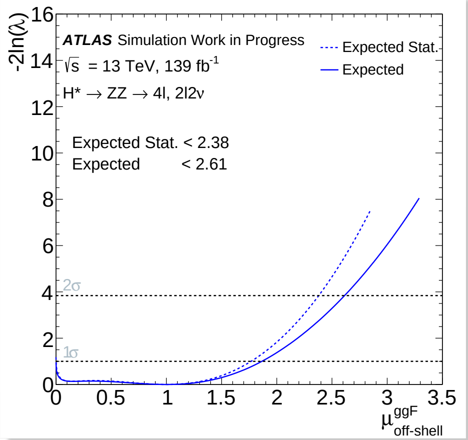
☐ Profiling $\mu^{VBF}_{\text{off-shell}}$ while scanning $\mu^{ggF}_{\text{off-shell}}$ and the other way round.

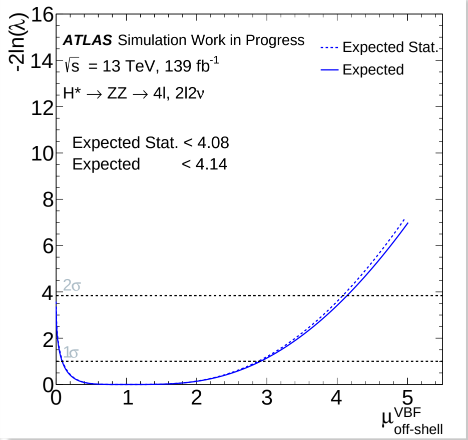
Additional slides

Two-dimensional scan of the $\mu^{ggF}_{\text{off-shell}}$ and $\mu^{VBF}_{\text{off-shell}}$ for $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$



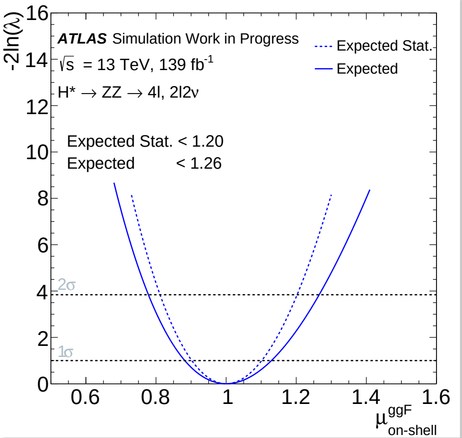
- ☐ Two-dimensional likelihood scan of the $\mu^{ggF}_{\text{off-shell}}$ and $\mu^{VBF}_{\text{off-shell}}$ for $ZZ \to 4\ell$ (left) and $ZZ \to 2\ell 2\nu$ (right).

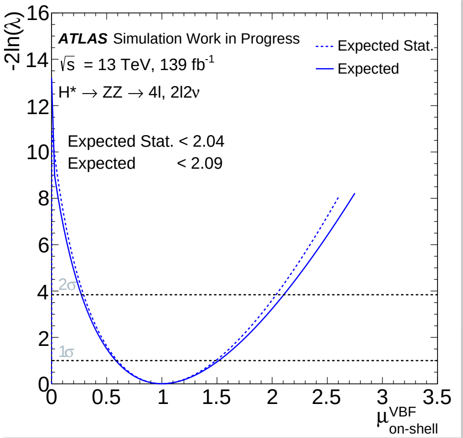




- ☐ Profiling one while scanning the other.

Combined results: the individual on-shell *ggF* and *VBF* production mode

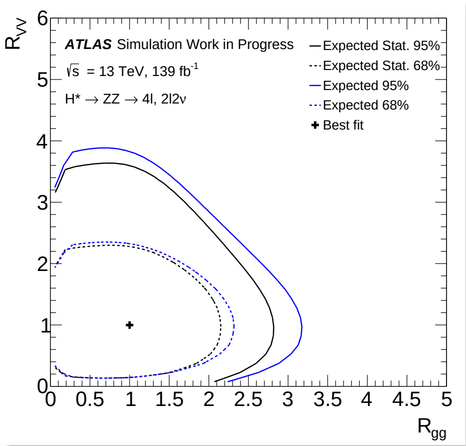


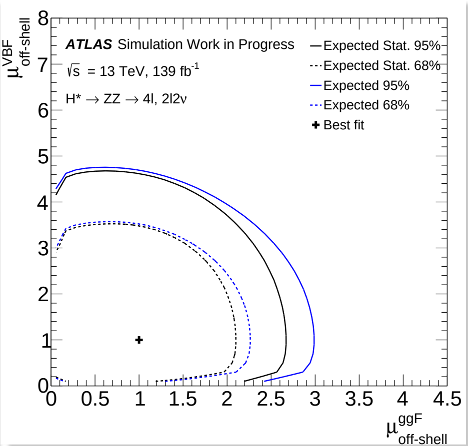


- ☐ Scanning $\Gamma_H/\Gamma_H^{\mathrm{SM}}$ while profiling $\mu_{\text{on-shell}}$

Additional slides

HZZ combined results: R_{gg}-R_{VV} vs $\mu^{ggF}_{\text{off-shell}}$-$\mu^{VBF}_{\text{off-shell}}$





- ☐ Two-dimensional likelihood scan of the R_{gg} & R_{VV} (left) and $\mu^{ggF}_{\text{off-shell}}$ & $\mu^{VBF}_{\text{off-shell}}$ (right).

Additional slides

Two-dimensional likelihood scan of the $\mu^{ggF}_{\text{on-shell}}$ and $\mu^{VBF}_{\text{on-shell}}$