Search for rare Higgs boson decays with ATLAS.

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ATLAS Collaboration

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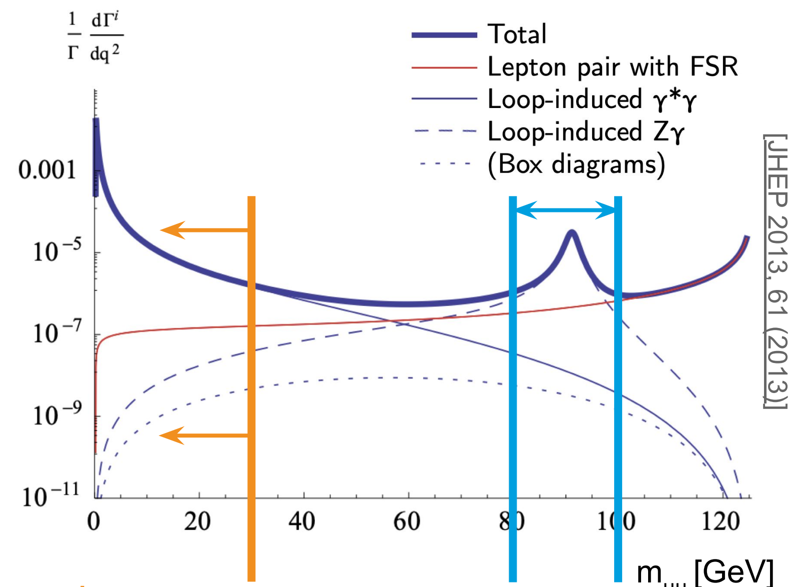
Motivation

- Higgs boson, discovered in 2012, is now observed in multiple channels: H→bb, H→WW, H→ττ, H→ZZ, H→γγ
- With more data from Run 2 it is becoming possible to explore rare decays, such as H→μμ (see talks: [ATLAS](), [CMS]()) and **H→llγ** (topic of this talk)
- Paving the way for
  - Future measurements, e.g. **CP violation in SM** with H→llγ (three-body final state)
  - Searches for **BSM couplings**

- H→llγ (l=e,μ) decays explored in ATLAS:
  - **H→Zγ→llγ**, with m_{ll} near Z peak
    Phys. Lett. B 809 (2020) 135754
  - **Low-m_{ll} H→llγ**: predominantly through H→γ*γ→llγ, with m_{ll}<30 GeV
    Phys. Lett. B 819 (2021) 136412
- Presenting results with full Run 2 dataset: **139 fb^{-1}** at $\sqrt{s}$=13 TeV



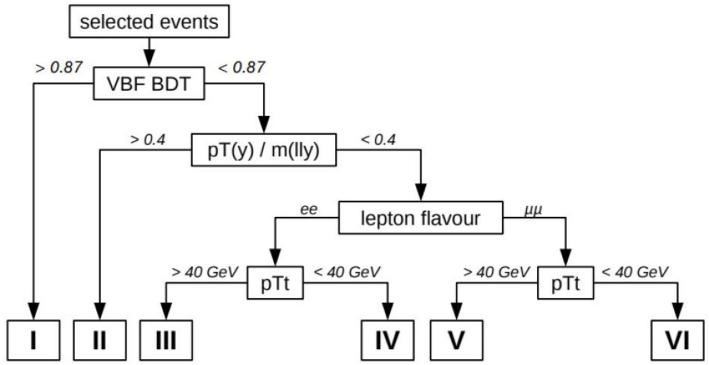
Low-m_{ll} H→llγ: m_{ll}<30 GeV

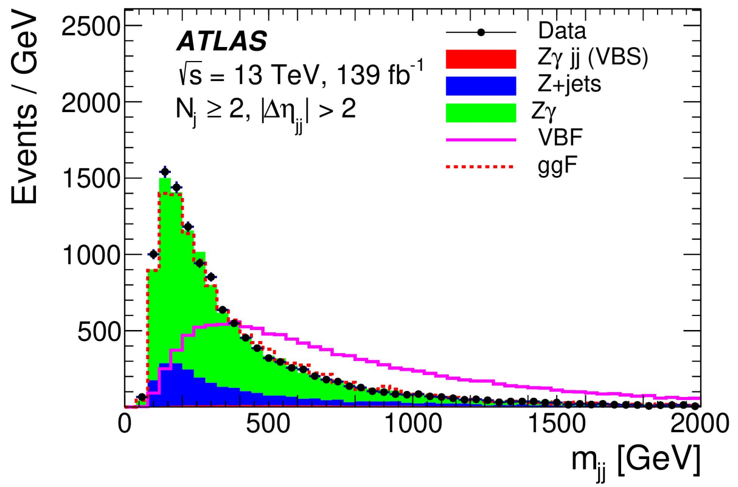
H→Zγ→llγ is concentrated around Z peak m_{ll}=91.2 ± ~10 GeV

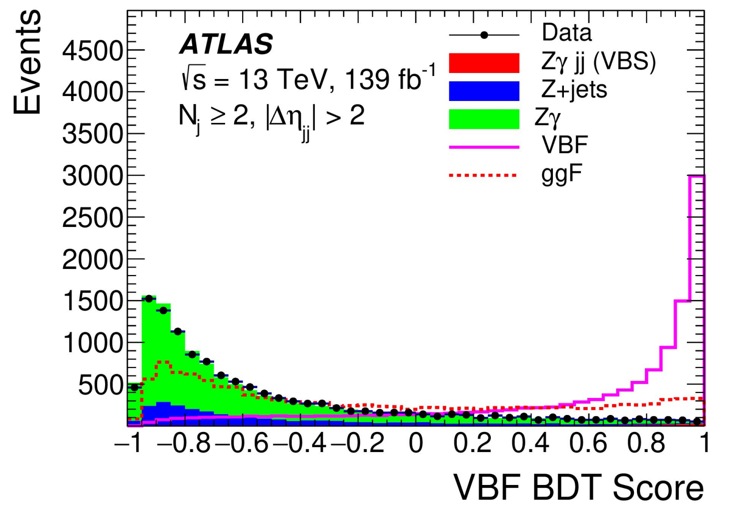
$H \to Z\gamma \to ll\gamma$ search.

$H \to Z\gamma \to ll\gamma$: event selection

- Select events with well-reconstructed $\mathbf{e^+e^-}$ or $\boldsymbol{\mu^+\mu^-}$ and a $\boldsymbol{\gamma}$
- For **Z boson candidates** ($50<m_{ll}<101$ GeV) apply a kinematic m_{ll} fit using the Z Breit-Wigner lineshape as a constraint
  - For $m_{\mu\mu}$ additionally correct for collinear FSR
  - Improves m_Z resolution 14% for ee and 10% for μμ
- **H candidate**: Z candidate + highest-p_T γ in the event, $105<m_{Z\gamma}<160$ GeV
- **BDT-based categorization** of VBF-like events + separation of high-$p_T^{\gamma}/m_{ll\gamma}$ and high-$\mathbf{p}_{Tt}^{Z\gamma}$ events for best sensitivity (6 categories total)





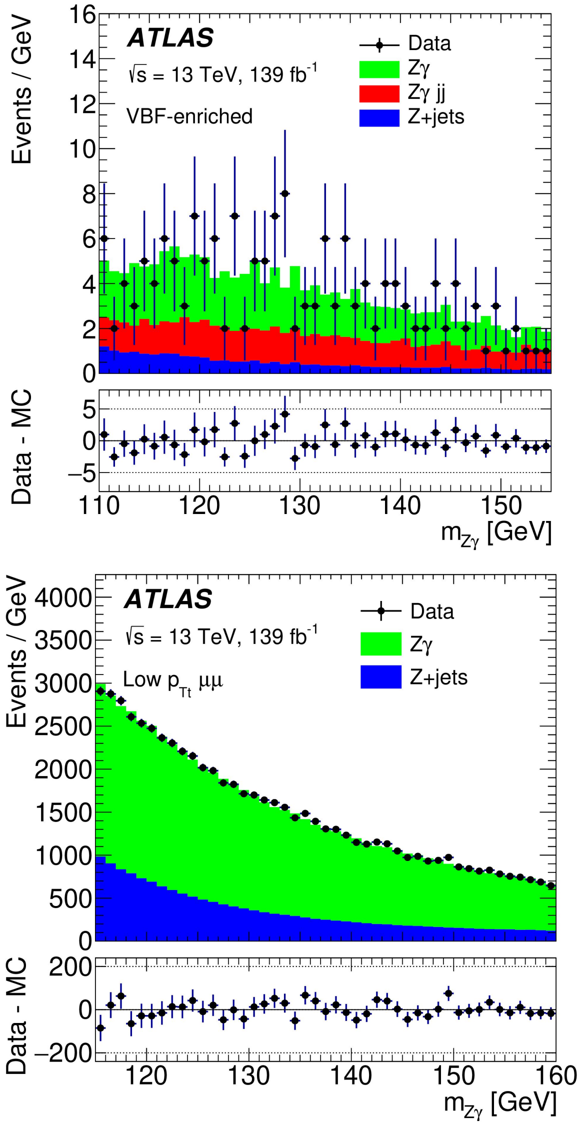


H→Zγ→llγ: signal and background model

- Fit $m_{ll\gamma}$ with Signal+Background functions
- Signal: for all categories fit with **Double-Sided Crystal Ball function** (gaussian core, power law tails)
- Background:
  - Construct background template:
    - **SM llγ** backgrounds: from MC: Zγ and Zγjj
    - **Z+jets**: from data
  - Choose background functions (per category)
    - **minimizing bias**:
      - fit S+B model with background template
      - any signal from the fit is *spurious* = bias
    - and with **fewest DOF**

Category	Function Type
VBF-enriched	Second-order power function
High relative p_T	Second-order exponential polynomial
ee high p_{Tt}	Second-order Bernstein polynomial
ee low p_{Tt}	Second-order exponential polynomial
$\mu\mu$ high p_{Tt}	Third-order Bernstein polynomial
$\mu\mu$ low p_{Tt}	Third-order Bernstein polynomial

Templates for function choice, compared to data



H→Zγ→llγ: results

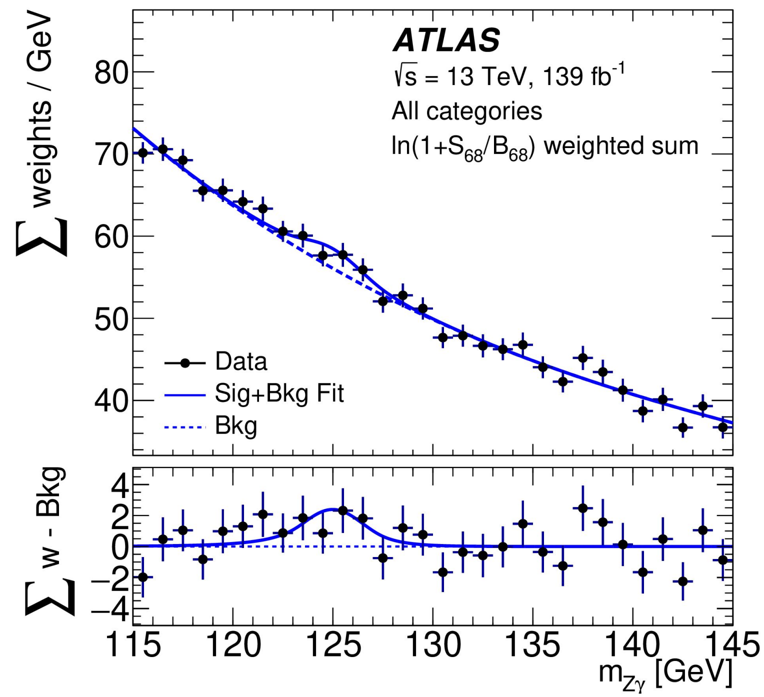
- The result is dominated by statistical uncertainty
- Very low branching ratio and high irreducible background

Main sources of systematic uncertainties:

- Background function bias (spurious signal)
- BR (theory)
- Missing higher-order QCD

- Observed significance: **2.2σ**
  - Expected: 1.2σ
- Observed 95% CL upper limit on the $\sigma(pp \rightarrow H) \cdot B(H \rightarrow Z\gamma)$: **3.6** times SM
  - Expected, assuming SM Higgs boson: 2.6 times SM
- Best-fit signal strength (times SM): **2.0±0.9** (stat.)$^{+0.4}_{-0.3}$(syst) = **$2.0^{+1.0}_{-0.9}$**

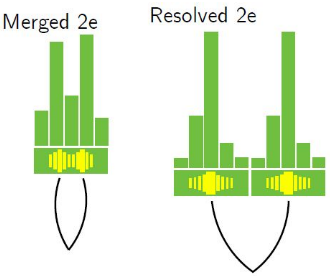
Weighted $m_{Z\gamma}$ distribution in data, signal+background model



[Phys. Lett. B 809 (2020) 135754](https://doi.org/10.1016/j.physletb.2020.135754)

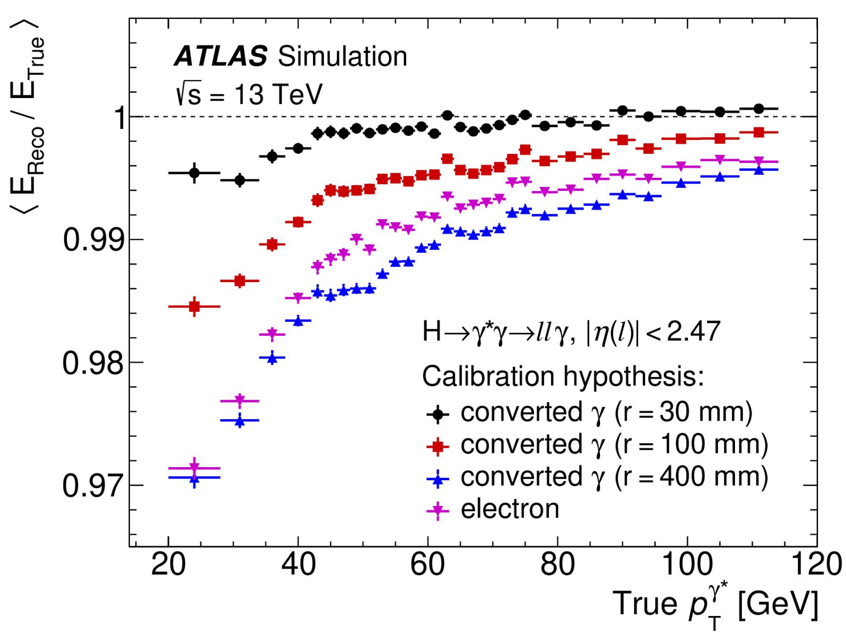
Low-m_{ll} $H \rightarrow ll\gamma$ search.

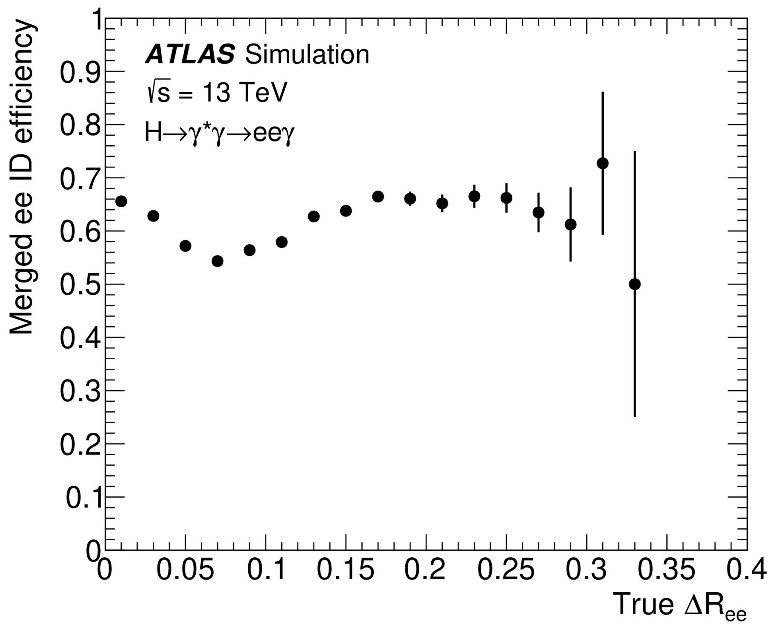
Low-m_{ll} H→llγ search: experimental challenge



Unique challenge: low invariant mass of the lepton pair
leptons are often collimated

- EM **calorimeter deposits** from 2 electrons often **merge**
  - **Special electron trigger** with relaxed EM shower shape cuts
  - **Dedicated merged electrons identification algorithm**
    - TMVA-based, using shower shapes, TRT ID, kinematics of cluster & tracks
  - Efficiency scale factors & energy calibration modelled using early converted photons
- **Isolation correction** for signal leptons: removing contribution to each other's isolation cones





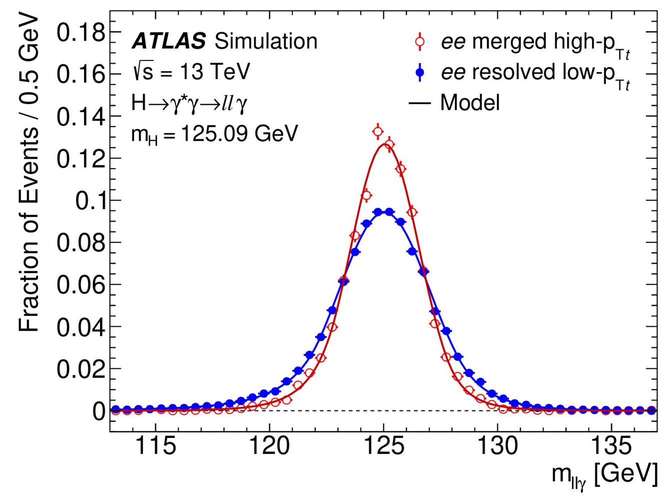
Low-m_{ll} H→llγ search: analysis strategy

Similar to Zγ, main differences:

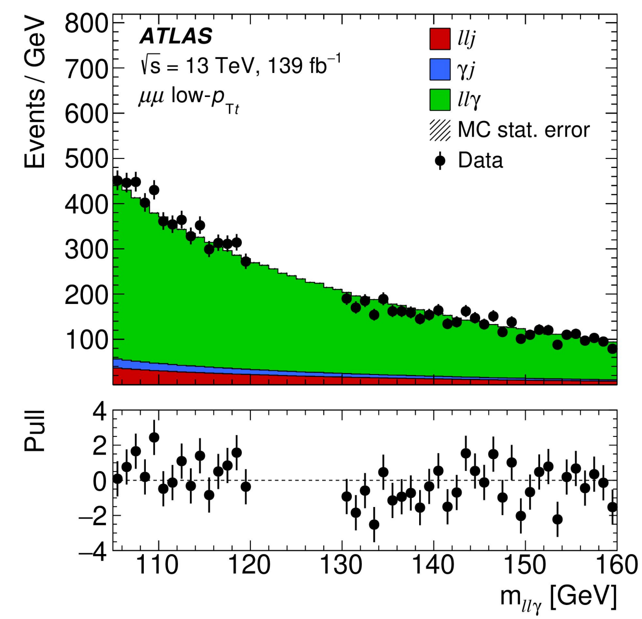
- For dilepton candidates:
  - **mll<30 GeV** cut to separate from Zγ
  - eeγ Resolved: electrons identified with standard reco
  - **eeγ Merged**: electrons identified using custom ID
- Cut-based categorization: VBF-like events, high-$\mathbf{p}_{Tt}^{\gamma^*\gamma}$ events, and the rest in μμγ, eeγ Resolved, eeγ Merged (9 categories total)
- Background:
  - Construct background template:
    - SM llγ backgrounds: generator-level llγ MC (with reco corrections)
    - **γ+jets, ll+jet**: shape & normalization from data
  - Background functions minimizing bias:

Category	Function Type
$\mu\mu$ VBF-enriched	Power function
ee Resolved VBF-enriched	Exponential function
ee Merged VBF-enriched	Power function
$\mu\mu$ high $p_{\mathrm{T}t}$	Power function
ee Resolved high $p_{\mathrm{T}t}$	Power function
ee Merged high $p_{\mathrm{T}t}$	Power function
$\mu\mu$ low $p_{\mathrm{T}t}$	Second-order exponential polynomial
ee Resolved low $p_{\mathrm{T}t}$	Power function
ee Merged low $p_{\mathrm{T}t}$	Second-order exponential polynomial

Signal model



Template for function choice, compared to data



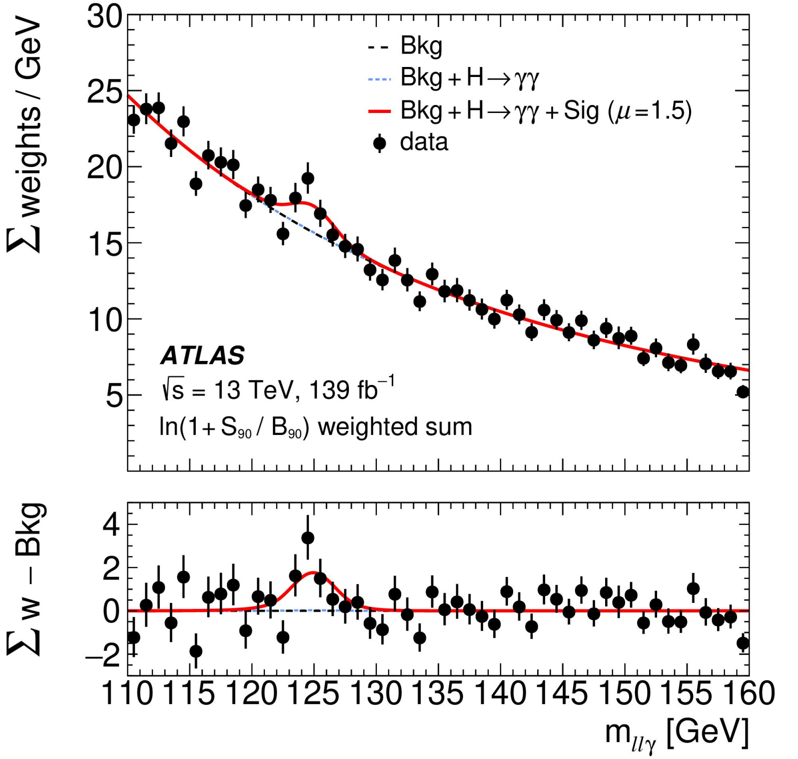
Low-m_{ll} $H \to ll\gamma$ search: results

Search is still **statistically limited**: systematic uncertainty is only 35% of the statistical uncertainty.

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	

- Observed significance: **3.2σ**
  - Expected: 2.1σ
- Best-fit signal strength (times SM): **1.5±0.5**(stat.)$^{+0.2}_{-0.1}$(syst.) = **1.5±0.5**
- Cross-section times BR for m_{ll}<30 GeV: **8.7±2.7**(stat.)$^{+0.6}_{-0.7}$(syst.) = **$8.7^{+2.8}_{-2.7}$ fb**

Weighted $m_{ll\gamma}$ distribution in data, signal+background model



Phys. Lett. B 819 (2021) 136412

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

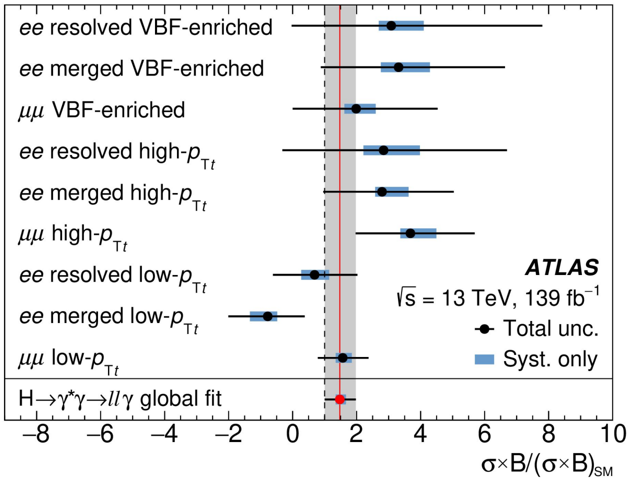
Summary & outlook

- With data from Run 2 it is becoming possible to explore rare Higgs boson decays, such as $H \to ll\gamma$
- This process is probed in two searches in ATLAS:
  - $H \to Z\gamma \to ll\gamma$: the result is still very statistically limited
  - Low-mll $H \to ll\gamma$: **first evidence of $H \to ll\gamma$** decay @ **3.2σ**!
  - **Data consistent with SM**
- Good potential for Run3 and beyond:
  - More precise measurement of **Higgs boson properties**, including **CP**
  - Searches for **BSM couplings**

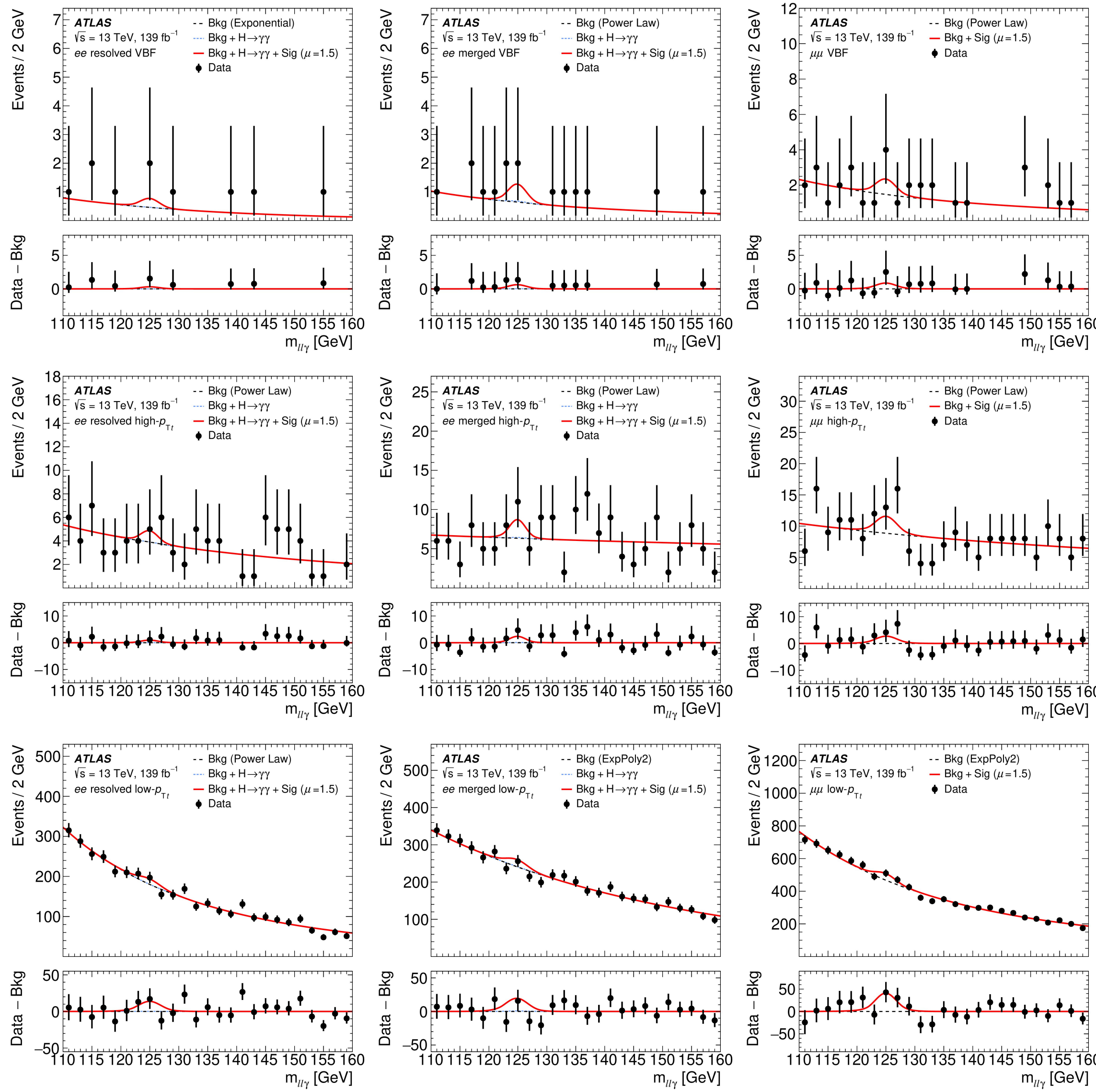
Backup.

Low-m_{ll} H→llγ search: additional results (I)

Multi-POI fits



Data (without reweighting) and post-fit S+B model

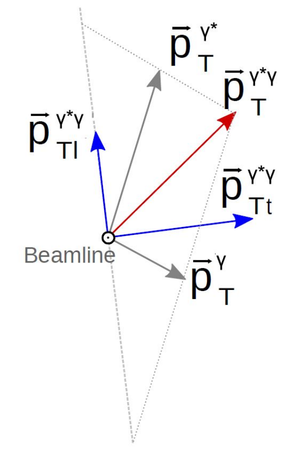


Sources of systematic uncertainties

<table>
<tr><th>Uncertainty source</th><th>μ</th><th>$\sigma \times \mathcal{B}$</th></tr>
<tr><td>Spurious Signal</td><td colspan="2">6.1</td></tr>
<tr><td>$\mathcal{B}(H \to \ell\ell\gamma)$</td><td>5.8</td><td>–</td></tr>
<tr><td>QCD scale</td><td>4.7</td><td>1.1</td></tr>
<tr><td>ℓ, γ, jets</td><td colspan="2">4.0</td></tr>
<tr><td>PDF</td><td>2.3</td><td>0.9</td></tr>
<tr><td>Luminosity</td><td colspan="2">1.7</td></tr>
<tr><td>Pile-up</td><td colspan="2">1.7</td></tr>
<tr><td>Minor prod. modes</td><td colspan="2">0.8</td></tr>
<tr><td>$H \to \gamma\gamma$ background</td><td colspan="2">0.7</td></tr>
<tr><td>Parton Shower</td><td colspan="2">0.3</td></tr>
<tr><td>Total systematic</td><td>11</td><td>7.9</td></tr>
<tr><td>Statistical</td><td colspan="2">31</td></tr>
<tr><td>Total</td><td>33</td><td>32</td></tr>
</table>

Low-m_{ll} H→llγ search: additional results (II)

Category	Events	S_{90}	B^N_{90}	$B_{H\to\gamma\gamma}$	f_{90} [%]	Z_{90}
ee resolved VBF-enriched	10	0.4	1.6	0.009	20	0.3
ee merged VBF-enriched	15	0.8	2.0	0.07	27	0.5
$\mu\mu$ VBF-enriched	33	1.3	5.9		18	0.5
ee resolved high-$p_{\mathrm{T}t}$	86	1.1	12	0.02	9	0.3
ee merged high-$p_{\mathrm{T}t}$	162	2.5	18	0.2	12	0.6
$\mu\mu$ high-$p_{\mathrm{T}t}$	210	4.0	34		11	0.7
ee resolved low-$p_{\mathrm{T}t}$	3713	22	729	0.5	2.9	0.8
ee merged low-$p_{\mathrm{T}t}$	5103	29	942	2	3.0	1.0
$\mu\mu$ low-$p_{\mathrm{T}t}$	9813	61	1750		3.4	1.4



p_T "thrust":

In the plane transverse to the beam, projection of the $\mathbf{p}_T^{\gamma^*\gamma}$ perpendicular to $\mathbf{p}_T^{\gamma^*}$ - $\mathbf{p}_T^{\gamma}$

highly correlated with $\mathbf{p}_T^{\gamma^*\gamma}$ but with better experimental resolution

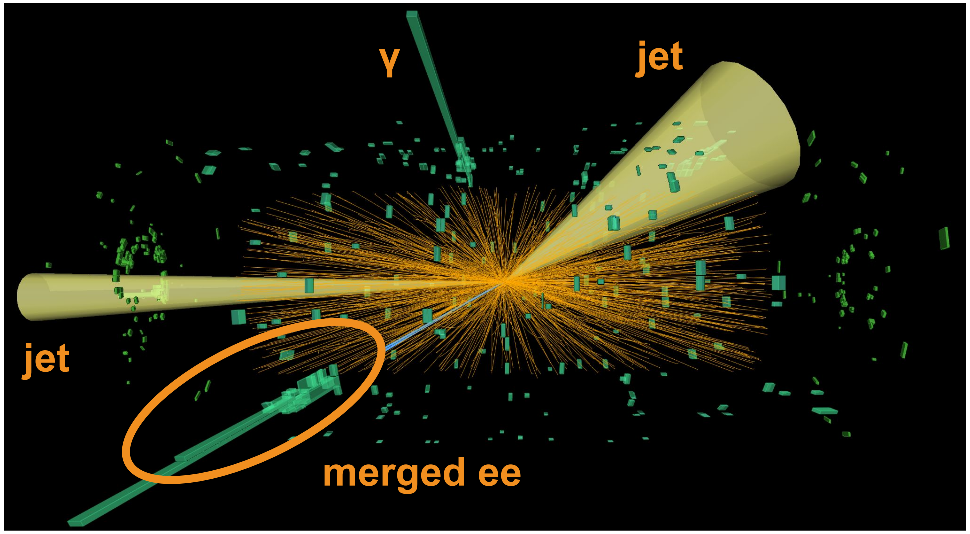
Backgrounds:

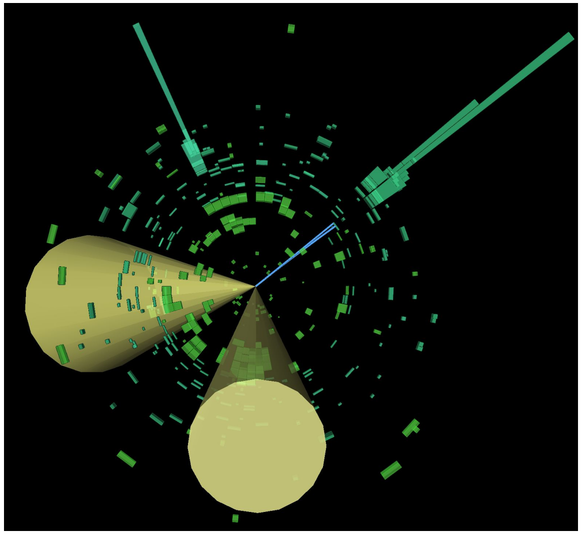
- After selection SM γ*γ dominates in all channels
- Estimated fake **γ** and leptons using using template fits (inverting ID and iso requirements)
- Fake γ consistent **10%** across channels and categories
- Fake leptons:
  - resolved ee low-p_{Tt}: **30%**
  - μμ low-p_{Tt}: **4%**
  - merged ee low-p_{Tt}: **2%**

    (other categories have large stat uncertainties)

Low-m_{ll} H→llγ search: merged electrons identification

- Candidate: electrons identified with standard ATLAS reconstruction [JINST 14 (2019) P12006] with multiple associated tracks
- Quality of candidates:
  - electrons: p_T > 20 GeV, $|\eta|<1.37$, $E_T(had)/E_T(EM) < 0.1$
  - tracks: p_T > 0.5 GeV, $|\eta|<2.5$, 7 hits in Si detectors
    - 1 hit in innermost pixel layer, to suppress conv. photons
  - track pair: oppositely charged, p_T-dependent requirement on max $\Delta\varphi$ at the IP
- TMVA-based ID using shower shapes, TRT ID, track-to-calorimeter pointing variables
  - Efficiency ~50% (combined ID + iso) measured with radiative Z events





H→Zγ→llγ search: additional results

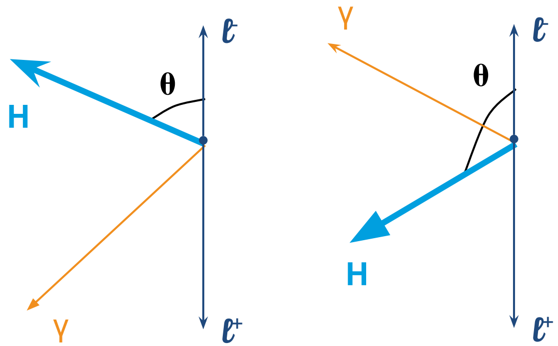
Category	Events	S_{68}	B_{68}	w_{68} [GeV]	S_{68}/B_{68} [10^{-2}]	$S_{68}/\sqrt{S_{68}+B_{68}}$
VBF-enriched	194	2.7	18.7	3.7	14.3	0.58
High relative p_T	2276	7.6	112.8	3.7	6.7	0.69
High p_{Tt} ee	5567	9.9	444.0	3.8	2.2	0.46
Low p_{Tt} ee	76 679	34.5	6654.1	4.1	0.5	0.42
High p_{Tt} $\mu\mu$	6979	12.0	610.8	3.9	2.0	0.48
Low p_{Tt} $\mu\mu$	100 876	43.5	8861.5	4.0	0.5	0.46
Inclusive	192 571	110.2	16 701.9	4.0	0.7	0.85

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_{Tt} ee	$4.7^{+3.0}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.7 (0.4)
Low p_{Tt} ee	$3.9^{+2.8}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.5 (0.4)
High p_{Tt} $\mu\mu$	$2.9^{+3.0}_{-2.8}$ $(1.0^{+2.8}_{-2.7})$	1.0 (0.4)
Low p_{Tt} $\mu\mu$	$0.8^{+2.6}_{-2.6}$ $(1.0^{+2.6}_{-2.5})$	0.3 (0.4)
Combined	$2.0^{+1.0}_{-0.9}$ $(1.0^{+0.9}_{-0.9})$	2.2 (1.2)

Measuring CP with H→llγ

- Can be done using forward-backward asymmetry of the decay [J. High Energy Phys. 61 (2013 2013)]:

$$\mathcal{A}_{\mathrm{FB}} = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \int_0^1 \frac{d\Gamma}{dq^2 d\cos\theta} d\cos\theta dq^2 - \int_{q^2_{\min}}^{q^2_{\max}} \int_{-1}^0 \frac{d\Gamma}{dq^2 d\cos\theta} d\cos\theta dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \int_0^1 \frac{d\Gamma}{dq^2 d\cos\theta} d\cos\theta dq^2 + \int_{q^2_{\min}}^{q^2_{\max}} \int_{-1}^0 \frac{d\Gamma}{dq^2 d\cos\theta} d\cos\theta dq^2}$$



dilepton rest frame: “forward” and “backward” decays