UNIVERSITÉ HASSAN II DE CASABLANCA
FACULTÉ DES SCIENCES AÏN CHOCK

NELSON MANDELA UNIVERSITY

The 3rd African Conference on Fundamental and Applied Physics

SOUTH AFRICAN INSTITUTE OF PHYSICS

ATLAS EXPERIMENT

Search for Axions in the $H \rightarrow aa \rightarrow 4\gamma$ decays at the LHC's ATLAS experiment

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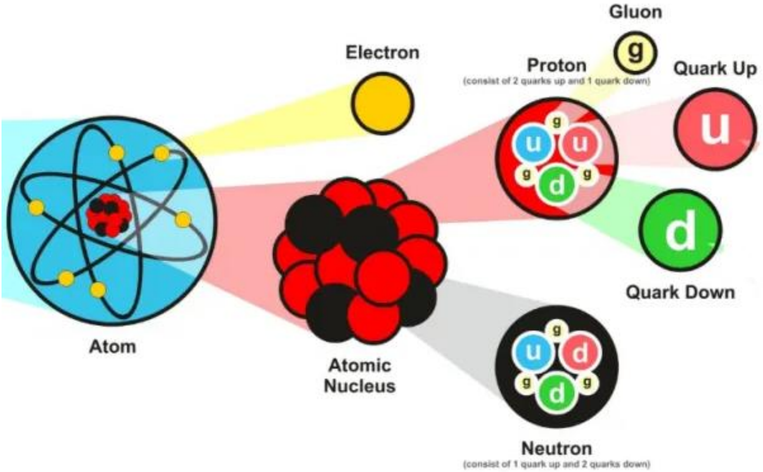
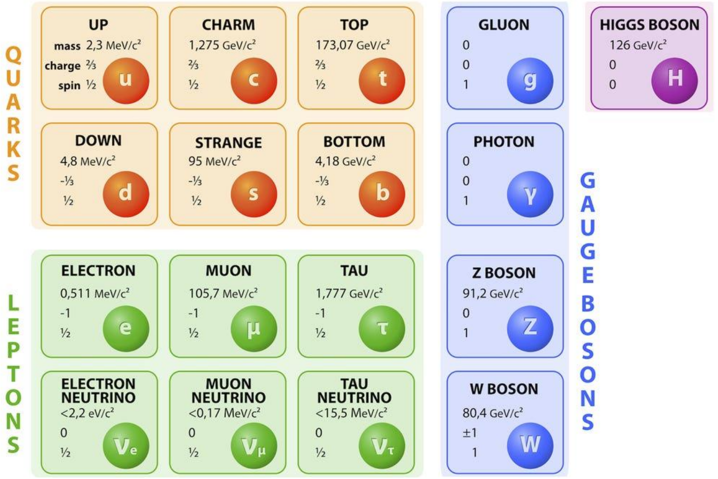
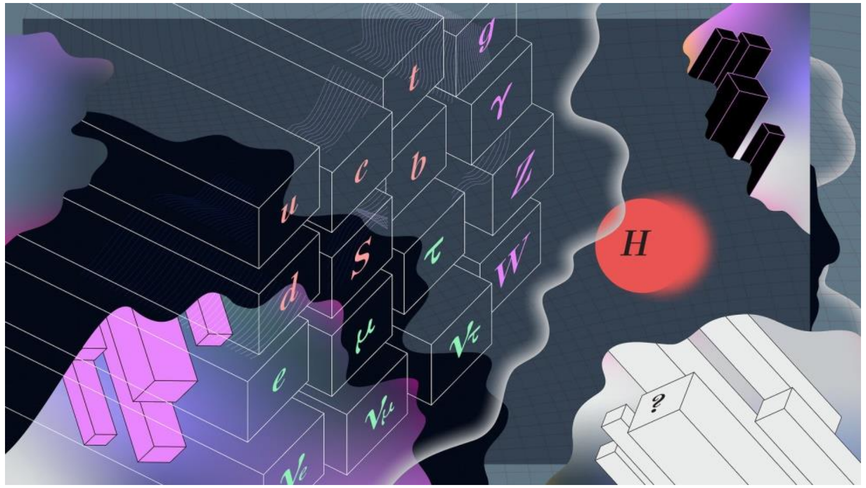
25-29 September 2023

Standard Model of Particle Physics







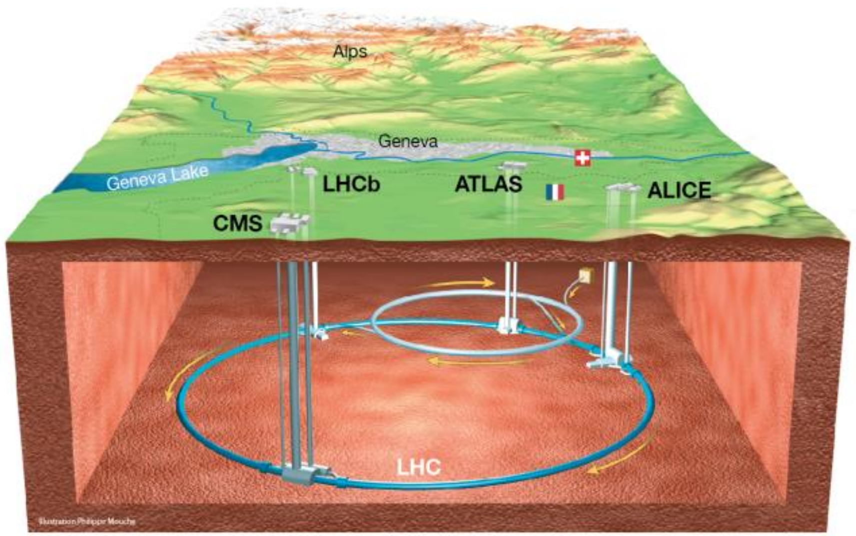
- Atoms ➔ Electrons + Protons + Neutrons ➔ Electrons + Quarks + Gluons
- Scientific theory that classifies elementary particles into distinct categories, including **quarks** and **leptons**, and that explains how fundamental particles interact through **forces**.
- Leads to numerous experimental confirmations, including the **Higgs** mechanism to explain the origin of particle masses.
- It does not incorporate gravity and is unable to explain dark energy or **dark matter**, leaving a significant portion of the universe's composition and fundamental forces unaccounted for.

Axion Particle

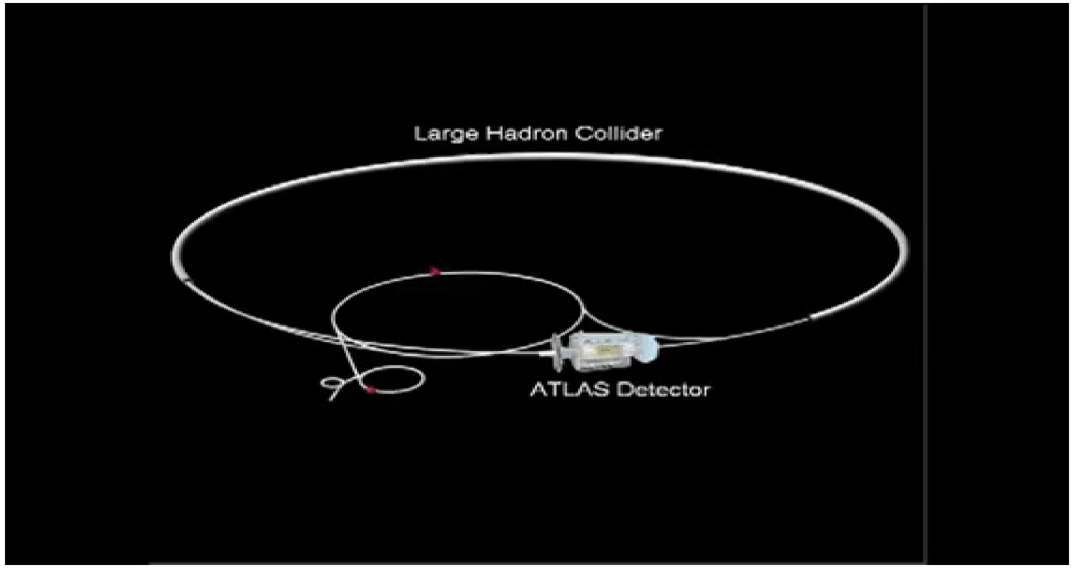
The Axion Particle is a Promising Solution to the CP Problem :

- Why in experiment no CP violation was observed for the strong interractions while the theory predict it?
  - ➔ CP Problem
- Peccei-Quinn proposed as a theory that could resolve this problem:
  - ➔ New symmetry called the Peccei-Quinn symmetry
- The Axions particles are scalar particle resulting from Peccei-Quinn symmetry breaking with light and weakly interacting properties.
- Axions can interact with photons due to Axion-photon coupling phenomenon which arises from the Axion's interaction with the electromagnetic field.

Large Hadron Collider (LHC)



- The world's largest and most powerful particle accelerator
- First started up on 10 September 2008.
- Consists of a 27-kilometre ring of superconducting magnets and located in a depth of 100m.
- Consists of number of accelerating structures to boost the energy of the particles along the way.
- 2 high-energy particle beams (p-p) travel at close to the speed of light before they are made to collide in opposite direction.

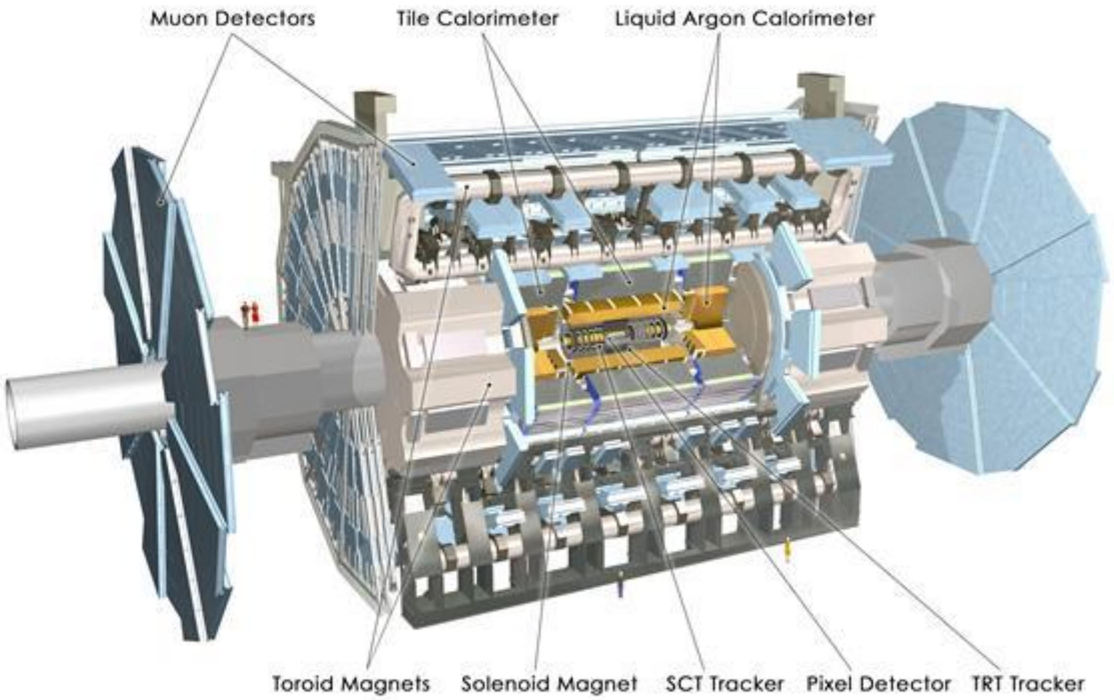


The two beams cross at four collision points which are the locations of the four major experiments of the LHC:

- Generalist detectors **ATLAS**, **CMS**: measure and test the predictions made by the Standard Model.
- **ALICE**: specialized in heavy-ion physics : measure and verify the predictions of quantum chromodynamics and the state of matter in primordial times.
- **LHCb**: study the b quarks allows to explore the differences between matter and antimatter.

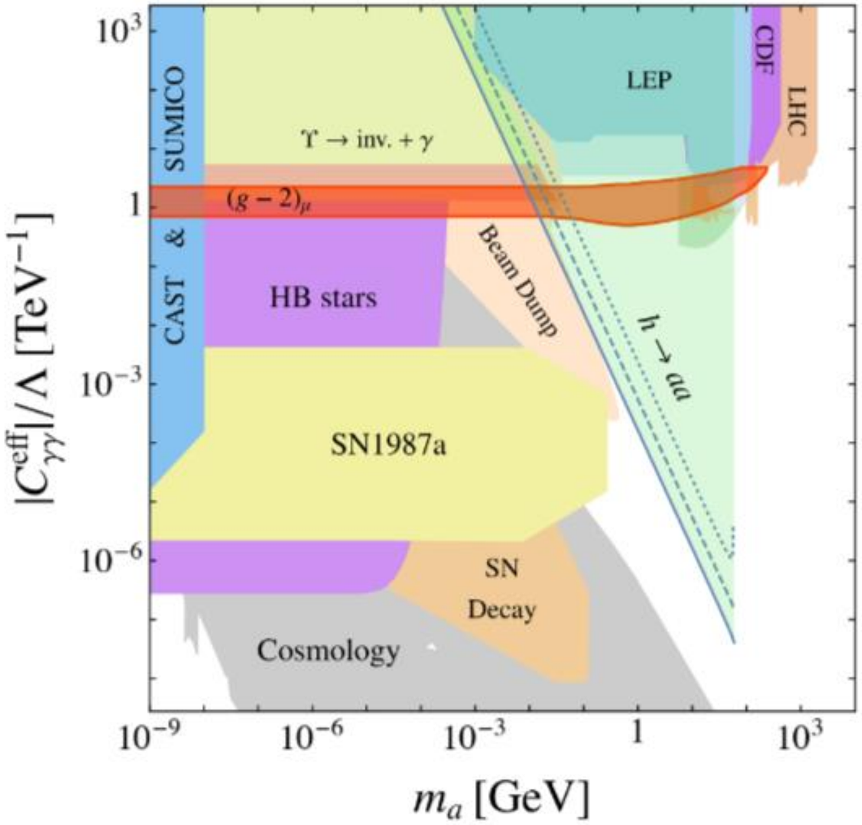
A Toroidal LHC ApparatuS (ATLAS)

- Seeks a broad range of particle physics, from the Higgs boson to signs of new physics
- 25 m high and 44 m long symmetric cylinder, with a weight of 7000 tons
- Consists of different detecting subsystems arranged in layers around the interaction point.
- In order, from innermost to outermost, these sub-detectors include:
  - ✓ **The inner detector:** to detect the charged particles traces and vertices.
  - ✓ **Calorimeters:** to measure particle energy.
  - ✓ **Muon spectrometer:** to determine the muon trajectories.
- Includes a solenoidal and toroidal magnet assembly producing the magnetic fields ➔ measure the momentum of charged particles.



$H \to aa \to 4\gamma$: Motivation

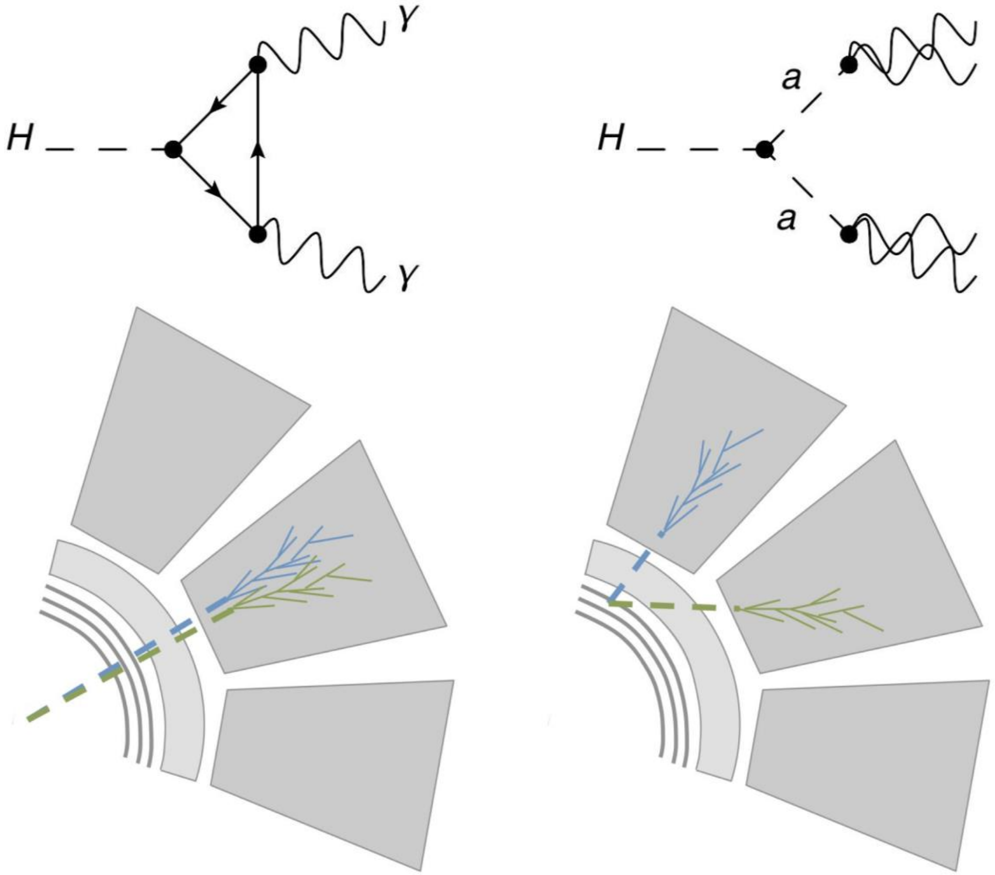
- Explore unconstrained $m_a - C_{a\gamma\gamma}$ parameter space For :
  - $(gg)H \to aa \to \gamma\gamma\gamma\gamma$
  - $0.5 \text{ GeV} \leq m_a \leq 62 \text{ GeV}$
  - $1\text{e-}5 \leq C_{a\gamma\gamma} \leq 1$
- Derive upper limits on ALP cross-section & excluding $m_a - C_{a\gamma\gamma}$ combinations
- Try to explain the anomalous magnetic moment of the muon by Axion-like particles that couple to photons and the Higgs



Challenges

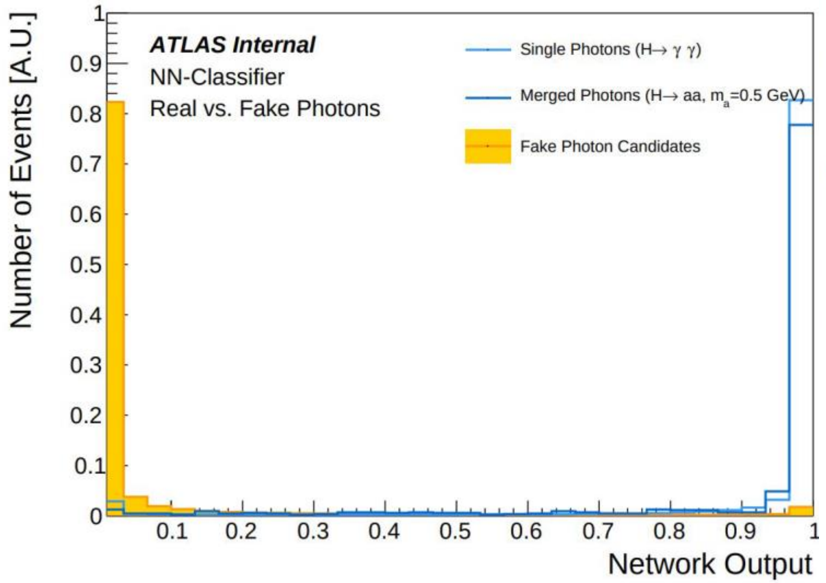
- Low decay width that poses a significant challenge for the detection of Axions in photon decay channels: $\Gamma_{a\gamma\gamma} = \frac{4\pi\alpha^2 m_a^3}{\Lambda^2} |C_{a\gamma\gamma}|^2$
- Axion like particles (ALPs) has long life time:
  - Might decays close to the Calorimeter
  - Detector design and photon reconstruction is optimized for photons from primary vertex

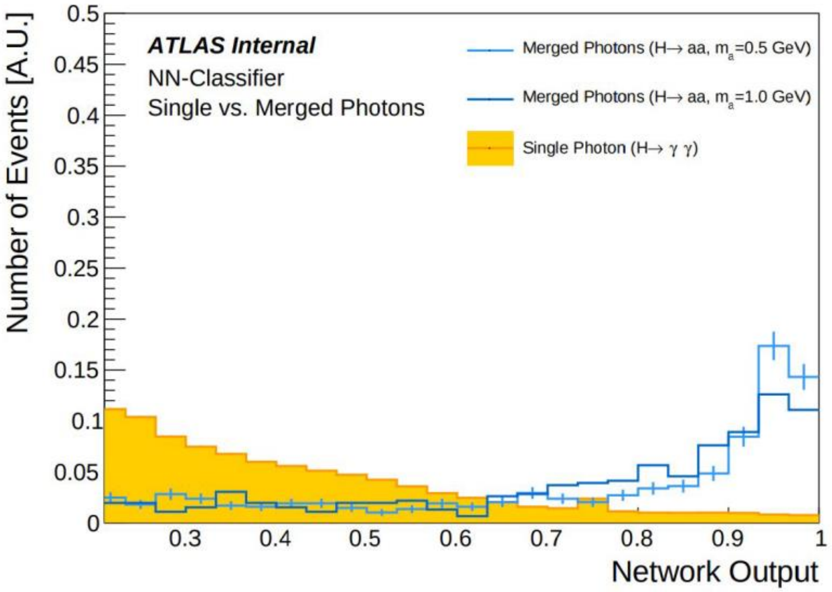
➔ Reduced reconstruction and identification efficiency



Event selection

- Preselection:
  - diphoton triggers
  - ≥ 1 reconstructed PV
  - ≥ 2 photons with p_T > 15 GeV and |η| < 2.37 (calo crack excluded)
  - track based isolation: with a relative isolation parameter $p_T^{cone20}/p_T < 0.05$
- Photon ID based on 2 Artificial Neural Networks (ANNs):

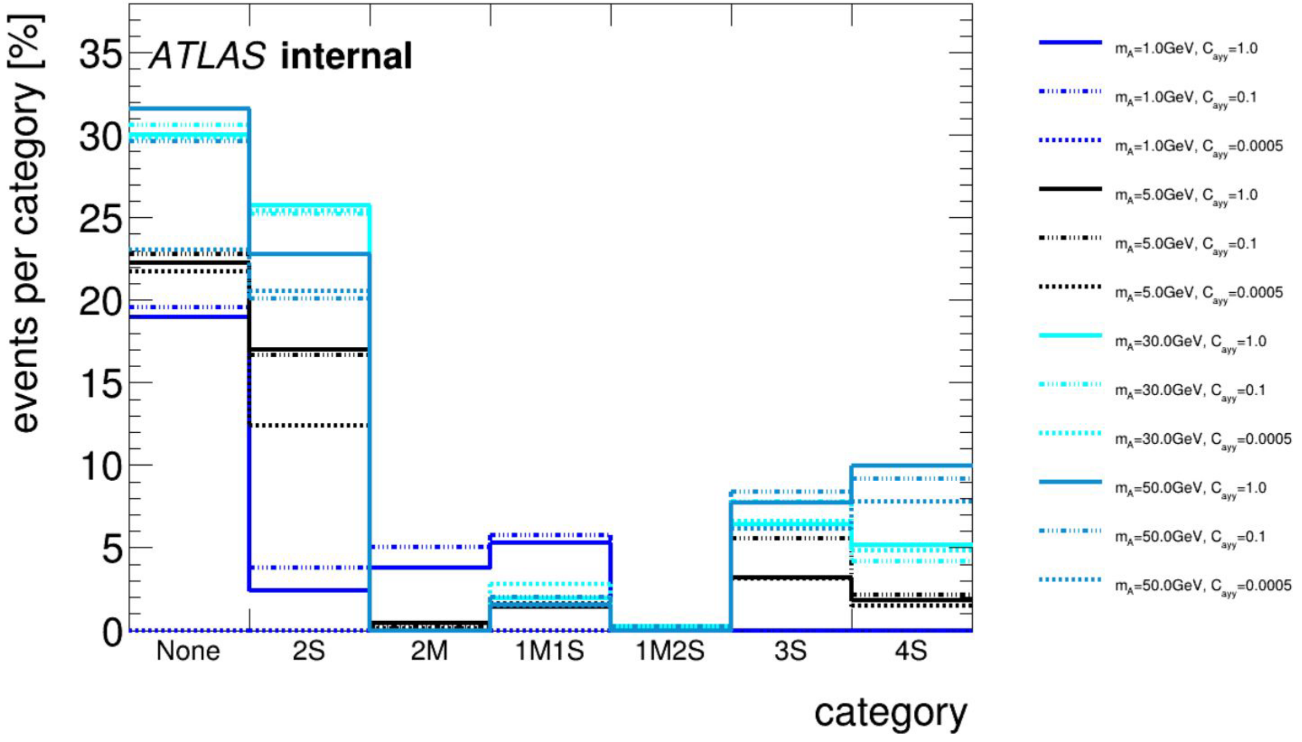




- ANN1: real vs. fake photons:
  - Signal: H→ aa, H → γγ
  - Background: selected data with photons with p_T > 15 GeV, and loosness isolation , m_{inv} > 60 GeV (Higgs region excluded)
- ANN2: merged vs. single photons:
  - Signal: H→aa →4γ merged photons
  - Background: H→aa→4γ single photons

Event categorization

- Each photon gets one of 3 labels:
  - merged (ANN1 > 0.98, ANN2 > 0.5, !tight)
  - loose
  - tight
- Resulting in 5 categories:
  - **4S**: 4 loose photons, at least 1 (3) tight photon
  - **3S**: 2 tight + 1 loose (3 tight) photons
  - **2M**: 2 merged photons
  - **1M1S**: 1 merged + 1 loose photon
  - **2S**: 2 tight photons



Background estimation

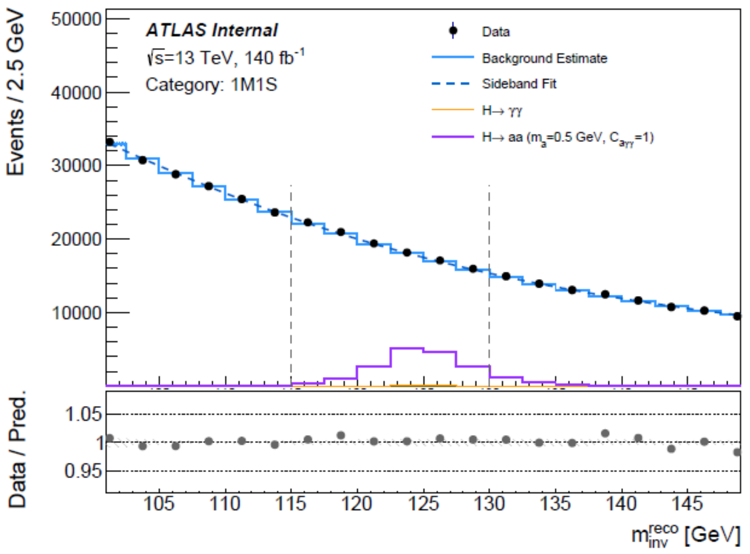
Long lived: 2S,1M1S,2M: Using a sideband in m_H distribution to fit the background contribution in [100, 150] GeV, excluding signal region based on data

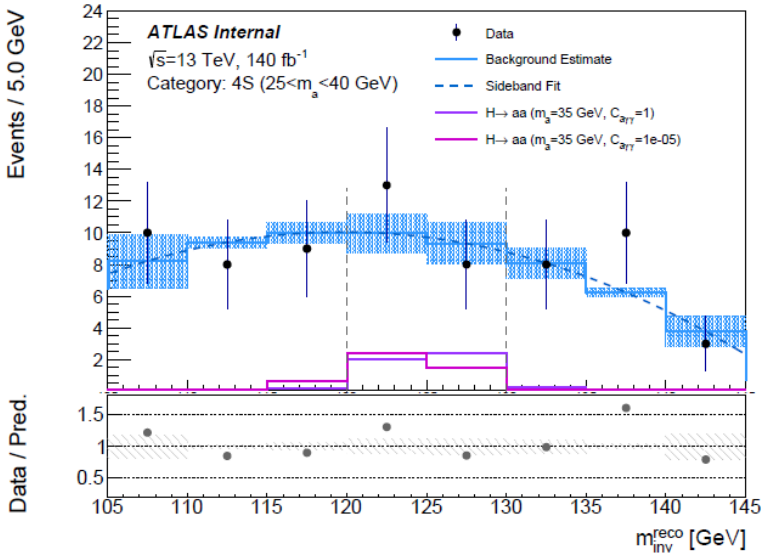
- Fit functions used:
  - 2S and 1M1S: Landau distribution
  - 2M: Polynomial of 3rd order

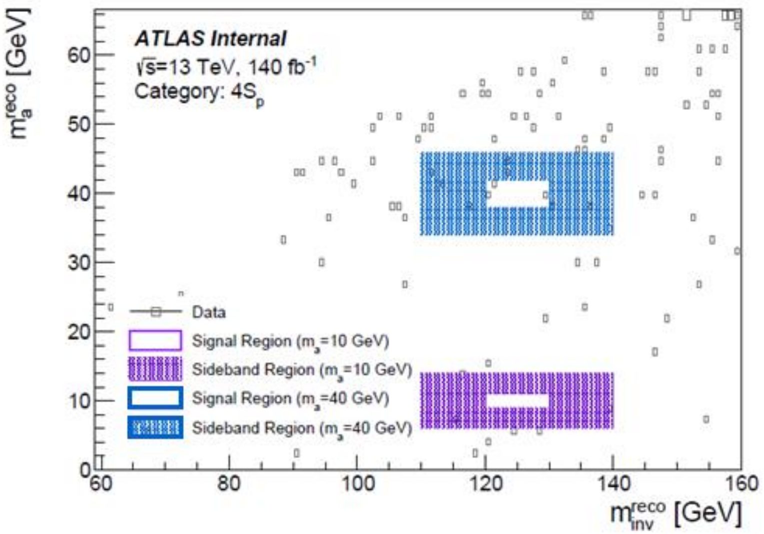
Long lived: 3S,4S: Using a sideband in m_H distribution to fit the background contribution in [85, 150] GeV and [90, 150] GeV for 3S and 4S respectively, excluding signal region

- Fit functions used:
  - polynomial of 3rd order

- Prompt: Considering only 4S case with $m_a > 5$GeV because of the low statistics due to harsher rejection of fake photon signatures
- Using a 2D sideband fit approach with the m_H^{reco} vs. m_a^{reco} spectra

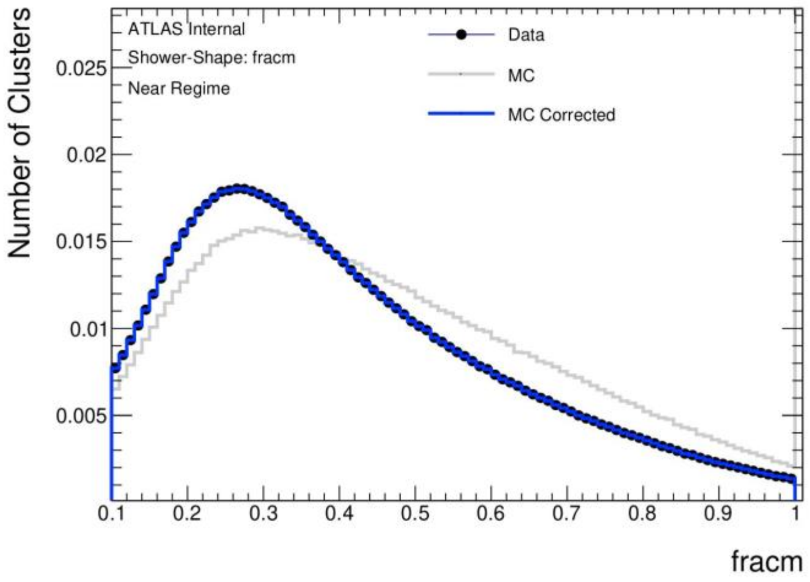


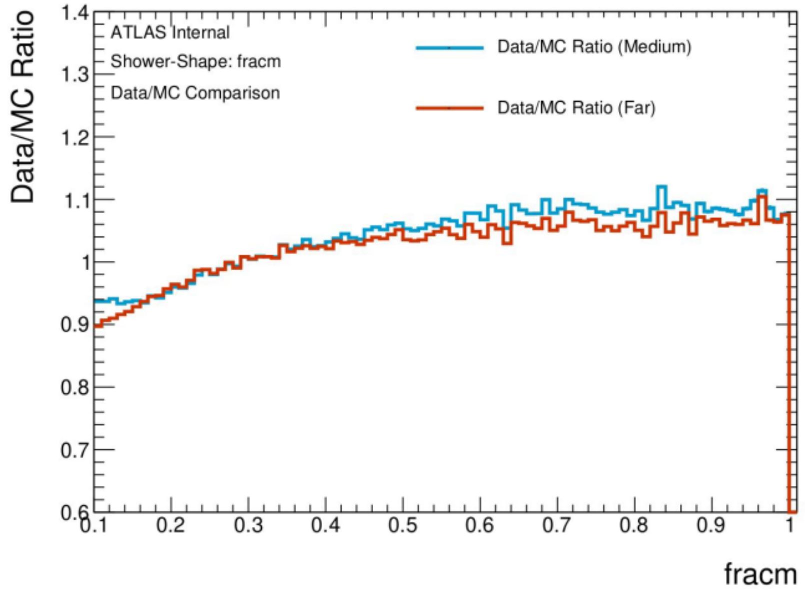




Systematic uncertainties - displaced vertices

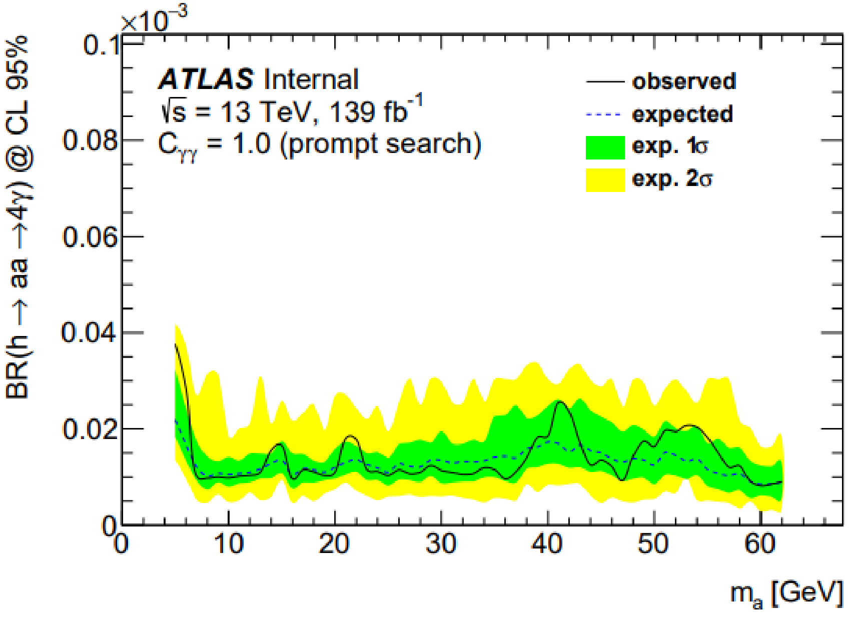
- Special attention paid to the systematic uncertainties due to displaced vertices and their effect on the shower shapes
- Using cluster shapes associated to tracks from displaced vertices of long lived hadrons (kaons) – comparing between data and Mc in 3 regions:
  - Near: vertices with longitudinal displacement $z_0 < 20$ mm and transverse displacement $d_0 < 1$ mm
  - Medium: 20 mm < z_0 < 500 mm, 1 mm < d_0 < 80 mm
  - Far: $z_0 > 500$ mm, $d_0 > 80$ mm
- The dependence of the mean and RMS of the shower shape distribution on the decay length fitted by a polynomial function
- Applied to shower shapes in our signal & propagated through the analysis

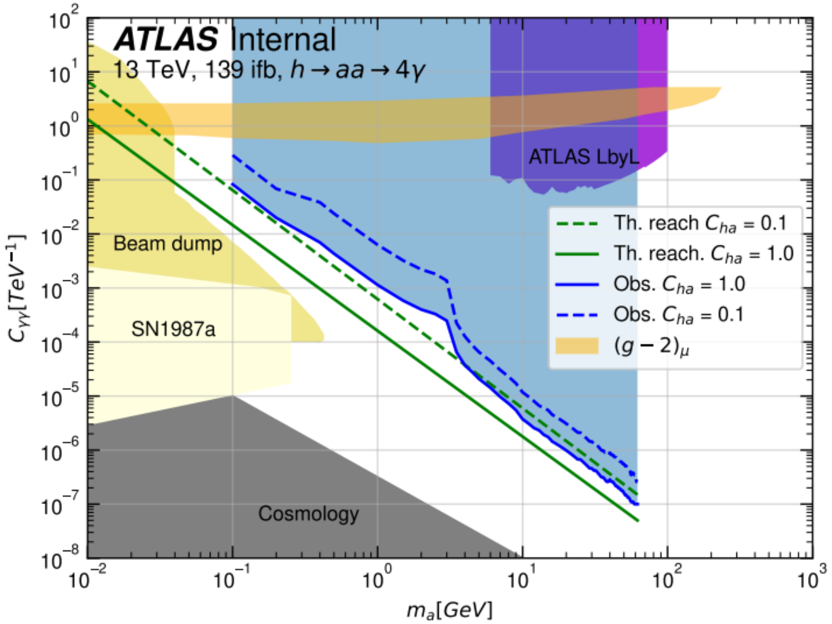




Results: exclusion limits

- **Unfortunately no discovery**, but Most strict limits on H→aa→4y prompt decays
- First time coverage of the full mass range between 500 MeV and 62 GeV
- Search for a large range of a→$\gamma\gamma$ coupling parameters and first limits in the $C_{a\gamma\gamma}$vs m_a plane using displaced photons
  - Data are inconsistent with the predictions of the $(g-2)_\mu$ Axion model





Conclusion

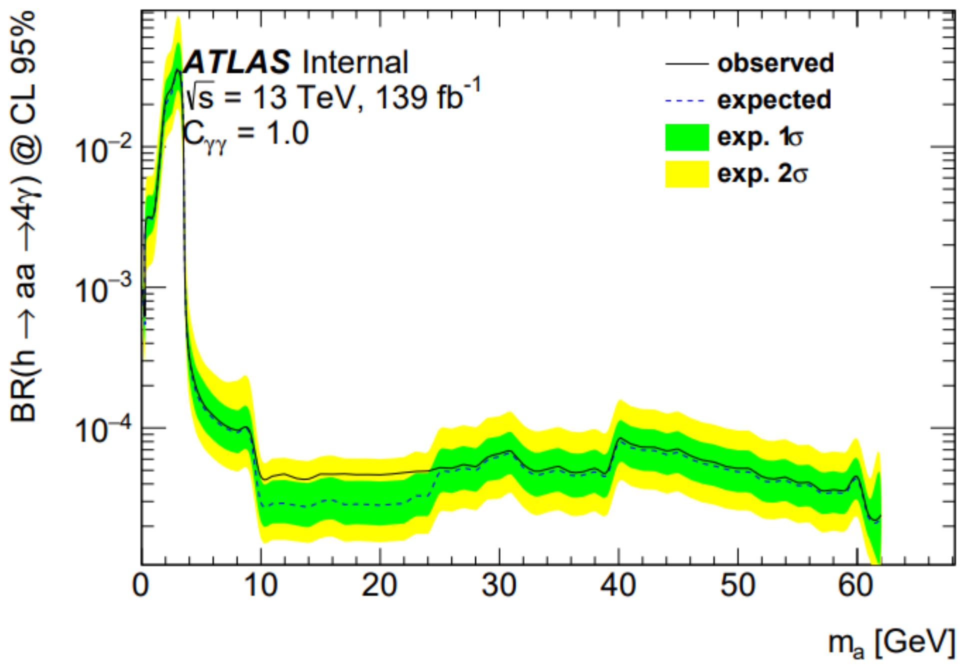
- The study focused on detecting Axion-like particles (ALPs) in the Higgs boson decay channel using the ATLAS experiment.
- Two search approaches were employed: a prompt search for larger coupling values and a long-lived search for smaller coupling values.
- Photon identification techniques, including Artificial Neural Networks, were used for selecting photons in low-mass axion scenarios.
- Systematic uncertainties, including those related to displaced vertices and their impact on shower shapes, were carefully considered.
- Upper limits on the branching ratio for $H \rightarrow aa \rightarrow 4\gamma$ were derived using the CLs technique, with results comparable to previous CMS studies in different mass ranges.

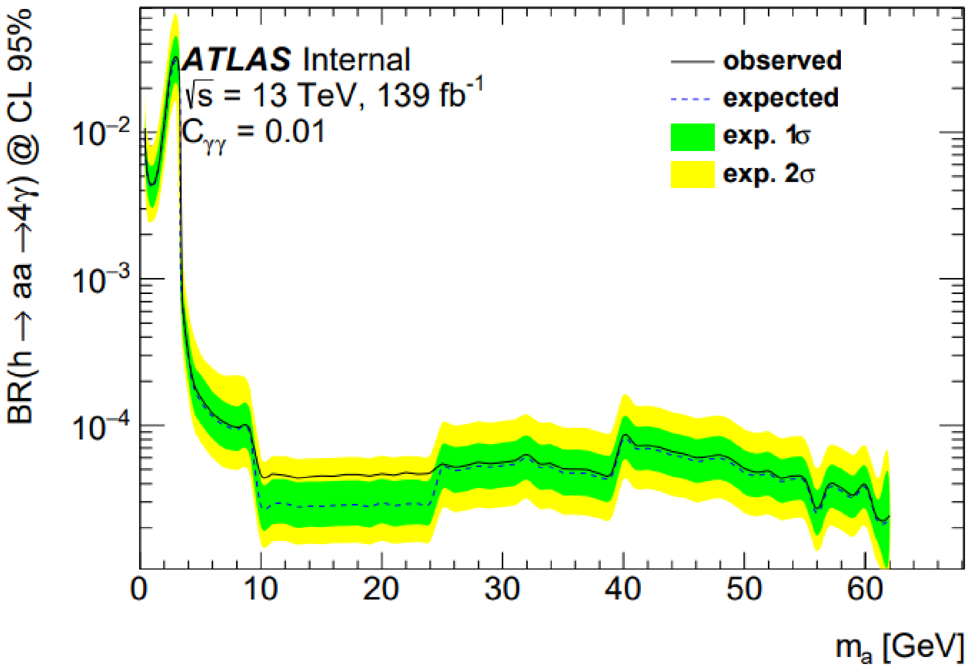
THANK YOU

Q & A

Backup

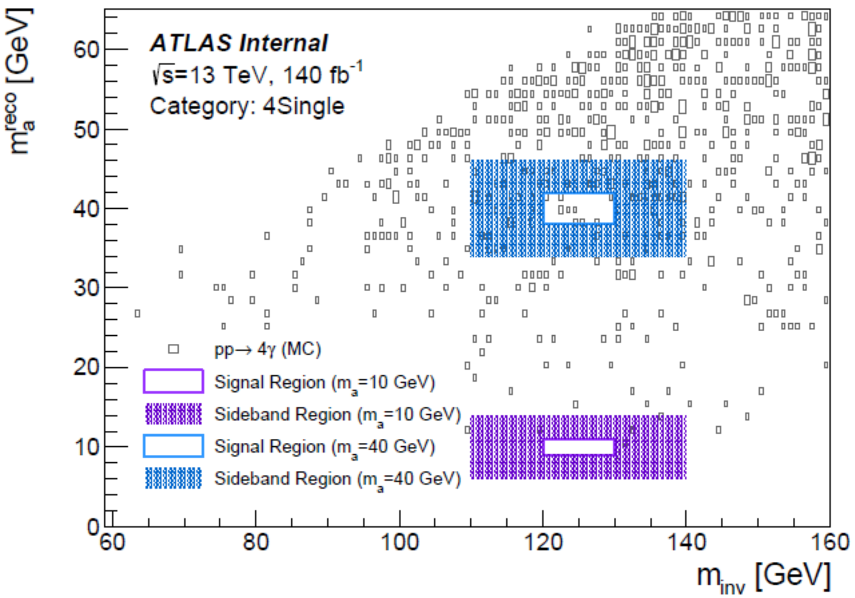
Results: exclusion limits (long-lived case)





Background estimation: prompt

- The SR and CR defined as:
  - SR: 120 GeV < m_H < 130 GeV and m_a in m_a ± stepsize
  - CR1: 110 GeV < m_H < 140 GeV and m_a in m_a ± stepsize × 1.5
  - CR2: 105 GeV < m_H < 145 GeV and m_a in m_a ± stepsize × 2.5



PS: The stepsizes are :

m_a range	Stepsize
$0 < m_a < 25\ GeV$	1 GeV
$25 < m_a < 40\ GeV$	2 GeV
$40 < m_a < 50\ GeV$	3 GeV
$50 < m_a < 55\ GeV$	5 GeV
$55 < m_a < 60\ GeV$	8 GeV

Systematic uncertainties - displaced vertices

- The dependence of the mean and RMS of the shower shape distribution on the decay length fitted by a polynomial function
  - Where the mean gives an idea of where the most energy is deposited, while the RMS provides information about the width or spread of the distribution
  - Pass from the medium and far regime to a broader range to apply it for our signal