Search for rare decays of the observed Higgs boson and additional Higgs bosons with the ATLAS detector

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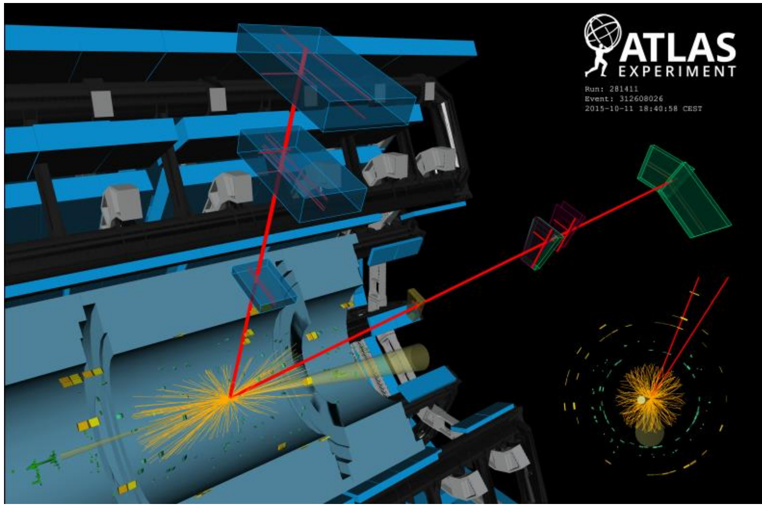
The 5th international conference on
particle physics and astrophysics

6 Oct. 2020

Introduction

- Searches for unobserved processes in the Higgs sector provide important probes for new physics
  - Search for rare decays of SM Higgs boson
  - Search for additional Higgs boson

- New results obtained in 2020 are presented
(Using full ATLAS Run 2 dataset corresponding to $139\ \mathrm{fb}^{-1}$)
  - Search for dimuon decay of SM Higgs
  arXiv:2007.07830
  - Search for $Z\gamma$ decay of SM Higgs
  Phys. Lett. B 809 (2020) 135754
  - Search for diphoton resonances
  ATLAS-CONF-2020-037



Search for $H \to \mu\mu$

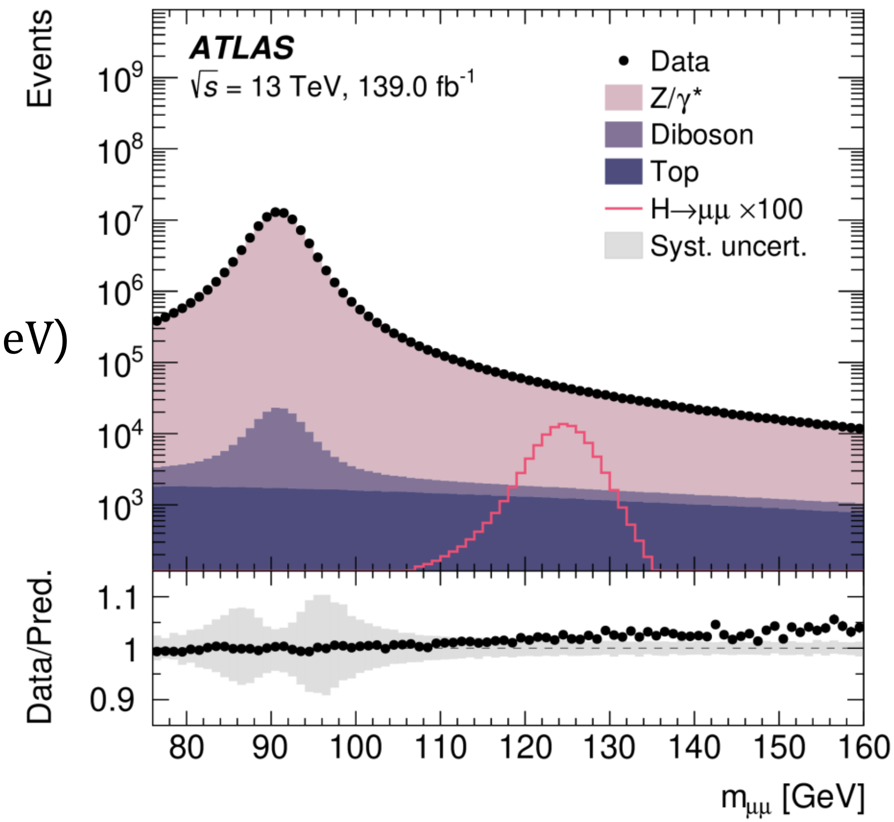
arXiv:2007.07830

- Measuring the Higgs Yukawa-coupling to the muon
  - Unique opportunity among the 2nd-generation fermions at the LHC

- Additionally, new physics can modify the branching ratio

- It is a rare process with $BR(H \to \mu\mu) = 2.17 \times 10^{-4}$ for SM

- Small S/B (~0.2% for $120 < m_{\mu\mu} < 130$ GeV) leads to experimental challenge
  - Dominant background: Drell-Yan

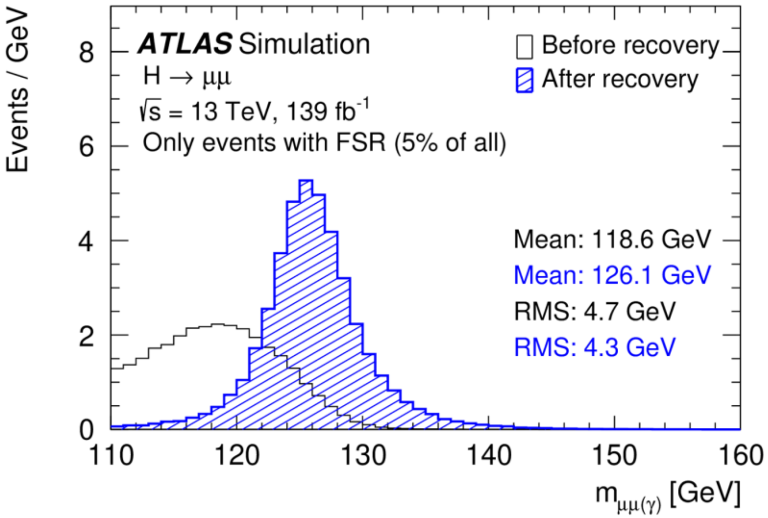


$H \to \mu\mu$: Analysis strategy

- Select two isolated muons with opposite charge

- Up to one FSR photon is added to $m_{\mu\mu}$ calculation

  (Improves mass resolution by 3%)



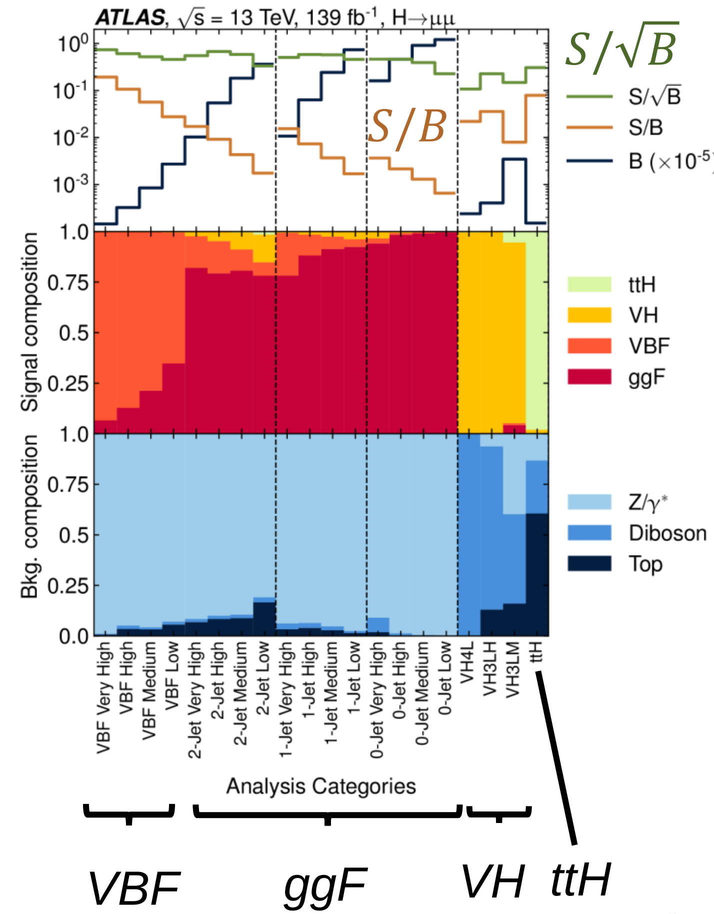
- Events are categorized into 20 orthogonal categories

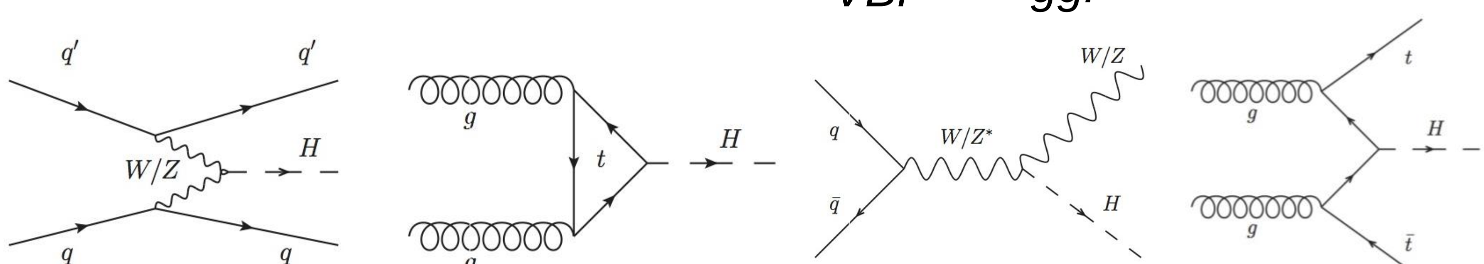
- Signal is extracted by simultaneous fit to $m_{\mu\mu}$ distribution of all categories

$H \to \mu\mu$: Categorization

- Categorization targets different production modes of the Higgs boson

- Signal and background are separated based on:
  - Number of jets
  - Number of b-tagged jets
  - Number of additional leptons (e, μ)
  - BDTs trained for each production mode



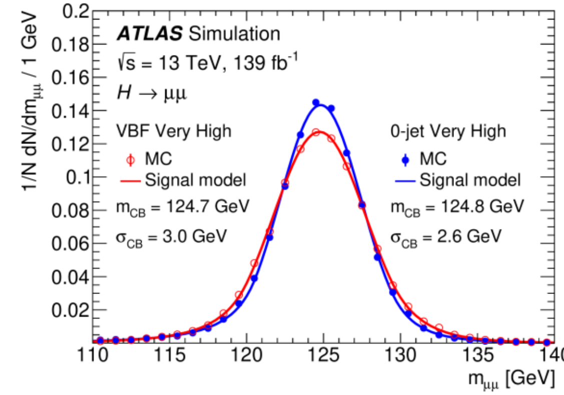


VBF ggF VH ttH

$H \to \mu\mu$: Signal and background modelling

Signal:

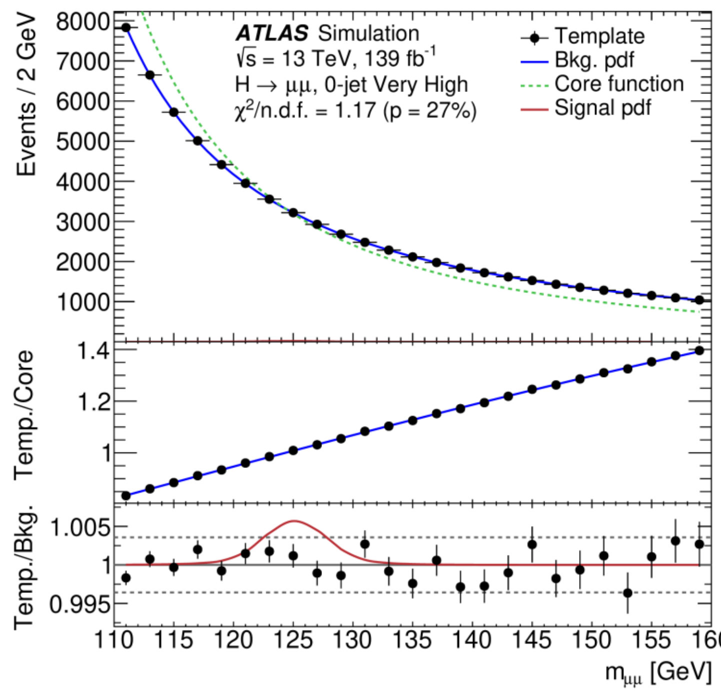
- Double-sided Crystal Ball function
- Parameters obtained from MC simulations



Background:

- Strategy: "Core" × "Empirical"
  - Core: LO DY line-shape convoluted with detector resolution (Gaussian)
  - Empirical: Describes distortions due to e.g. selections and minor backgrounds

Function	Expression
PowerN	$m_{\mu\mu}^{(a_0+a_1 m_{\mu\mu}+a_2 m_{\mu\mu}^2+\ldots+a_N m_{\mu\mu}^N)}$
EpolyN	$\exp(a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + \ldots + a_N m_{\mu\mu}^N)$



- Validation is performed using fast-simulation DY samples with high statistical precision (for ggF/VBF categories)

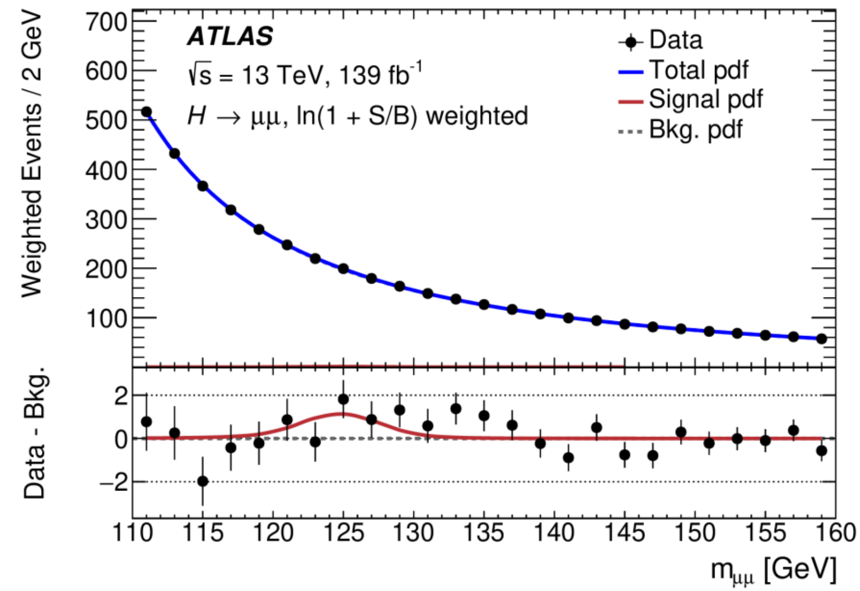
$H \to \mu\mu$: Results

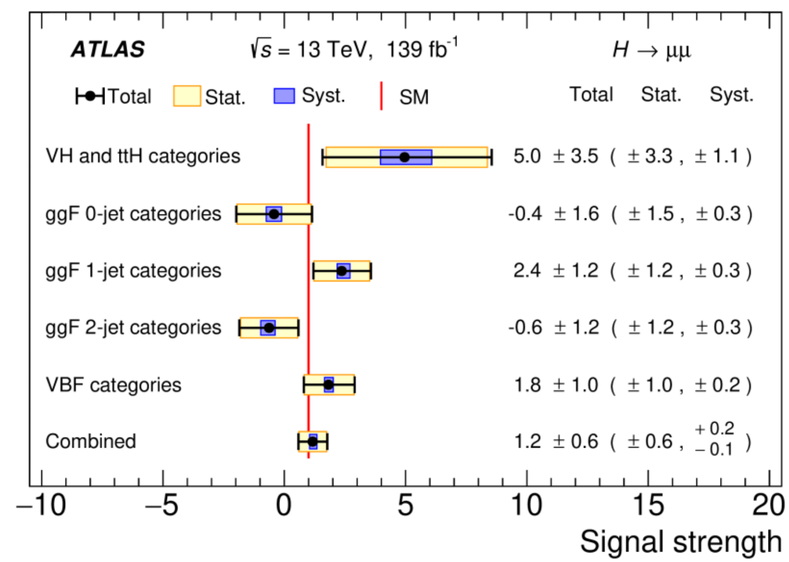
- Observed significance: 2.0σ
  (Expected: 1.7σ)

- Signal strength: $\mu = 1.2 \pm 0.6$
  Uncertainties:
  - Statistics ± 0.58
  - Signal theory systematics $^{+0.13}_{-0.08}$
  - Experimental systematics $^{+0.07}_{-0.03}$
  - Background modelling ± 0.10

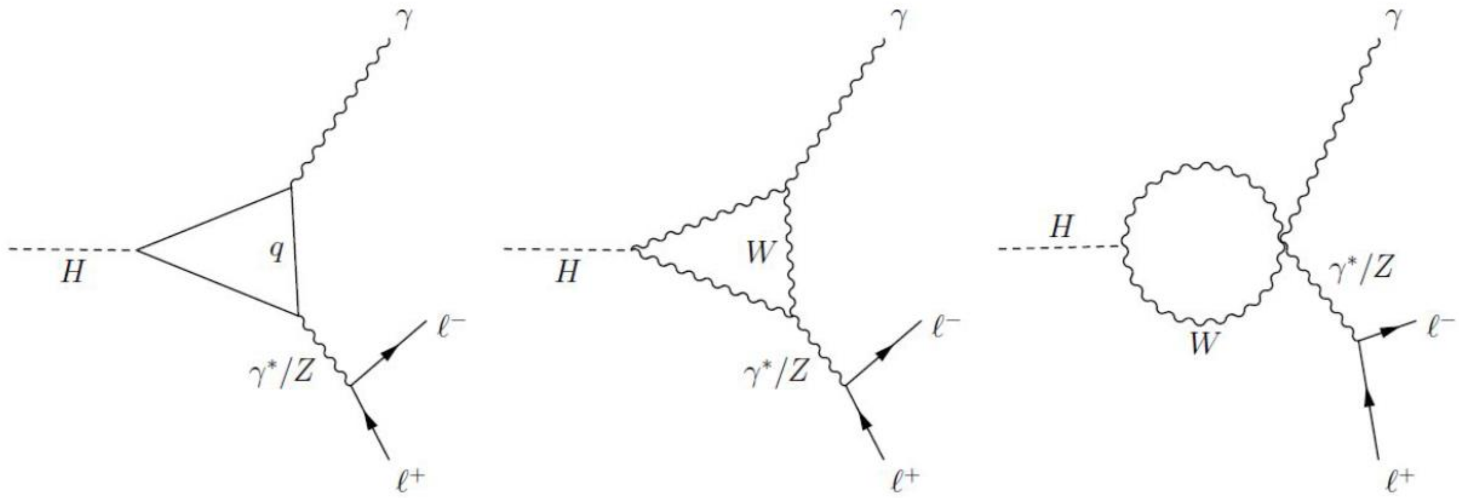
- Observed limit: $\mu < 2.2$ at 95% CL
  (Expected $\mu < 2.0$ assuming SM)

- $\times$ 2.5 sensitivity improvement compared to previous publication using $36\ \mathrm{fb}^{-1}$ (~25% due to analysis improvement)





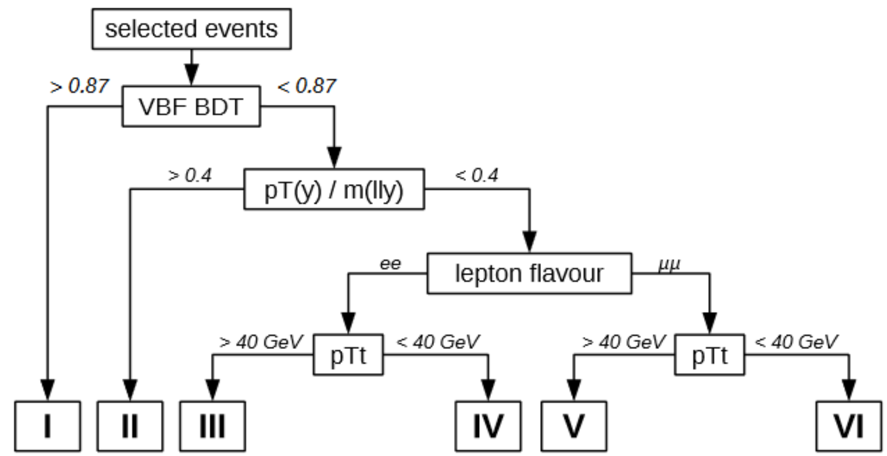
Search for $H \to Z\gamma$ Phys. Lett. B 809 (2020) 135754



- $BR(H \to Z\gamma) = 1.54 \times 10^{-4}$ for SM
- Sensitive to new physics contributing to the loop diagrams (e.g. new charged particles)
- Search is performed in the $ee\gamma$ and $\mu\mu\gamma$ final states
  - Corresponding to BR~7% of Z
  - Good mass resolution, low background

$H \to Z\gamma$: Analysis strategy

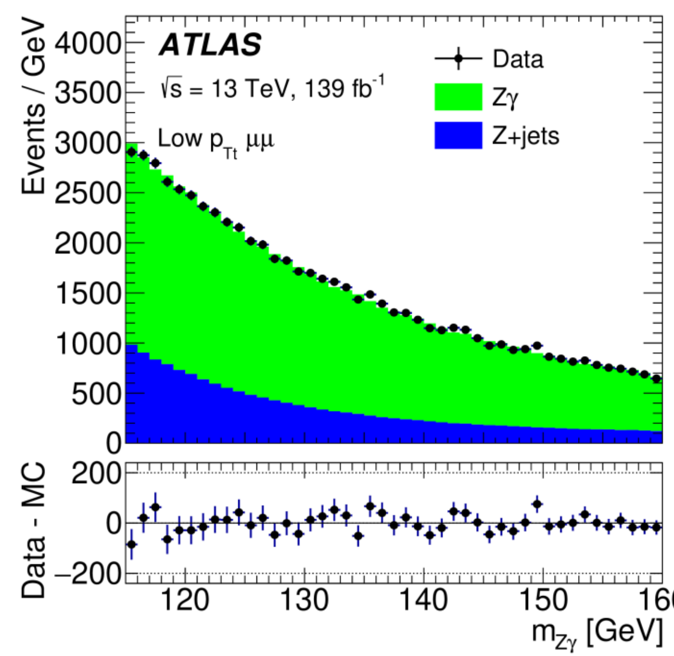
- Select opposite-sign lepton pair (ee or $\mu\mu$) and photon



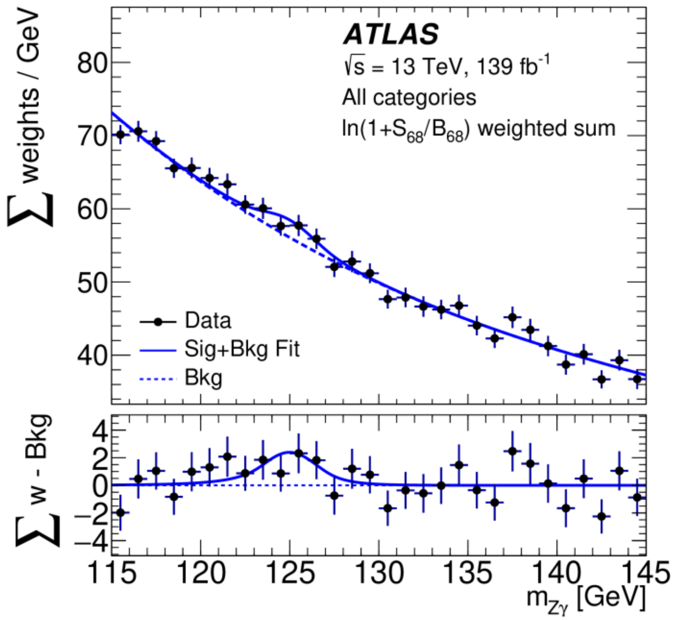
- Introduce six categories based on BDT and kinematics

- Signal:
  - Double-sided Crystal Ball function

- Background:
  - Analytic function with free parameters
  - Validation performed by fit to “templates”
    - $Z\gamma$ template: MC samples
    - Z+jets template: derived from data control region (reversed photon ID)



$H \rightarrow Z\gamma$: Results



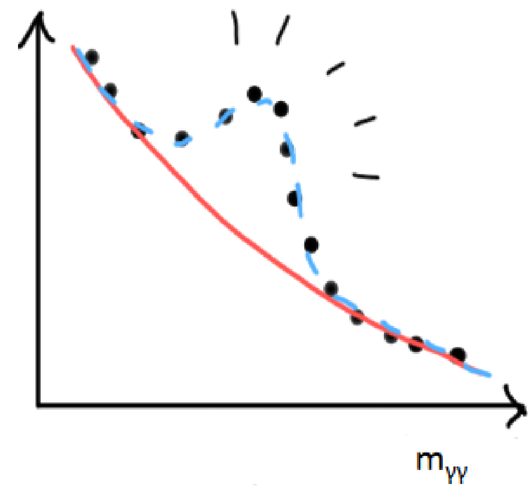
Category	μ	Significance
VBF-enriched	$0.5^{+1.9}_{-1.7}$ $(1.0^{+2.0}_{-1.6})$	0.3 (0.6)
High relative p_{T}	$1.6^{+1.7}_{-1.6}$ $(1.0^{+1.7}_{-1.6})$	1.0 (0.6)
High $p_{\mathrm{T}t}$ ee	$4.7^{+3.0}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.7 (0.4)
Low $p_{\mathrm{T}t}$ ee	$3.9^{+2.8}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.5 (0.4)
High $p_{\mathrm{T}t}$ $\mu\mu$	$2.9^{+3.0}_{-2.8}$ $(1.0^{+2.8}_{-2.7})$	1.0 (0.4)
Low $p_{\mathrm{T}t}$ $\mu\mu$	$0.8^{+2.6}_{-2.6}$ $(1.0^{+2.6}_{-2.5})$	0.3 (0.4)
Combined	$2.0^{+1.0}_{-0.9}$ $(1.0^{+0.9}_{-0.9})$	2.2 (1.2)

- Signal strength: $\mu = 2.0 \pm 0.9\ (\mathrm{stat})\ ^{+0.4}_{-0.3}\ (syst)$
  - Uncertainty is statistically dominated
  - Largest source of systematic uncertainty: background modelling
- Observed limit: $\mu < 3.6$ at 95% CL (Expected $\mu < 2.6$ assuming SM)
- $\times$2.4 sensitivity improvement compared to previous publication using $36\ \mathrm{fb}^{-1}$ (~20% due to analysis improvement)

Search for diphoton resonance

ATLAS-CONF-2020-037

- Search for new resonance in $m_{\gamma\gamma} > 160$ GeV
  - Spin-0 resonance from e.g. extended Higgs sector
    - Assume width of up to $\Gamma_X/m_X < 10\%$
  - Spin-2 resonance from e.g. RS graviton



- For spin-0, limits are evaluated for fiducial cross-sections to be model independent

Diphoton resonance: Analysis strategy

- Select two isolated photon candidates

- Signal: Double-sided Crystal Ball function
  (convoluted with relativistic Breit-Wigner for large width)

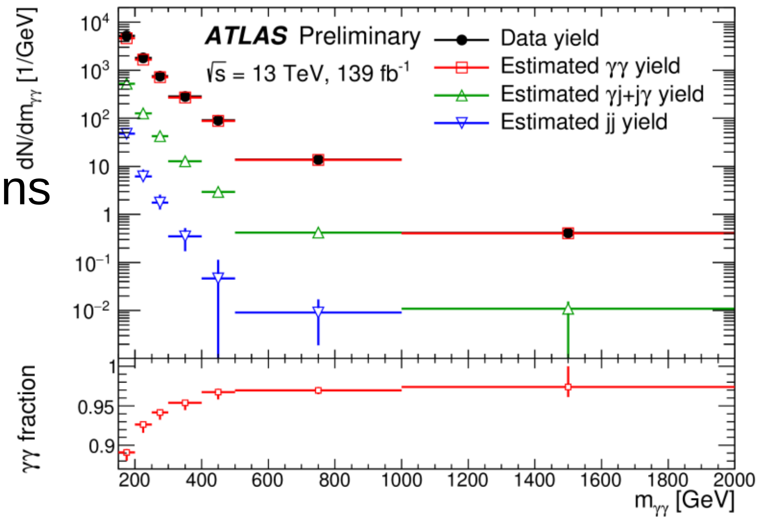
- Background:
  Analytic function with free parameters

$$f(x; b, a_0, a_1) = N\left(1 - x^{\frac{1}{3}}\right)^{b} x^{a_0 + a_1 \log(x)}$$

- Validation performed by fit to “templates”
  - $\gamma\gamma$ template: MC samples

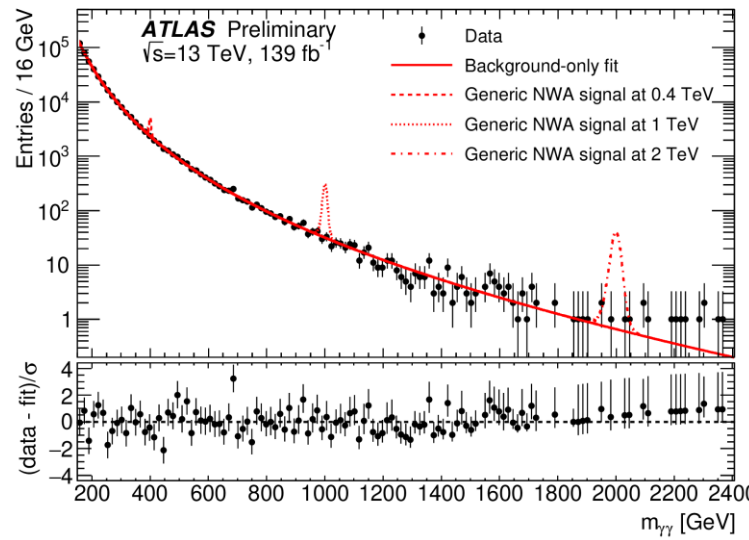
    To suppress the impact of statistical fluctuations on the validation, smoothing is applied using the functional decomposition method

  - γ+jets template: derived from data control region (reversed photon ID)

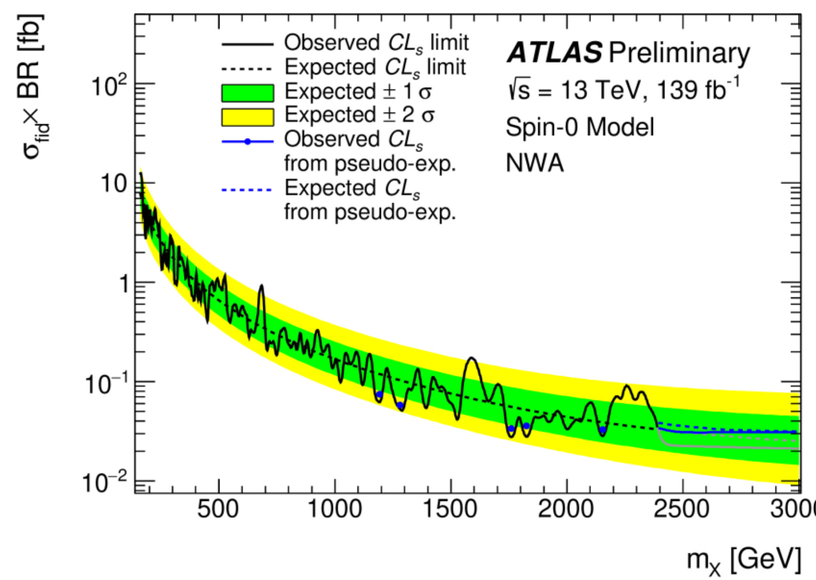


Diphoton resonance: Results

- No significant excess is observed
- Largest deviation:
  3.29σ locally at $m_X = 684$ GeV
  (corresponding to 1.3σ globally)



- Spin-0 resonance limits: Right figure (for narrow-width assumption)
- Spin-2 resonance limits:
  - Similar results as spin-0
  - RS1 model excluded for $m_{G^*} < 4.5$ TeV for $k/\bar{M}_{Pl} = 0.1$



Summary

- Searches in the Higgs sector provide probes for new physics

- New results using the full ATLAS Run 2 dataset are presented
  - Search for $H \rightarrow \mu\mu$:
    $\mu = 1.2 \pm 0.6$ and 2.0σ significance
  - Search for $H \rightarrow Z\gamma$:
    $\mu = 2.0^{+1.0}_{-0.9}$ and 2.2σ significance

  $\sim 2\sigma$ sensitivity for rare processes with $BR \sim 10^{-4}$

  - Search for diphoton resonance:
    - No significant excess is observed
    - Limits are placed down to 0.03 fb for $m = 3$ TeV

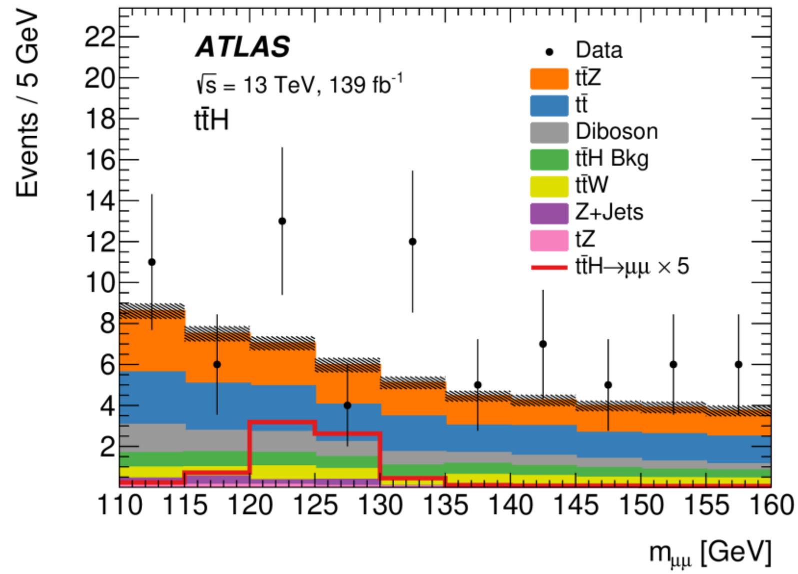
- These results improved w.r.t. past results thanks to increase in dataset, and improvements in analysis techniques

Backup

$H \to \mu\mu$: ttH/VH categories

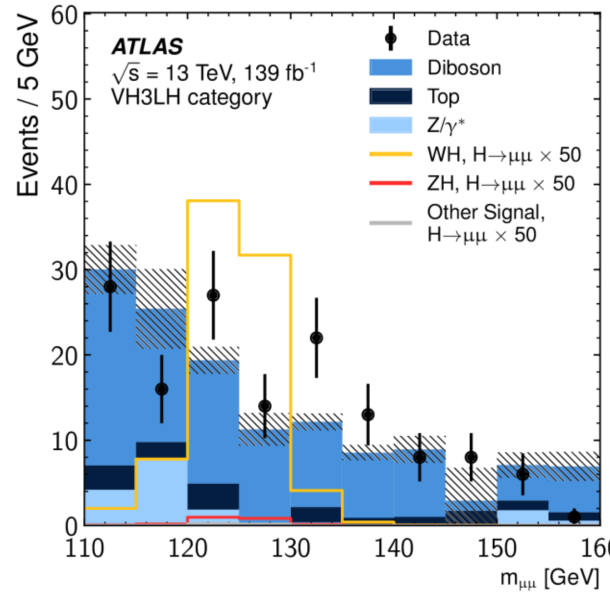
ttH category:

- At least one additional lepton (μ or e) and one b-jet
- BDT discriminant based on 12 variables (e.g. jet multiplicity, $p_T^{\mu\mu}$)

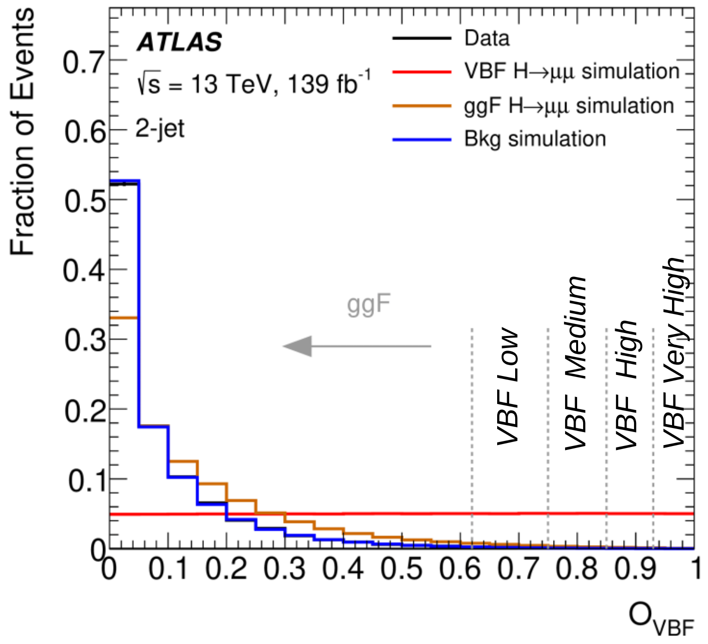


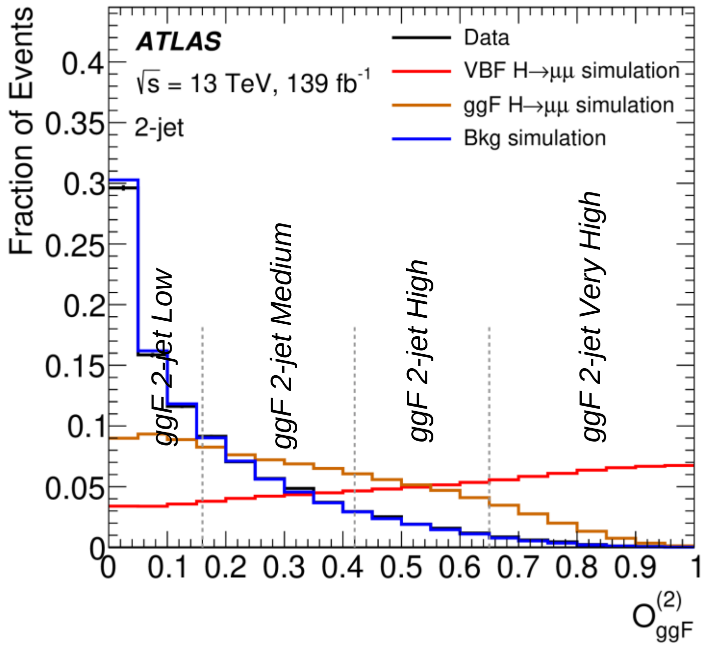
VH category:

- At least one additional lepton (μ or e) and no b-jet
- 3-lepton region (targeting $W \to l\nu$): Two categories based on BDT
- 4-lepton region (targeting $Z \to ll$): One category based on BDT



$H \to \mu\mu$: VBF/ggF categories





- No additional muon, no b-jets
- Based on jet multiplicities (0, 1, or ≧2),
  different BDTs are used based on different variables
  - Four categories are defined for VBF
  - Four categories are defined for each jet multiplicity of ggF