Measurement of the Higgs boson decay to a low-mass dilepton system and a photon in *pp* collisions at $\sqrt{s}$ =13 and 13.6 TeV with the ATLAS detector

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Introduction

- **Goal of this talk:**

Presentation of a **newly published** results from the ATLAS Collaboration, **probing the Higgs sector** in one of its **rarest decay channel** using new Run-3 data (√s=13.6TeV), in addition to Run-2 (√s=13TeV):

"Higgs boson decaying into a pair of photons $H \rightarrow \gamma^{*}\gamma$ ($\rightarrow \ell\ell\gamma$),
and where γ^{*} decays into a pair of electrons and muons"

Run-2 corresponds to data taking between 2015-2018
Run-3 corresponds to data taking between 2022-2026
Here: Partial Run-3, between 2022-2024

- **Publicly available material:** arxiv:2608.03369 [August 4, 2026] (submitted to JHEP)

Analysis motivation (1/4)

- **Perfect opportunity to test the Standard Model (SM) and the Higgs sector predictions through rare decay channels.**
  - Reminder: The Higgs boson naturally couples to particles through the electroweak symmetry-breaking interactions that generate their **masses**.
  - But as the photon is **massless**, the only decays from the Higgs are predicted through loops of massive particles (at tree level): **rare** decay channel.

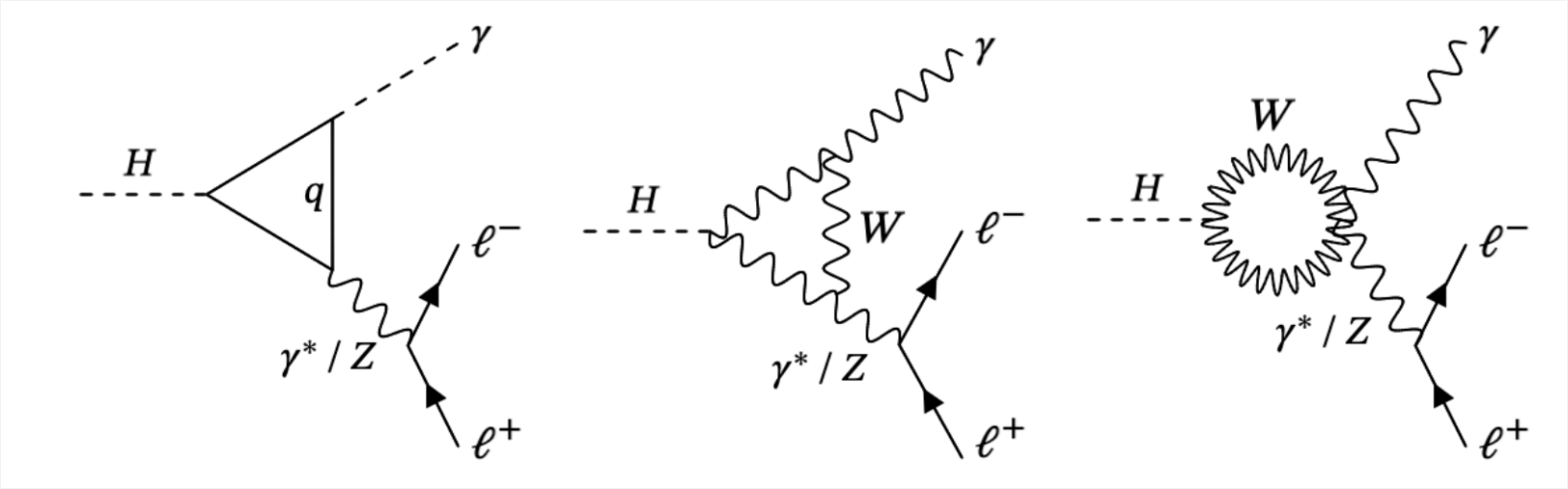


Figure 1: Loop-induced Higgs decay into a pair of photons (on of which is virtual)

Analysis motivation (2/4)

- **Higgs Boson Branching Ratios (BRs):**

  Higgs decay measurements are reaching impressive precision levels. The **key next steps** are therefore for rare decays:

Branching Ratio of a Higgs boson decaying (loop induced) into a pair of photons is already extremely rare.

Here: either virtual photon γ^* or Z^*. Even rarer !

Yet $H \to \gamma^*\gamma$ physically interesting for :

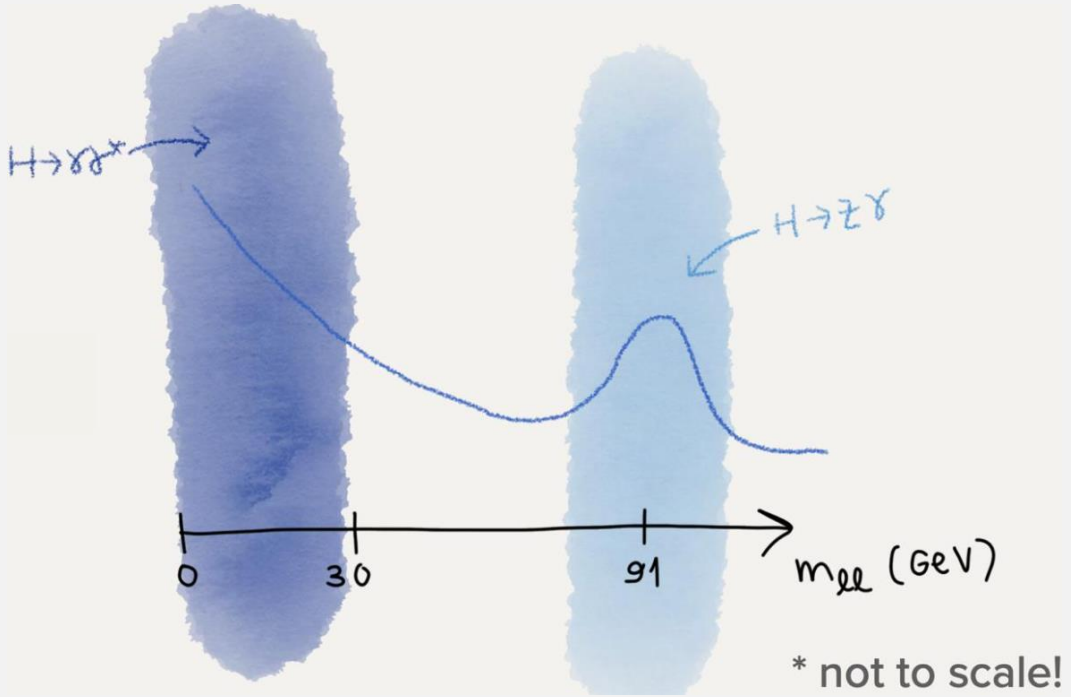
- Testing the loop-induced Higgs-photon interaction using the $H \to \gamma^*\gamma \to \ell\ell\gamma$ and $H \to \gamma\gamma$ decay-rate ratio.
- CP properties probes via forward-backward asymmetries of the decay products.

Higgs Decay channel	BR (%)
$H \to b\bar{b}$	**58.2**
$H \to W^+W^-$	**21.4**
$H \to \tau^+\tau^-$	**6.27**
$H \to ZZ$	**2.62**
$H \to \gamma\gamma$	**0.227**
$H \to Z\gamma$	**0.153**
$H \to \mu^+\mu^-$	**0.0218**
…	…
$H \to e^+e^-\gamma$	**0.00720**
$H \to \mu^+\mu^-\gamma$	**0.00342**

Analysis motivation (3/4)

- **Perfect opportunity to test the Standard Model (SM) and the Higgs sector predictions through rare decay channels.**

- This analysis targets $H \rightarrow \gamma^{*}\gamma$ ($\rightarrow \ell\ell\gamma$), with $m_{\ell\ell} < \mathbf{30\ GeV}$:
  - low $m_{\ell\ell}$ region dominated by the decay through γ^{*},
  - orthogonal and complementary to $\boldsymbol{H \rightarrow Z\gamma}$ searches (arxiv:2507.12598).



credit: Martina Ojeda

Run-3 signal and backgrounds Monte Carlo (MC) samples

- **Run-3 MC Signal:**
  - Mass of the Higgs generated at m_H=125 GeV, with corresponding width of Γ_H =4.07 MeV.
  - New addition since Run-2: The $ggZH$ and ttH production modes were added.
  - 6 main production modes:

Production mode	Cross section [pb]	Scale [%]	PDF + α_S [%]
ggH	52.17	$^{+4.6}_{-6.7}$	3.2
VBF	4.075	$^{+0.5}_{-0.3}$	2.1
WH	1.453	$^{+0.4}_{-0.7}$	1.8
ZH	0.9422	$^{+3.8}_{-3.2}$	1.6
ttH	0.5688	$^{+6.0}_{-9.3}$	3.5
ggZH	0.1359	$^{+3.9}_{-3.0}$	1.6

Table not from the paper

bbH is included in the ggH yield as a 1% cross-section increase.

- **Run-3 MC Backgrounds:**
  - Dominant background comes from **non-resonnant low-mass $ll\gamma$** production.
  - Minor backgrounds: The $H\to\gamma\gamma$ ggF and VBF samples are used to estimate the resonant background.

Event selection

- **For $H \to \gamma\gamma^*$, we look for events with 2 leptons and 1 photon in the final state ($\ell\ell\gamma$):**
  - $m_{\ell\ell} < 30$ GeV.
  - $m_{\ell\ell\gamma} \in [110; 160]$ GeV to target the Higgs boson mass window.

- **To maximize the sensitivity to the signal:**

❖ **3 topology categories are defined: VBF, high- p_T^{thrust} and low-p_T^{thrust}**

(where p_T^{thrust} is the component of the Higgs-candidate transverse momentum, perpendicular to the thrust axis defined by its decay products)

- VBF: 2 jets with $p_T > 30$ GeV+ $m_{jj} > 500$ GeV+ $\Delta\eta_{jj} > |2.7|$ + additional topology selections on di-jet vs $\ell\ell\gamma$ system
- High-p_T^{thrust}: fails VBF selection + $p_T^{thrust}(\ell\ell\gamma) > 100$ GeV
- Low-p_T^{thrust}: fails VBF selection + fails high-p_T^{thrust} selection

credit: (updated from) Martina Olega

❖ **With three channels for each of them : $\mu\mu\gamma$, resolved eeγ and merged eeγ**

❖ **In total: 3x3 = 9 categories:**

Category		
$\mu\mu$ low – p_{Tt}	$\mu\mu$ VBF	$\mu\mu$ high – p_{Tt}
ee resolved low – p_{Tt}	ee resolved VBF	ee resolved high – p_{Tt}
ee merged low – p_{Tt}	ee merged VBF	ee merged high – p_{Tt}

Table not from the paper

Background modelling

- **With a special focus on the non-resonant background:**

- Main contribution comes from **non-resonant low-mass $\ell\ell\gamma$**:
  - Reweighted final yield* is used to select the analytic background function in each category through the spurious-signal test (e.g. power law, exponential, exponential of polynomial).

- *Minor contributions from misidentified photons and leptons "**Fakes**":
  - "**Fakes**" stacked with **low-mass prompt $\ell\ell\gamma$** MC histogram.
  - Then contributions are smoothly included as a reweight of the **low-mass prompt $\ell\ell\gamma$** template.

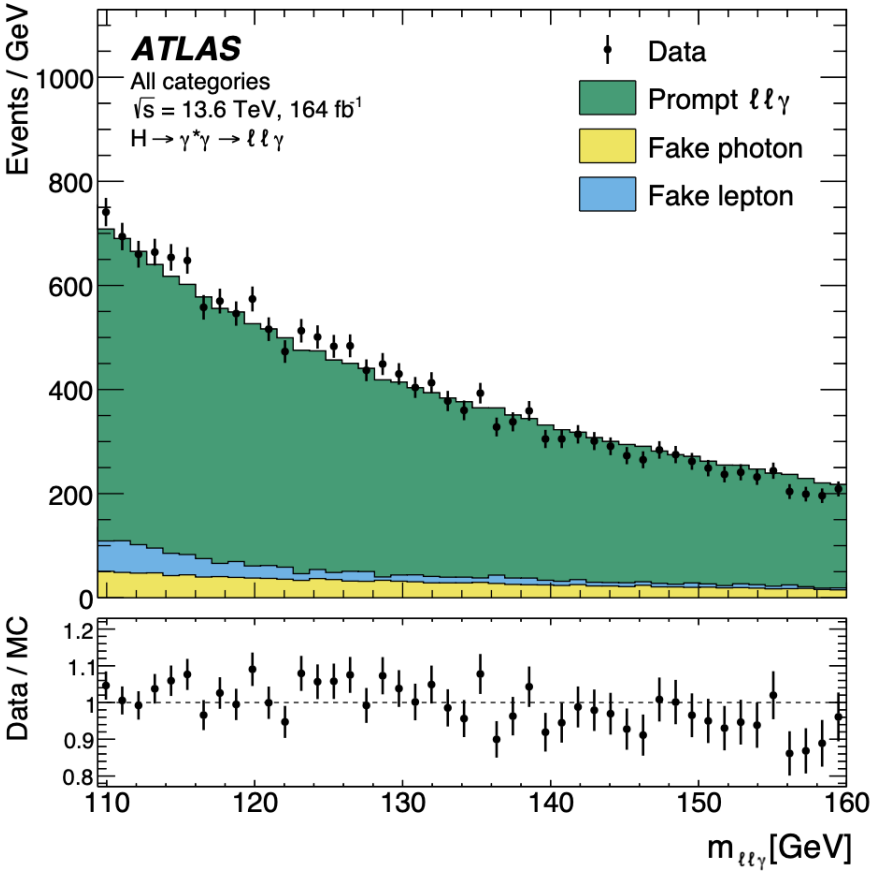


Figure 2: The $m_{\ell\ell\gamma}$ distribution for events satisfying the $H \to \gamma^*\gamma \to \ell\ell\gamma$ selection in data for all categories. The data are shown as the black points with statistical uncertainties. The contribution from the non-resonant $\ell\ell\gamma$ process (green), the extra contributions from the fake processes (blue and yellow) are shown for illustration. The total background estimate is normalised to the number of data events in the sideband. The bottom panel shows the ratio of the data with respect to the sum of background components.

Background modelling (a little more detail 1/2)

- **How to obtain the "Fake" yields, and the Figure 2:**

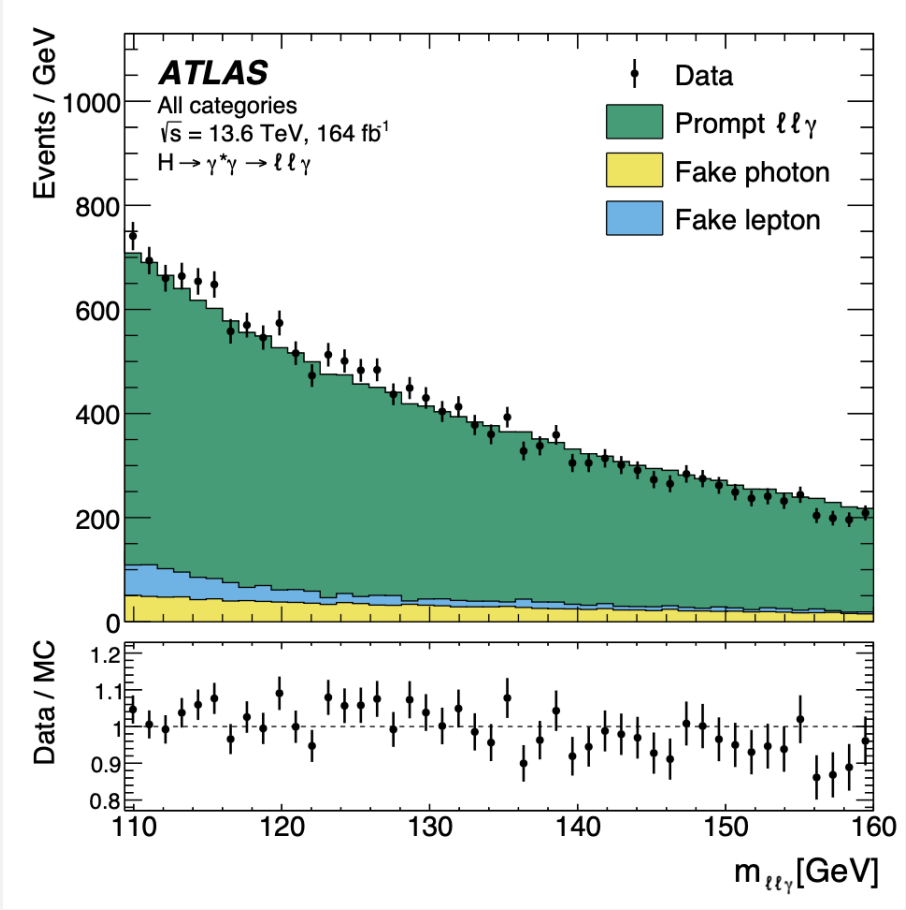
- **Data points**: are obtained in the Signal Region (SR) for data.
  It means we are selecting events passing all the analysis cutflows.

- **Prompt $ll\gamma$ MC**: are also obtained for events passing the SR.

- Fake template:
  1. Infer number of **Data** passing Control Region (CR): $data_{CR}$
  2. Infer number of Prompt $ll\gamma$ MC passing CR: $ll\gamma_{CR}$
  3. Compute the **fake yield** using the following subtraction scheme:

$$data_{CR} - \mathbf{k} \times ll\gamma_{CR}$$

(with an extra k-factor, see next slide)



Background modelling (a little more detail 2/2)

- **How to obtain the "Fake" templates, and the Figure 2:**

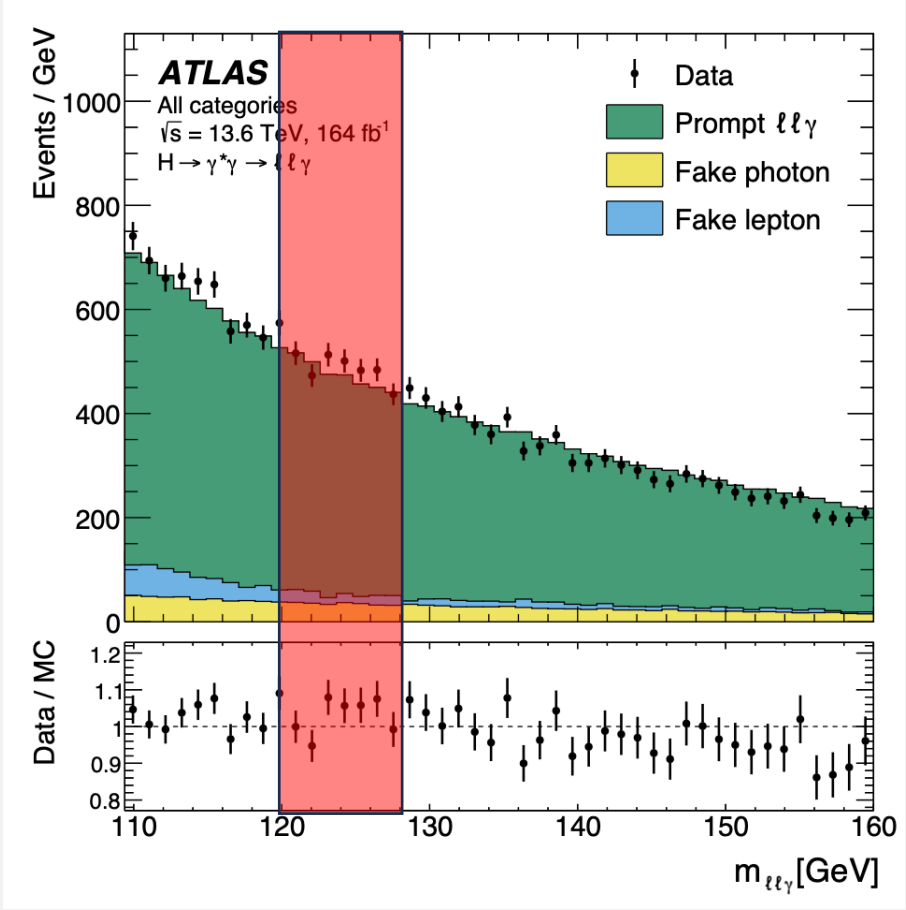
- **But** the previous subtraction scheme ($data_{CR} - \mathbf{k} \times ll\gamma_{CR}$) do not provide with the final yield yet as event counts are enriched in fakes. It needs to be normalized using **fake fractions**.

- Fake fractions F_P and F_L (and the k-factor) are extracted from data sidebands (SB) in the control regions (determined separately for each of the 9 categories).

- To obtain Figure 2:
  MC prompt $ll\gamma$ and the **Fakes** are added together so they match the yield of the **data** in the SB:

$$\mathbf{Data}_{\mathrm{YIELD,SB}} = X \cdot \mathbf{Prompt}\ ll_{\mathrm{YIELD,SB}} + F_P \cdot \mathbf{Fake\ photon}_{\mathrm{YIELD,SB}} + F_L \cdot \mathbf{Fake\ lepton}_{\mathrm{YIELD,SB}}$$

(The normalization constant X is defined so that the equality above holds)



Systematic Uncertainties

- **Systematic uncertainties in the signal modelling arise from both theory and experimental sources:**

• Experimental

Signal Shape	Electron, photon, and muon energy scale and resolution
Signal Yield	all uncertainties on electron, photon, muon, and jets (simplified schemes), PRW, luminosity (1.9%), trigger.

• Background modelling

Non-resonant	Spurious signal uncertainty from background modeling studies
Resonant	$H \to \gamma\gamma$: 9.4% cross-section uncertainty. 50% fake-rate uncertainty

• Theoretical

Follow the scheme used in partial Run-3 $\boldsymbol{H \to Z\gamma}$.

Include: Parton Density Function,
Strong coupling constant α_S,
QCD scale,
Parton Shower,
Branching Ratio,
m_H (~0.19%)

credit: presentation style and content by Danning Liu

Total fit model and first Run-3 result

- **Unbinned extended likelihood :**
- Performed after spurious-signal test, by constructing an unbinned extended likelihood function as the product of the parameterized signal-plus-background probability density functions across all categories.

Category	$[\mu_{CB} - \sigma_{90}, \mu_{CB} + \sigma_{90}]$	S_{90}	B_{90}	$H \to \gamma\gamma_{90}$	$f_{90}[\%]$	Z_{90}
$\mu\mu$ low-p_{Tt}	[121.3, 128.7]	57.0	1778	–	3.1	1.4
ee resolved low-p_{Tt}	[120.9, 129.4]	22.2	1034	0.79	2.1	0.7
ee merged low-p_{Tt}	[121.0, 128.8]	36.7	1459	6.80	2.4	1.0
$\mu\mu$ VBF	[121.0, 129.0]	1.58	6.8	–	19	0.6
ee resolved VBF	[121.6, 128.7]	0.53	3.6	0.01	13	0.3
ee merged VBF	[121.7, 128.2]	1.19	3.3	0.21	25	0.6
$\mu\mu$ high-p_{Tt}	[121.1, 129.0]	5.7	41.4	–	12	0.9
ee resolved high-p_{Tt}	[121.8, 128.2]	1.65	16.7	0.02	9.0	0.4
ee merged high-p_{Tt}	[122.1, 128.1]	4.6	28.8	0.54	13	0.8

Table 2: Expected signal ($S90$) and background ($B90$) events in the smallest window containing 90% of the signal events in each category. Where μ is the signal strength (i.e. the ratio of the observed signal yield to the one expected in the Standard Model).

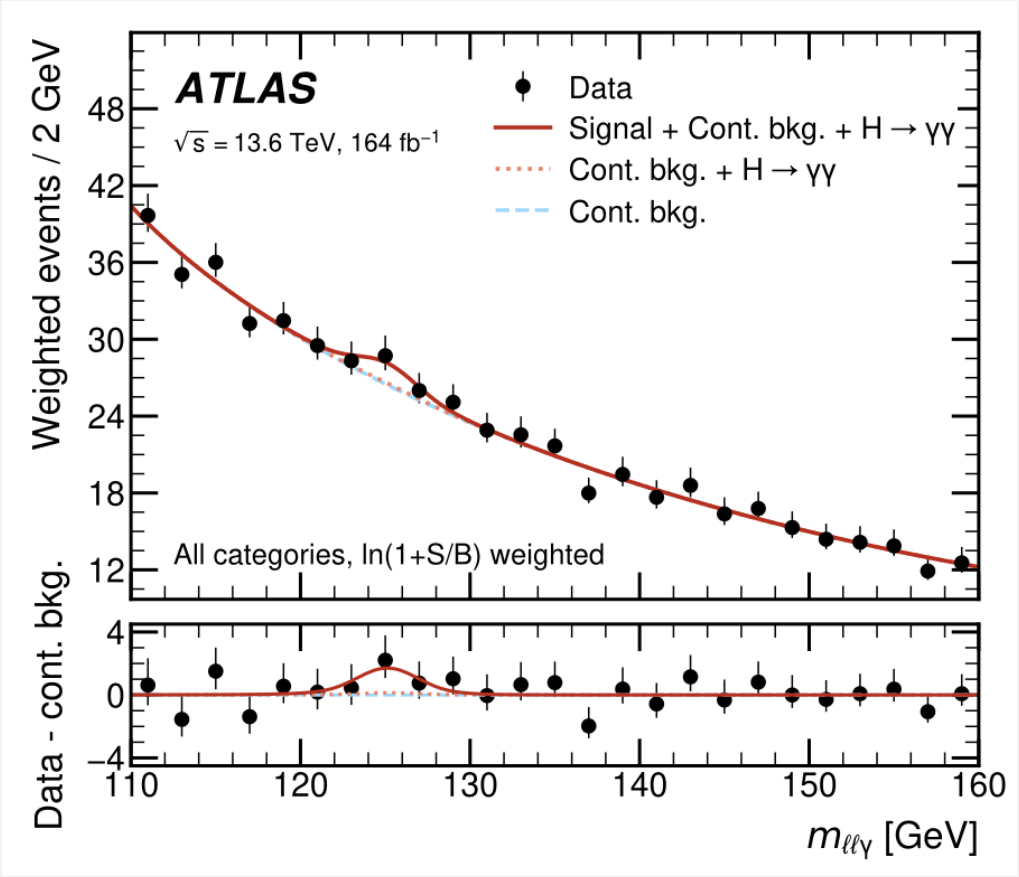


Figure 5

Results of Run-3 Analysis

- **The expected result is:**

- Signal strength $\mu = 1.00^{+0.47}_{-0.41} = 1.00^{+0.41}_{-0.40}(\text{stat.})^{+0.23}_{-0.11}(\text{syst.})$
- Corresponds to a significance over the background-only hypothesis of **2.5σ** .

- **The observed result is:**

- Signal strength $\mu = 0.64^{+0.44}_{-0.39} = 0.64^{+0.40}_{-0.39}(\text{stat.})^{+0.18}_{-0.08}(\text{syst.})$
- Corresponds to a significance over the background-only hypothesis of **1.7σ** .

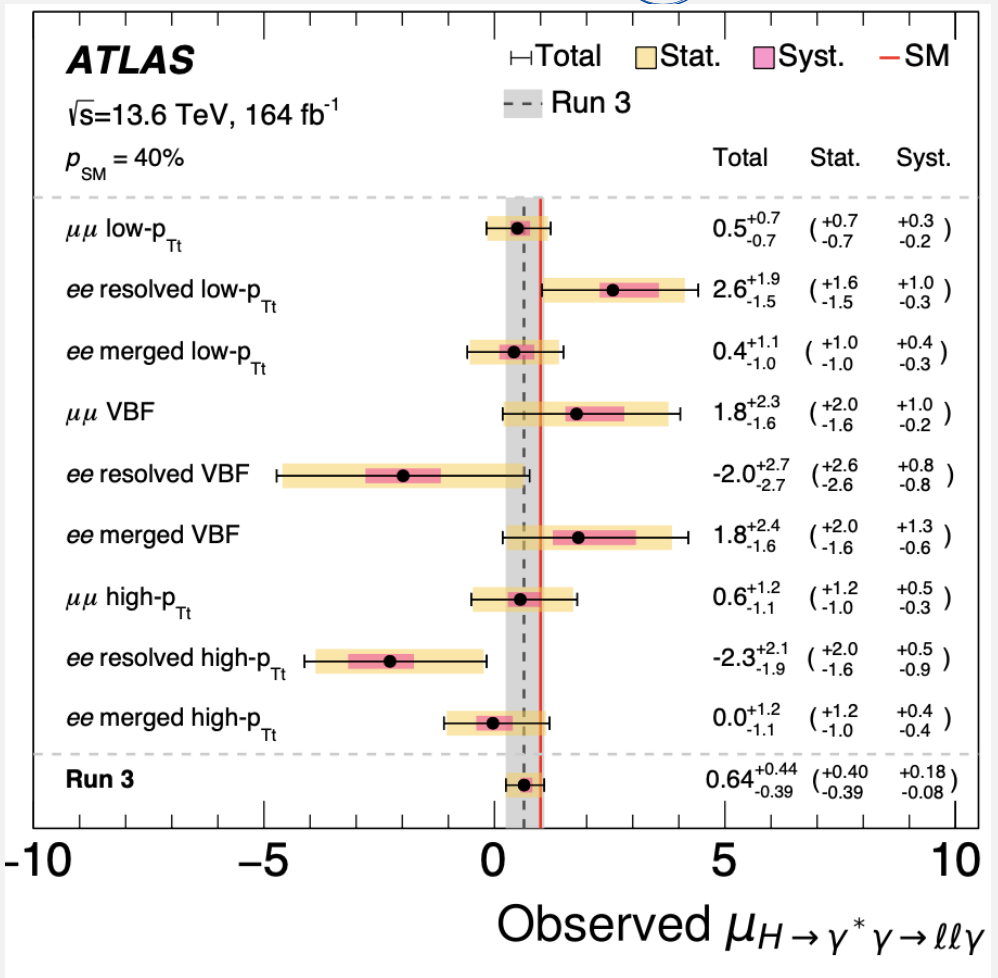


Figure 3: Observed best-fit values of the signal strengths and corresponding uncertainties in each analysis category, in a fit where the signal strength in each category is allowed to float independently, compared with the result of the Run-3 global fit (last line, black vertical line) including its total uncertainty (grey band) and with the SM (red vertical line). The error bars correspond to the total uncertainties and the coloured bands indicate the statistical and systematic uncertainties.

Combination of Run-2 and Run-3 Results (1/2)

Another important result of this analysis is the combination with Run-2 data:

- **(Previously obtained) Run-2 results:**

- Expected: $\mu = 1.00^{+0.51}_{-0.48} = 1.00^{+0.48}_{-0.47}(\text{stat.})^{+0.17}_{-0.11}(\text{syst.})$
- Observed: $\mu = 1.47^{+050}_{-0.47} = 1.47^{+0.46}_{-0.45}(\text{stat.})^{+0.19}_{-0.13}(\text{syst.})$
- Corresponds to a significance of **3.2 (2.1)** σ observed (expected).

- **Combination Run-2 and Run-3 results:**

- Expected: $\mu = 1.00^{+0.35}_{-0.32} = 1.00^{+0.31}_{-0.31}(\text{stat.})^{+0.16}_{-0.08}(\text{syst.})$
- Observed: $\mu = 1.03^{+0.35}_{-0.32} = 1.03^{+0.31}_{-0.30}(\text{stat.})^{+0.16}_{-0.12}(\text{syst.})$
- Corresponds to a significance of **3.4 (3.3)** σ observed (expected).

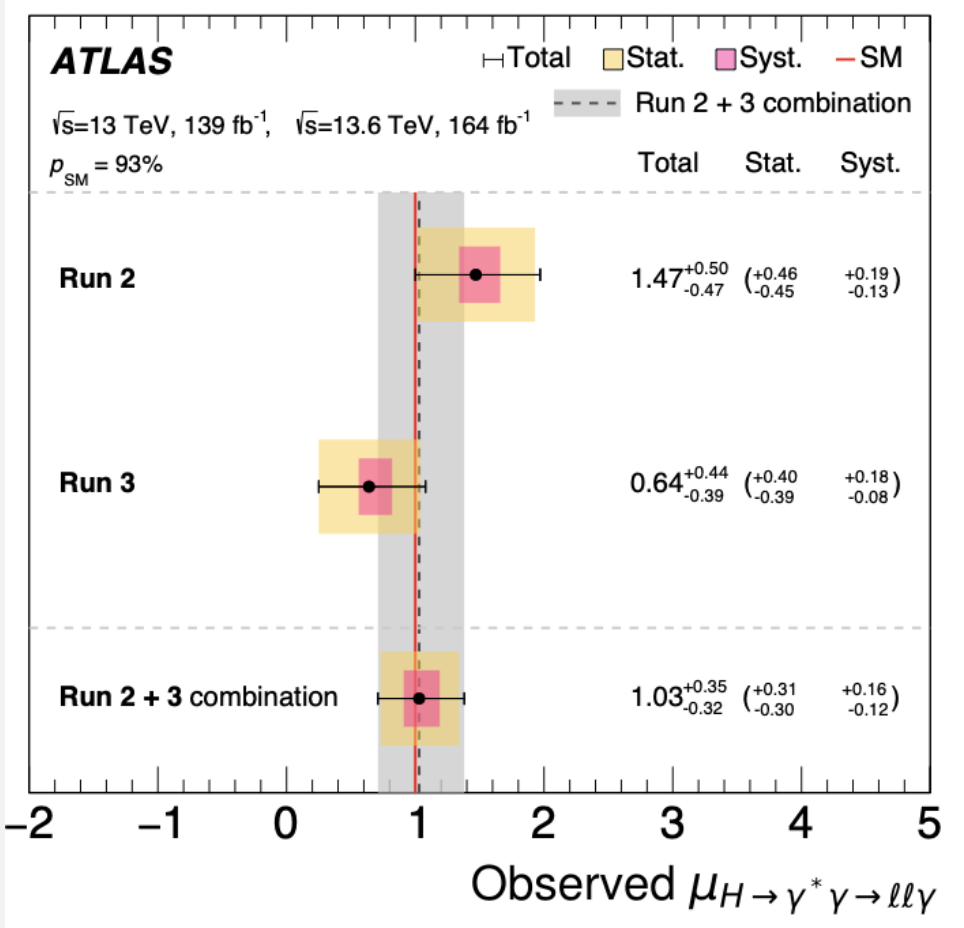


Figure 6

Combination of Run-2 and Run-3 Results (2/2)

- **Profile likelihood scan of the signal strength for the observed result:**

- Clear impact of the combination (in red) in the signal strength best-fit extraction.

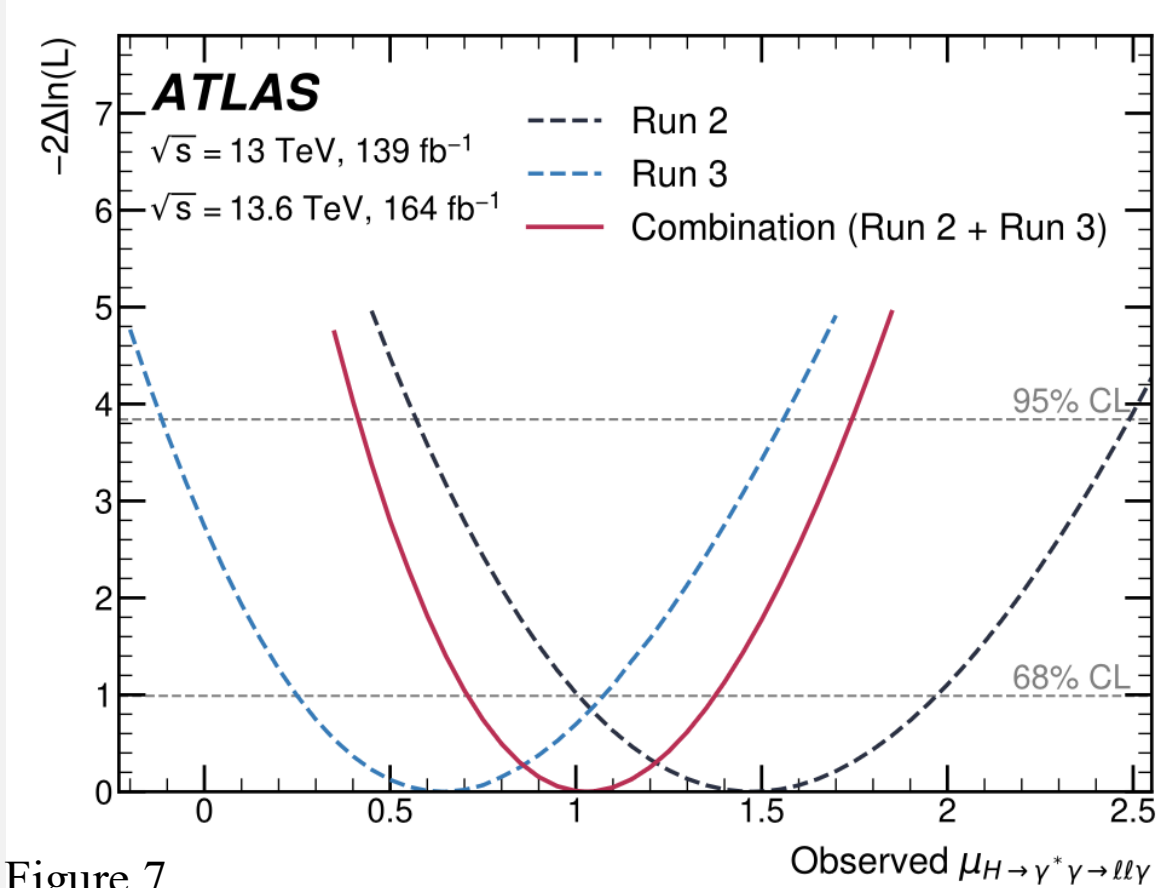


Figure 7

Conclusion

- **Presentation of newly published result from the ATLAS Collaboration:**

  In **probing the Higgs sector** in one of its **rarest (loop induced) decay channel** : $H \rightarrow \gamma^{*}\gamma$ ($\rightarrow \ell\ell\gamma$), using both Run-2 ($\sqrt{s}$=13TeV) and Run-3 ($\sqrt{s}$=13.6TeV) data.

  arxiv:2608.03369 [August 4, 2026] (submitted to JHEP)

- **(Partial) Run-3 results:**

  Signal strength measured to be: $\mu = 0.64^{+0.44}_{-0.39}$, corresponding to a significance value of 1.7σ .

- **Combination of Run-2 and (Partial) Run-3 results:**

  Signal strength measured to be: $\mu = 1.03^{+0.35}_{-0.32}$, corresponding to a significance value of 3.4σ .
  Resulting in improving both the precision and sensitivity of the $H \rightarrow \gamma^{*}\gamma$ measurement.

Outlook

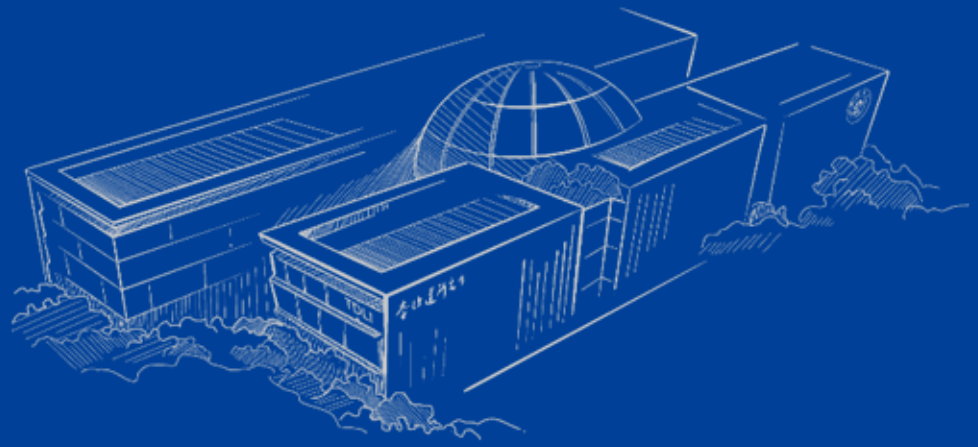
- **Possible next directions to explore:**

  - The next logical step after reaching evidence at 3σ would be to aim for **observation** (**beyond 5σ**).

  - Using the full Run-3 dataset: We currently used 164 fb^{-1} out of the ~ 330 fb^{-1} collected from 2022-2026. Combination with Run-2 could even help us reach around ~ 470 fb^{-1} of data. The analysis being very statistically limited, **increasing the integrated luminosity can lead to further improvements**.

  - Other interesting directions:
    - Improving the identification algorithm of boosted e^+e^- pairs.
    - Conducting **CP-sensitive observable studies**, thanks to the **the extra angular degrees of freedom provided by the decay of the virtual photon** (therefore not possible with $H \longrightarrow \gamma\gamma$).

谢 谢！



Appendix: Object reconstruction and event selection

Object selection

Same definitions as Run2: see HggStarEventSelection.md

SELECTION STAGE	MUON	RESOLVED ELECTRON	MERGED ELECTRON	PHOTON	JET
PRESELECTION	pT > 5 GeV |η| < 2.5	pT > 4.5 GeV |η| < 2.47	pT > 4.5 GeV |η| < 2.37	pT > 20 GeV |η| < 2.37 exclude 1.37–1.52 ID: Loose	anti-k_t, R = 0.4 (Pflow) pT > 20 GeV |η| < 4.4
OVERLAP REMOVAL	ΔR(μ, γ) > 0.4	ΔR(e, γ) > 0.4, ΔR(e, j) > 0.2		—	ΔR(j, γ) > 0.4 ΔR(j, e) > 0.2 ΔR(j, μ) > 0.4
FINAL SELECTION	pT lead > 15 GeV |z_0 sinθ| < 0.5 mm |d_0|/σd_0 < 3 ID: Medium Iso: CloseByCorrected Tight	pT lead > 18 GeV |z_0 sinθ| < 0.5 mm |d_0|/σd_0 < 5 ID: Medium Iso: CloseByCorrected Loose	pT > 20 GeV |z_0 sinθ| < 0.5 mm |d_0|/σd_0 < 5 ID: Custom Iso: Tight	ID: Tight Iso: Loose	—

credit: slide taken from Danning Liu's (PAM internal presentation)

Appendix: Signal modeling

Signal modeling

- $H \to \gamma^*\gamma \to \ell\ell\gamma$ signal is modelled by a double-side Crystal Ball (DSCB) function in each category × channels (9 in total)
  - Combining all production modes together with Standard Model cross-section
- Signal samples are generated at m_H = 125 GeV
  - A shift of 0.09 GeV is applied to the position of the signal peak to match the measured Higgs boson mass (m_H = 125.09 GeV)
- Good fit quality observed for all categories

credit: slide taken from Danning Liu's (PAM internal presentation)