Search for rare decays of the Standard Model Higgs boson with the ATLAS detector

Aaron White on behalf of the ATLAS collaboration
10 November, 2022
Higgs 2022

HARVARD UNIVERSITY

ATLAS EXPERIMENT

Outline

Four investigations of rare processes predicted by the SM

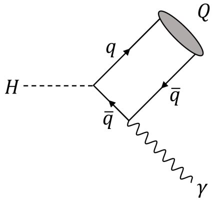
These results were covered in Giulio Umoret's talk on Tuesday

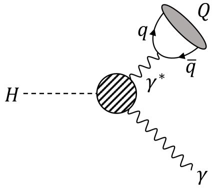
- Higgs (or Z) to a quarkonium state ($\mathcal{Q} = J/\psi, \Upsilon$) and a photon 2208.03122
  - $\mathcal{B}(H \to J/\psi\ \gamma) \approx 10^{-6}$
  - $\mathcal{B}(H \to \Upsilon\gamma) \approx 10^{-9}$
  - $\mathcal{B}(Z \to \mathcal{Q}\gamma) \approx 10^{-8}$
- Higgs to a Z and a photon 2005.05382
  - $\mathcal{B}(H \to Z\gamma) = 1.5 \pm 0.1 \times 10^{-3}$
- Higgs to two muons 2007.07830
  - $\mathcal{B}(H \to \mu\mu) = 2.2 \times 10^{-4}$
- Higgs to two leptons and a photon 2103.10322
  - $\mathcal{B}(H \to \ell\ell\gamma) \approx 10^{-5}$

Most of these analyses are 139fb^{-1} updates of partial Run-2 results

Search for $H(Z) \to \mathcal{Q}\gamma$

- Motivation:
  - Indirect search for $H \to cc$, which may be sensitive to deviations of the quark Yukawa couplings
  - $\Upsilon\gamma$ final state is sensitive to the sign of the Hbb coupling, making it complementary to direct $H \to bb$ measurements
- Target: Higgs decay to a photon and $\mathcal{Q} = J/\psi$, $\psi(2S)$, or $\Upsilon(1S,2S,3S)$
- Final state: $\gamma + \mathcal{Q}(\to \mu\mu)$
- Previous limits on branching ratio:
  - $\mathcal{B}(H \to J/\psi\gamma) < 3.5 \times 10^{-4}$
  - $\mathcal{B}(H \to \psi(2S)\gamma) < 2.0 \times 10^{-3}$ 1807.00802
  - Results from CMS: 1810.10056
- Note: this paper also studies the equivalent processes substituting a Z for the Higgs





Analysis

Challenge

- Difficult to model "inclusive" multi-jet and γ+jet background with simulation due to its complex composition and misidentified objects

Strategy

- Selects photons with $p_T^{\gamma} > 35$ GeV, opposite charge muon pair, (sub)-leading $p_T > (3)18$ GeV
- The Drell-Yan background is modeled by a fit to simulation
- The "inclusive" background is modeled using toy events drawn from data distributions in a control region

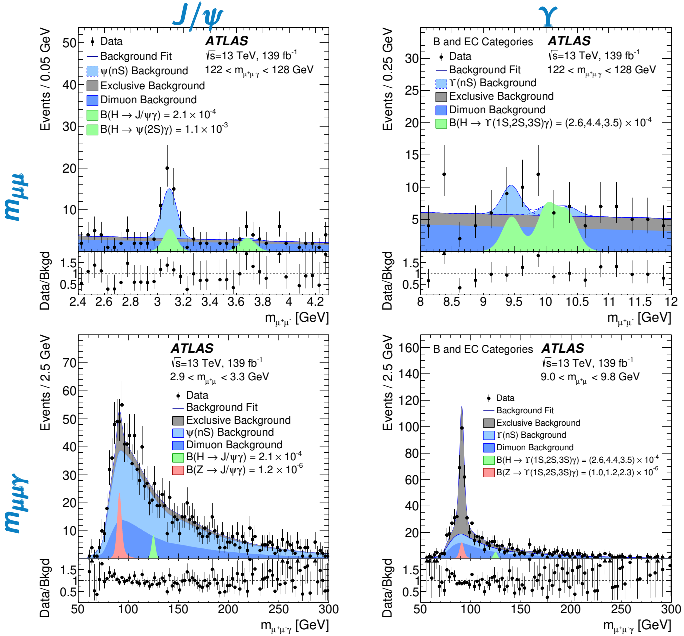
Categorization of events

Common event selection		
$m_{\mu\mu} \in [2.4, 4.3]$ GeV for J/ψ, $\psi(2S)$	$m_{\mu\mu} \in [8.0, 12.0]$ GeV for $\Upsilon(1S,2S,3S)$	
Inclusive	Barrel (all $\eta_\mu < 1.05$)	Endcap (any $\eta_\mu > 1.05$)

- Selections on $m_{\mu\mu}$ target J/ψ, $\psi(2S)$, $\Upsilon(1S,2S,3S)$
- The categories targeting Υ events are divided by muon η to separate events based on Υ resolution

Results

- Two dimensional fits are performed in $m_{\mu\mu}$ and $m_{\mu\mu\gamma}$
- One fit is performed for each meson (5) boson (2) combination
  - For each limit, the other meson/boson signal strengths are treated as nuisance parameters
- These plots show the signal corresponding to $H \rightarrow \mathcal{Q}\gamma$ in green, and $Z \rightarrow \mathcal{Q}\gamma$ in red
  - Fit shown is background-only



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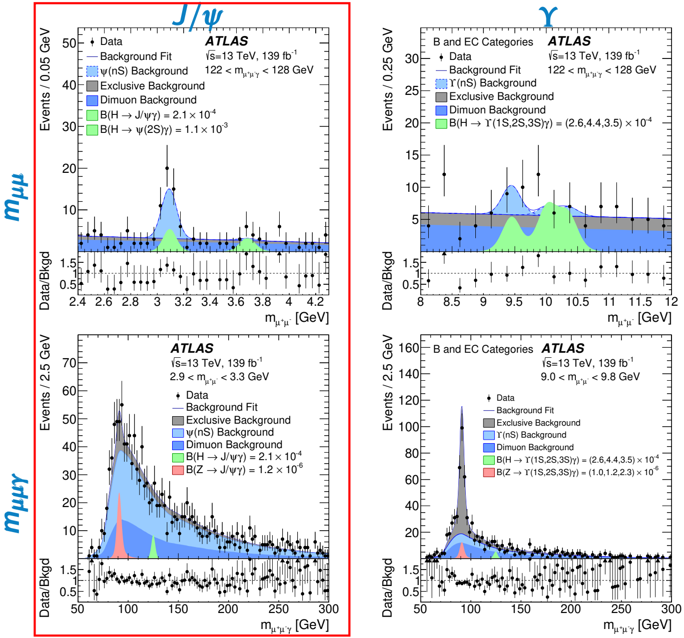

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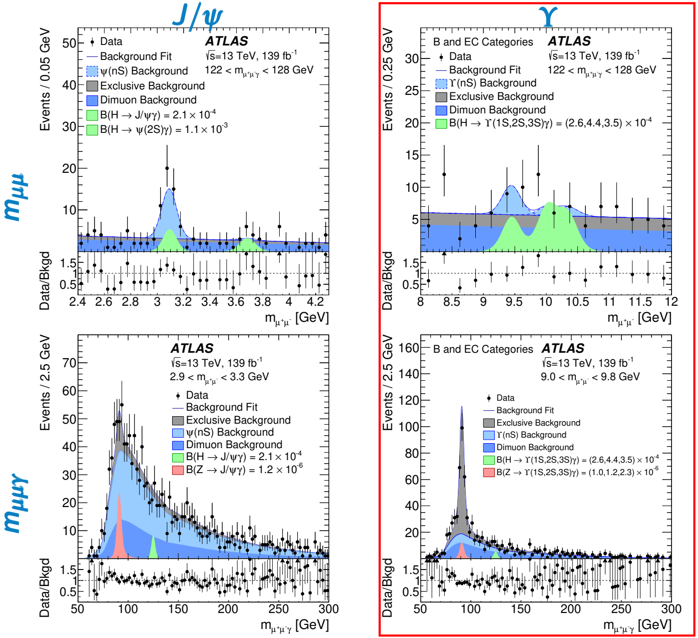
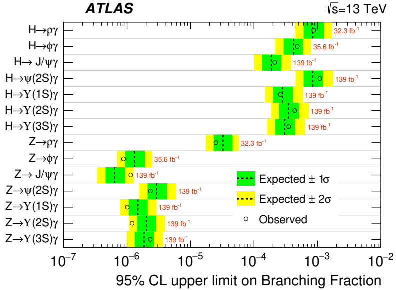


Results

Decay channel	Branching fraction: Higgs boson [10^{-4}] Expected	Higgs boson [10^{-4}] Observed	Z boson [10^{-6}] Expected	Z boson [10^{-6}] Observed	$\sigma \times \mathcal{B}$: Higgs boson [fb] Observed	Z boson [fb] Observed
	95% CL_s upper limits					
$J/\psi\,\gamma$	$1.9^{+0.8}_{-0.5}$	2.1	$0.6^{+0.3}_{-0.2}$	1.2	12	71
$\psi(2S)\,\gamma$	$8.5^{+3.8}_{-2.4}$	10.9	$2.9^{+1.3}_{-0.8}$	2.3	61	135
$\Upsilon(1S)\,\gamma$	$2.8^{+1.3}_{-0.8}$	2.6	$1.5^{+0.6}_{-0.4}$	1.0	14	59
$\Upsilon(2S)\,\gamma$	$3.5^{+1.6}_{-1.0}$	4.4	$2.0^{+0.8}_{-0.6}$	1.2	24	71
$\Upsilon(3S)\,\gamma$	$3.1^{+1.4}_{-0.9}$	3.5	$1.9^{+0.8}_{-0.5}$	2.3	19	135

- The result is statistically limited
- The observations are compatible with the expected background
- Limits are set, in particular:
  - $\mathcal{B}(H \to J/\psi\ \gamma) < 2.1 \times 10^{-4}$
- This is interpreted as a limit on the ratio of coupling modifiers ($\kappa^2 = \sigma/\sigma_{SM}$)
  - $\frac{\kappa_c}{\kappa_\gamma} \in (-136, 178)$, an indirect constraint on the Higgs coupling to charm quarks
  - For comparison, $\kappa_c < 8.5(12.4)$ from the direct search 2201.11428



- Overview of the limits set in this paper
- Note: ϕ and ρ results are from 1712.02758

Results

	95% CL_s upper limits					
	Branching fraction				$\sigma \times \mathcal{B}$	
Decay channel	Higgs boson [10^{-4}] (Higgs)		Z boson [10^{-6}] (Z)		Higgs boson [fb]	Z boson [fb]
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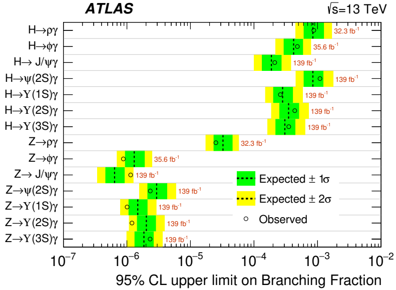

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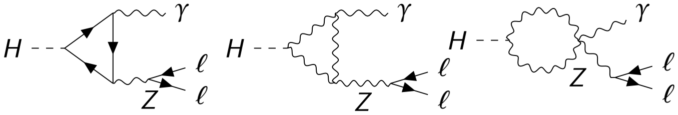
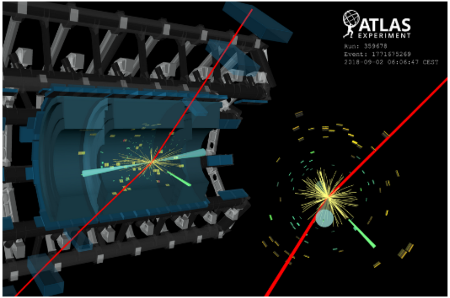
Search for $H \to Z\gamma$

- Motivation: The $H \to Z\gamma$ cross section can be modified by new particles coupled to the Higgs, contributing loop corrections
- Target: Higgs decay into $Z\gamma$ via a loop
- Final state: $\gamma + \ell\ell$
- Previous limits on cross-section times $\mathscr{B}$:
  - ATLAS: $6.6(5.2) \times$ SM 1708.00212
  - CMS: $7.4(6.0) \times$ SM 1806.05996





- Candidate $\gamma + \mu\mu$ event with two electrons (closely spaced green) identified as a photon conversion, and two muons (red) from a Z candidate

Analysis

Backgrounds

- Non-resonant production of $Z\gamma$
- Z+jets with a jet identified as a photon

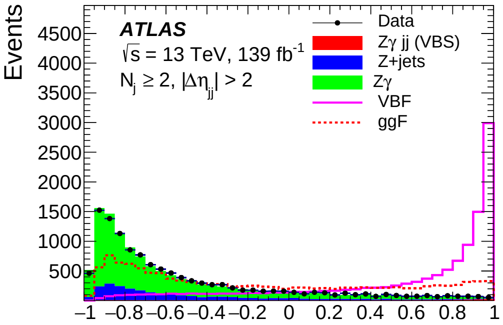
Strategy

- Select γ and a same-flavor opposite charge lepton pair ($p_{\mathrm{T}} > 10$ GeV)
- $m_{\ell\ell} \in [81, 101]$ GeV to select a Z
- $m_{\ell\ell\gamma} \in [105, 160]$ GeV to select a Higgs

Six categories:

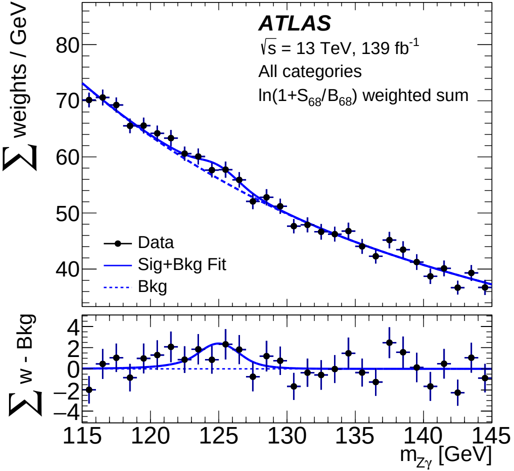
- VBF-enriched, based on a BDT cut
- High relative p_T^{γ}, if $p_T^{\gamma}/m_{\ell\ell\gamma} > 0.4$
- Four categories: $(ee/\mu\mu) \times$ (high/low $p_{\mathrm{T}t}$)
  - $p_{\mathrm{T}t}$ is the component of $p_T^{Z\gamma} \perp (\vec{p}^Z - \vec{p}^{\gamma})$
  - Divided by $p_{\mathrm{T}t}$ =40 GeV

The VBF BDT distribution separates VBF from both *ggF* and backgrounds



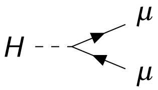
Results

- Uncertainty is primarily statistical, with a subleading spurious signal uncertainty
- Observed signal strength: $\mu = 2.0 \pm 0.9(\text{stat})^{+0.4}_{-0.3}(\text{syst})$
- Observed (expected) significance: $2.2\sigma(1.2\sigma)$
- Limit on $\sigma \times \mathscr{B}$: $3.6(2.6)\times$ SM
- 20% of the improvement compared to the previous result is due to changes in the analysis
  - Event categorization
  - Optimized ℓ/γ identification

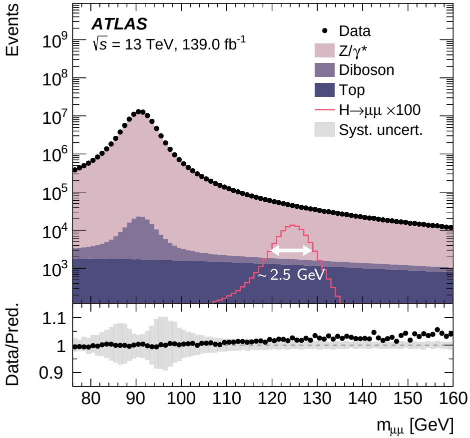


Search for $H \to \mu\mu$

- Motivation: measure Higgs coupling with second generation fermions
- Target: direct decay of $H \to \mu\mu$



- Final state: two oppositely charged muons, and additional leptons/jets depending on the production mechanism
- Previous limits on signal strength:
  - ATLAS: $\mu < 2.8(2.9) \times \mathrm{SM}$ 1705.04582
  - CMS: $\mu < 2.9(2.2) \times \mathrm{SM}$ 1807.06325



- Signal width: 2.6-3.2 GeV depending on category
- Note: the simulated events are used to illustrate signal and background composition, while a analytic background estimate is used for the measurement

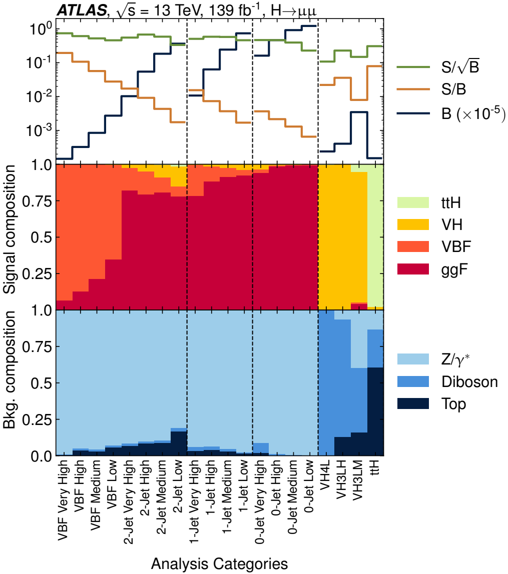
Analysis

Challenge

- Large Drell-Yan (DY) background
- Significant diboson and top backgrounds

Strategy

- Target *ttH* using b-tagged jets and an additional lepton
- Target *VH* using additional leptons to remove DY
- Target VBF production with a 2-jet selection
- 0, 1, 2 jet categories target *ggF*
- All categories use `xgboost` BDTs to enhance sensitivity
- 20 categories in total with different signal, background composition



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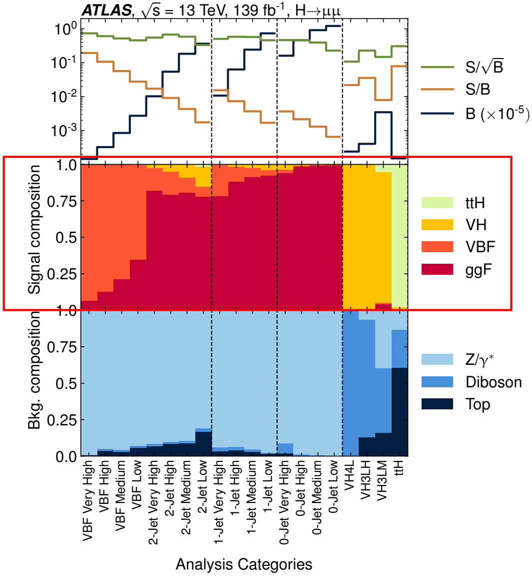

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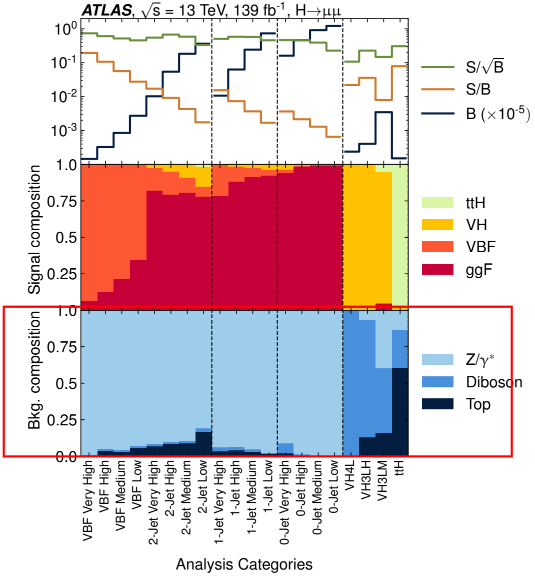
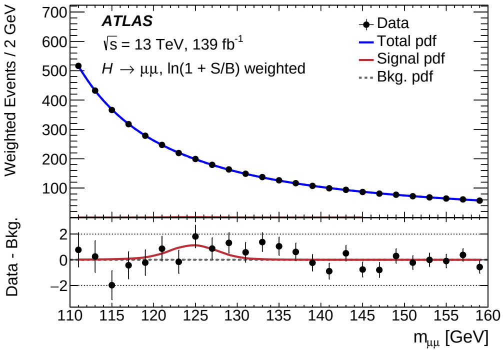
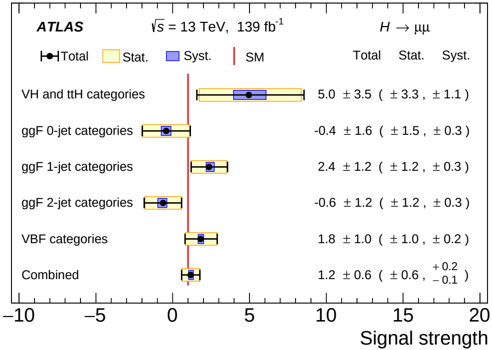


Results





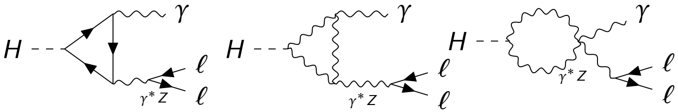
- Result is limited by statistical uncertainty
- Observed signal strength: $\mu = 1.2 \pm 0.6$
- 95% CL upper limit on signal strength (expected): $\mu < 2.2(1.1) \times \text{SM}$
- Observed (expected) significance: $2.2\sigma(1.7\sigma)$

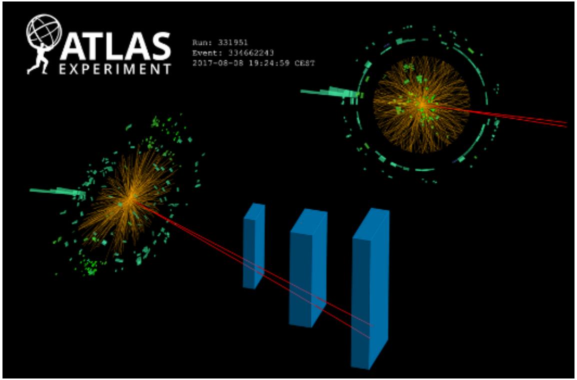
- Note on category definitions

ttH	additional lepton, at least one b-jet
WH	one additional lepton, no b-jets
ZH	at least two additional leptons, no b-jets
VBF	no additional muons, no b-jets, two jets
ggH	no additional muons, no b-jets, 0, 1, or 2 jets

Search for $H \to \ell\ell\gamma$ with a low $\ell\ell$ mass

- Motivation: probe for coupling modifications to the SM
- Target: Higgs decays to *low-mass* ($m_{\ell\ell}$ <30 GeV) dilepton pairs and a photon
- Final state: $\gamma + \ell\ell$
  - *ee* may be merged or unmerged
- Previous results: CMS $\mu < 4.0(2.2) \times \text{SM}$ 1806.05996
- Event display showing two muons and a photon





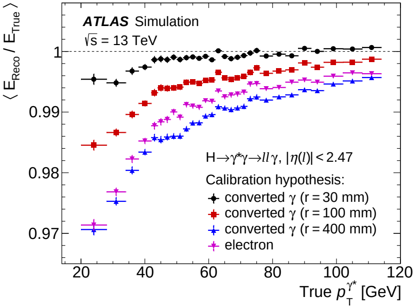
Analysis

Challenges

- Using $\gamma^* \to ee$ when ee pairs are merged in the calorimeter
- Dominant background: non-resonant $\ell\ell\gamma$

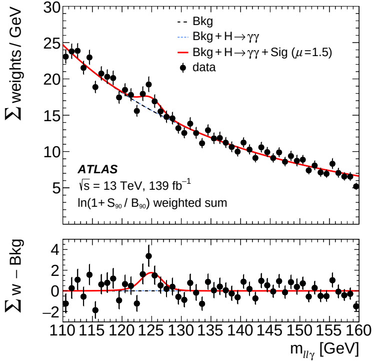
Strategy

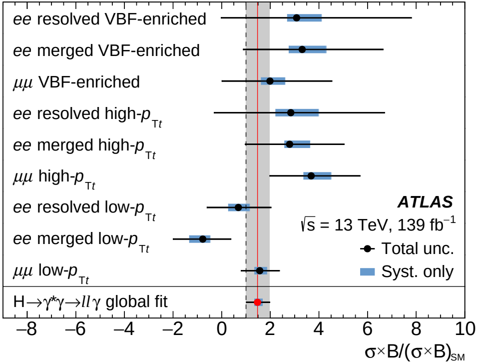
- Cuts on $m_{\ell\ell}$ remove Z, J/ψ, Υ
  - $m_{\ell\ell} < 30$ GeV, $m_{\mu\mu} \notin [2.9, 3.3]$ GeV, $m_{ee} \notin [2.5, 3.5]$ GeV
- A $\Delta R(\gamma, \ell) > 0.4$ separation helps remove FSR
- A multivariate discriminant is trained to select merged-ee pairs
- Three selections ($\mu\mu$, ee, merged-ee) are each divided:
  - VBF defined by kinematics (Jet p_T, $\Delta\eta$ and ΔR)
  - High $p_{Tt} > 100$ GeV
  - Low $p_{Tt} \leq 100$ GeV



- Ratio of reconstructed/true energy for merged-ee pairs, for various conversion radius hypothesis

Results

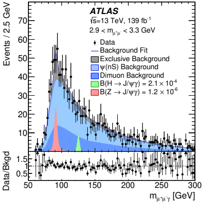




- Result is statistically limited
- Observed signal strength: $\mu = 1.5 \pm 0.5(\text{stat})^{+0.2}_{-0.1}(\text{syst})$
- Evidence of $H \to \ell\ell\gamma$ with observed (expected) significance: $3.2\sigma(2.2\sigma)$
- The $H \to \ell\ell\gamma$ crosssection times branching ratio in this region is:
  - $8.7 \pm 2.7(\text{stat})^{+0.7}_{-0.6}(\text{syst})$ fb

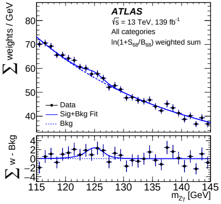
Summary: Four Results

$H(Z) \to \mathcal{Q}\gamma$



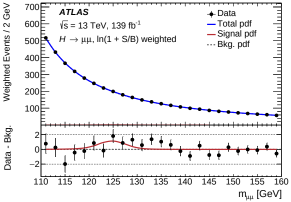
- Limit on $\mathscr{B}(H \to J/\psi\ \gamma)$ lowered from 3.5×10^{-4} to 2.1×10^{-4}

$H \to Z\gamma$



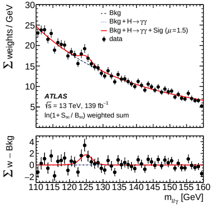
- Limit on $\sigma\mathscr{B}$ lowered from $6.6(5.2)\times$ SM to $3.6(2.6)\times$ SM

$H \to \mu\mu$



- A factor of **2.5** improvement in expected sensitivity

$H \to \gamma\gamma^*(\to \ell\ell)$



- New measurement from ATLAS

In general

- Each of these studies (except $H \to \ell\ell\gamma$) report a significant improvement over their partial Run-2 predecessor
- Due in large part to the increased luminosity, and also to improvements in the analysis
- Each result is statistically limited, and will benefit from the addition of data from Run-3