Search for H$\to aa \to \gamma\gamma\gamma\gamma$ with the ATLAS detector

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Analysis [ATLAS-CONF-2023-040]

Axion Like Particles (ALPs)

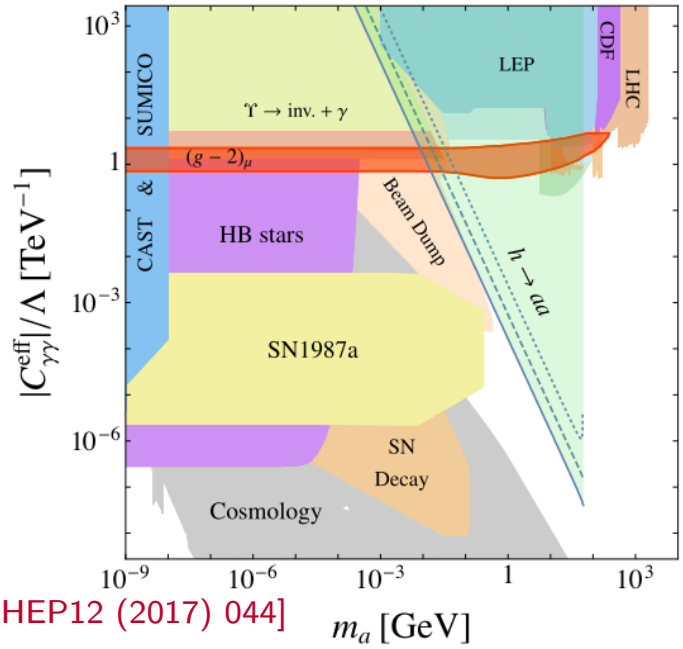
- Pseudo-scalar particle
- Could solve long standing problems

Higgs boson properties:

- $\mathcal{B}(H \to \text{invisible}) < 10.7\%$
- $\mathcal{B}(H \to \text{undetected}) < 12\%$

[physletb.2023.137963], [Nature 607, 52–59 (2022)], [Nature 607, 60–68 (2022)]

- Process: $H \to aa \to \gamma\gamma\gamma\gamma$

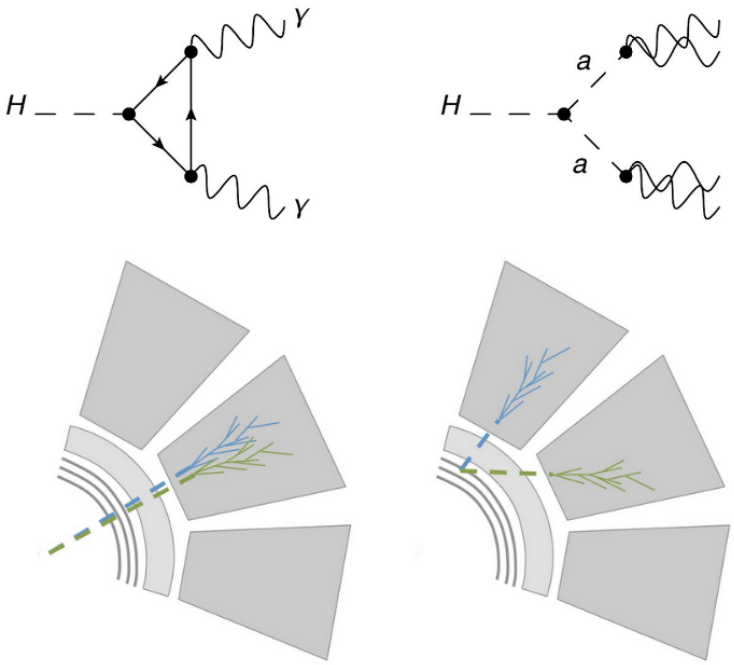


[JHEP12 (2017) 044]

Analysis overview

- Wide ALP parameter space
  - $0.1\,\text{GeV} \leq m_a \leq 62\,\text{GeV}$
  - $10^{-5} \leq C_{a\gamma\gamma} \leq 1$
- Fits for different mass/coupling
- Exclude mass/coupling combinations

Analysis challenges



- Final state signature largely dependent on m_a and $C_{a\gamma\gamma}$
  different approaches/categories needed
- Low m_a $\rightarrow$ collimated photon-pairs reconstructed as one
- Same final state as $H \rightarrow \gamma\gamma$
  $\Rightarrow$ Distinguish collimated photon-pairs from resolved photons
- Small $C_{a\gamma\gamma} \rightarrow$ Displaced vertices

Analysis - step by step

- Preselection: events with 2,3,4 photons
  kinematic cuts on p_T, η and isolation
- Fake photon reduction:
  Regular pID: low efficiency for merged photons
- Different kinds of photons: Single or Merged
- Data driven background estimation

- Select event category (4S, 3S, 2M, 1M1S, 2S - additionally $4S_P$)

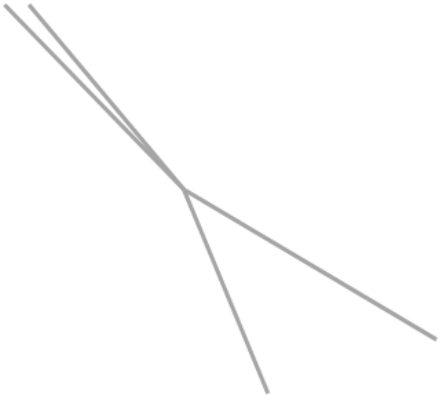
Analysis - step by step

Categories

2 Single photon candidates

1 Single, 1 Merged photon candidates

2 Merged photon candidates



2 Single, 1 Merged photon candidates

3 Single photon candidates

4 Single photon candidates

Analysis - step by step

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- Profiled likelihood fit
- Calculate exclusion limits on m_a and $C_{a\gamma\gamma}$

Analysis - step by step

- Preselection: events with 2,3,4 photons
  kinematic cuts on p_T, η and isolation
- Fake photon reduction:
  Regular pID: low efficiency for merged photons $\Rightarrow$ ANN-1
- Different kinds of photons: Single or Merged
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Analysis - step by step

- Preselection: events with 2,3,4 photons
  kinematic cuts on p_T, η and isolation
- Fake photon reduction:
  Regular pID: low efficiency for merged photons $\Rightarrow$ ANN-1
- Different kinds of photons: Single or Merged $\Rightarrow$ ANN-2
- Data driven background estimation

- Select event category (4S, 3S, 2M, 1M1S, 2S - additionally $4S_P$)
- Profiled likelihood fit
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Analysis - step by step

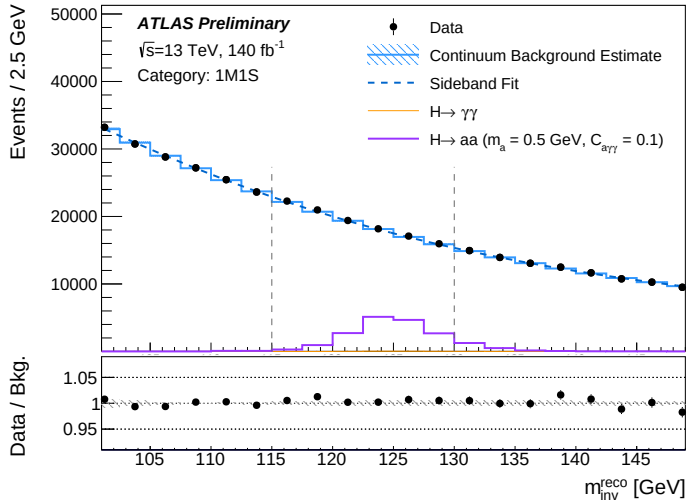
- Preselection: events with 2,3,4 photons
  kinematic cuts on p_T, η and isolation
- Fake photon reduction:
  Regular pID: low efficiency for merged photons $\Rightarrow$ ANN-1
- Different kinds of photons: Single or Merged $\Rightarrow$ ANN-2
- Data driven background estimation
  $\Rightarrow$ Use ANNs to reconstruct Axion (3γ and 4γ)
- Select event category (4S, 3S, 2M, 1M1S, 2S - additionally $4S_P$)
- Profiled likelihood fit
- Calculate exclusion limits on m_a and $C_{a\gamma\gamma}$

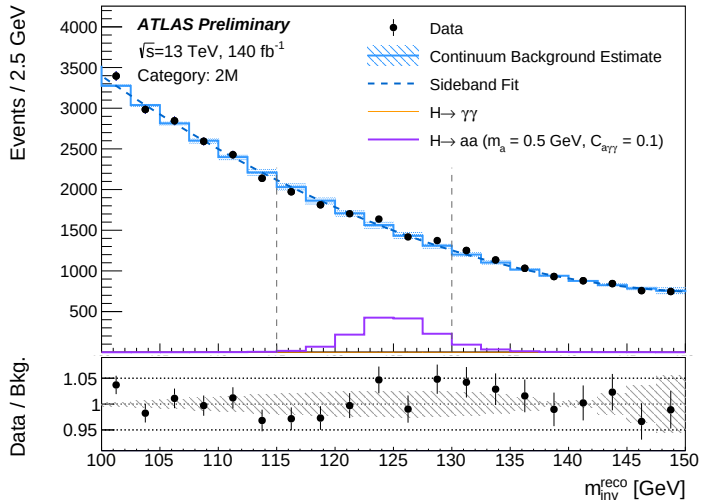
Background estimation

- **Data driven sideband** fitting method
- Blind m_{inv}^{reco} distribution around $m_h = 125\,\text{GeV}$
- Alternative fitting function for spurious signal uncertainty
- Reduced fitting range used to assess additional systematic uncertainty
- Methodology validated with data and MC validation regions

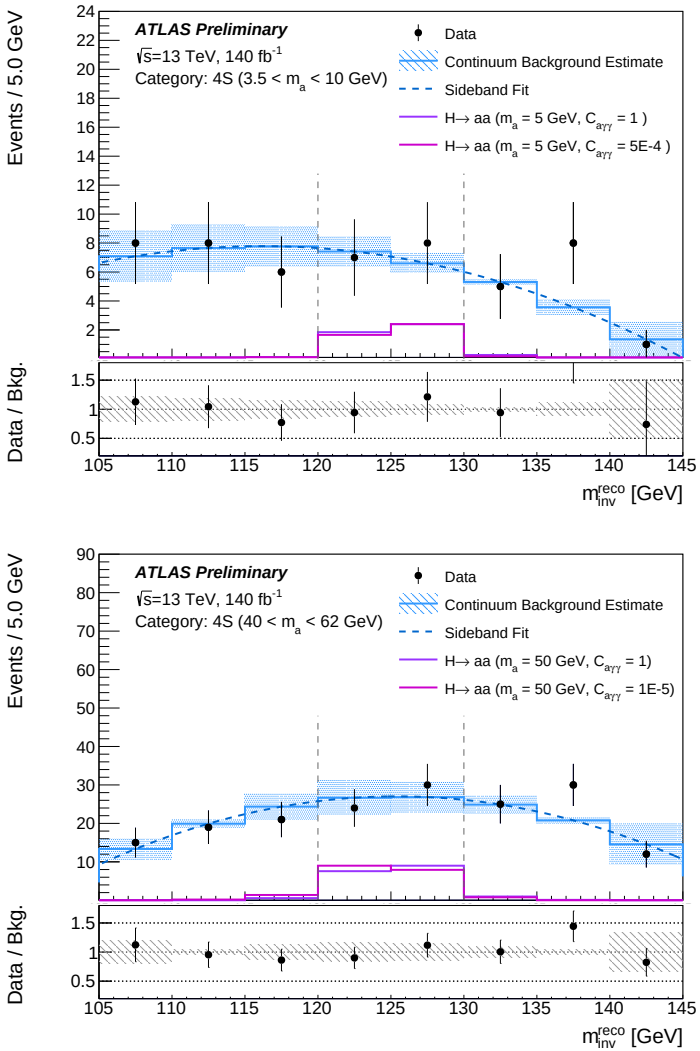
Background estimation
2M, 1M1S and 2S categories

- Sideband fit region $100 - 150\,\text{GeV}$
- Landau fitting function (2S, 1M1S)
- 2nd order polynomial fitting function (2M)
- $H \to \gamma\gamma$ background from MC simulation





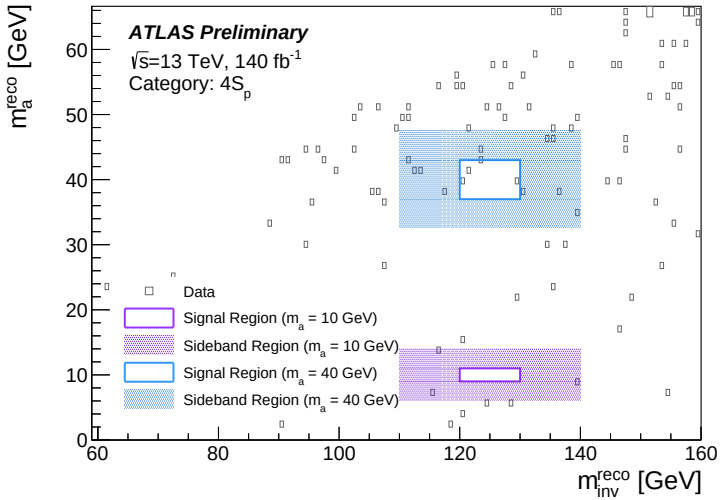
Background estimation
3S and 4S category



- Sideband fit region
  $80(105) - 150(145)$ GeV 3S (4S)
- 3rd (3S) and 2nd (4S) order polynomials
- Additionally 4 bins in m_a^{reco}
  $(0-10, 10-25, 25-40, 40-62\,\text{GeV})$

Background estimation
Prompt photon analysis ($4S_P$)

- Stricter requirements on PID to reject fake photons
- Tight selection around the m_a^{reco} parameter
- Background yield in (shaded) sideband region scaled by the ratio of signal and sideband areas
- Systematic uncertainty evaluated using an enlarged sideband region
- Methodology validated with multi-photon MC samples



Sytematic uncertainties

- Commonly used experimental uncertainties
  - Integrated luminosity: 0.8%
  - Imperfect modeling of pileup: below 1%
  - Trigger efficiency: from 2 to 3%
  - Standard photon ID, photon isolation, photon scale and resolution below 3% (promptly decaying ALPs)
- Uncertainty on NN output obtained from $Z \rightarrow ee$ events: up to 15%
- Background uncertainties:
  - Spurious Signal: $n_{evts}^{bestfit}$ with alternative sideband fit
  - Shape uncertainty: reduce range of sideband fit
- Theoretical uncertainties: around 6%

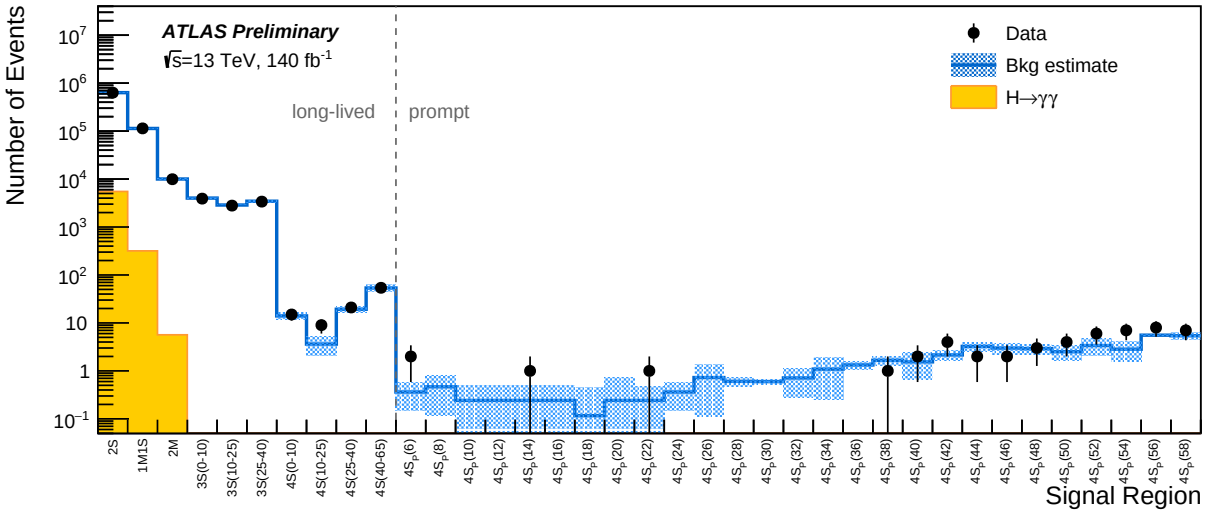
Systematic uncertainties

Custom uncertainties for long-lived ALPs

Additional customized uncertainties for photons with displaced vertices

- Estimated by studying the decay of long-lived hadrons
- Rescaled shower shape variables for displaced vertices
- Re-evaluated photon ID and NN classifiers
- Uncertainty on ANN-1 (real vs. fake photon classification) is 3%
- ANN-2 and photon ID: range from 4 to 23% depending on the displacement

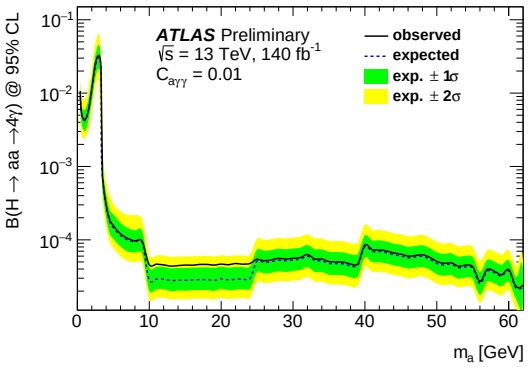
Statistical analysis



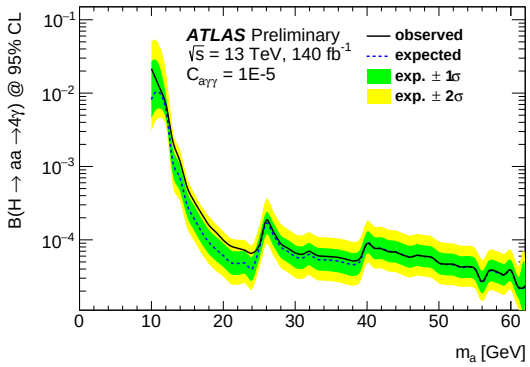
- Long-lived ALP search:
  - Maximum-likelihood fit of the binned m_{inv}^{reco} distribution in the 2 most sensitive categories
  - 2M and 1M1S for $m_a \leq 3.5\,\text{GeV}$
  - 4S and 3S for $m_a > 3.5\,\text{GeV}$
- Promptly decaying ALP search:
  - Maximum-likelihood fit with one bin
- Upper limits on $\mathcal{B}(H \to aa \to 4\gamma)$ derived using the CLs technique
- Limits on the branching ratio can be converted into a limit on the coupling of ALPs to photons

Results
1D-Limits

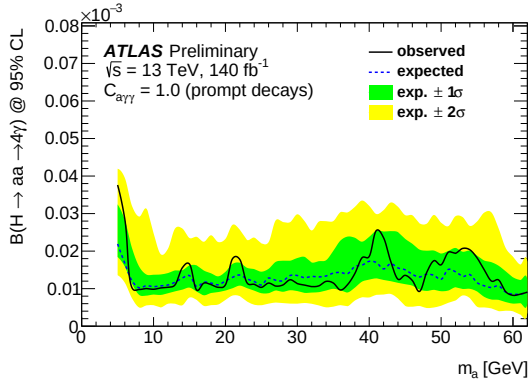
$C_{a\gamma\gamma} = 0.1$



$C_{a\gamma\gamma} = 10^{-5}$



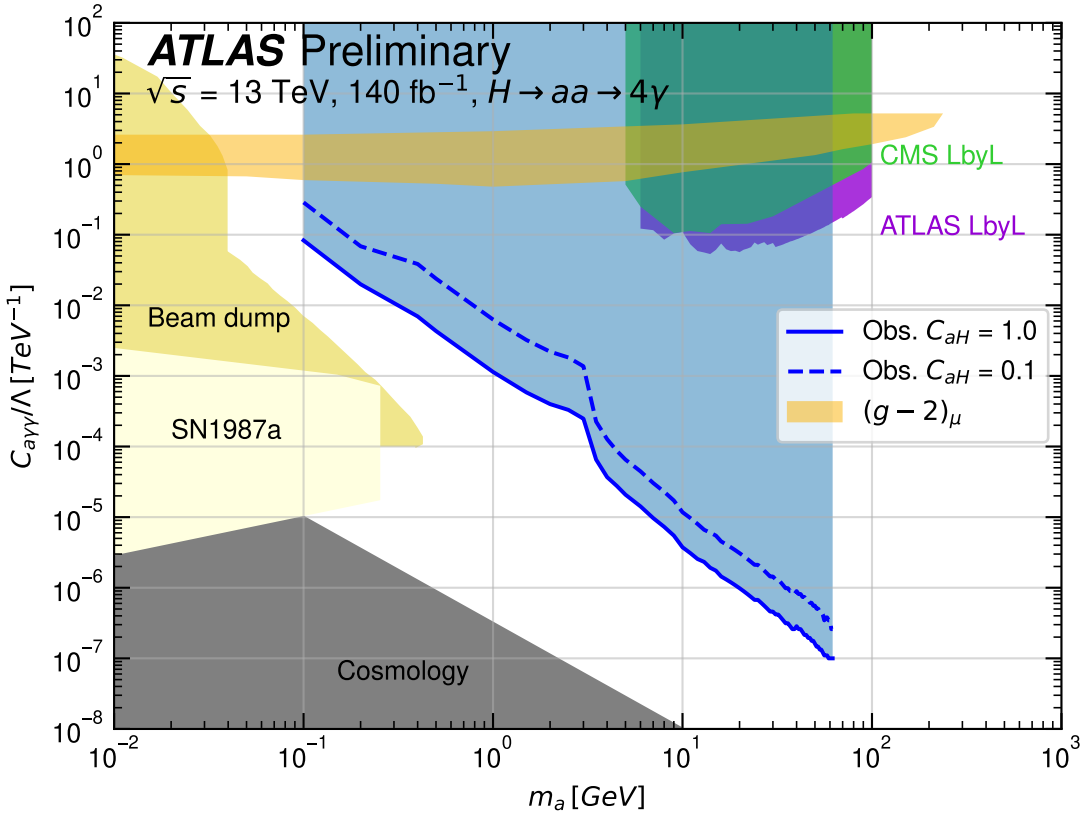
prompt



- Limits are provided on $\mathcal{B}\left(\mathrm{H} \to aa \to 4\gamma\right)$ for different couplings
- This results in the most stringent limits to date

Results

2D-exclusion plot



- Convert limits on branching ratio to 2D exclusion in $C_{a\gamma\gamma}/m_a$ plane
- Exclude much of the remaining $(g-2)_\mu$ parameter space

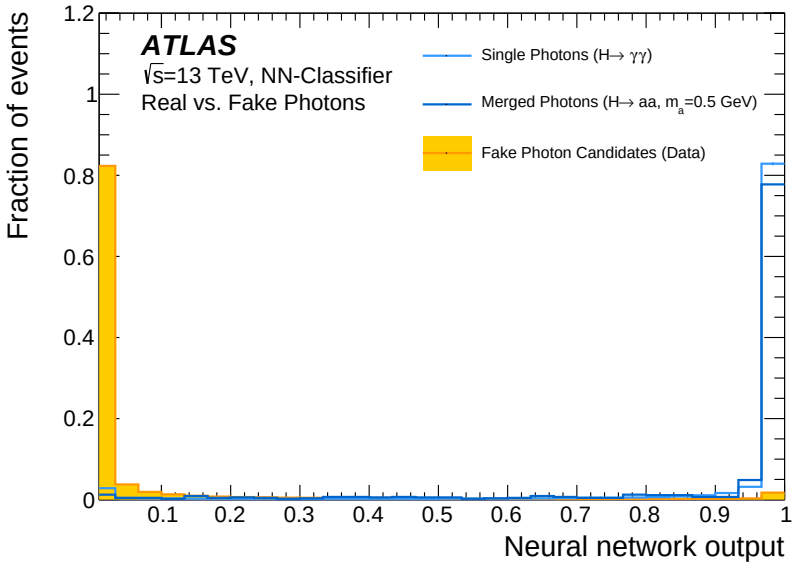
Conclusion and Outlook

- Search for a resonance between 0.1 and 62 GeV, $\Delta^{a}_{\mathrm{R_{decay}}} \leq 1970$ mm
- NN classification: single and collimated photon signatures
- **A dedicated search strategy for long-lived ALP decays has been developed for the first time**
- **These limits exclude much of the remaining parameter space that could explain the $(\mathrm{g}-2)_{\mu}$ discrepancy**

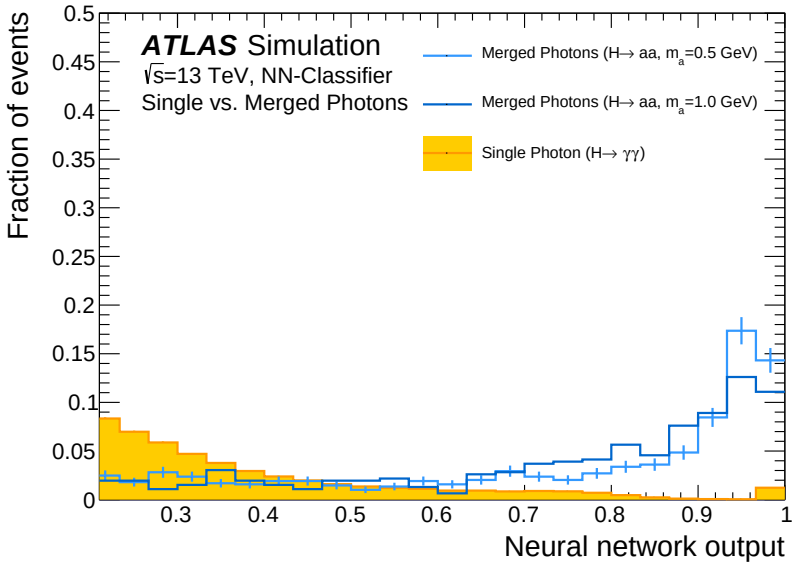
- Further studies on:
  - Merged photon classification
  - Displaced (photon) vertices
  - Other Higgs boson decays (e.g. $\mathrm{H} \rightarrow \mathrm{Z}a$)

Backup

Neural Networks



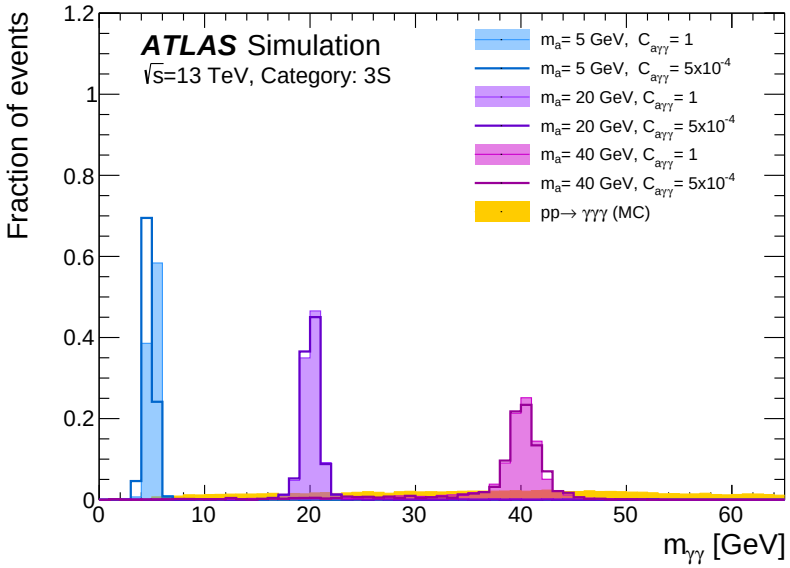
(a)



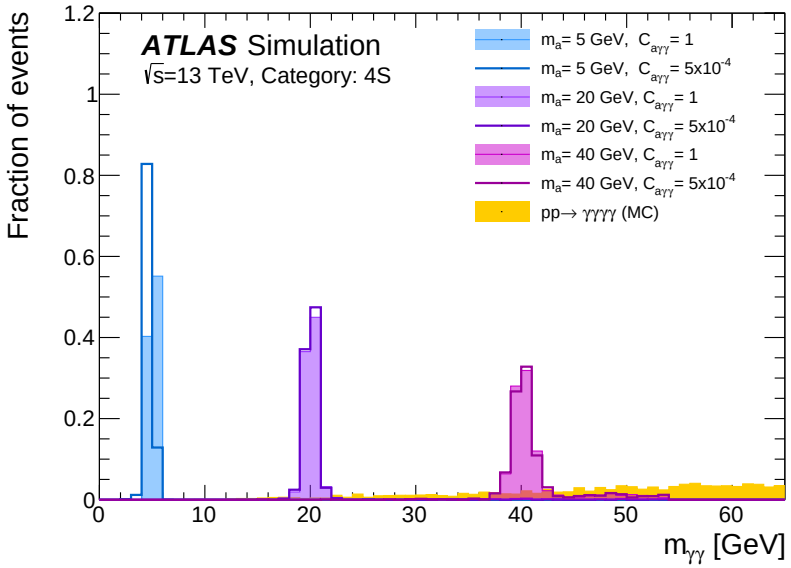
(b)

Figure: Output of the neural network classifier to distinguish (a) real from fake photons, and (b) single from merged photons.

ALP mass reconstruction



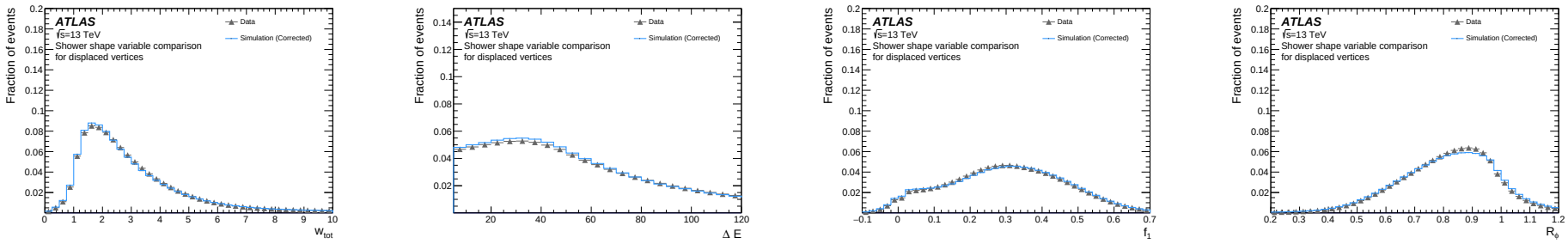
(a)



(b)

Figure: Reconstructed ALP mass for various axion mass models for the 3S (a) and 4S (b) category.

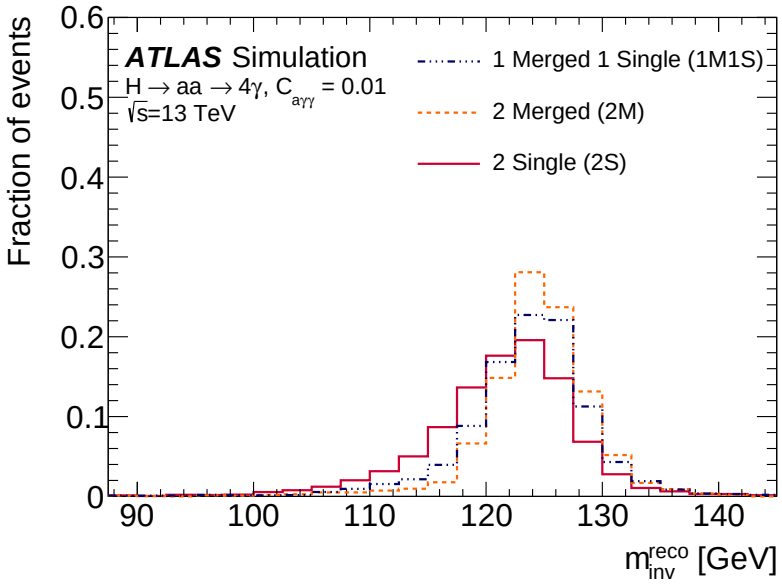
Displaced vertices



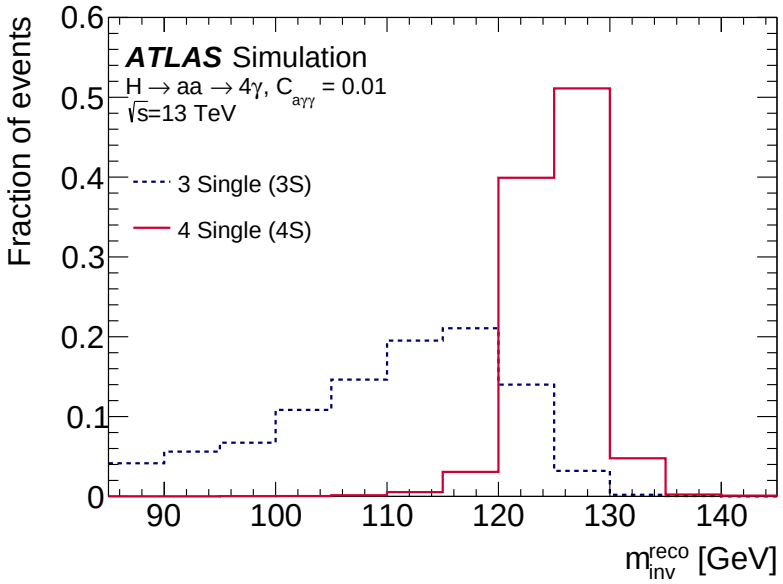
(a) (b) (c) (d)

Figure: Comparison of shower-shape distributions from reconstructed clusters in the electromagnetic calorimeter from charged particles that are produced with different distances from the collision vertex, ranging from 500 to 800 mm. The tracks have been reconstructed using specific large radius tracking algorithms and are selected by the position of a secondary production vertex in a minimum bias data-set. (a) Total lateral shower width, w_{tot}; (b) Difference between the energy of the two leading energy measurements in the first layer of the calorimeter cluster, ΔE; (c) Ratio of the energy in the first calorimeter layer to the total energy in the electromagnetic calorimeter, f_1; (d) ratio on ϕ of cell energies in 3x3 and 3x7 cells, R_Φ.

Signal shape comparisson



(a)



(b)

Figure: Comparison of the m_{inv}^{reco} for (a) the different two-photon categories and (b) the three- and four-photon categories.

Photon identification efficiency

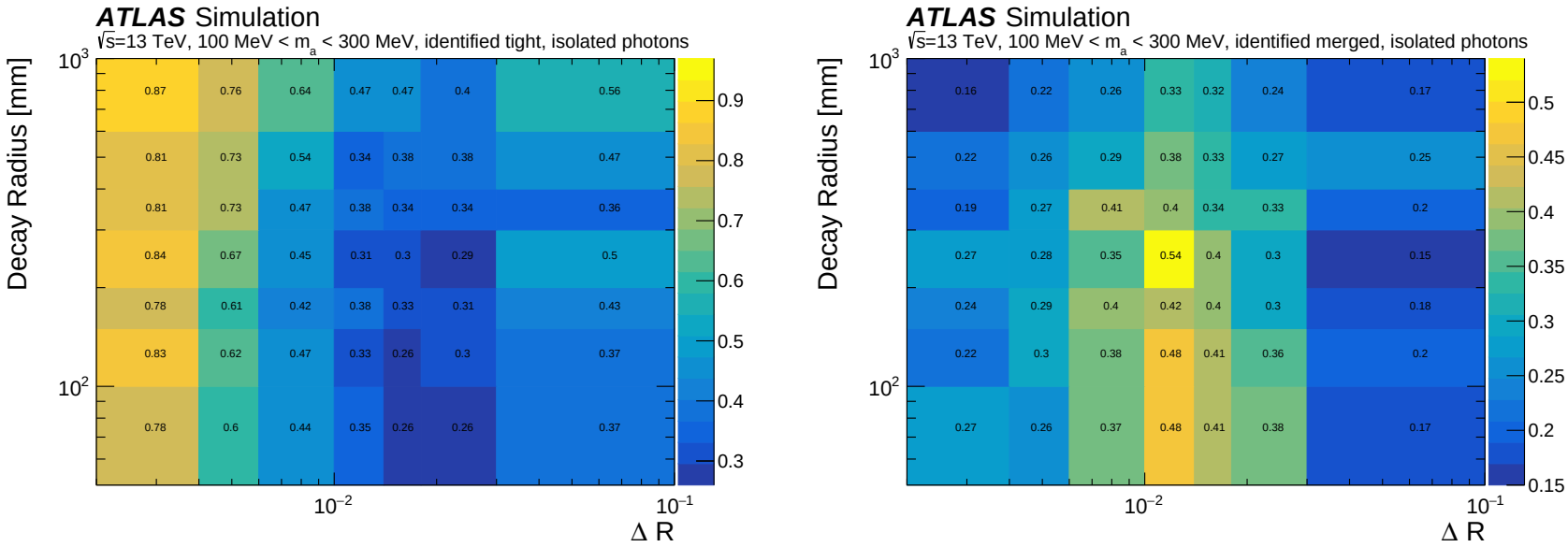
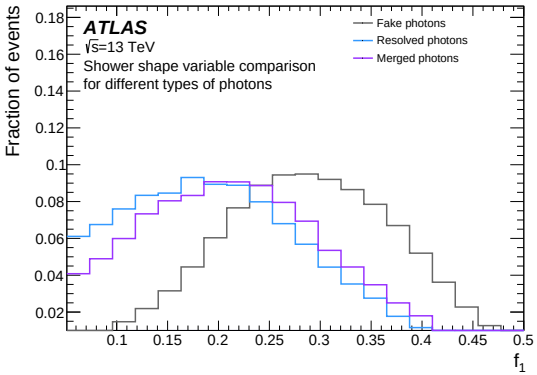
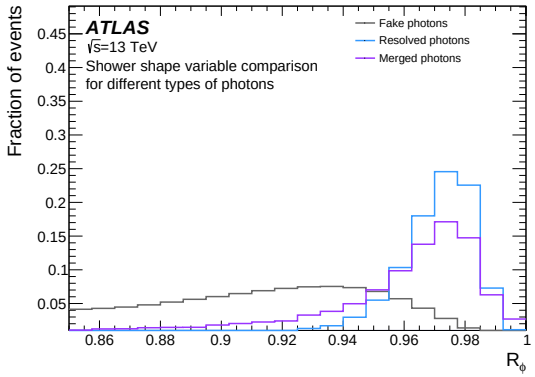


Figure: Shown are (a) the photon identification efficiency for isolated photons that pass the tight photon ID requirements and (b) for classified merged isolated photons as a function of the opening angle in ΔR of both decay photons of the axion and the decay radius of the originating axion from the primary vertex for axions with masses between 100 MeVand 300 MeV. All four ALP decay photons on MC truth level are required to fulfil $|\eta| < 2.5$ and $p_T > 5$ GeV. Only a mild dependency on the decay radius can be seen, since the distance between the two photons is small and hence the combined decay signature in the calorimeter still points to the primary vertex.

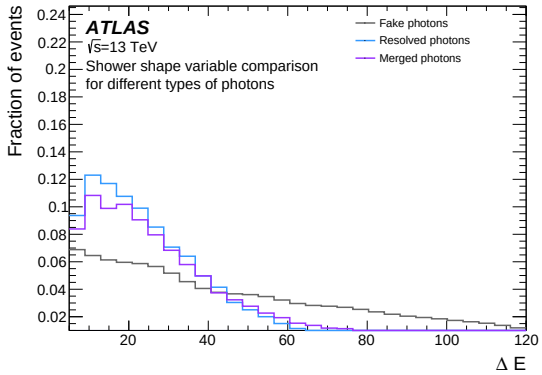
ANN input



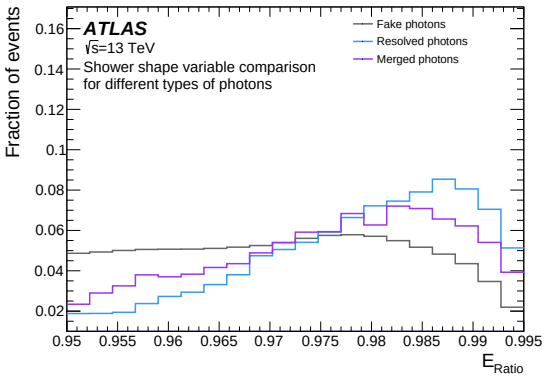
(a)



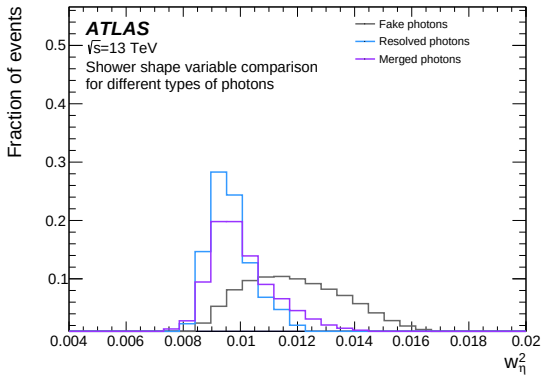
(b)



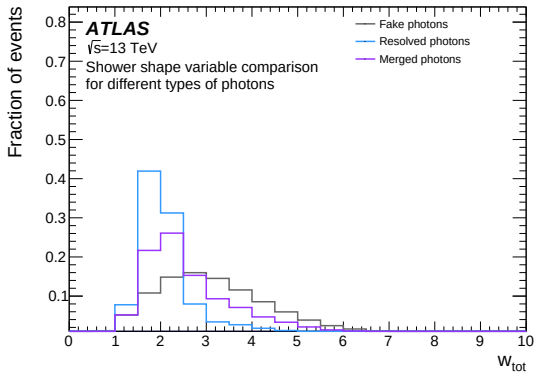
(c)



(d)



(e)



(f)

Figure: Comparison of different shower-shape variables for merged photons (purple), resolved photons (blue) and fake photons (grey).