PROCEEDINGS OF SCIENCE

Searching for anomalous H→$aa \rightarrow \gamma\gamma\gamma\gamma$ decays with the ATLAS detector

Peter Krämer* **and Olivera Vujinović on behalf of the ATLAS collaboration**

[a] *Johannes Gutenberg Universität,*
Staudingerweg 7, Mainz, Deutschland

E-mail: peter.kramer@cern.ch, olivera.vujinovic@cern.ch

A dedicated search for anomalous Higgs boson decays into two axion-like-particles (ALPs) is presented, using the full Run-2 data-set recorded by the ATLAS experiment. The ALPs are assumed to decay into two photons, providing sensitivity to various recently proposed models that could explain the famous $(g-2)_\mu$ discrepancy. This poster presents details of the search in the ALP mass range between 100 MeV and 3.5 GeV, where the signature includes highly collinear photons. A dedicated identification of collinear photons was developed and is presented along with the upper limits placed on the branching ratio of the Higgs boson to the the four photon final state.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

*Speaker

https://pos.sissa.it/

PoS(EPS-HEP2023)480

1. Introduction

Axion-like particles (ALPs) are hypothetical (pseudo-) scalar particles that could solve long standing problems in particle physics, such as the anomaleous magnetic moment of the muon ($(g-2)_\mu$) and the strong CP problem. Various ALP models predict couplings to Standard Model (SM) particles such as photons or the Higgs boson, which was discovered in 2012 at the Large Hadron Collider by the ATLAS and CMS collaborations [1, 2]. These couplings permit a possible anomalous decay of the SM Higgs boson into a pair of ALPs with a subsequent decay of each ALP into a pair of photons ($H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$), which can be recorded with the ATLAS detector.

This article summarizes the analysis of data recorded with the ATLAS detector between 2015 and 2018 described in [3].

2. Analysis overview

This analysis aims to search for ALPs in Standard Model Higgs boson decays, each decaying further to a pair of photons. The phase space that can be assessed is determined by the Higgs boson mass on one hand and the limit on the ALPs decay length due to the geometry of the ATLAS detector on the other hand. It spans over a range of ALP masses from 62 GeV down to 100 MeV and a range of ALP-photon couplings of $C_{a\gamma\gamma} = 1$ down to $C_{a\gamma\gamma} = 10^{-5}$. This large parameter space results in differences in the kinematic properties and thus in the reconstructed signature of the final state.

For small ALP masses, the ALPs get a hight boost and the decay photons are strongly collimated and therefor not reconstructed as separate photons but as one single photon object. Events with two of those merged photon objects have an irreducible background from the SM $H \rightarrow \gamma\gamma$ decay. Furthermore, small ALP-photon couplings lead to a significant lifetime of the ALP. This means, that the ALP decay can happen displaced from the primary vertex leading to a reduced efficiency in the photon identification.

These challenging signatures are tackled using several efforts. Customized systematic uncertainties for displaced decaying ALPs are introduced for the first time. To identify merged photon objects, two different Neural Network classifiers are constructed. With these classifiers, all events can be assigned to five orthogonal categories depending on the number and type of the reconstructed photons. These are: four Single (4S), three Single (3S), two Merged (2M), one Merged one Single (1M1S) and two Single (2S). In events with at least three photons it is possible to reconstruct the ALP by combining the decay photons. To find the correct combinations of photons, an additional Neural Network classifier is used. With this ALP reconstruction, the 3S and 4S categories can be further split into four mass regions.

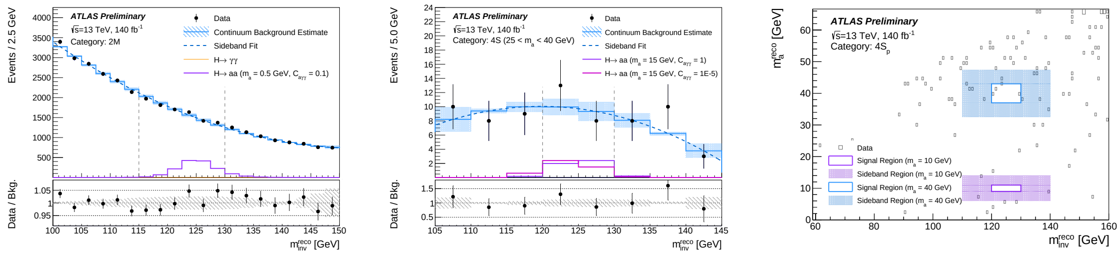
Additionally, another category is introduced targeting events with four photons from promtly decaying ALPs using stricter selection criteria ($4S_P$). This category is analyzed independently.

The continuous background is estimated completely datadriven, while the $H \rightarrow \gamma\gamma$ background is estimated using Monte-Carlo simulations.

Upper limits on the branching ratio $\mathcal{B}(H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma)$ in the case of long-lived ALPs are derived using the CL_S technique with a maximum-likelihood fit simultaneously in the two most sensitive categories for several $C_{a\gamma\gamma}$–m_a hypotheses. In the analysis targeting promptly decaying ALPs, a maximum-likelihood fit on a single bin for every probed mass point is performed.

3. Background estimation

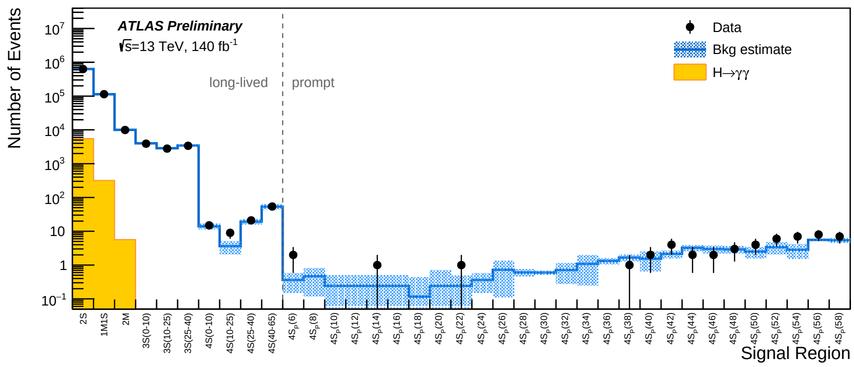
For each category, the background is estimated via a sideband fitting method. First the data distribution of the invariant photon masses $m_{\mathrm{inv}}^{\mathrm{reco}}$ are build. To be agnostic about the signal, a mass region around the Higgs mass containing at least 90% of every signal distribution is blinded. The continuous region of the data, which is roughly between 90 GeV and 140 GeV depending on the category is fitted using continuous functions such as Polynomials or Landau functions. This method is validated in data and Monte-Carlo validation regions. Figure 1 shows the $m_{\mathrm{inv}}^{\mathrm{reco}}$ spectrum of the 2M (a) and the 4S category for ALP masses between 25 GeV and 40 GeV (b).



(a) **(b)** **(c)**

Figure 1: Background estimation for the 2M (a), $4S_{25-40\,\mathrm{GeV}}$ (b) and $4S_P$ (c) categories

To estimate the background in the $4S_P$ analysis, a two-dimensional approach is used. All events passing the stricter selection criteria are filled in a 2D histogram with the reconstructed invariant mass of the four photons $m_{\mathrm{inv}}^{\mathrm{reco}}$ on the x-axis and the reconstructed axion mass m_a^{reco} on the y-axis. For each probed mass point the number of events in a sideband region around the signal region is extrapolated to the signal region. This is shown in Figure 1 (c) for 10 and 40 GeV .



(a)

Figure 2: Comparison of background estimation and data in different categories.

The comparison of data and background estimates are shown in Figure 2. The background estimation agrees with data in most categories.

4. Systematic uncertainties

Although the sensitivity of the analysis is mostly limited by statistical uncertainties, there are several sources of systematic uncertainties that are taken into account.

Theoretical uncertainties on the Higgs boson cross section due to the choice of renormalization and factorization scale and the uncertainties on the Higgs bosons branching fraction are found to be below 6% and are propagated through the complete analysis.

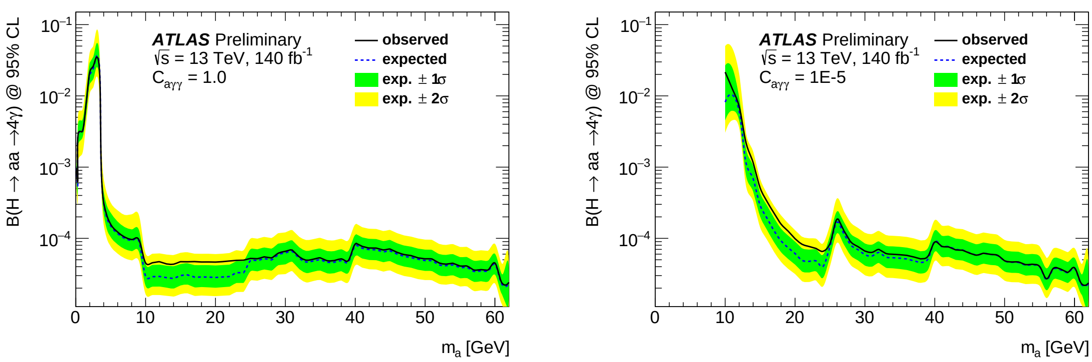
Several sources of uncertainties due to the experimental setup are considered. The uncertainty for the integrated luminosity of the full LHC Run 2 is 0.8% [4]. The uncertainty due to imperfect modelling of pile-up is below 1%. The trigger efficiency gets corrected with an uncertainty of 2% to 3% depending on the category. Uncertainties on standard photon identification, isolation, scale and resolution are below 3% for promptly decaying ALPs. Moreover, the uncertainty on the neural network output was estimated to be up to 15%.

Additionally, customized uncertainties for the treatment of long-lived ALPs are estimated using long-lived hadron events. With these events, the shower-shape variables are rescaled and the photon ID as well as the NN classifiers are re-evaluated. This results in uncertainties ranging from 3% to 23%

5. Results and Conclusion

The analysis uses 140 fb^{-1}of proton-proton collision data at a center-of-mass energy of 13 TeV recorded with the ATLAS detector to search for a light pseudo-scalar particle a in SM Higgs boson decays (H$\to$ aa). The search aims to find a narrow resonance with a mass between 100 MeV and 62 GeV that decays with a displacement up to 1970 mm, but no excesses are found.

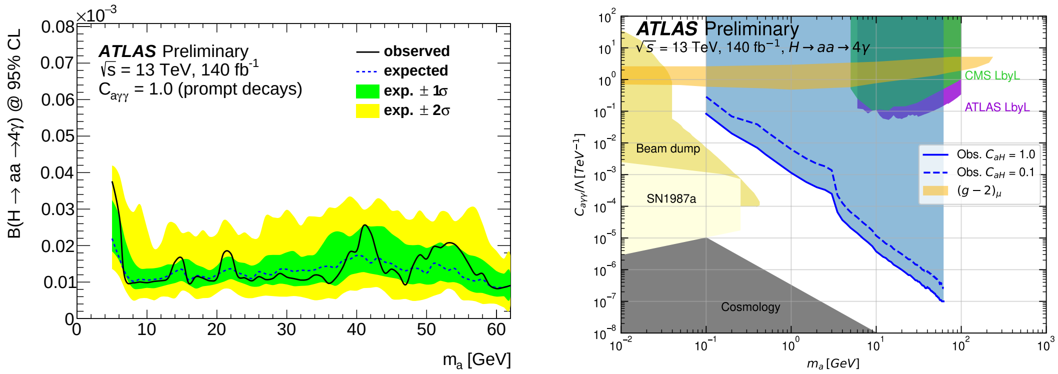
Upper limits on $\mathcal{B}(H\to aa\to\gamma\gamma\gamma\gamma)$ are derived using the CL$_S$-method. Limits for C$_{a\gamma\gamma}$ = 1 and C$_{a\gamma\gamma}$ = 10^{-5} are shown in Figure 3. The limits for the prompt analysis is shown in Figure 4 (a). These are the most stringent limits to date.



(a) **(b)**

Figure 3: Upper Limits on $\mathcal{B}(H\to aa\to\gamma\gamma\gamma\gamma)$ for C$_{a\gamma\gamma}$ = 1 (a) and C$_{a\gamma\gamma}$ = 10^{-5} (b)

The limits can be transformed to exclude an area in the (m$_a$–C$_{a\gamma\gamma}$) plane. Figure 4 (b) shows the parameter space with the excluded region. The red band shows the region which could explain the $(g-2)_\mu$discrepancy. This analysis excludes a large part of the remaining parameter space where ALPs could solve the $(g-2)_\mu$ discrepancy.



(a) **(b)**

Figure 4: Upper limits for the prompt analysis (a) and exclusion limits on m_a and $C_{a\gamma\gamma}$ converted from the long-lived analysis results

References

[1] ATLAS Collaboration. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Phys. Lett. B*, 716:1, 2012. doi:10.1016/j.physletb.2012.08.020.

[2] CMS Collaboration. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Phys. Lett. B*, 716:30, 2012. doi:10.1016/j.physletb.2012.08.021.

[3] ATLAS Collaboration. Search for short- and long-lived axion-like particles in $H \to aa \to 4\gamma$ decays with the ATLAS experiment at the LHC. Technical report, CERN, Geneva, 2023. All figures including auxiliary figures are available at https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-040.

[4] ATLAS Collaboration. Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC. Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC. *Eur. Phys. J. C*, 83(10):982, 2023. doi:10.1140/epjc/s10052-023-11747-w. 74 pages in total, 36 figures, 10 tables, submitted to EPJC. All figures including auxiliary figures are available at https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/DAPR-2021-01.