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

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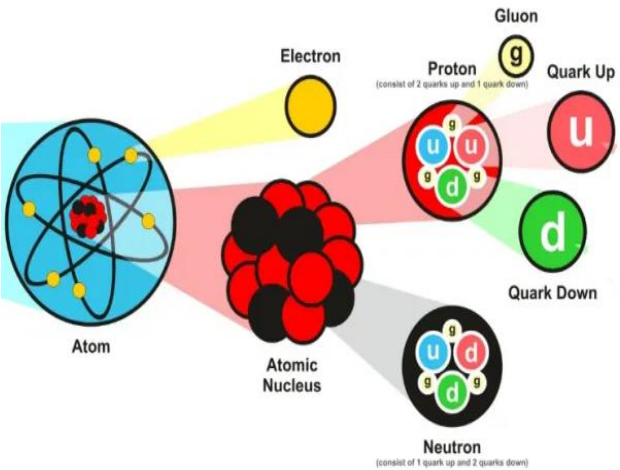
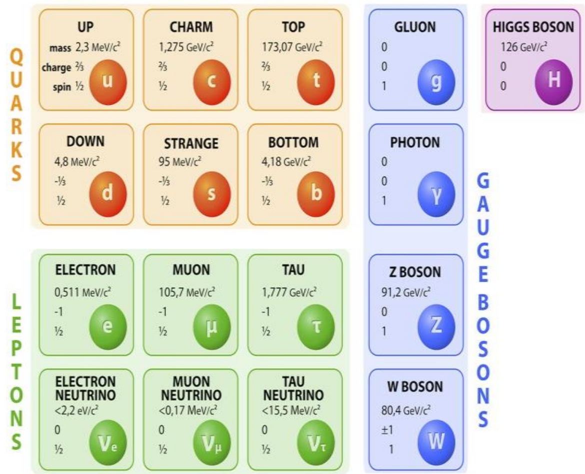
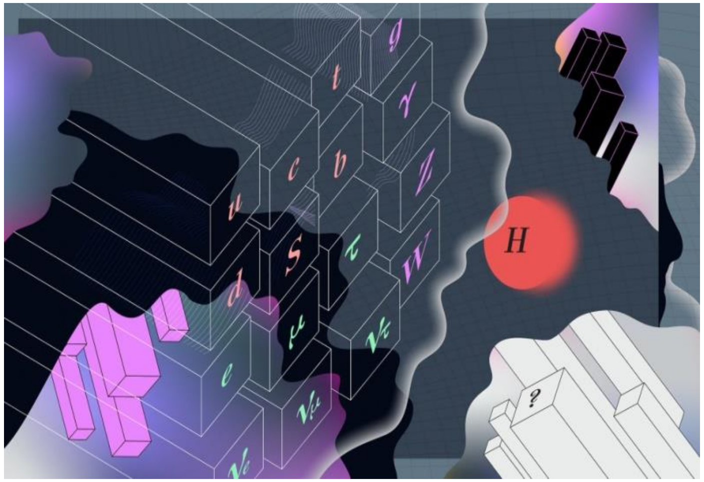
Standard Model of Particle Physics







- Atoms ➔ Electrons + Protons + Neutrons ➔ Electrons + Quarks + Gluons
- Scientific theory that classifies elementary particles into distinct categories, including **quarks**, **leptons**, and bosons.
- Leads to numerous experimental confirmations, including the **Higgs** mechanism that explains the particle masses origine.
- Leaves a large part of the universe's composition and fundamental forces unexplored, such as the **dark matter**.

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

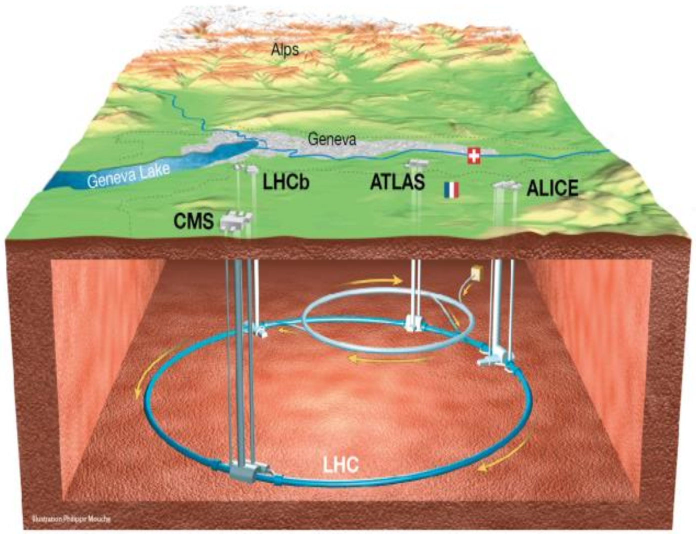
- Peccei-Quinn proposed as a theory that could resolve this problem:

  ➔ New symmetry called the Peccei-Quinn symmetry

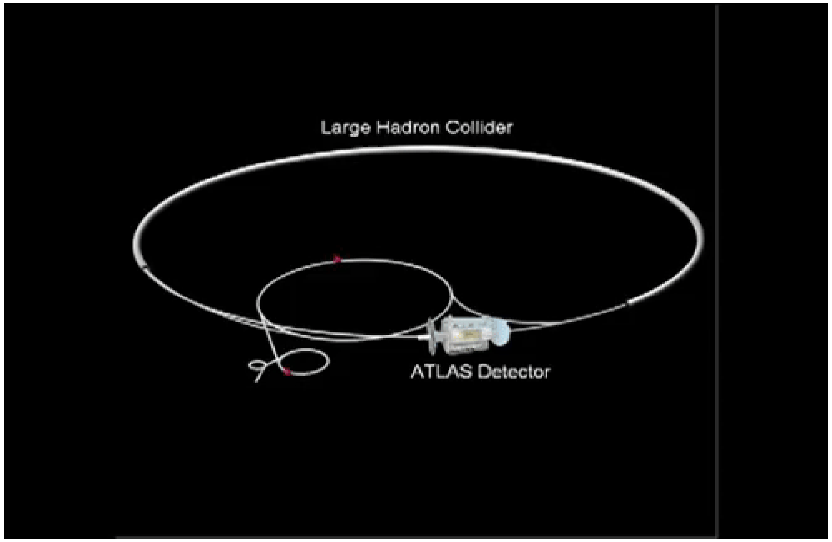
- The Axions particles are scalar particle resulting from Peccei-Quinn symmetry breaking with light and weakly interacting properties.

- 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)



- Launched in 2008, with 27-km ring that accelerates proton beams to close to the speed of light.
- Facilitates collisions of these high-energy particles, revealing the fundamental secrets of the universe.

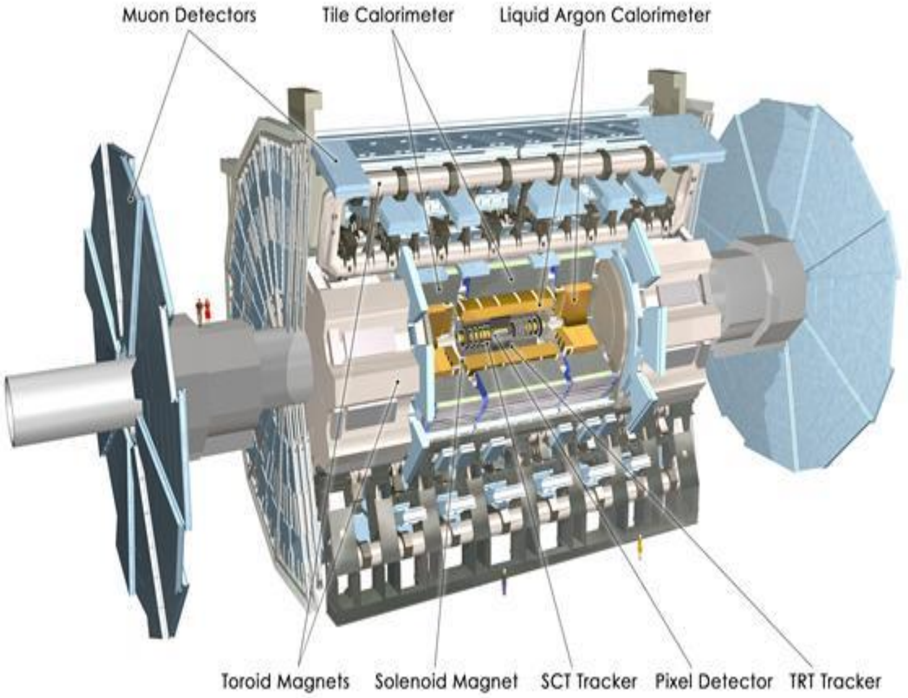


The proton beams cross at four collision points which are the locations of the four major experiments of the LHC:

- The most generalist experiments are the sisters : **ATLAS**, **CMS**

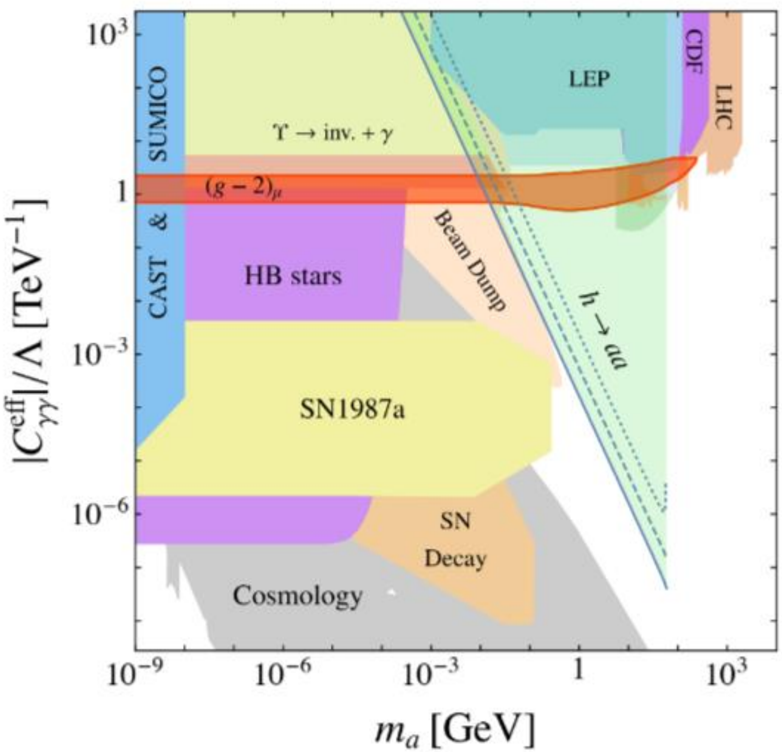
A Toroidal LHC ApparatuS (ATLAS)

- 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 that include:
  - **The inner detector:** to detect the charged particles traces and vertices.
  - **Calorimeters:** to measure particle energy.
  - **Muon spectrometer:** to determine the muon trajectories.
- & employs solenoidal and toroidal magnet assembly to measure the momentum of charged particles.



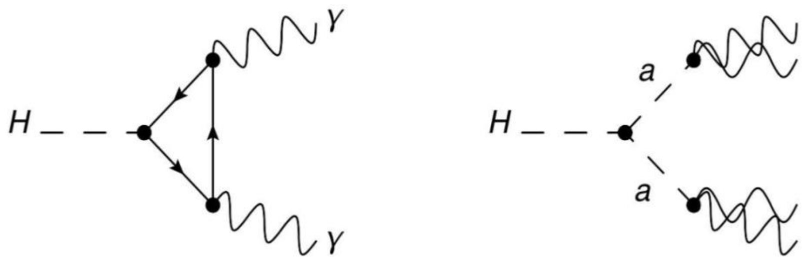
$H \to aa \to 4\gamma$: Motivation

- Explore unconstrained $m_a - C_{a\gamma\gamma}$ parameter space for :
  - $H \to aa \to \gamma\gamma\gamma\gamma$
  - 0.1 GeV $\leq m_a \leq$ 62 GeV
  - 1e-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



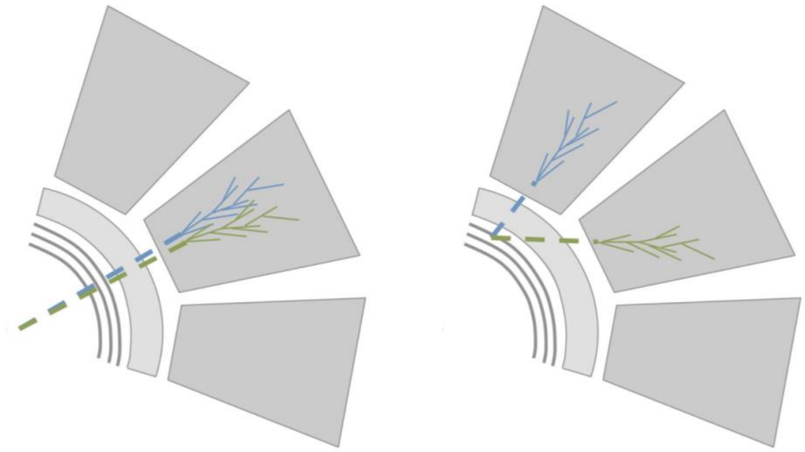
Challenges

- 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
  - & The detector design and the 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 samples
    - Background: Data with photons with p_T > 15 GeV & loose isolation & m_{inv} > 60 GeV excluding the Higgs region
  - 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

- For m_a> 5 GeV: most significant categories are the 4S and 3S categories, other categories could be neglected.
- For m_a < 3 GeV: most significant categories are 2M and 1M1S.
- 2S category used as control region as in $120 < m_a < 130$ GeV, the $H \to \gamma\gamma$ process is more relevant

Background estimation

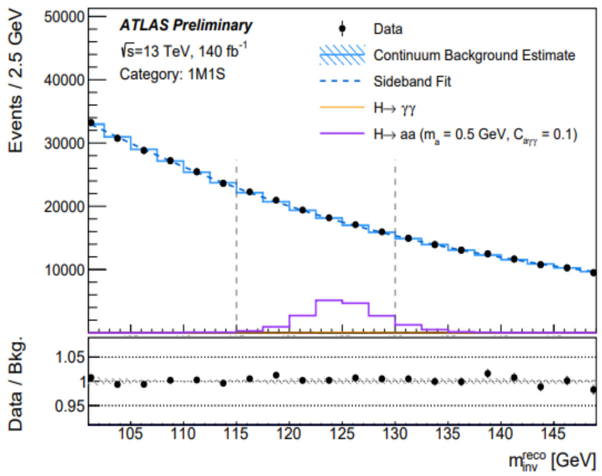
Long lived: 2S,1M1S,2M: Using a sideband in m_H distribution to fit the background contribution in [100, 150] GeV, excluding signal region based on data

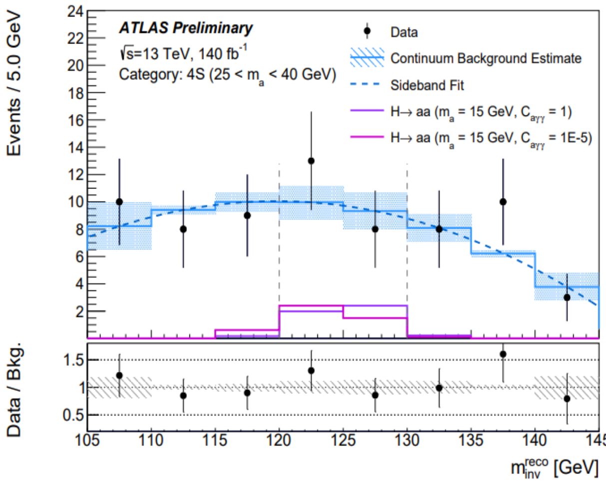
- Fit functions used:
  - 2S and 1M1S: Landau distribution
  - 2M: Polynomial of the 3rd order

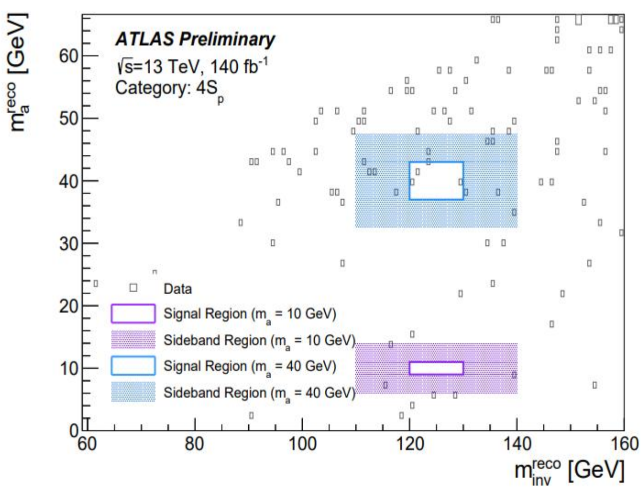
Long lived: 3S,4S: Using a sideband in m_H distribution to fit the background contribution in [85, 150] GeV for 3S, and [90, 150] GeV for 4S, excluding the signal region:

- Fit functions used:
  - polynomial of the 3rd order

- Prompt: Considering only 4S case with $m_a > 5\text{GeV}$
- 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 from the IP:
  - 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 distributions on the decay length fitted by a polynomial function to cover the remain decay lengths.
- The fits have applied to correct the shower shapes in our signal and used to ameliorate the identification & reconstruction in the analysis.

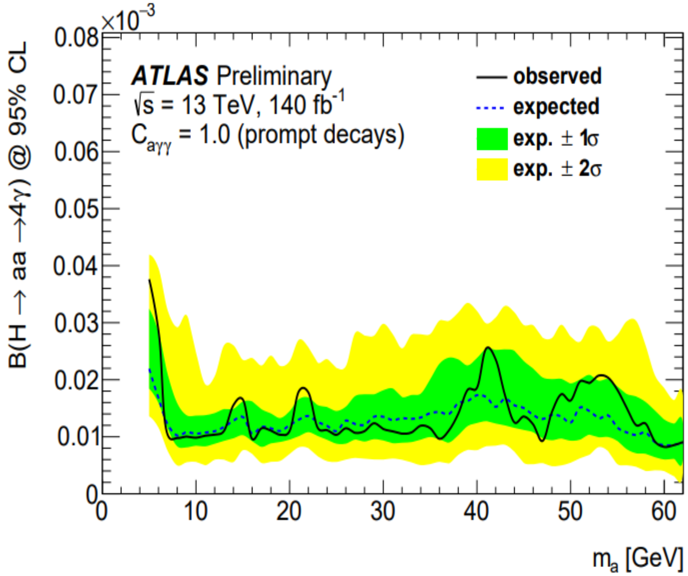
Results: exclusion limits

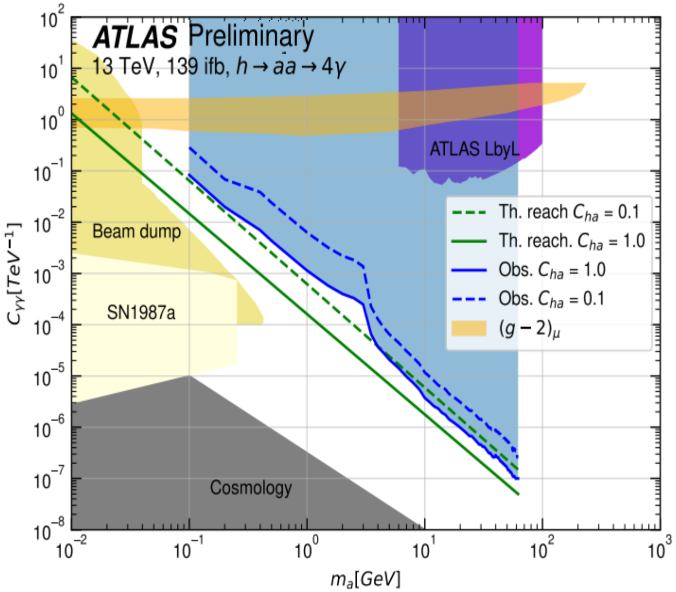
- **Unfortunately no discovery**, but most strict limits on $H\rightarrow aa\rightarrow 4\gamma$ prompt decays

- First time coverage of the full mass range between 0.1 and 62 GeV.

- Search for a large range of $a\rightarrow\gamma\gamma$ coupling parameters and first limits in the $C_{a\gamma\gamma}$ vs m_a plane using displaced photons.

➔ Most stringent limits to date.





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 $H \to aa \to 4\gamma$ were derived using the CLs technique, with results comparable to previous CMS studies in different mass ranges.

THANK YOU

Q & A