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

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Light@LHC project

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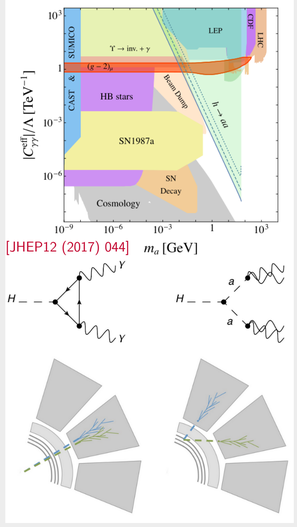
Analysis overview



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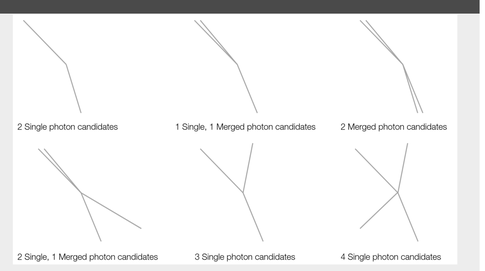
- Limits on Higgs boson branching ratios to invisible or undetected states motivate searches for Higgs boson decays to BSM particles
- Probe exotic Higgs boson decays into 2 ALPs
  - Model could explain the muon (g-2) discrepancy
  - ALPs are dark matter candidates
- This analysis searches for light pseudo-scalar particles in the decay of the 125 GeV Higgs boson in a final state with 4 photons
- 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 reconstructed signature as $H \to \gamma\gamma$ $\Rightarrow$ Distinguish collimated photon-pairs from resolved photons
  - Small $C_{a\gamma\gamma}$ $\Rightarrow$ Displaced vertices

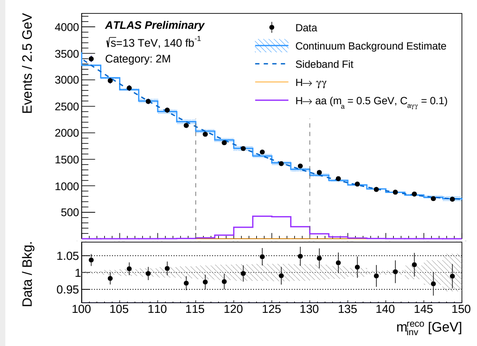
Analysis steps

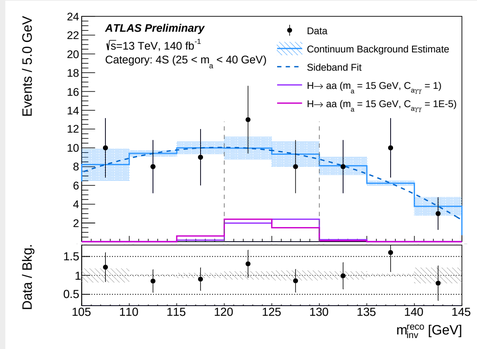
- Preselection: events with 2,3,4 photons $(p_T(\gamma) > 15\,\text{GeV}, |\eta|(\gamma) < 2.37, \text{isolation})$
- Merged photons:
  - Standard Photon ID: low efficiency for merged photons:
  - Dedicated approach for rejecting fake photons $\Rightarrow$ ANN-1
  - Different kinds of photons: Single or Merged $\Rightarrow$ ANN-2
- Select event category (see right-hand side)
- Data driven background estimation $\Rightarrow$ Use ANNs to reconstruct ALP (3γ and 4γ)
- Profiled likelihood fit
- Calculate exclusion limits on m_a and $C_{a\gamma\gamma}$



- 6 (5 used) categories for long-lived ALP search
- Dedicated search for promptly decaying ALPs (stricter selection criteria)

Background estimation - Long lived ALP search

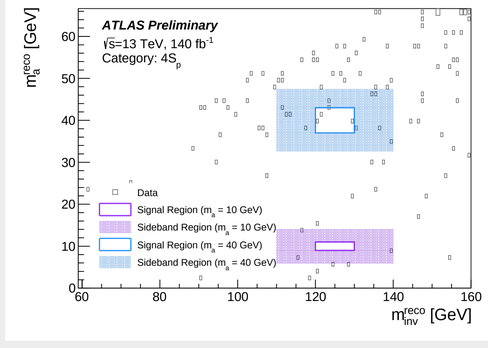




- **Data driven sideband** fitting method
- Blind m_{inv}^{reco} distribution around $m_h = 125\,\text{GeV}$
- 2 photon categories:
  - Sideband fit region $100 - 150\,\text{GeV}$
  - Landau fitting function (2S, 1M1S)
  - 2nd order polynomial fitting function (2M)
  - $H \to \gamma\gamma$ background from MC simulation
- 3 and 4 photon categories:
  - Sideband fit region $80(105) - 150(145)\,\text{GeV}$ 3S (4S)
  - 3rd (3S) and 2nd (4S) order polynomials
  - Separate 4 different regions in m_a^{reco} $(0-10, 10-25, 25-40, 40-62\,\text{GeV})$
- 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 - Promptly decaying ALP search

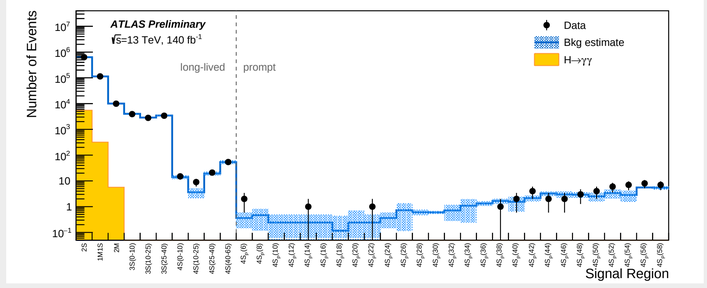
- Stricter requirements on PID to reject fake photons
- Tight selection around the m_a^{reco} parameter
- Background yield in (shaded) sideband region scaled by the ratio of signal and sideband areas
- Systematic uncertainty evaluated using an enlarged sideband region
- Methodology validated with multi-photon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



Systematic uncertainties

- **Analysis sensitivity is limited by the available data statistics**
- 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 $Z \to ee$ events: up to 15%
- **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
- Theoretical uncertainties: around 6%

Statistical Analysis

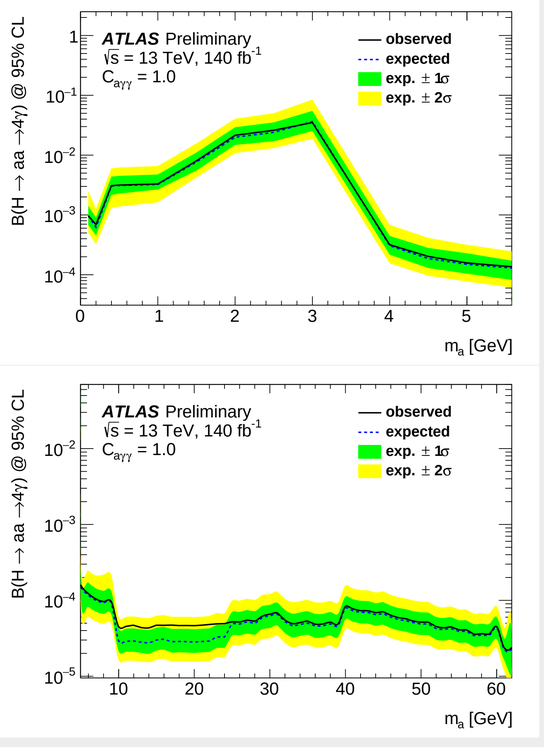


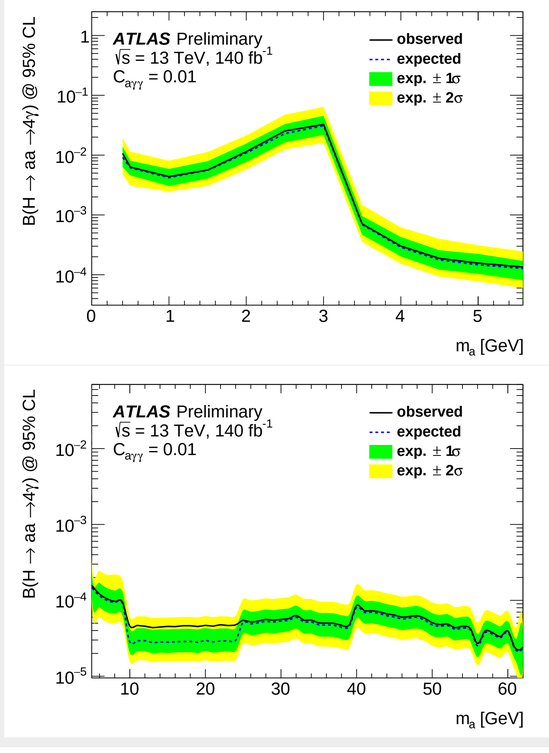
- Long-lived ALP search:
  - Perform maximum-likelihood fit of the m_{inv}^{reco} distribution in the 2 most sensitive categories
  - 2M and 1M1S for $m_a \leq 3.5\,\text{GeV}$
  - 4S and 3S for $m_a > 3.5\,\text{GeV}$
- Promptly decaying ALP search:
  - Maximum-likelihood fit with one bin
- Upper limits 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

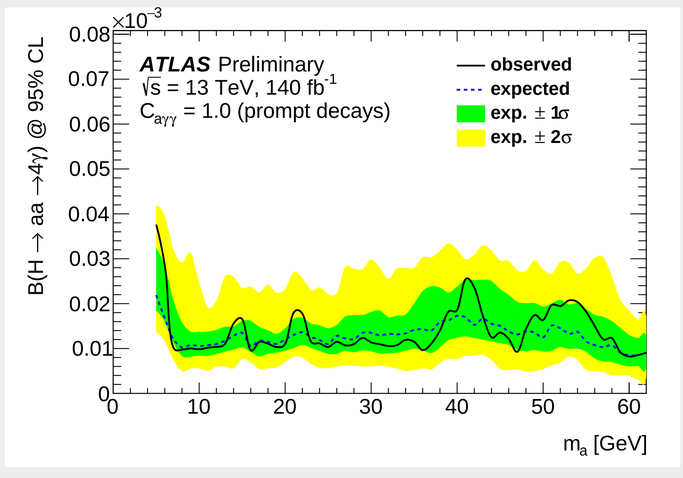
Conclusion

- The search aims to identify a narrow resonance with a mass between 0.1 and 62 GeV with a resonance decay up to a distance of 1970 mm
- NN classifiers are applied to distinguish between single and collimated photon signatures
- **A dedicated search strategy for long-lived ALP decays has been developed for the first time**
- **This results in the most stringent limits to date**
- **These limits exclude much of the remaining parameter space that could explain the $(g\text{-}2)_\mu$ discrepancy**

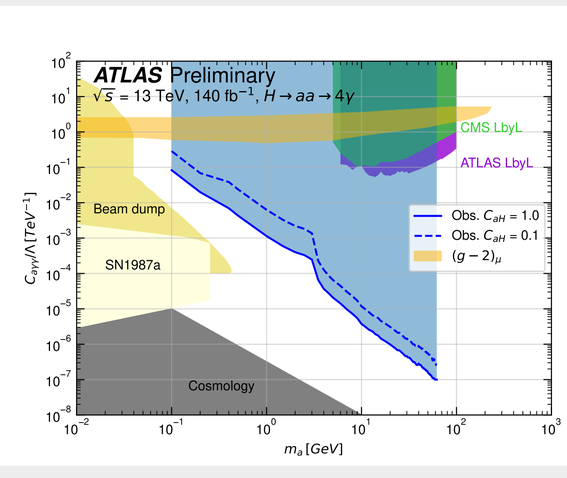
Results







- Limits are provided on $\mathcal{B}(H \to aa \to 4\gamma)$ for different couplings



- Convert limits on branching ratio to 2D exclusion in $C_{a\gamma\gamma}/m_a$ plane