Searches for rare and lepton flavour violating decays of the Higgs boson with the ATLAS detector

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On behalf of the ATLAS Collaboration

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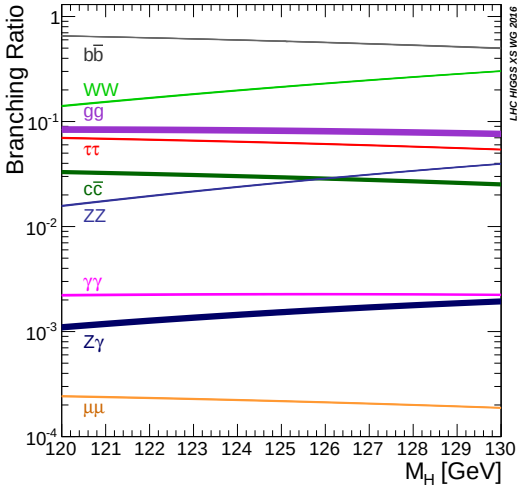
Introduction

- Following the discovery of the Higgs boson ***ATLAS*** has now searched for many of the various decay channels
- $H \to b\bar{b}$, $H \to WW$, $H \to \tau\tau$, $H \to ZZ$ and $H \to \gamma\gamma$ decays have now all been observed by ***ATLAS***
- Higgs decays to second generation fermions, $H \to c\bar{c}$ and $H \to \mu\mu$ discussed by
  Maria Mironova
- I will cover ***ATLAS*** searches for $H \to Z\gamma$ and $H \to \gamma^*\gamma$ in this talk
- In addition, many beyond the SM Higgs decays have been proposed. I will discuss ***ATLAS*** searches for lepton flavour violating **(LFV)** Higgs decays



$H \to Z\gamma$ and $H \to \gamma^*\gamma$

$H \to Z\gamma$ and $H \to \gamma^*\gamma$

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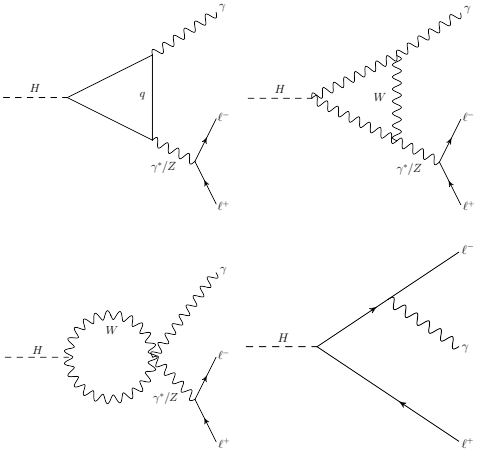
- The $\boldsymbol{H \to \ell^+\ell^-\gamma}$ decay can be seperated into two channels: $\boldsymbol{H \to Z\gamma}$ and $\boldsymbol{H \to \gamma^*\gamma}$
- We can select events dominated by one process or the other using $m_{\ell\ell}$, the invariant mass of the lepton pair
- The $\boldsymbol{H \to Z\gamma}$ analysis requires $m_{\ell\ell}$ to be consistent with m_Z, while the $\boldsymbol{H \to \gamma^*\gamma}$ analysis requires $m_{\ell\ell} < 30$ GeV (excluding J/ψ and Υ resonances)
- The analysis strategy is similar in both cases. Events are selected with a photon and two opposite sign leptons before being categorised and a peak in the $m_{\ell\ell\gamma}$ distribution at m_H is searched for
- Both analyses use the full Run 2 dataset (139 fb^{-1})



Event categories

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$H \to Z\gamma$

Six categories

- VBF-enriched
- High relative p_{T} ($\frac{p_{\mathrm{T}}^{\gamma}}{m_{\ell\ell\gamma}} > 0.4$)
- High-$p_{\mathrm{T}t}$ *ee*
- High-$p_{\mathrm{T}t}$ $\mu\mu$
- Low-$p_{\mathrm{T}t}$ *ee*
- Low-$p_{\mathrm{T}t}$ $\mu\mu$

$H \to \gamma^*\gamma$

Nine categories

- VBF-enriched *ee* resolved/merged
- VBF-enriched $\mu\mu$
- High-$p_{\mathrm{T}t}$ *ee* resolved/merged
- High-$p_{\mathrm{T}t}$ $\mu\mu$
- Low-$p_{\mathrm{T}t}$ *ee* resolved/merged
- Low-$p_{\mathrm{T}t}$ $\mu\mu$

- VBF requirements detailed in back-up
- $p_{\mathrm{T}t} = |\vec{p}_{\mathrm{T}}^{\ell\ell\gamma} \times \hat{t}|$ where $\hat{t} = \frac{\vec{p}_{\mathrm{T}}^{\ell\ell} - \vec{p}_{\mathrm{T}}^{\gamma}}{|\vec{p}_{\mathrm{T}}^{\ell\ell} - \vec{p}_{\mathrm{T}}^{\gamma}|}$, highly correlated with $p_{\mathrm{T}}^{\ell\ell\gamma}$ but better experimental resolution
- High/low $p_{\mathrm{T}t}$ distinction at 40 GeV for $Z\gamma$ and 100 GeV for $\gamma^*\gamma$
- Resolved/merged *ee* candidates detailed on next slide

$H \to \gamma^*\gamma$: merged *ee* candidates

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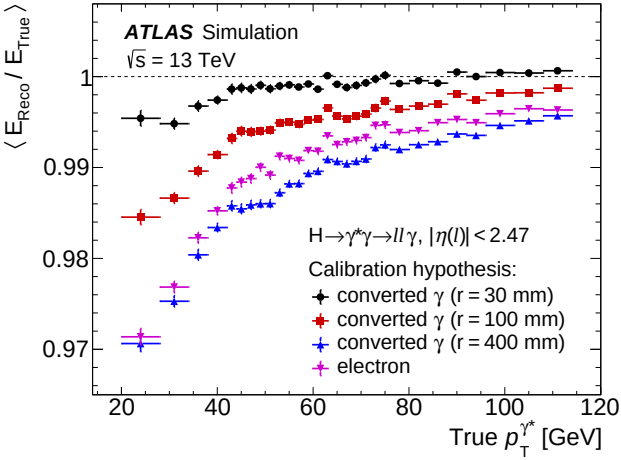
- Generally it is required that events contain one photon and two opposite charge leptons
- Due to the event kinematics of $H \to \gamma^*\gamma$, it is common for the energy deposits of the two electrons in the EM calorimeter to be reconstructed as a single cluster. These events are known as **merged** *ee* as opposed to **resolved** *ee* and a dedicated reconstruction and calibration of merged *ee* candidates is performed.



Uncertainties

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- In both analyses the total uncertainty is dominated by the statistical uncertainty
- The leading systematic uncertainty is the non-resonant background modelling in both analyses
- Other uncertainties, including signal uncertainties, currently have negligible impact on the results

$H \to Z\gamma$ results

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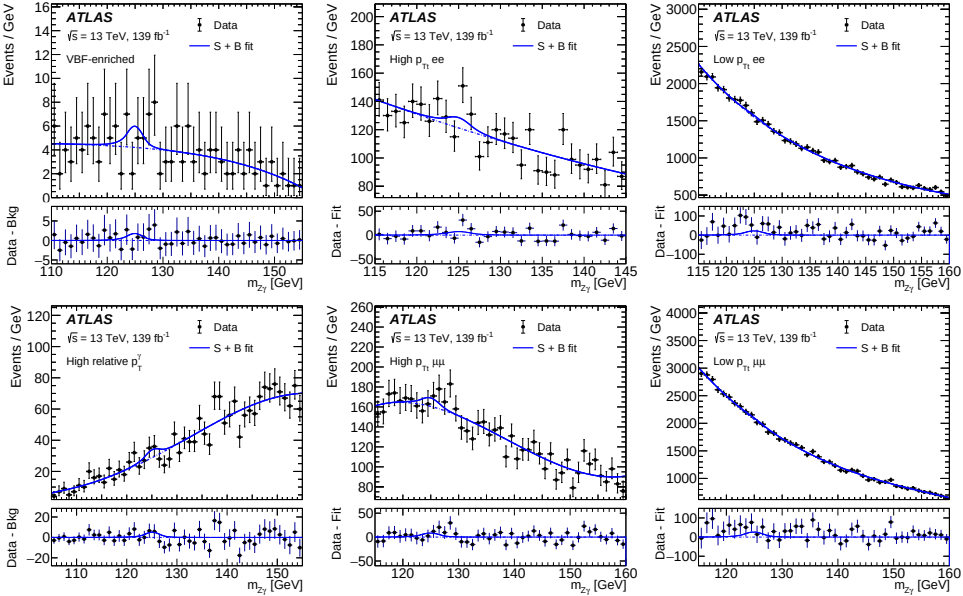

$H \to Z\gamma$ results

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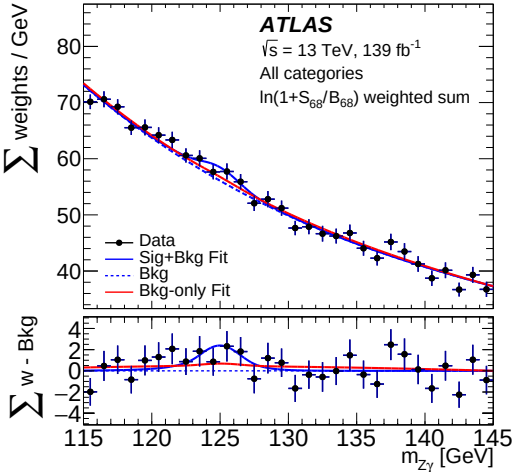
$H \to Z\gamma$ results

- $\mu = 2.0^{+1.0}_{-0.9} = 2.0 \pm 0.9\,(\mathrm{stat})^{+0.4}_{-0.3}\,(\mathrm{syst})$
- $\mu < 3.6$ at 95% CL
- $\sigma(pp \to H) \cdot B(H \to Z\gamma) < 305$ fb at 95% CL
- $B(H \to Z\gamma) < 0.55\%$ at 95% CL assuming SM $\sigma(pp \to H)$



$H \to \gamma^*\gamma$ results

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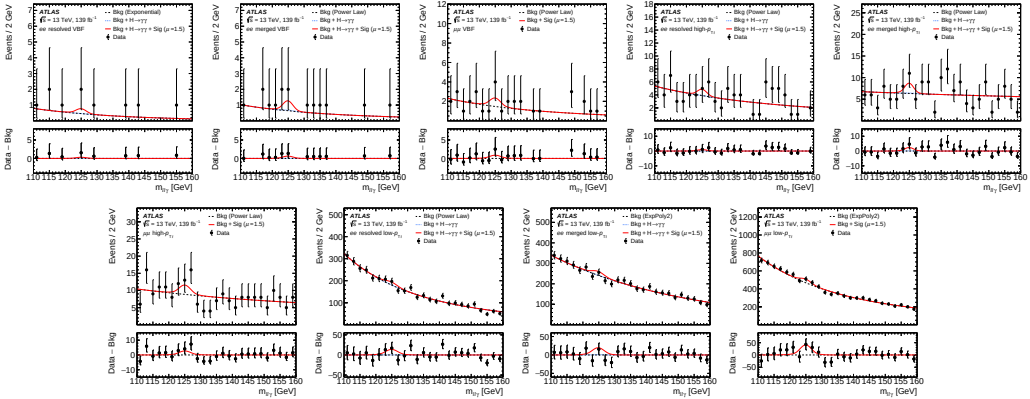

$H \to \gamma^*\gamma$ results

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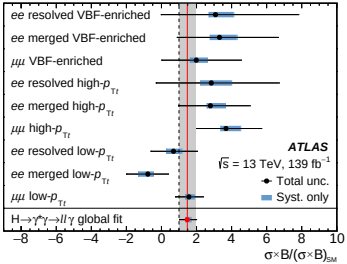
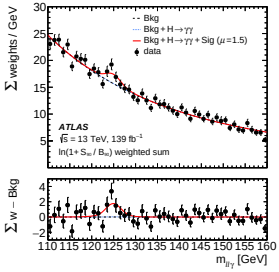
$H \to \gamma^*\gamma$ results

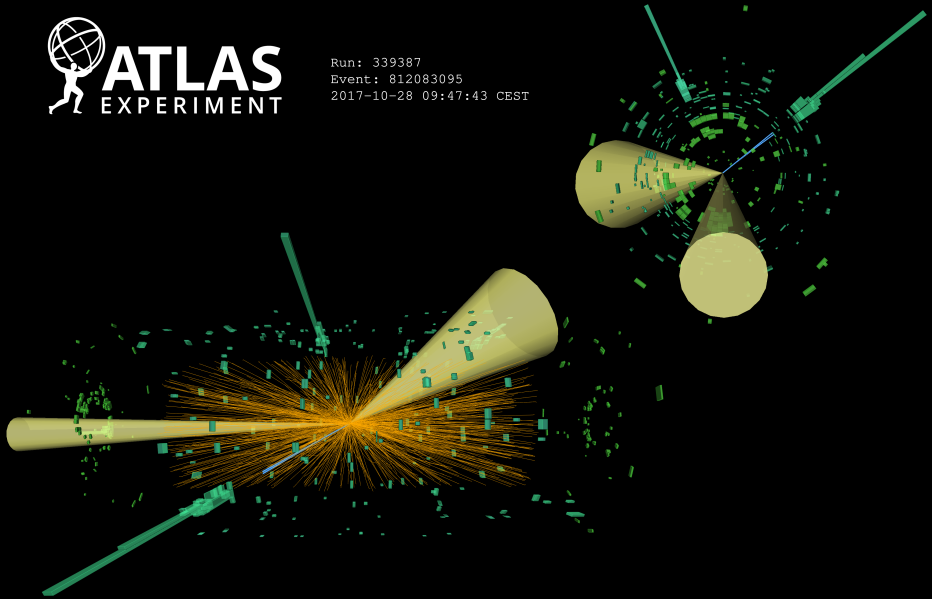
- $\mu = 1.5 \pm 0.5 = 1.5 \pm 0.5\,(\text{stat})^{+0.2}_{-0.1}\,(\text{syst})$
- Observed (expected) significance over the background-only model of 3.2σ (2.1σ)
- The Higgs boson production cross-section times the $H \to \ell\ell\gamma$ branching fraction for $m_{\ell\ell} < 30$ GeV is determined to be

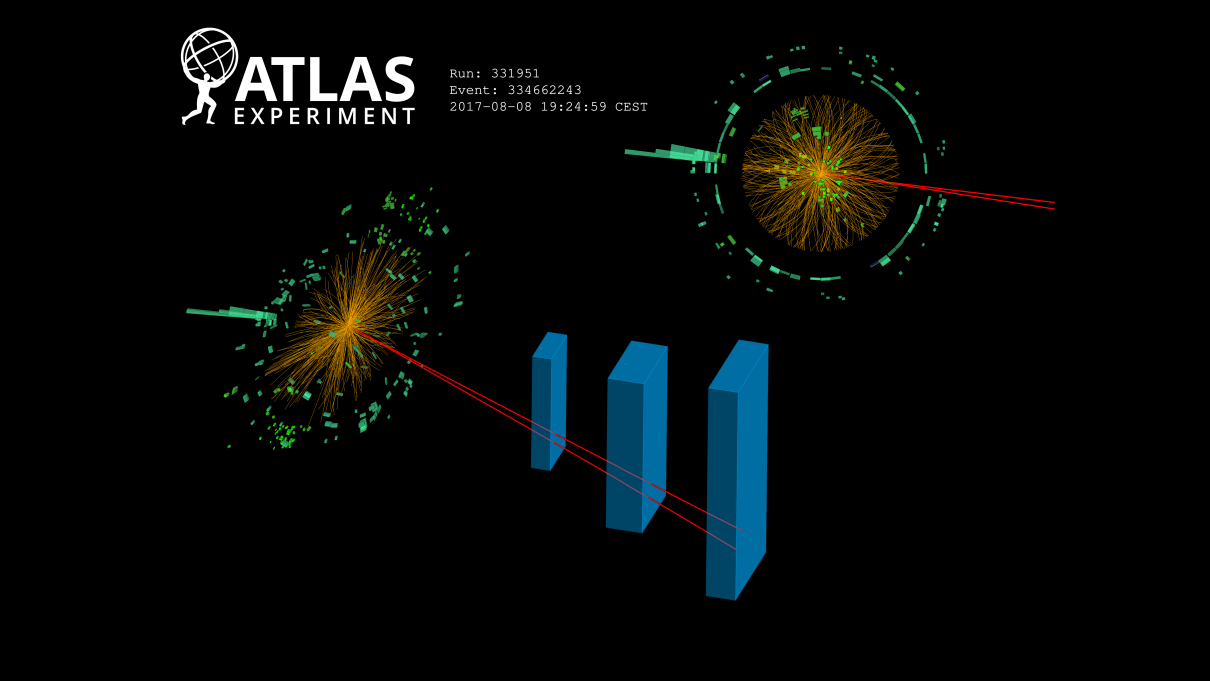
$$8.7^{+2.8}_{-2.7} = 8.7 \pm 2.7\,(\text{stat})^{+0.7}_{-0.6}\,(\text{syst})\ \text{fb}$$

First evidence for the decay of a Higgs boson into a photon and a pair of leptons






ATLAS
EXPERIMENT
Run: 339387
Event: 812083095
2017-10-28 09:47:43 CEST


ATLAS
EXPERIMENT
Run: 331951
Event: 334662243
2017-08-08 19:24:59 CEST

LFV Higgs decays

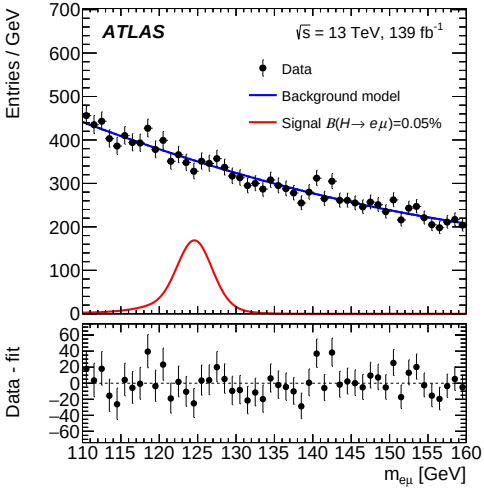
LFV Higgs decays

- Lepton flavour violation is not allowed in the SM. However, the observation of neutrino oscillations indicates that **LFV** occurs in nature!
- ***ATLAS*** has also searched for **LFV** Higgs boson decays in which $H \to \ell\ell'$
- These decays are forbidden at tree level in the SM, but many BSM models include them
- The searches have been performed in the $e\mu$, $e\tau$ and $\mu\tau$ channels
- The $e\mu$ analysis uses the full Run 2 dataset, while the $e\tau$ and $\mu\tau$ analyses use only data from 2015–2016, corresponding to 36 fb^{-1}

$H \to e\mu$

Phys. Lett. B 801 (2020) 135148

- The $H \to e\mu$ analysis follows a similar strategy to the $H \to Z\gamma$ and $H \to \gamma^*\gamma$ analyses
- Events are selected with one electron and one muon and are categorised
- Eight categories are defined
  - A **low-p_{T}^{ℓ}** category in which one of the selected leptons has $p_{\mathrm{T}} < 27$ GeV
  - A **VBF** category for events with two jets with $|\Delta\eta_{jj}| > 3$ and $m_{jj} > 500$ GeV
  - Remaining events are categorised as **central** if both leptons have $|\eta_{\ell}| < 1$, otherwise they are categorised as **non-central**
  - These events are then classified based on $p_{\mathrm{T}}^{\ell\ell}$ as **low** ($p_{\mathrm{T}}^{\ell\ell} \leq 15$), **mid** ($15 < p_{\mathrm{T}}^{\ell\ell} \leq 50$) or **high-p_{T}** ($p_{\mathrm{T}}^{\ell\ell} > 50$)
- This paper also includes a search for extremely rare $H \to e^+e^-$ decays



$H \to e\tau$ and $H \to \mu\tau$

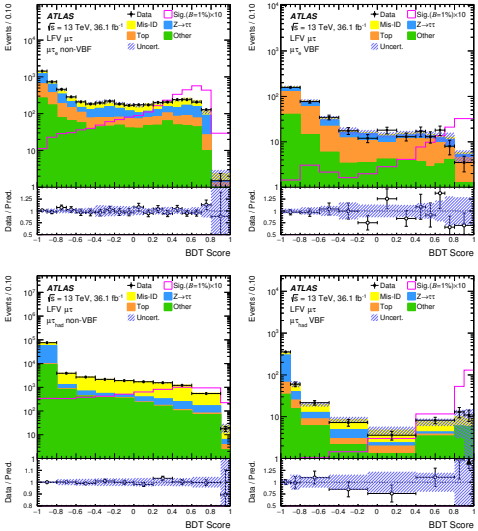
Phys. Lett. B 800 (2020) 135069

- Search includes both **hadronically** and **leptonically** decaying τ leptons
- Backgrounds are taken from MC ($Z \to \tau\tau$, top, diboson, $H \to \tau\tau$ and $Z \to \ell\ell$) and data (jets misidentified as hadronic taus or leptons)
- Events are selected with zero b-tagged jets (to suppress top background) and:

$\ell\tau_{\mathrm{lep}}$: Two light leptons (e or μ) of different flavour and opposite charge

$\ell\tau_{\mathrm{had}}$: One hadronic lepton and one light lepton with opposite charge

- Events are categorised as **VBF** or **non-VBF** events
- An boosted decision tree is trained in each analysis region to distinguish the LFV signal from the background



LFV Higgs decays

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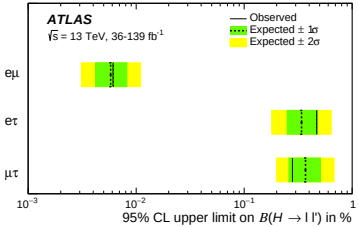
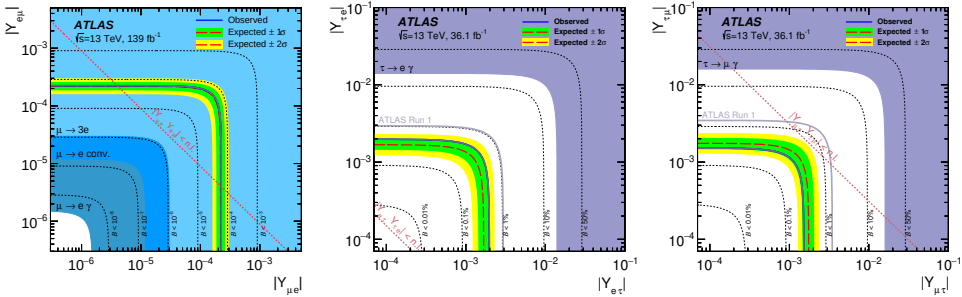
- No significant excesses over the SM prediction are found
- Upper limits on the LFV Higgs branching fractions are set at 95% CL
  - $B(H \to e\mu) < 0.061\%$
  - $B(H \to e\tau) < 0.47\%$
  - $B(H \to \mu\tau) < 0.28\%$
- Branching fraction limits converted to limits on off-diagonal Yukawa couplings





Summary

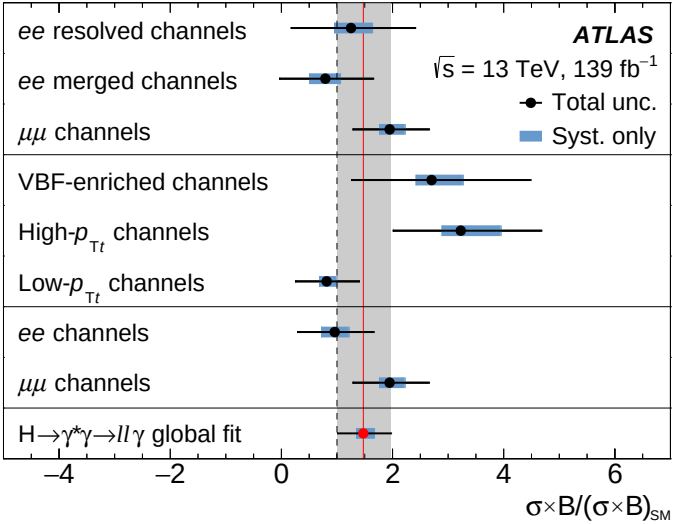
- ***ATLAS*** has now observed many of the SM Higgs boson decay channels
- Searches are have been performed for those not yet observed
- ***ATLAS*** now has **evidence** for the $H \to \gamma^* \gamma$ decay. The first evidence for the decay of the Higgs boson into a photon and a pair of leptons
- Searches have also been performed for **LFV** Higgs boson decays and no evidence has yet been found

Back up

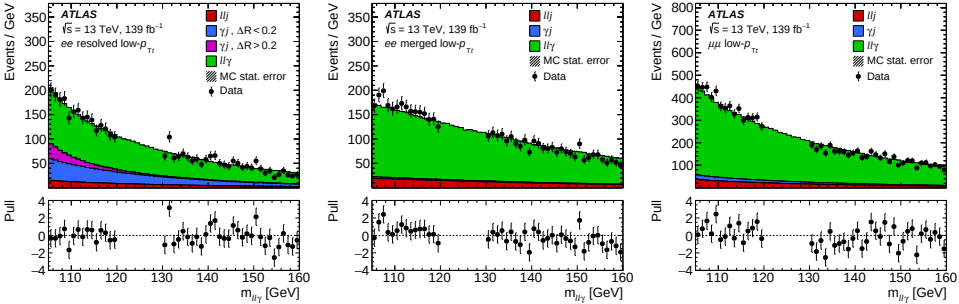
$H \to \gamma^* \gamma$ VBF selection

- ≥ 2 jets with $p_{\mathrm{T}} > 25$ GeV
- If the leading or sub-leading jet has $|\eta| > 2.5$ it is required to have $p_{\mathrm{T}} > 30$ GeV
- $m_{jj} > 500$ GeV
- $|\Delta\eta_{jj}| > 2.7$
- $|\eta_{\ell\ell\gamma} - 0.5(\eta_{j1} + \eta_{j2})| < 2.0$
- $\Delta R(\ell, j) > 1.5$ and $\Delta R(\gamma, j) > 1.5$
- $\Delta\phi(\ell\ell\gamma, jj) > 2.8$

$H \to \gamma^*\gamma$ breakdown



$H \to \gamma^*\gamma$ backgrounds



- Non-resonant $\ell\ell\gamma$ from MC
- Other backgrounds from data control regions

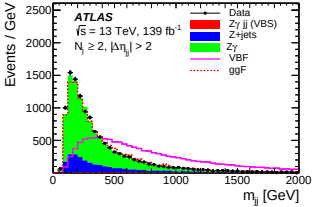
$H \to \gamma^*\gamma$ uncertainties

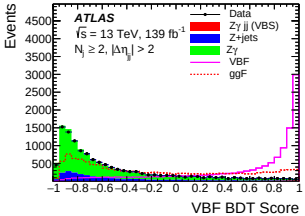
Uncertainty source	μ	$\sigma \times \mathcal{B}$
Spurious Signal	6.1	
$\mathcal{B}(H \to \ell\ell\gamma)$	5.8	–
QCD scale	4.7	1.1
ℓ, γ, jets	4.0	
PDF	2.3	0.9
Luminosity	1.7	
Pile-up	1.7	
Minor prod. modes	0.8	
$H \to \gamma\gamma$ background	0.7	
Parton Shower	0.3	
Total systematic	11	7.9
Statistical	31	
Total	33	32

- Spurious signal is the uncertainty on the non-resonant background parametrisation
- Statistical uncertainties approximately 3–4 times larger than systematic uncertainties

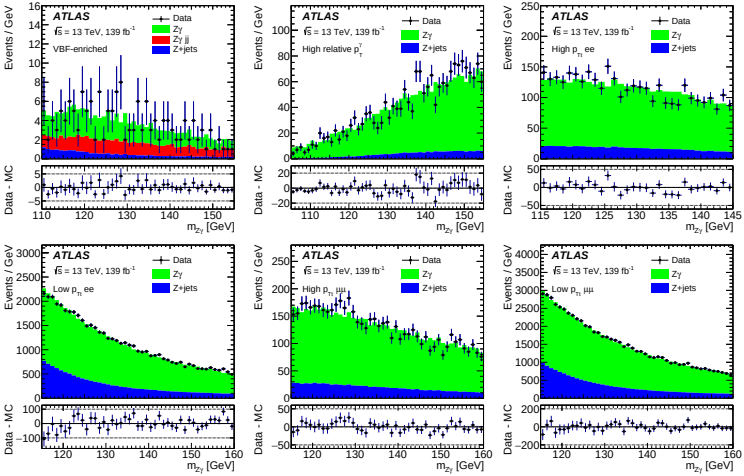
$H \to Z\gamma$ VBF selection

- A BDT is trained to separate VBF signal events
- The variables included are:
  - The p_{T} of the highest-p_{T} jet, p_{T}^{j1}
  - $\Delta\eta_{jj}$
  - $\Delta R^{\min}_{\gamma \text{ or } Z,j}$
  - m_{jj}
  - $|\eta_{Z\gamma} - 0.5(\eta_{j1} + \eta_{j2})|$
  - $\Delta\phi(Z\gamma, jj)$
  - $\Delta\phi(Z, \gamma)$
  - $p_{\mathrm{T},t}$





$H \to Z\gamma$ backgrounds



- QCD $Z\gamma$ (green), EW $Z\gamma jj$ (red) from simulation
- Z+jets (blue) from data control regions

$H \to Z\gamma$ uncertainties

Sources	$H \to Z\gamma$
Luminosity [%]	
Luminosity	1.7
Signal efficiency [%]	
Modelling of pile-up interactions	0.0–0.2
Photon identification efficiency	0.8–1.8
Photon isolation efficiency	0.7–1.9
Electron identification efficiency	0.0–2.3
Electron isolation efficiency	0.0–0.1
Electron reconstruction efficiency	0.0–0.5
Electron trigger efficiency	0.0–0.1
Muon selection efficiency	0.0–0.6
Muon trigger efficiency	0.0–1.6
Jet energy scale	0.0–3.5
Jet resolution	0.0–15
Jet pile-up	0.0–7.5
Jet flavor	0.0–11
Signal modelling on σ_{CB} [%]	
Electron and photon energy resolution	0.5–3.4
Muon – Inner detector resolution	0.0–1.2
Muon – Muon spectrometer resolution	0.0–3.4
Signal modelling on μ_{CB} [%]	
Electron and photon energy scale	0.09–0.15
Muon momentum scale	0.0–0.03
Higgs boson mass measurement	0.19
Background modelling [number of spurious signal events]	
Spurious signal	1.5–39

Sources	
Total cross-section and efficiency [%]	
ggF Underlying event	1.3
perturbative order	4.7–9.6
PDF and α_s	1.8–2.8
$B(H \to Z\gamma)$	5.7
Total (total cross-section and efficiency)	7.5–11
Category acceptance [%]	
ggF Underlying event	0.1–11
ggF H p_T perturbative order	0.3–0.4
ggF in VBF-enriched category	37
ggF in high relative p_T category	21
ggF in other categories	10–15
Other production modes	1.0–15
PDF and α_s	0.4–3.5
Total (category acceptance)	11–37