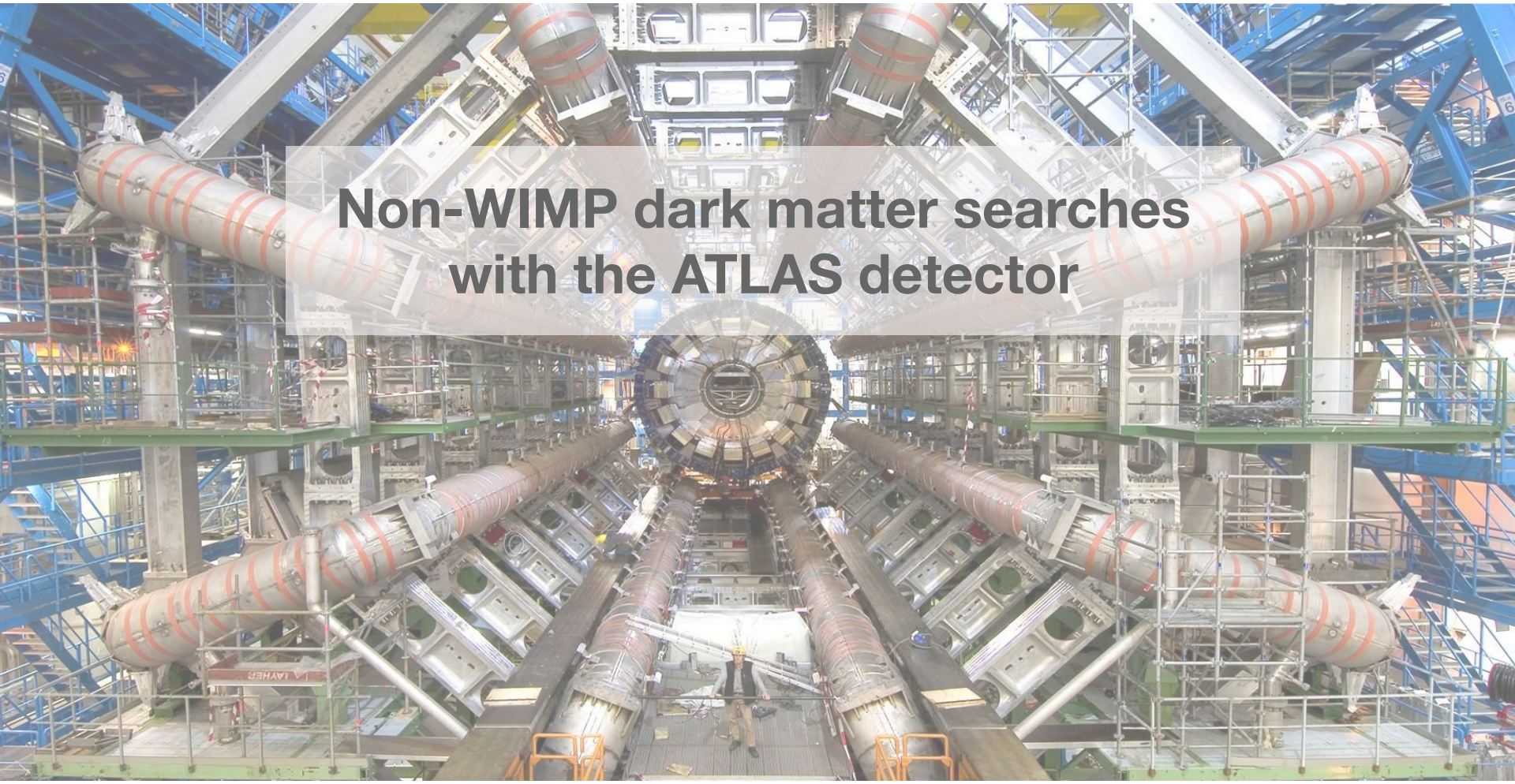


Non-WIMP dark matter searches with the ATLAS detector

Olivera Vujinović on behalf of the ATLAS Collaboration

Introduction

- Overview of results of recent searches on the dark sector, dark photons, LLPs, ALPs, dark QCD, semi-visible jets obtained with data collected in *pp* collisions at $\sqrt{s}$ = 13 TeV

- **Covered analyses:**
  - Search for neutral LLPs from Higgs boson decays via VBF production [ATLAS-CONF-2023-051]
  - Search for dark photons in rare Z boson decays [arXiv:2306.07413]
  - Search for an ALP with forward proton scattering in association with photon pairs [arXiv:2304.10953]
  - Search for short- and long-lived ALPs in $H \rightarrow aa \rightarrow 4\gamma$ decays with ATLAS [ATLAS-CONF-2023-040]

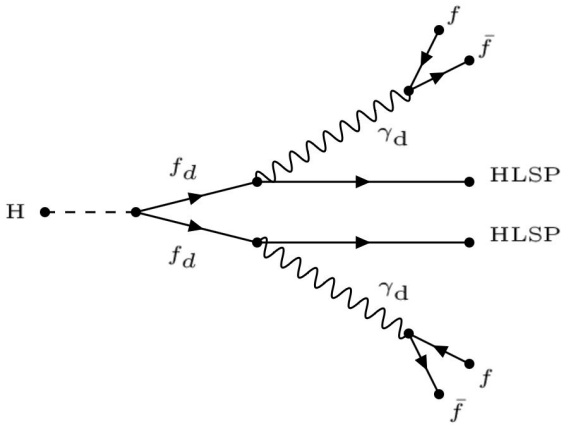
- **Other interesting results:**
  - Search for non-resonant production of semi-visible jets [arXiv:2305.18037]
  - Search for dark mesons decaying to top and bottom quarks [ATLAS-CONF-2023-021]
  - Search for resonant production of dark quarks in the di-jet final state [ATLAS-CONF-2023-047]

Search for neutral LLPs from Higgs boson decays via VBF production

[ATLAS-CONF-2023-051]

Analysis overview & motivation

- Search for dark photons with masses in range of 0.1 - 15 GeV
- Using full LHC Run-2 *pp* dataset (139 fb^{-1})
- Complements previous ATLAS searches in ggF and WH production channels
- Kinetic mixing parameter $\varepsilon(\gamma_d, \gamma_{SM}) < 10^{-5}$ results in:
  - displaced decays of dark photons
  - dark-photon masses in ~ MeV-GeV



f_d = dark fermion
γ_d = dark photon
γ_{SM} = Standard Model (SM) photon
HLSP = hidden lightest stable particle (stable dark fermion)

Search for neutral LLPs from Higgs boson decays via VBF production

[ATLAS-CONF-2023-051]

Analysis strategy

Muonic dark-photon jets (μDPJ)

- minimum 2 MS tracks; not matched to prompt muon candidates; no jets within $\Delta R = 0.4$
- **cosmic-ray tagger**: DNN used to distinguish signal from cosmic-ray bkg; output > 0.5; signal efficiency > 95%

Calorimeter dark-photon jets (caloDPJ)

- single jets with low EMF with $p_T > 20$ GeV and within $|\eta| < 2.5$
- **QCD tagger**: CNN used to reduce fake caloDPJs arising from prompt jets; output > 0.5; signal efficiency > 70%
- **BIB tagger**: CNN used to reject low EMF signatures in HCAL resulting from radiative losses by muons arising from BIB

Event selection

- only leading DPJ used to classify the events as μDPJ or caloDPJ
- ≥ two jets with $p_T \geq 30$ GeV
- $m_{jj} \geq 1000$ GeV
- $|\Delta\eta_{jj}| > 3$
- $|\Delta\phi_{jj}| < 2.5$ rad
- exactly 0 leptons
- exactly 0 b-tagged jets
- $E_T^{miss} \geq 100$ GeV

DPJ = dark-photon jets (collimated group of fermions)
MS = Muon Spectrometer
EMF (electromagnetic fraction) = ratio of the energy deposited in the EM calorimeter to the total jet energy
BIB = beam induced background

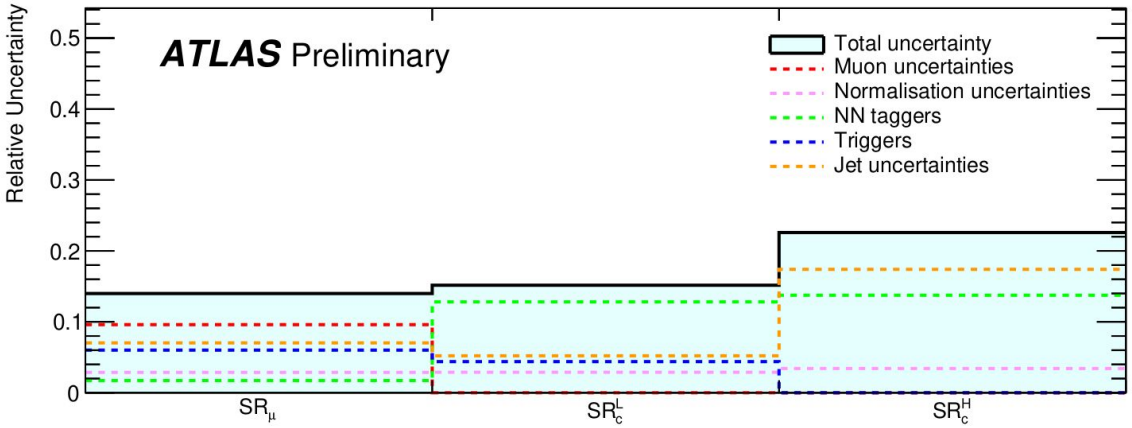
Search for neutral LLPs from Higgs boson decays via VBF production

[ATLAS-CONF-2023-051]

Dominant backgrounds

	E_T^{miss} [GeV]	Main bkg process	Bkg estimation technique
SR_μ	> 100	punch-through jets from rare multi-jet events	data-driven "ABCD" method
SR_c^L	[100, 225]	multi-jet and electroweak W and Z production	
SR_c^H	> 225		

Systematic uncertainties

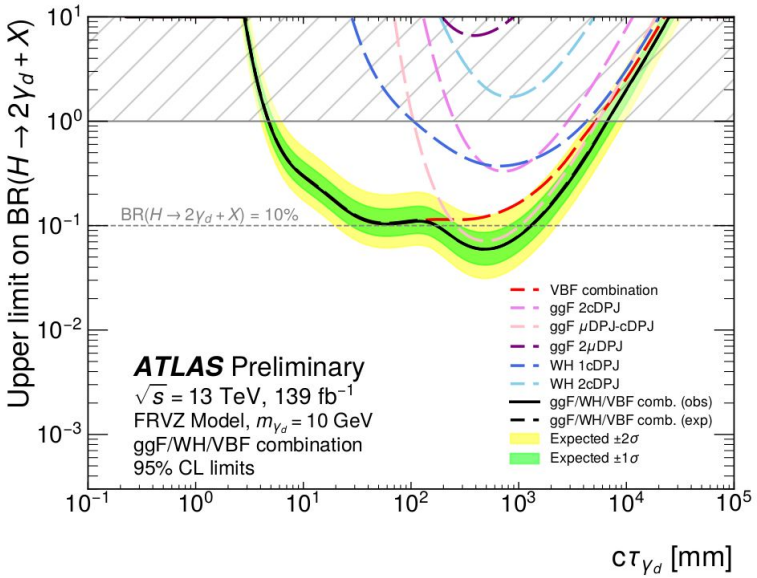


- Comparison of the relative uncertainty in the signal yield in each SR, showing the contributions from the different sources of uncertainty
- Averaged over different γ_d masses

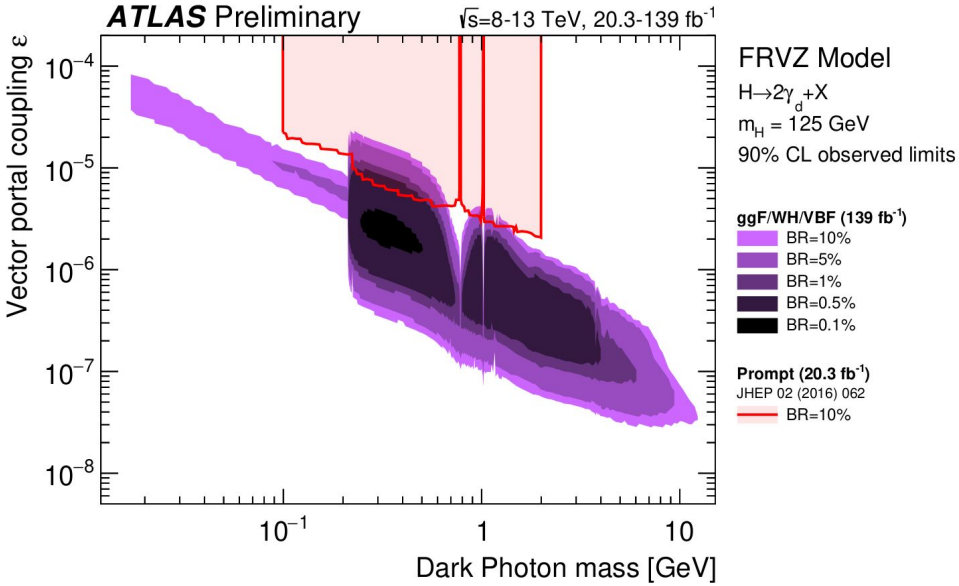
Search for neutral LLPs from Higgs boson decays via VBF production

[ATLAS-CONF-2023-051]

Analysis results



- Branching fractions above 10% can be excluded at 95% CL for $H \to 2\gamma_d + X$ decays for dark photons with mean proper decay length between 173 and 1296 mm and mass of 10 GeV, a 34% (26%) **improvement** in the low (high) range compared to the previous search including only ggF and WH production modes.



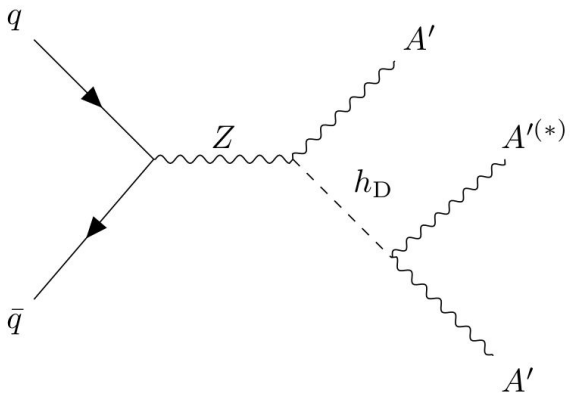
- The 90% CL exclusion contours of the $BR(H \to 2\gamma_d + X)$ as a function of the γ_d mass and ε
- Limits obtained assuming the SM cross-section for a 125 GeV Higgs boson and branching fractions between 0.1% and 10% for Higgs boson decays resulting in dark photons

Search for dark photons in rare Z boson decays

[arXiv:2306.07413]

Analysis overview & motivation

- Search for dark photons with masses in range of 5 - 40 GeV except for the Y mass window [8.8, 11.1] GeV
- Using full LHC Run-2 *pp* dataset (139 fb^{-1})
- Process: $pp \rightarrow Z \rightarrow A'h_D \rightarrow A'A'A'^{(*)}$
- Kinetic mixing parameter $\varepsilon(A', \gamma_{SM}) > 10^{-6}$ results in:
  - prompt decays of dark photons
- Hidden-sector gauge coupling α_D: coupling of the A' to DS particles



h_D = dark Higgs boson
A' = dark photon which decays to SM fermions
γ_{SM} = Standard Model (SM) photon

Search for dark photons in rare Z boson decays

[arXiv:2306.07413]

Event selection

- muon candidates: p_T > 15 GeV; electron candidates: p_T > 4.5 GeV
- ≥ two same-flavour and opposite-charge (SFOC) lepton pairs
- $m_{4\ell} < m_Z - 5$ GeV to suppress the SM $pp \to 4\ell$ background
- the lepton quadruplet is selected such that $|m_{\ell+\ell-} - m_{\ell'+\ell'-}|$ is minimal
- $m_{\ell 3 \ell 4}/m_{\ell 1 \ell 2} > 0.85$ to ensure both originate from an *A*' decay
- same- (different-) flavored leptons are required to have an angular separation of $\Delta R > 0.1$ (0.2)
- $m_{\ell+\ell-} > 5$ GeV

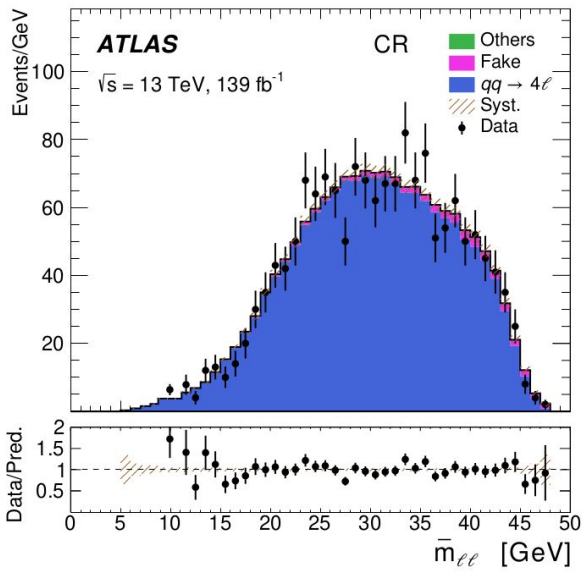
Background contribution

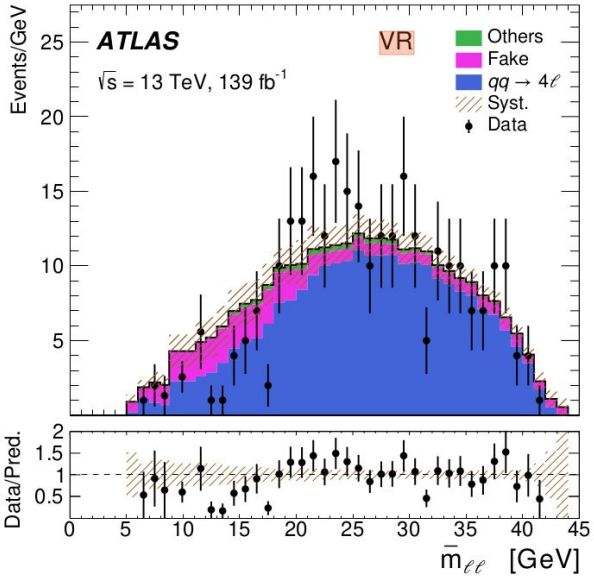
- Dominant bkg in SR: $qq \to 4\ell$ process
- CR: $m_Z - 5$ GeV $< m_{4\ell} < m_Z + 5$ GeV; VR: same as SR but $m_{\ell 3 \ell 4}/m_{\ell 1 \ell 2} < 0.85$
- Subleading bkg: from processes involving the production of Z+jets, top-quark and $WZjj$ events, with non-prompt leptons from hadron decays or misidentification of jets
- $pp \to H \to 4\ell$, the $gg \to ZZ \to 4\ell$ continuum, and triboson and ttZ processes < 5%

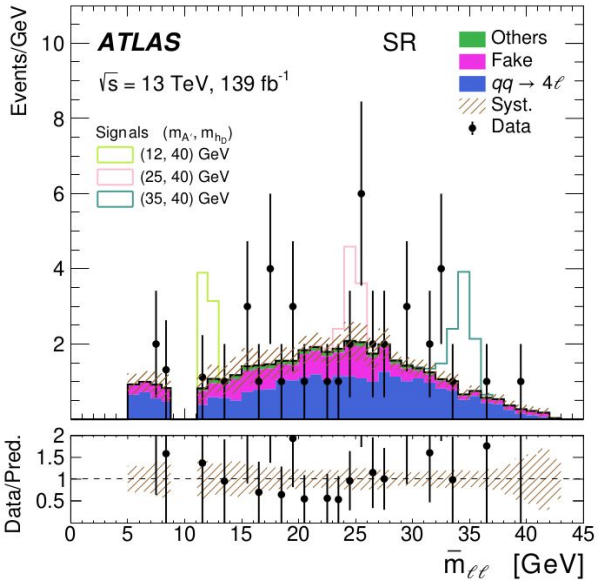
Search for dark photons in rare Z boson decays

[arXiv:2306.07413]

Expected background and observed data yields





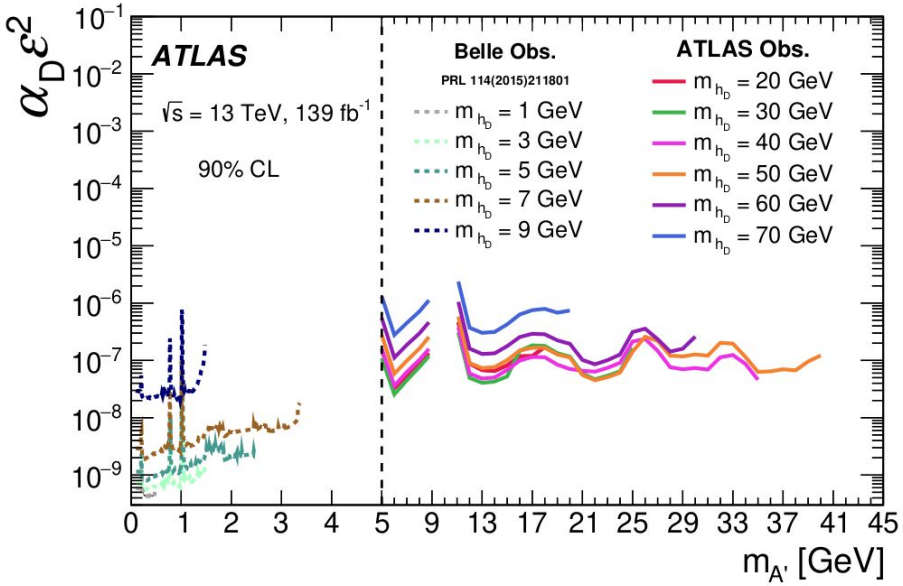


- Data found to be consistent with the background expectation in all three regions
- No significant deviation from the SM background hypothesis is observed

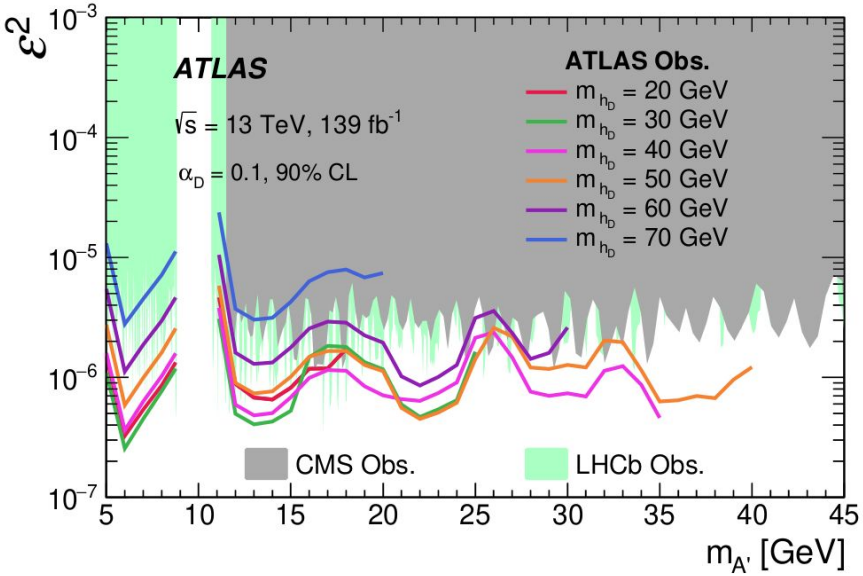
Search for dark photons in rare Z boson decays

[arXiv:2306.07413]

Analysis results



- Observed 90% CL upper limits on $\alpha_D\varepsilon^2$, as a function of $m_{A'}$ with different h_D masses
- **The search is sensitive to a set of $m_{A'}$ and m_{h_D} masses complementary to those in a similar search reported by the Belle Collaboration**



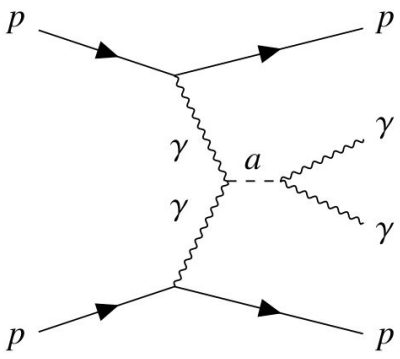
- Observed 90% CL upper limits on ε^2 , assuming of α_D = 0.1, as a function of $m_{A'}$ with 20 GeV < m_{hD} < 70 GeV
- For $m_{h_D} \lesssim 60$ GeV and $\alpha_D \gtrsim 0.1$, the **exclusion sensitivity of this search is comparable to, or better than, that of the LHCb and CMS searches**

Search for an ALP with forward proton scattering in association with photon pairs

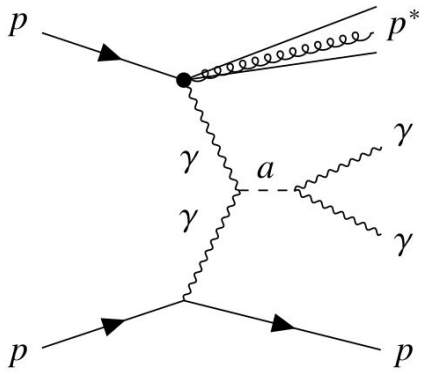
[arXiv:2304.10953]

Analysis overview & motivation

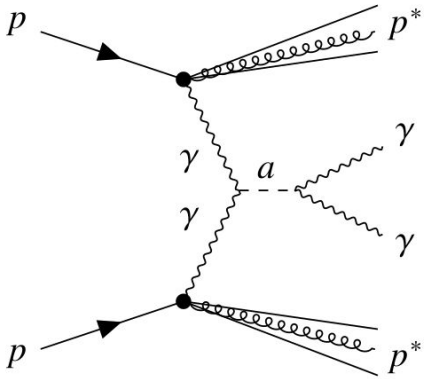
- Covering diphoton-mass range of 150 - 1600 GeV
- Using 14.6 fb^{-1} of data collected in *pp* collisions at $\sqrt{s}$ = 13 TeV
- Pair of outgoing photons detected in the central detector around IP while scattered protons are detected by ATLAS Forward Proton (AFP) spectrometer system (proton tagging)



exclusive light-by-light scattering



single-dissociative (SD) light-by-light scattering

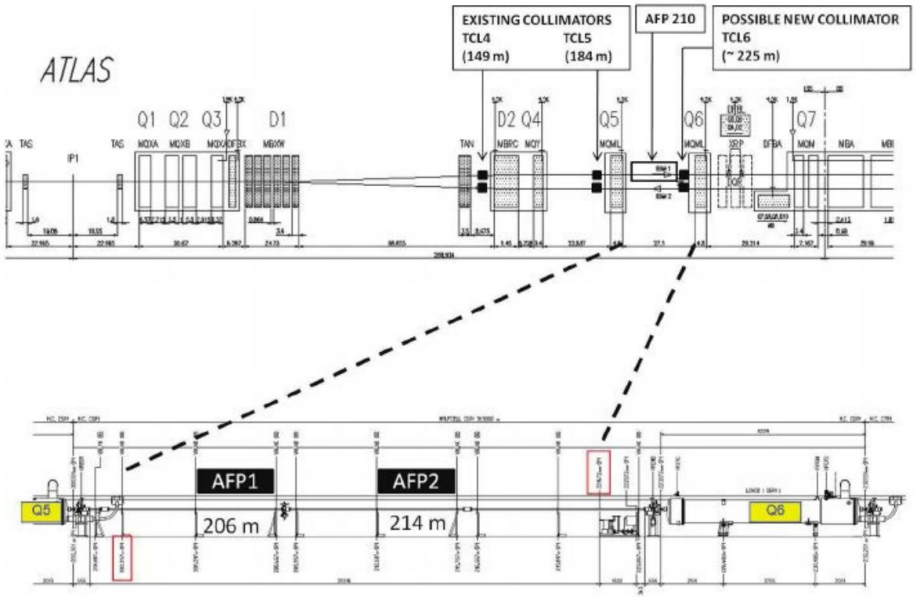


double-dissociative (DD) light-by-light scattering

Search for an ALP with forward proton scattering in association with photon pairs

[arXiv:2304.10953]

Experimental setup



- ATLAS Forward Proton (AFP) spectrometer system: Roman Pot systems used to detect forward scattered protons
- 4 tracking units located at $z = \pm 205$ m (Near station) and ± 217 m (Far station); each pair on A and C side

- Protons transported to the AFP by the beamline magnets leave hits in its silicon trackers ⇒ processed by per-plane clustering and per-station track-finding algorithms ⇒ tracks are reconstructed from clusters found in at least two planes in each station

Search for an ALP with forward proton scattering in association with photon pairs

[arXiv:2304.10953]

Event selection

ATLAS ECAL

- ≥ 2 photon candidates with $p_T > 40$ GeV and $|\eta| < 2.37$, excluding $1.37 < |\eta| < 1.52$
- azimuthal misalignment between the pair of photons was required to be small, as determined by an acoplanarity $A_\phi^{\gamma\gamma} = 1 - |\Delta\phi_{\gamma\gamma}|/\pi < 0.01$

AFP

- Track spatial coordinates ⇒ proton energy and momentum at the IP, using the known beam optics ⇒ reconstruction:

fractional energy loss of the scattered proton: $\xi_{\text{AFP}} = 1 - E_{\text{scattered}}/E_{\text{beam}}$

ξ using the kinematics of the central photon pair: $\xi_{\gamma\gamma}^{\pm} = (m_{\gamma\gamma}/\sqrt{s})\, e^{\pm\eta\gamma\gamma}$

- Proton-tagged diphoton pairs required on at least one AFP side (forward-proton matching):

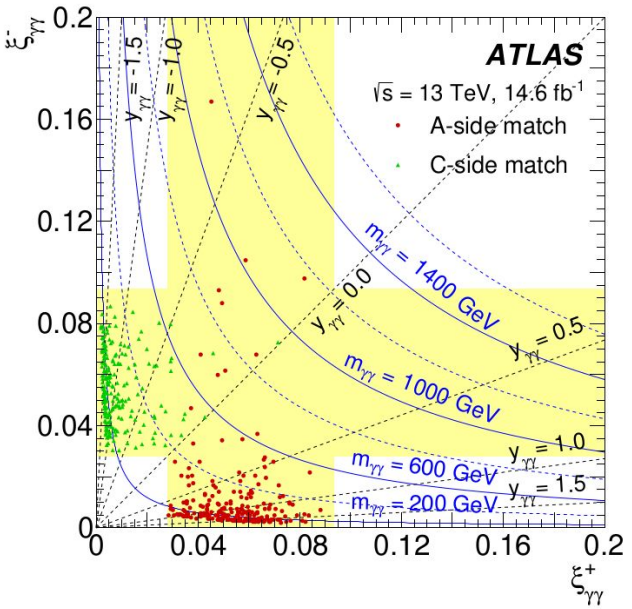
$$|\Delta\xi| = \xi_{\text{AFP}} - \xi_{\gamma\gamma} < \xi_{\text{th}} \; ; \; \xi_{\text{th}} = 0.004 + 0.1\xi_{\gamma\gamma}$$

Search for an ALP with forward proton scattering in association with photon pairs

[arXiv:2304.10953]

Selection efficiency

- A total of 441 events observed in range $150 < m_{\gamma\gamma} < 1600$ GeV
- 219 (222) events passed the matching selection for the A(C)-side
- No event passed the matching requirement for both the A-side and C-side



Dominant backgrounds

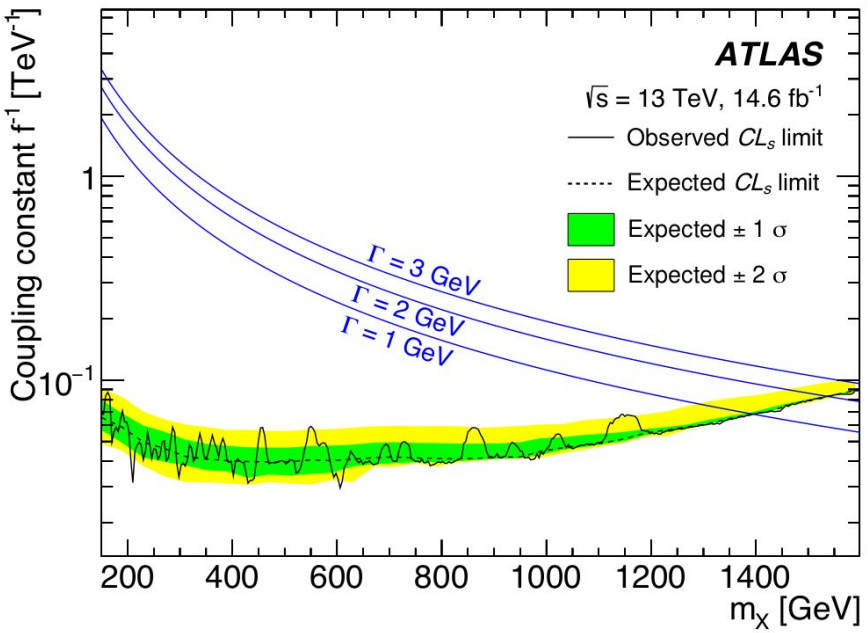
- Combinatorial backgrounds: pair of photons (or hadronic jets misidentified as photons) produced in a pp interaction other than that giving the detected forward protons but within the same bunch crossing
- single-vertex backgrounds: $\gamma\gamma \to \ell^+\ell^-$, $\gamma\gamma \to \gamma\gamma$, gluon-initiated central exclusive production (CEP)

Search for an ALP with forward proton scattering in association with photon pairs

[arXiv:2304.10953]

Analysis results

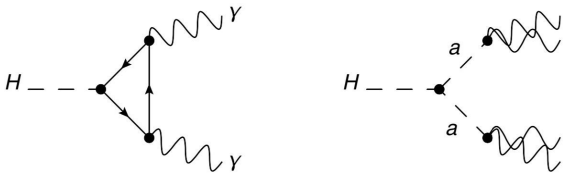
- Inferred upper limit on the ALP coupling constant, assuming a 100% decay branching ratio into two photons: in the range 0.04 – 0.09 TeV^{-1} at 95% CL
- Results **comparable to those of the** CMS-TOTEM collaboration and **extending** their measured mass range to lower values



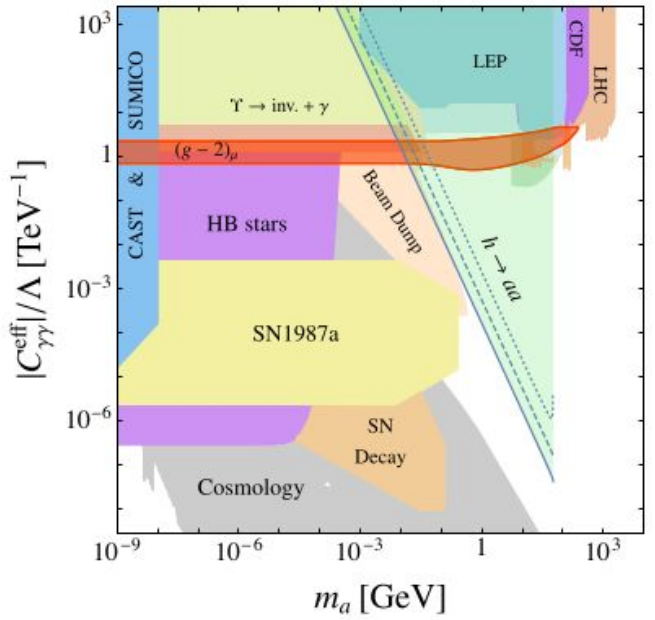
Search for short- and long-lived ALPs in $H \to aa \to 4\gamma$ decays with ATLAS

[ATLAS-CONF-2023-040]

Analysis motivation



- Probing unconstrained m_a - $C_{\gamma\gamma}$ parameter space:
  - $(gg)H \to aa \to \gamma\gamma\gamma\gamma$
  - 100 MeV ≤ m_a ≤ 62 GeV
  - 1e-5 ≤ $C_{\gamma\gamma}$ ≤ 1

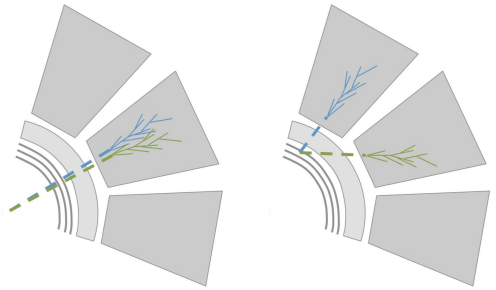


M. Bauer, M. Neubert, and A. Thamm, J. High Energ. Phys. 2017, 44 (2017)

Challenges

- ALPs with long lifetimes can decay close to ECAL
- Requiring that axions decay within ECal (< 1970 mm)

$$\Gamma_{a\gamma\gamma} = \frac{4\pi\alpha^2 m_a^3}{\Lambda^2}|C_{a\gamma\gamma}|^2$$



Search for short- and long-lived ALPs in $H \to aa \to 4\gamma$ decays with ATLAS

[ATLAS-CONF-2023-040]

- **Photon ID** based on 2 NNs (each with 2 hidden layers - 7 and 5 nodes; with shower shapes used as input variables):

NN1: real vs. fake photons

- Signal: H→ aa, H → γγ
- Background: selected data with photons such that $p_T > 15$ GeV, fail loose ID, isolated (ETCone40/$p_T < 0.1$), $m_{inv} > 60$ GeV (Higgs region excluded)

NN2: merged vs. single photons

- Signal: H→aa →γγγγ merged photons
- Background: H→aa →γγγγ single photons

- Each photon gets one of 3 labels:
  - merged (ANN1 > 0.98, ANN2 > 0.5, !tight)
  - loose
  - tight

Search for short- and long-lived ALPs in $H \to aa \to 4\gamma$ decays with ATLAS

[ATLAS-CONF-2023-040]

- Resulting in 5 categories:
  - **4S**: 4 loose photons, at least 1 (≥ 3) tight photon
  - **3S**: 2 tight + 1 loose photons
  - **2M**: 2 merged photons
  - **1M1S**: 1 merged + 1 loose photon
  - **2S**: 2 tight photons (dominated by H → γγ background)

Prompt analysis ($4S_p$): more stringent categorization criteria (loosened needed for long-lived case as ID efficiency drops for axions decaying closer to the ECal

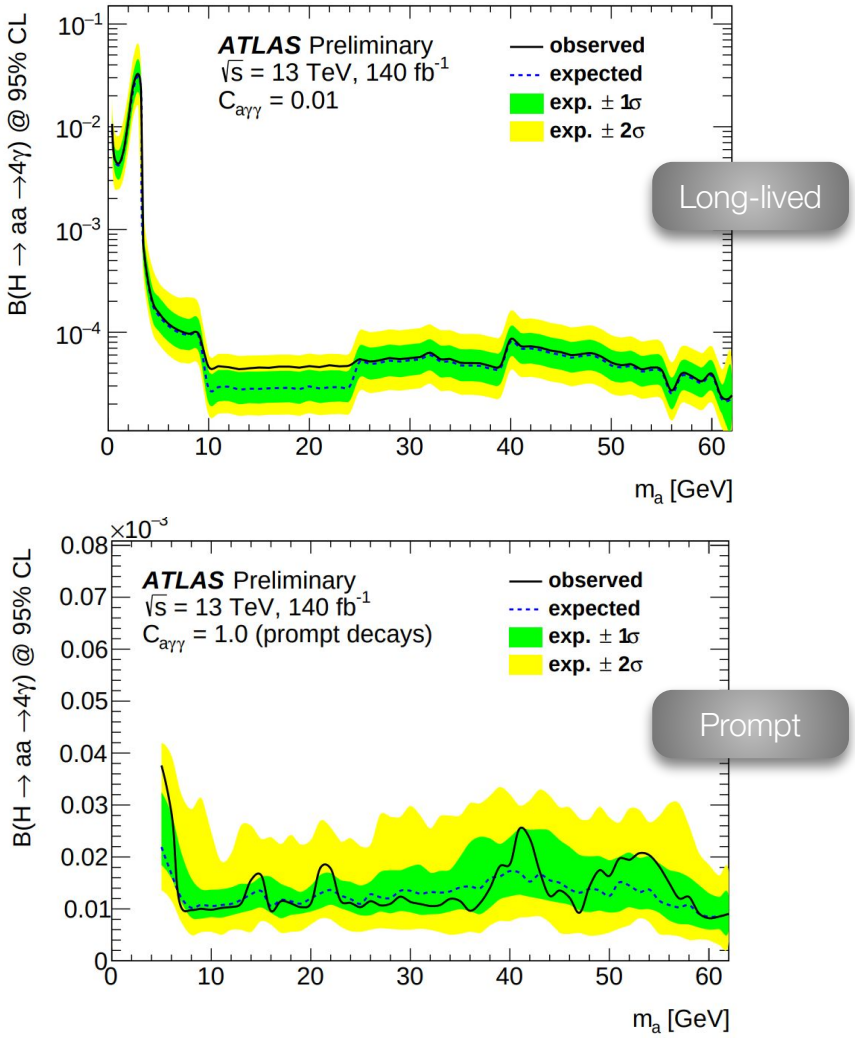
- **Axion mass reconstruction**: only possible in 3S and 4S categories; used to define SR and CR (by inverting the axion mass requirement)
- 2 NNs for each case:
  - Input: m_{inv} of all possible di-photon combinations, pairwise differences in p_T, pairwise differences in direction
  - Labels based on MC truth information

Search for short- and long-lived ALPs in $H \to aa \to 4\gamma$ decays with ATLAS

[ATLAS-CONF-2023-040]

Limits

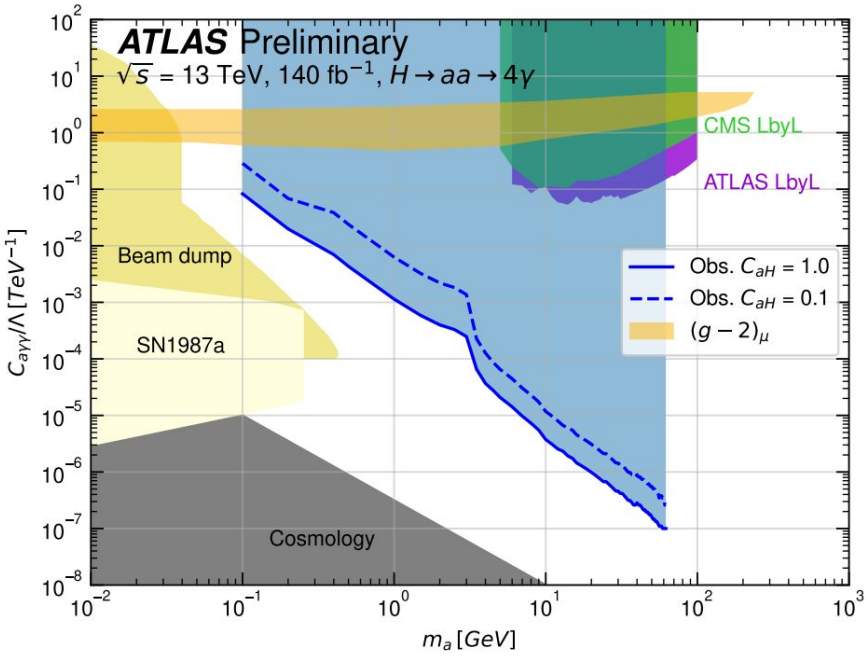
- Setting upper limits on B ($H \to aa \to 4\gamma$) at 95% CL as a function of the axion mass and for different ALP-photon couplings
- The long-lived searches significantly less sensitive than the prompt searches due to the looser signal selection and consequently larger background contributions
- The observed limits agree well with the expected limits



Search for short- and long-lived ALPs in $H \to aa \to 4\gamma$ decays with ATLAS

[ATLAS-CONF-2023-040]

- Limits on ALP masses with $m_a > 15$ GeV:
  - ~ one order of magnitude more stringent than previous ATLAS analyses using 8 TeV data
  - similar to slightly better sensitivity as previous analyses from CMS using 132 fb^{-1} of $\sqrt{s}$ = 13 TeV data
- First limits on ALPs with masses < 10 GeV derived at ATLAS
  - 40% more stringent compared to the previous results from CMS using 136 fb^{-1} of $\sqrt{s}$ = 13 TeV
- **Most stringent limits to date**
- Excluded most of the remaining parameter space that could explain the **$(g\text{-}2)_\mu$ discrepancy**



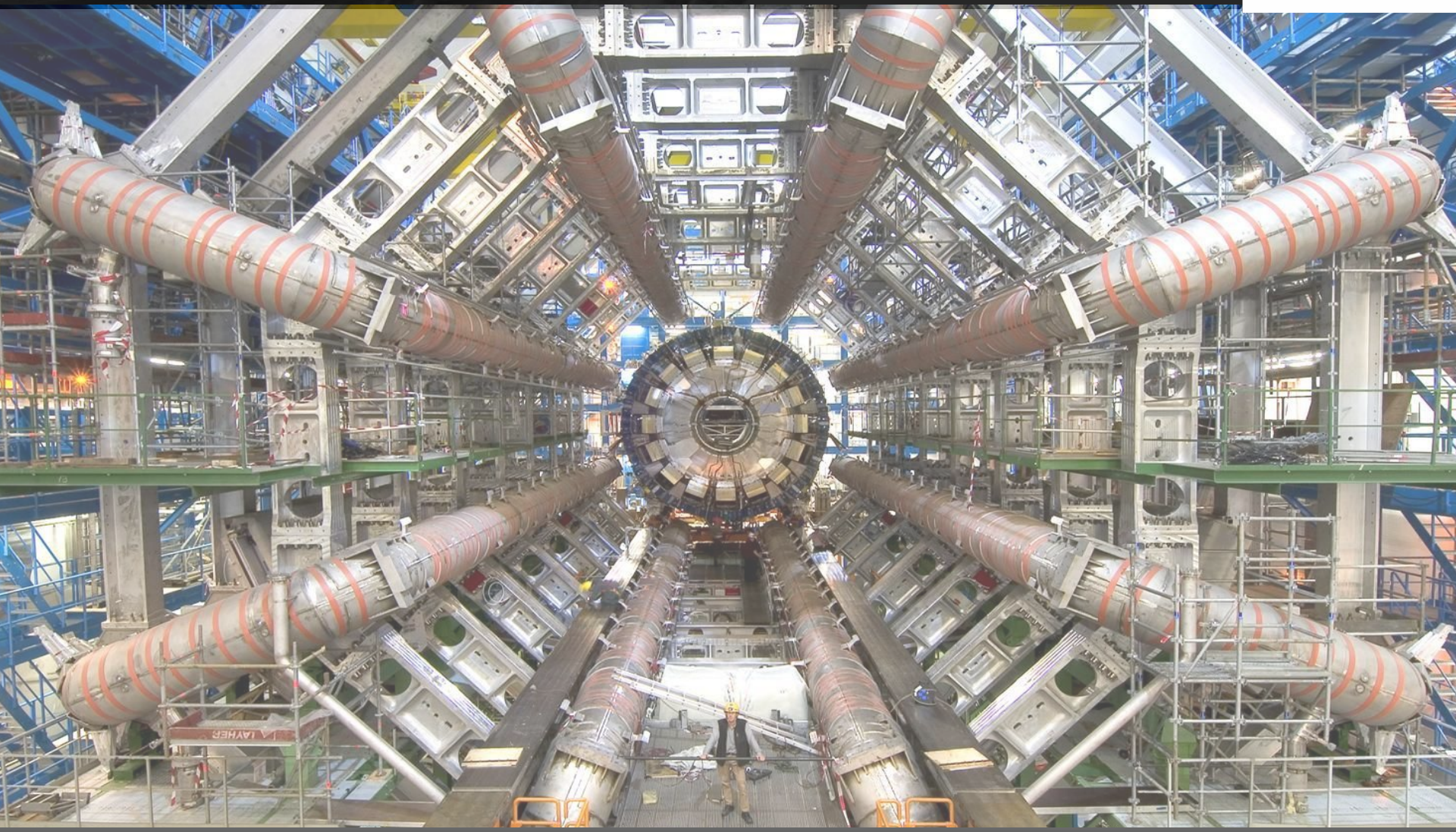
Limits on the ALP mass and coupling to photons at 95% CL, assuming $|C_{aH}^{eff}|/\Lambda^2 = 1$ TeV^{-2} (solid line) and $|C_{aH}^{eff}|/\Lambda^2 = 0.1$ TeV^{-2} (dashed line)

Summary

- **Search for neutral LLPs from Higgs boson decays via VBF production** [ATLAS-CONF-2023-051]: 34% (26%) improvement in the low (high) range compared to the previous search including only ggF and WH production modes
- **Search for dark photons in rare Z boson decays** [arXiv:2306.07413]: results complementary to, and higher than, results by the Belle Collaboration; exclusion sensitivity omparable to, or better than, results by LHCb and CMS searches
- **Search for an ALP with forward proton scattering in association with photon pairs** [arXiv:2304.10953]: comparable to results by CMS-TOTEM collaboration and extending their measured mass range to lower values
- **Search for short- and long-lived ALPs in $H \to aa \to 4\gamma$ decays with ATLAS** [ATLAS-CONF-2023-040]: First limits on ALPs with masses < 10 GeV derived at ATLAS; 40% more stringent compared to the previous results from CMS using 136 fb^{-1} of $\sqrt{s}$ = 13 TeV

- ATLAS focuses on furthering the searches for BSM physics
- More theoretical models needed

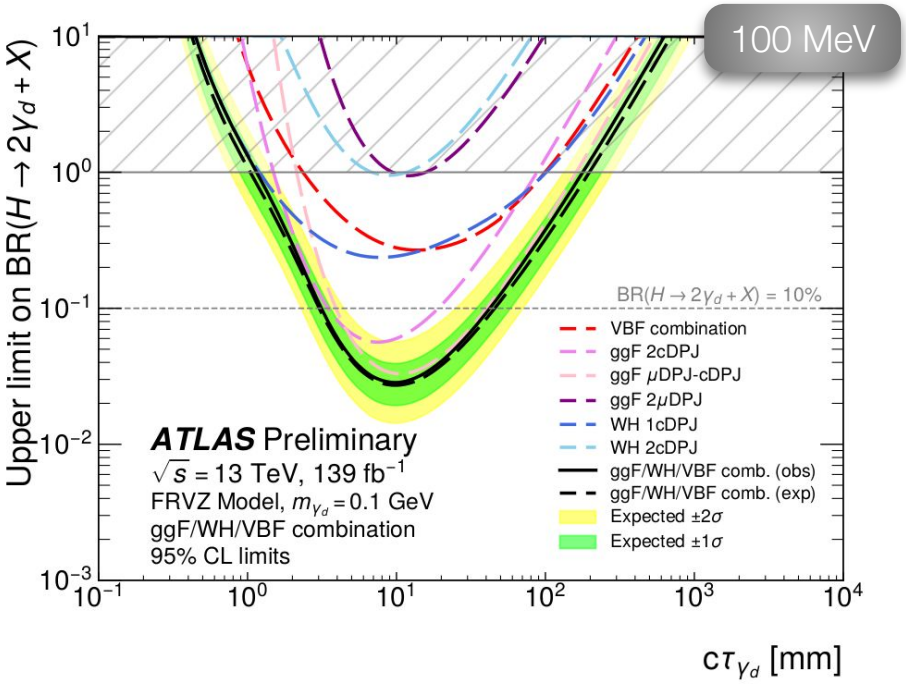
Back-up slides

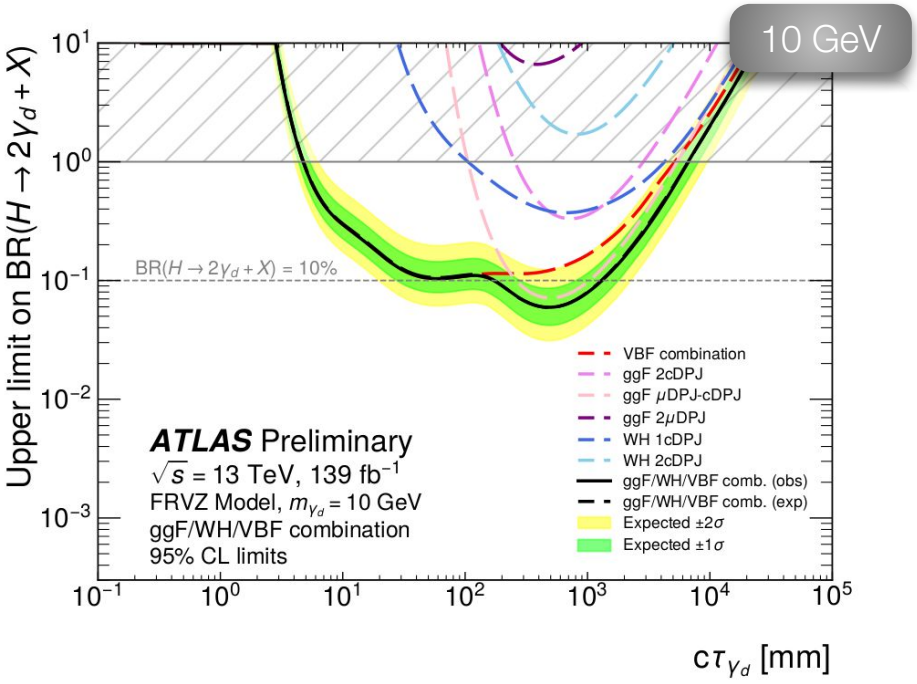


Search for neutral LLPs from Higgs boson decays via VBF production

[ATLAS-CONF-2023-051]

Analysis results

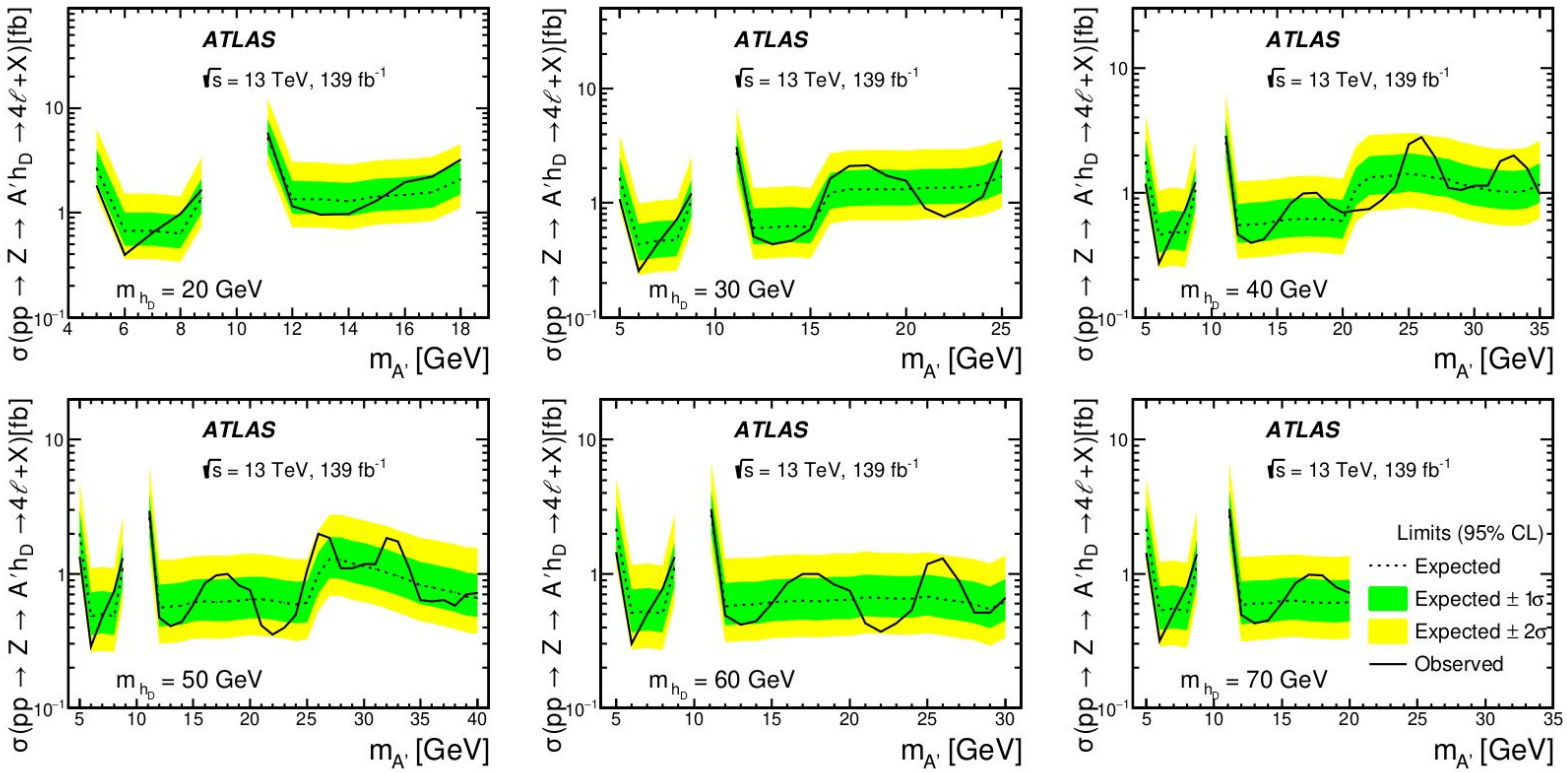




Search for dark photons in rare Z boson decays

[arXiv:2306.07413]

Observed and expected upper limits

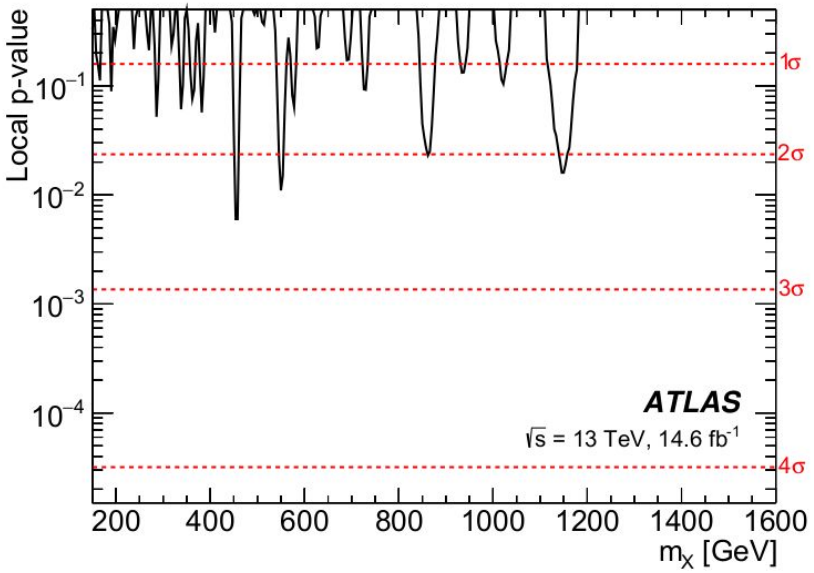


Search for an ALP with forward proton scattering in association with photon pairs

[arXiv:2304.10953]

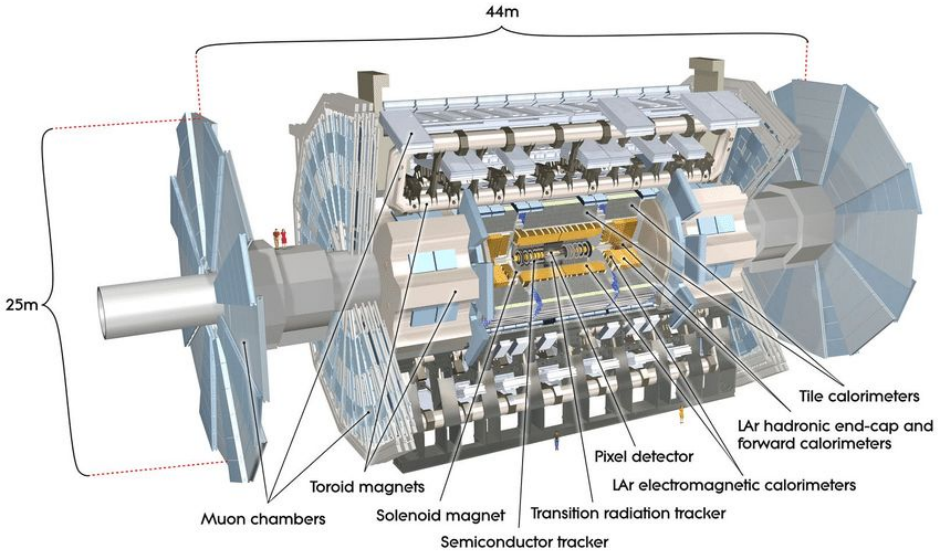
Statistical procedure

- The probability of compatibility with the background-only hypothesis, quantified as the local p-value, is shown as a function of the hypothesised ALP resonance mass
- The most significant excess, observed at m_X = 454 GeV, has a local significance of 2.51σ
- The global p-value for the null hypothesis is larger than 0.5, from which it is concluded that no significant excess over the background-only hypothesis is observed

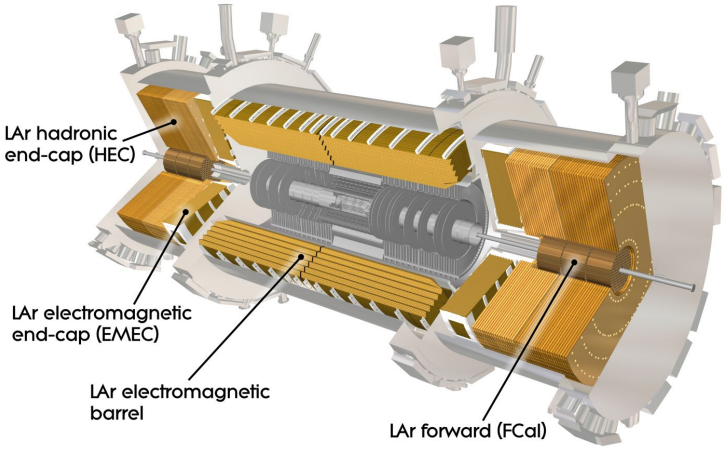


Photon identification & reconstruction in ATLAS

[ATLAS-CONF-2023-040]



Calorimeter system



- Liquid argon calorimeter (LAr)
  - specially designed to identify electrons and photons; honeycomb pattern
  - kept at -184°C
  - features layers of metal (either tungsten, copper or lead) that absorb incoming particles, converting them into a “shower” of new, lower energy particles, which ionise liquid argon sandwiched between the layers, producing an electric current that is measured

Photon identification & reconstruction in ATLAS

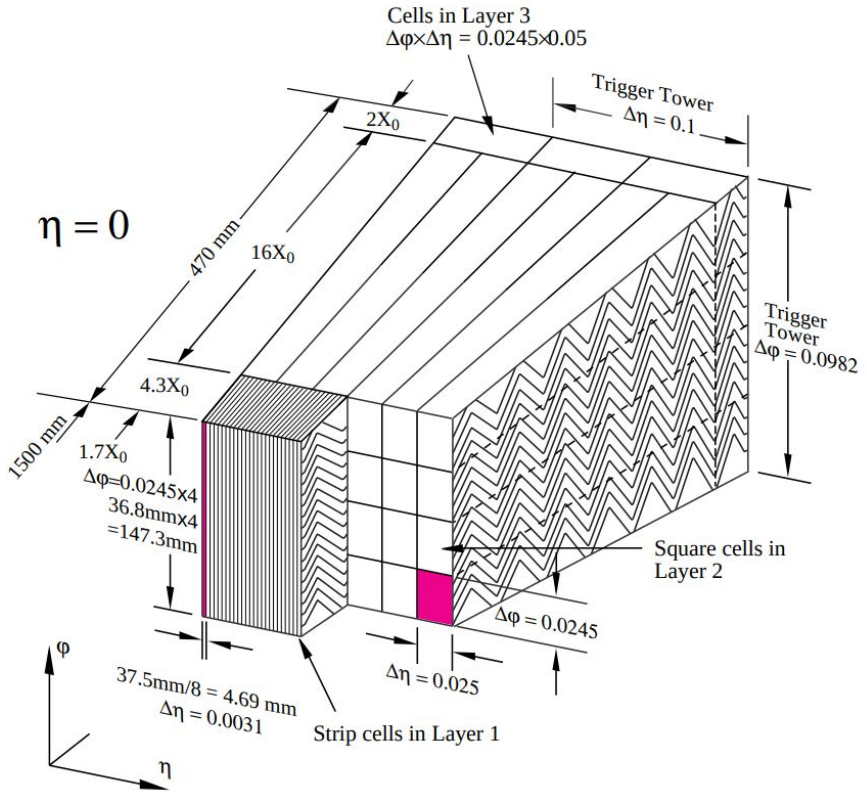
[ATLAS-CONF-2023-040]

- 9 discriminating variables (DVs) based on energy in cells of ECAL and leakage in hadronic calorimeter HCAL

- Loose ID:
  - exploits the DVs in the HCAL and in the ECAL middle layer
  - used by triggers or as background control region

- Tight ID:
  - tighter cuts on DVs than the ones used by Loose ID
  - using also ECAL strip layer
  - used for offline analysis

- Sketch of a barrel module with the granularity of cells depicted in η and ϕ



Photon identification & reconstruction in ATLAS

[ATLAS-CONF-2023-040]

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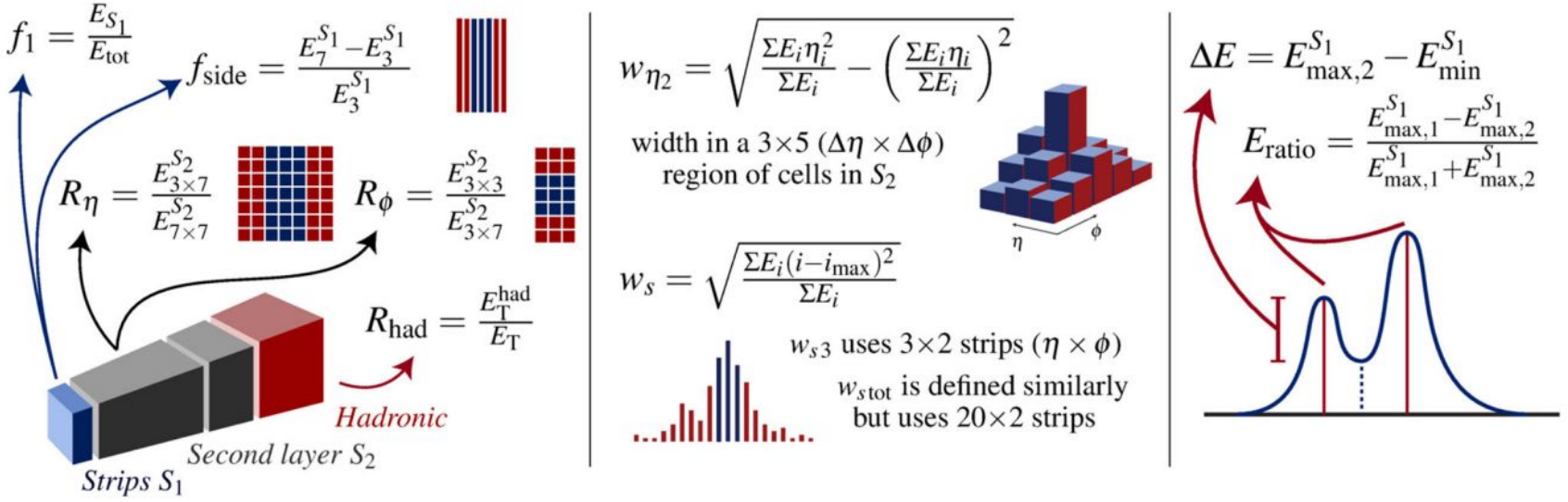


Fig. 2 Schematic representation of the photon identification discriminating variables, from Ref. [23]. $E_C^{S_N}$ identify the electromagnetic energy collected in the N-th longitudinal layer of the electromagnetic calorimeter in a cluster of properties C, identifying the number and/or properties of selected cells. E_i is the energy in the i-th cell, η_i the pseudorapidity centre of that cell

Taken from: https://link.springer.com/content/pdf/10.1140/epjc/s10052-019-6650-6.pdf

Event selection

[ATLAS-CONF-2023-040]

Event selection

- Preselection:
  - diphoton triggers
  - ≥ 1 reconstructed PV
  - > 2 photons with p_T > 15 GeV and $|\eta| < 2.37$ (calo crack excluded)
  - track based isolation: $p_T^{cone20}/p_T < 0.05$

Search for short- and long-lived ALPs in $H \to aa \to 4\gamma$ decays with ATLAS

[ATLAS-CONF-2023-040]

2-photon final states

- Using a sideband in m_H distribution to fit the background contribution in [100, 150] GeV, excluding signal region
- Used fit functions:
  - 2S and 1M1S: Landau
  - 2M: Polynomial of 3rd order
- Cross-checks:
  - 2y QCD MC
  - data driven: inverted isolation cut

3- and 4-photon final states

- 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
- Used fit functions:
  - Polynomial of 3rd order
- Cross-checks:
  - 3y, 4y QCD MC
  - data driven: inverted axion mass requirement

Prompt final states

- Considering only 4S case with $m_A > 5$GeV; 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 with 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
- Background estimated as an average of data events in the CR

Search for short- and long-lived ALPs in $H \to aa \to 4\gamma$ decays with ATLAS

[ATLAS-CONF-2023-040]

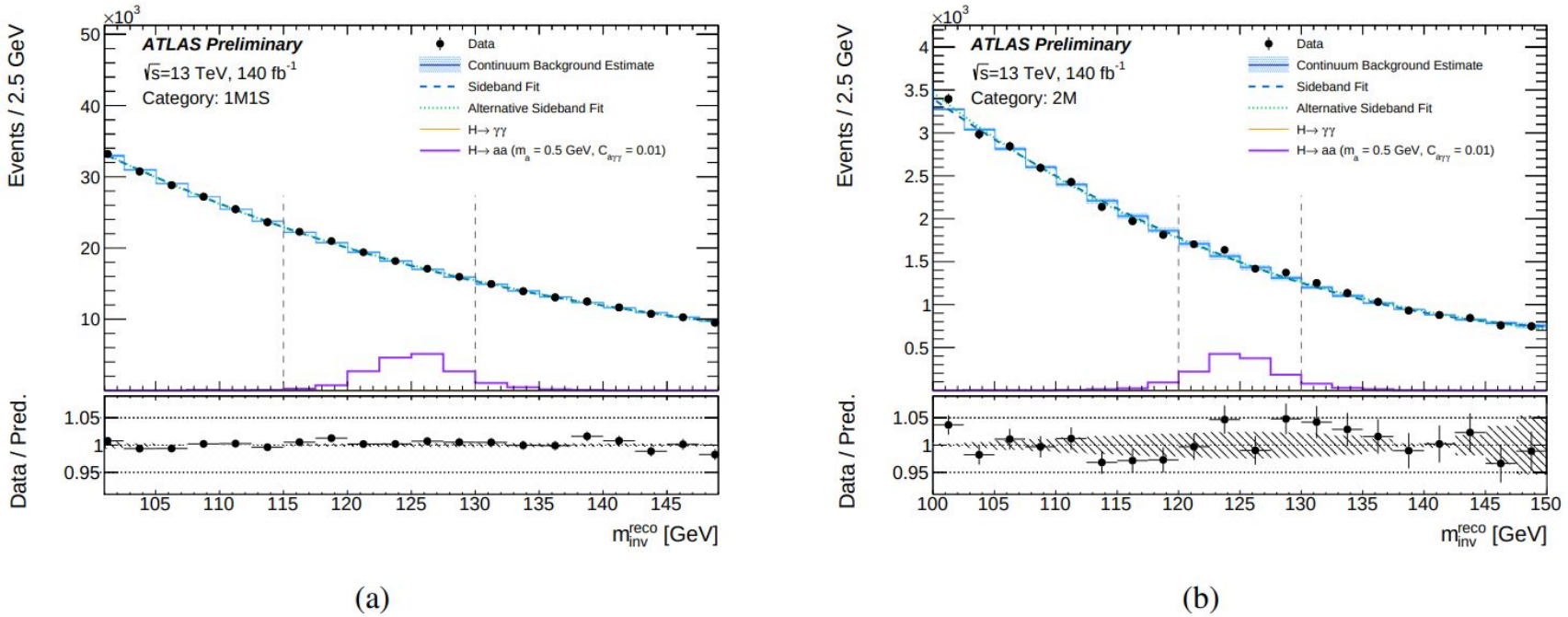
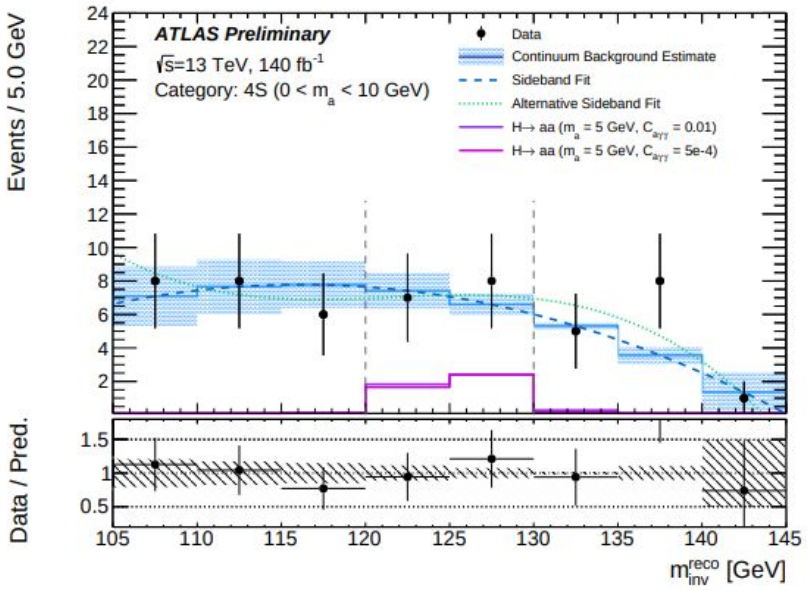


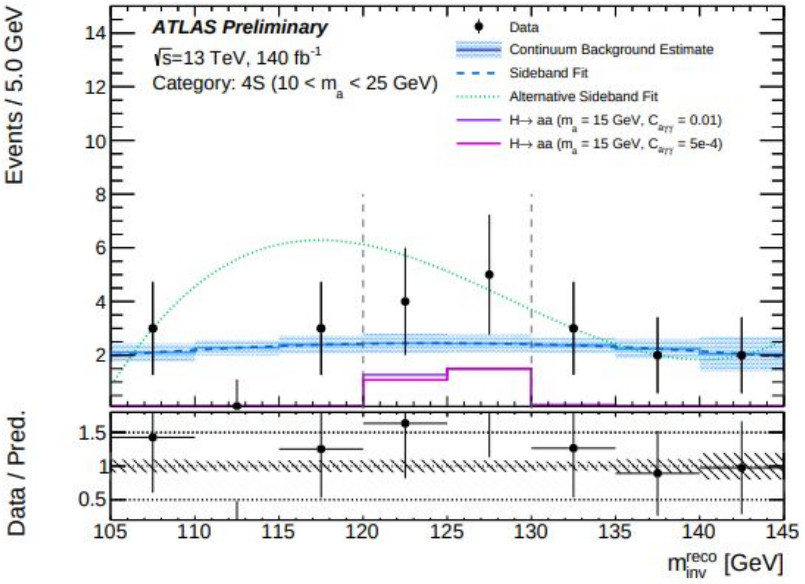
Figure 1: $m_{\text{inv}}^{\text{reco}}$ distribution for the nominal signal selection for the (a) 1M1S, and (b) 2M category. The nominal sideband fitting function as well as its systematic variation is shown for both cases. The expected signal shape for $C_{ayy} = 0.1$ is also shown with an arbitrary normalization. The signal region selection on $m_{\text{inv}}^{\text{reco}}$ is indicated as dashed lines.

Search for short- and long-lived ALPs in $H \to aa \to 4\gamma$ decays with ATLAS

[ATLAS-CONF-2023-040]



(a)



(b)

Search for short- and long-lived ALPs in $H \to aa \to 4\gamma$ decays with ATLAS

[ATLAS-CONF-2023-040]

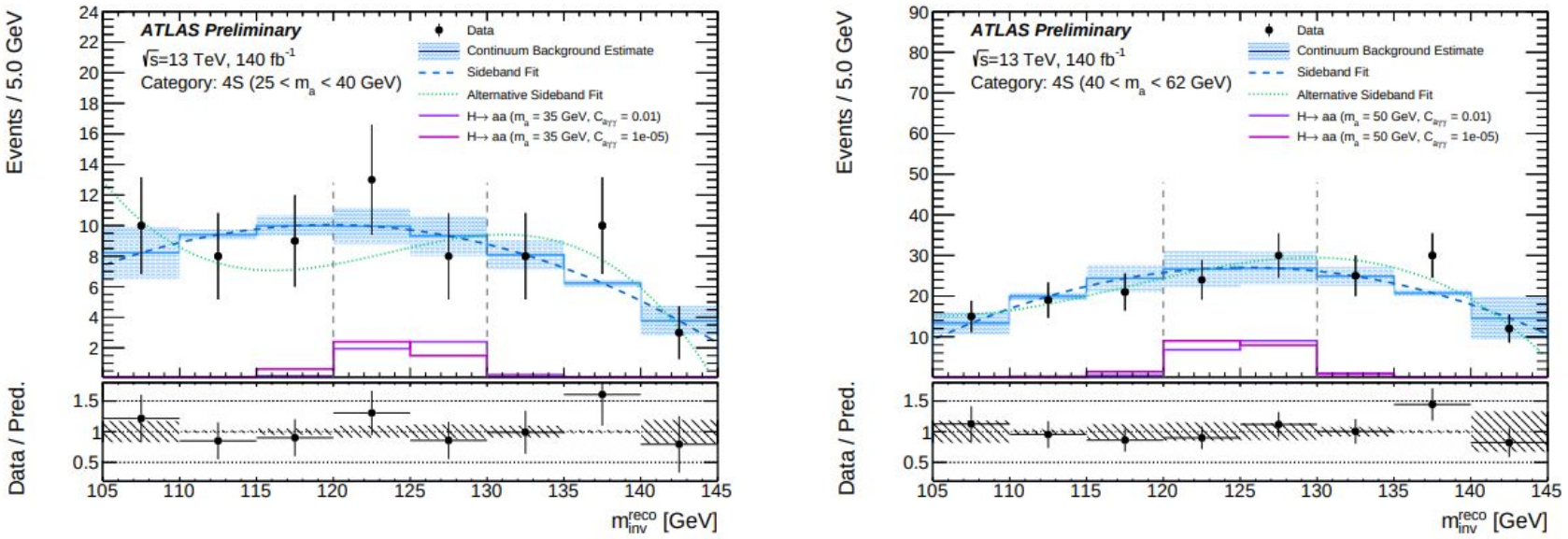
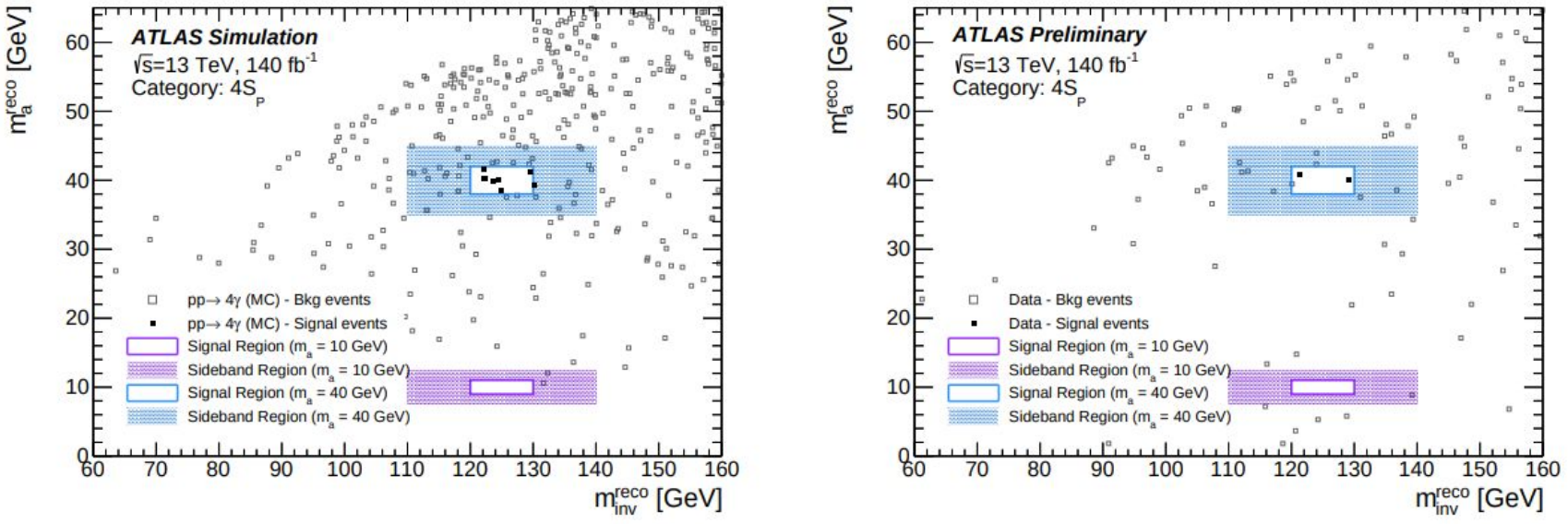


Figure 2: 4S category in the search for long-lived ALPs: $m_{\text{inv}}^{\text{reco}}$ distribution for the nominal signal selection including the nominal and alternative sideband fitting functions, the estimated background from the sideband fit in the signal region as well as the expected signal shape for two ALP-photon couplings with arbitrary normalization. The 4 plots show different ALP mass ranges: (a) $0 < m_a < 10\,\text{GeV}$, (b) $10 < m_a < 25\,\text{GeV}$, (c) $25 < m_a < 40\,\text{GeV}$, (d) $40 < m_a < 62\,\text{GeV}$. The signal region selection on m_a^{reco} is applied while the signal region selection on $m_{\text{inv}}^{\text{reco}}$ is indicated as dashed lines.

Search for short- and long-lived ALPs in $H \to aa \to 4\gamma$ decays with ATLAS

[ATLAS-CONF-2023-040]



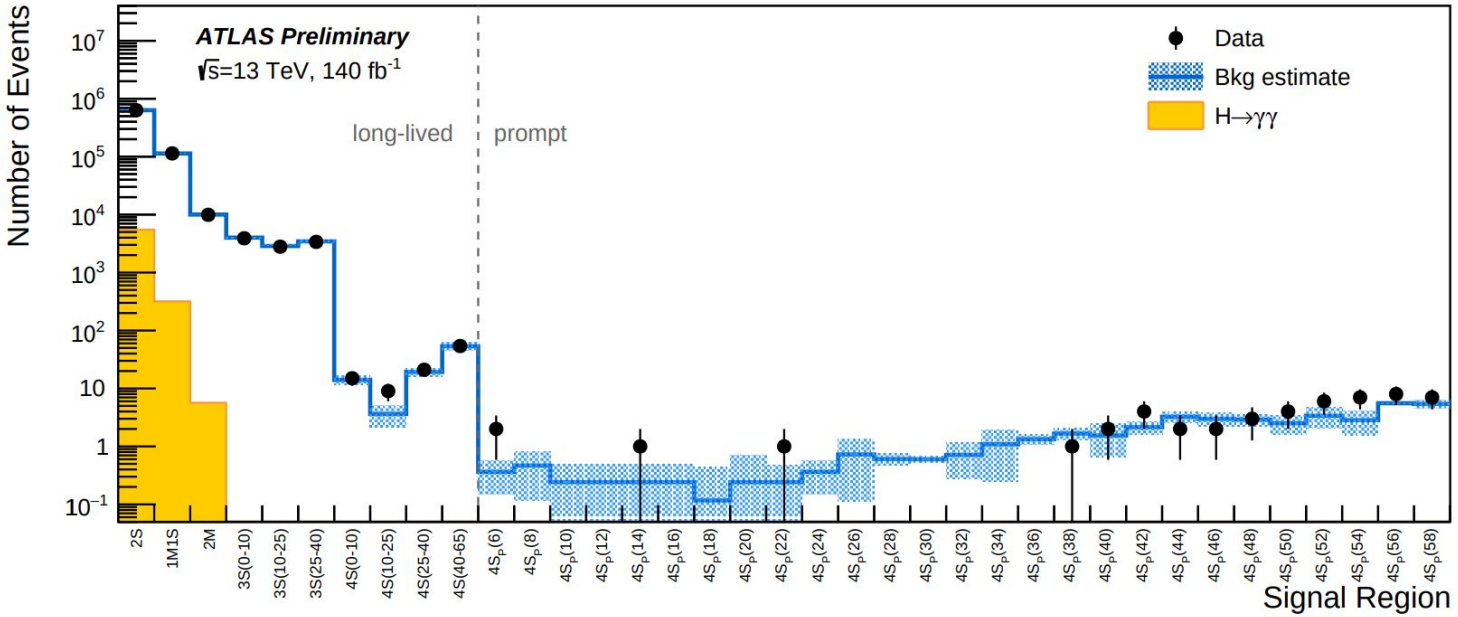
(a) MC (b) Data

Figure 3: $m_{\text{inv}}^{\text{reco}}$ vs. m_a^{reco} for the $4S_p$ categories in the search for promptly decaying ALPs, for (a) simulated $pp \to 4\gamma$ sample and (b) for data. The signal (sideband) regions are indicated as solid lines (shaded areas) for the searches for ALPs with masses of 10 and 40 GeV.

Background estimation

[ATLAS-CONF-2023-040]

- Overview of estimated background events compared to measured data events in the signal region of the most sensitive categories
- The $H \rightarrow \gamma\gamma$ background is only visible in the first three bins, corresponding to the 2-photon categories



Search for short- and long-lived ALPs in $H \rightarrow aa \rightarrow 4\gamma$ decays with ATLAS

[ATLAS-CONF-2023-040]

Nominal uncertainties

- Nominal (as recommended) systematic uncertainties are evaluated for:
  - Lumi 0.8%
  - Pileup < 1%
  - Trigger 2% - 3%
  - Photon ID, ISO, scale, resolution ≤ 3% on selected events

Real vs. fake: 3%
Merged vs. resolved: 4% to 15%
Loose ID: 7% to 23%
Tight ID: 6% to 21%

Custom uncertainties

- 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) - data and MC
- 3 regions:
  - **near**: $z_0 < 20$ mm, $d_0 < 1$ mm
  - **medium**: 20 mm < z_0 < 500 mm, 1 mm < d_0 < 80 mm
  - **far**: 500 mm < z_0, d_0 > 80 mm

- The dependence of the mean and RMS of the shower shape distribution on the decay length fitted by a polynomial
- Applied to photon clusters in our signal MC; ID/classification efficiency recalculated after shower shape fudging

NN classifiers:

- $Z \rightarrow ee$ events used comparing MC and data, electron shower shape variables used as inputs
- Difference propagated through analysis: up to 15% normalisation uncertainty in the 2M and 1M1S categories