Exotic Higgs Decays with ATLAS

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on behalf of the ATLAS Collaboration

LHCP conference

Boston (US)

6 June 2024

ATLAS EXPERIMENT

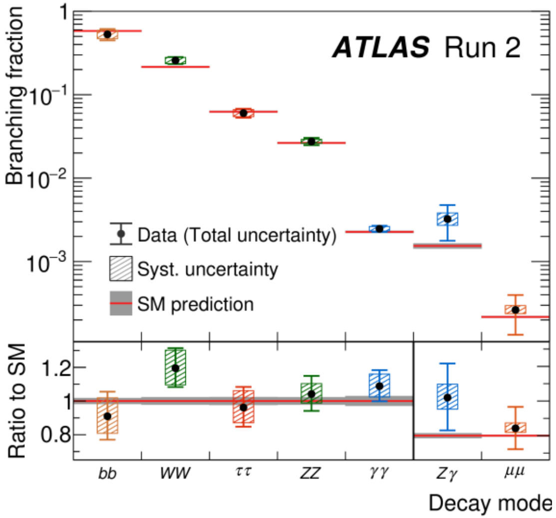
IFAE

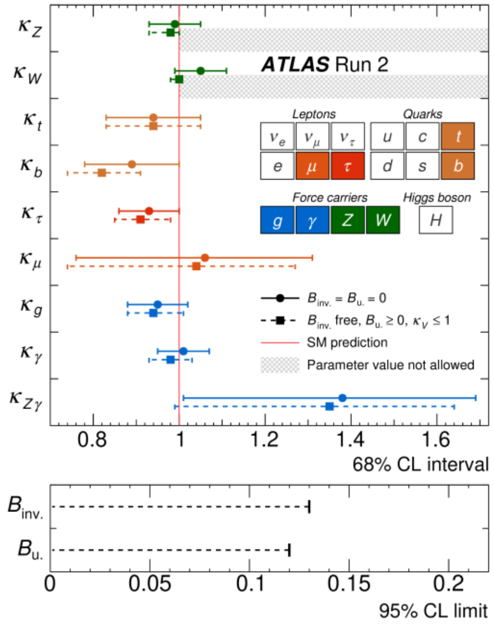
Institut de Física d'Altes Energies

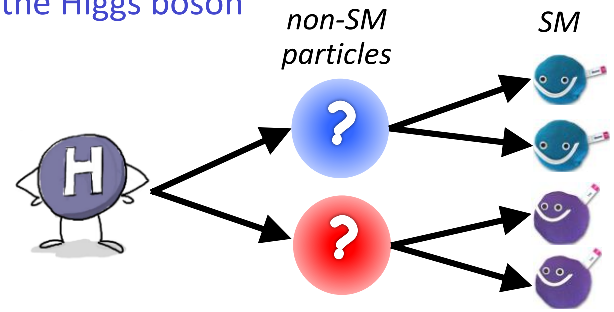
Introduction

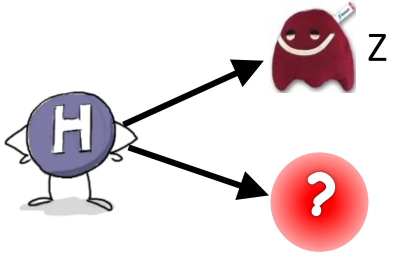
- **Higgs measurements today:**
  - Main production and decay modes observed
  - Excellent agreement with the SM prediction
- **Current constraints:**
  - From combined fits to the SM Higgs coupling:
    - BR_{inv} (H→invisible) < 13%
    - **BR_{u} (H→undetected) < 12%**
- **Higgs as a portal to BSM:**
  - New physics could couple to the SM through the Higgs boson

ATLAS, Nature 607, 52 (2022)



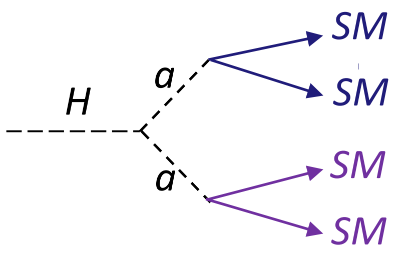






Non-SM decays of the Higgs boson

- **Example of non-SM Higgs decays: H→ aa:**



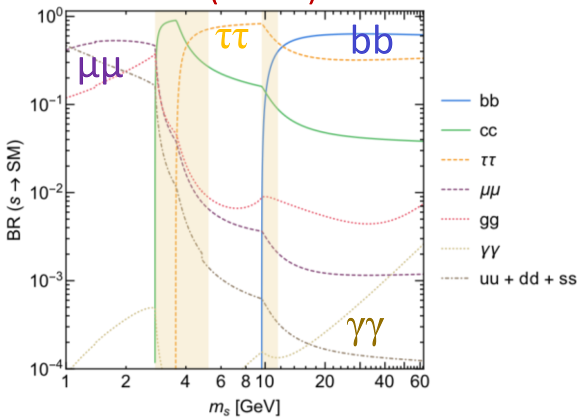
  - Inspired by 2HDM+S, which introduces a mediator in a light singlet (pseudo)scalar
  - Inherits Yukawa-like couplings from mixing with the Higgs doublets
  - Couplings proportional to mass. Large BR to *b*'s and τ's
  - Many analyses have already been performed (see ATL-PHYS-PUB-2021-008)

- **In this talk, will describe recent analyses of full Run 2:**
  - H→aa→γγ γγ
  - H→Za→Z γγ
  - $H \to D^{*0}\gamma$
  - $H \to \gamma\gamma_d$

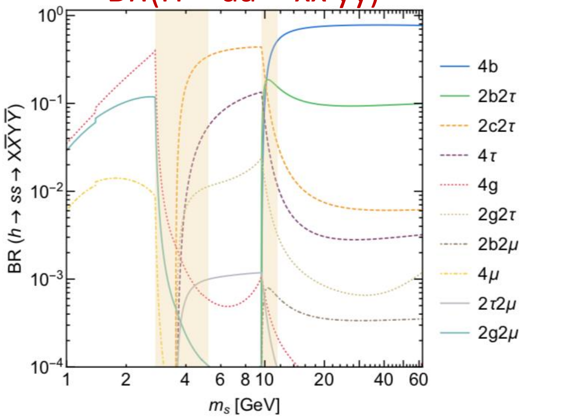
See also Shigeki Hirose's talk on Monday

arXiv:1312.4992

BR(a→xx)



BR(H→aa→xx yy)

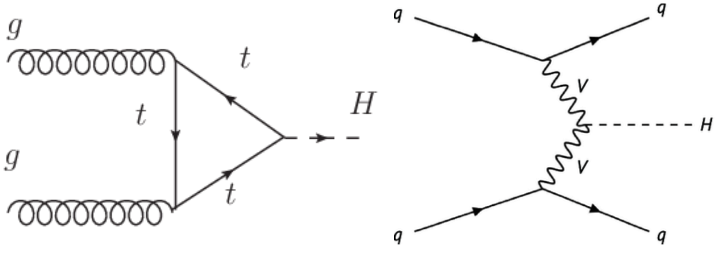


Search for H→aa→4γ – introduction

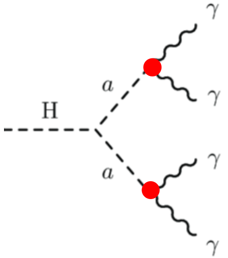
arXiv:2312.03306 (Dec 2023)

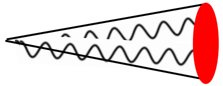
- **Introduction:**
  - Probe Higgs decays into 2 axion-like particles (ALP)
  - Model could explain the $(g-2)_\mu$ discrepancy
  - **First time long-lived decays are explored**
- **Signature kinematics:**
  - Dependent on m(a) and $C_{a\gamma\gamma}$ coupling:
    - Low m(a) : collimated γγ reconstructed as one γ
    - Small $C_{a\gamma\gamma}$: displaced vertices
- **Analysis strategy:**
  - 2γ triggers and various dedicated NNs used:
    - for rejecting fake photons
    - to classify single and merged γ's
    - to select the correct γ pairing in 3S, 4S
  - Signal regions for single (S) and merged (M) γ's:
    - ≥2γ : 2S, 1S1M, 2M, 3S, 4S

Higgs-production mechanisms

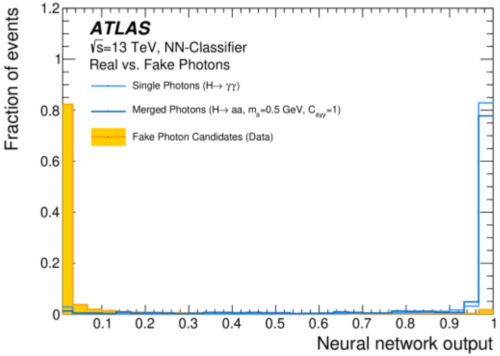


Higgs decay

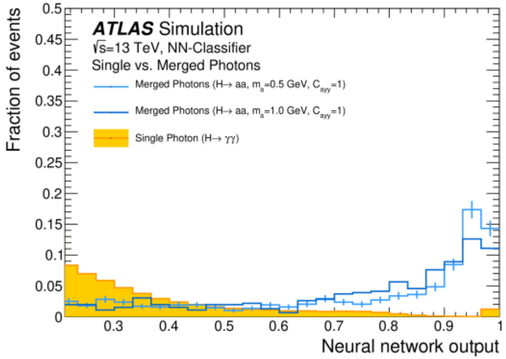




Real vs Fake photons NN output



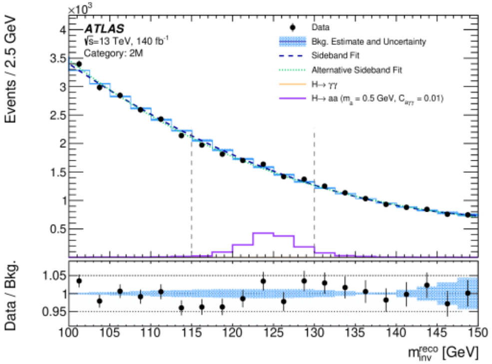
Single vs merged γ's NN output



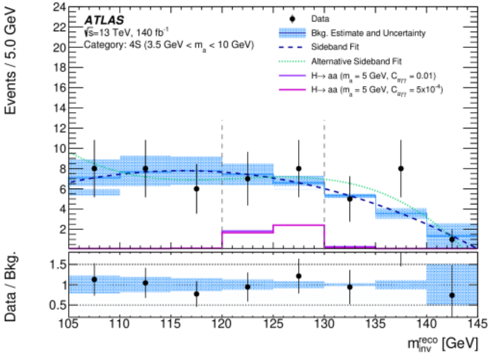
Search for H→aa→4γ – analysis

- **Search for long-lived decays:**
  - m(a) < 3.5 GeV: 2S, 1M1S, 2M are most sensitive
  - m(a) > 3.5 GeV: 3S, 4S are the most sensitive
  - Data-driven background using sideband fits in the SR w/ m(a)-dependent sel. in m_{inv}^{reco} of all γ's and m_a^{reco}
  - Fit of m_{inv}^{reco}
- **Search for prompt decays:**
  - Only considered for m(a) > 5 GeV and used only $4S_p$
  - Selection:
    - Strict requirements on PID to reject fake photons
    - Tight selection around m_{inv}^{reco}, m(a)-dep. for m_a^{reco}
  - Data-driven background 2D area-scaling sideband yields
  - Single bin fit in the m_{inv}^{reco} versus m_a^{reco} plane

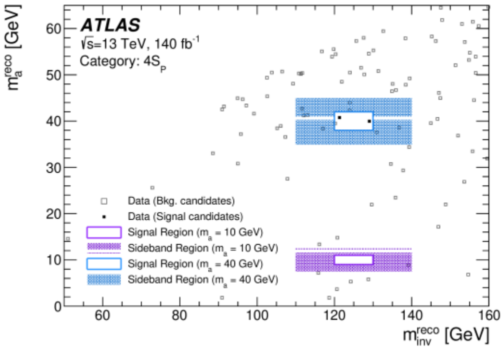
m_{inv}^{reco} in the 2M region



m_{inv}^{reco} in the 4S region
3.5 GeV < m(a) < 10 GeV



m_{inv}^{reco} vs m_a^{reco} in the $4S_p$ region



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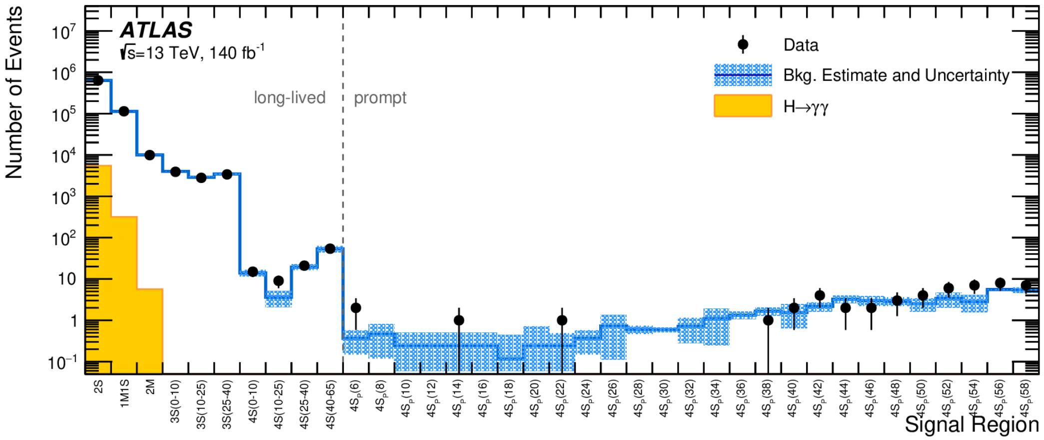
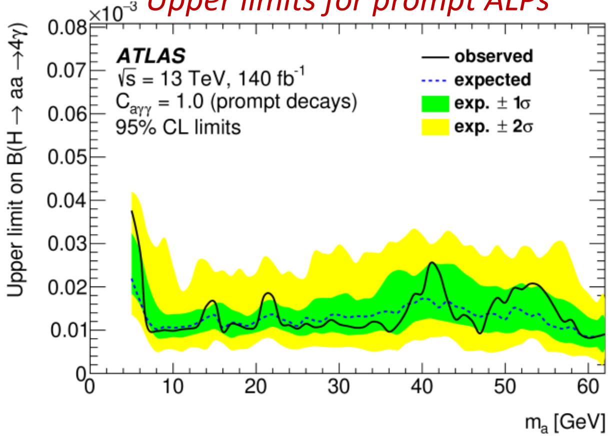
Number of data and estimated background events in the signal regions



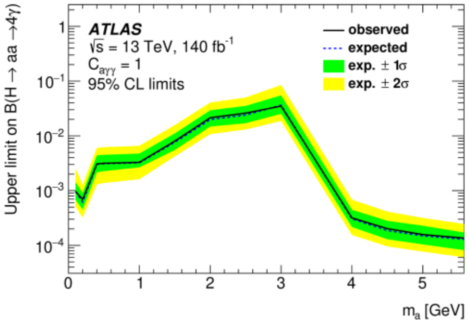
Search for H→aa→4γ – results

Upper limits on BR(H→aa→4γ) provided depending on $C_{a\gamma\gamma}$: more stringent than previous results

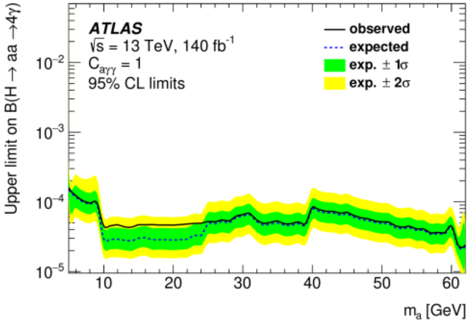
Upper limits for prompt ALPs



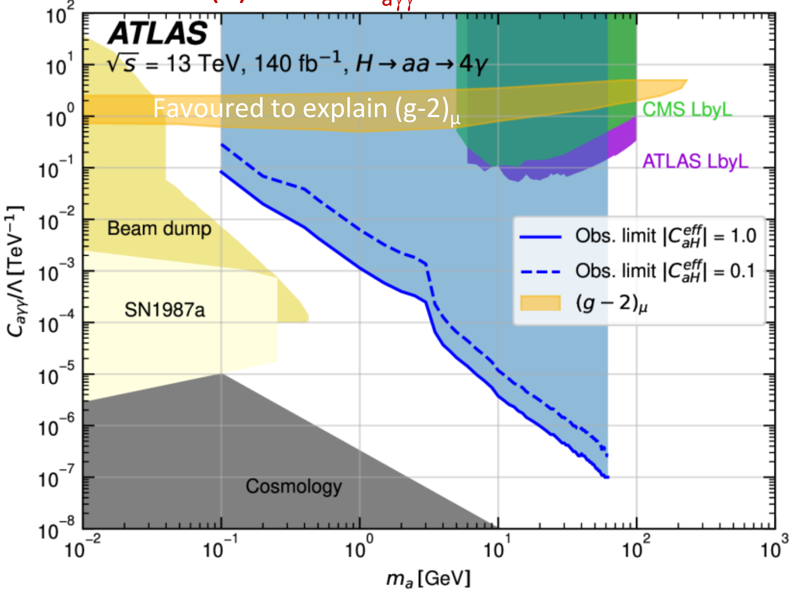
Upper limits for m(a) < 5 GeV



Upper limits for m(a) > 5 GeV



m(a) *versus* $C_{a\gamma\gamma}$ *exclusion contours*

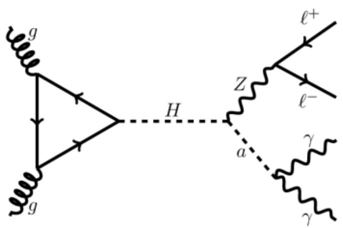


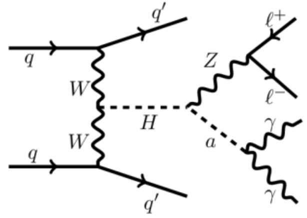
Excluded much of the remaining parameter space that could explain the $(g\text{-}2)_\mu$ discrepancy

Search for H→Za, a→γγ – strategy

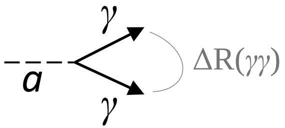
Phys. Lett. B 848 (2024) (Dec 2023)

- **Introduction:**
  - Studied ggF and VBF production modes (separately)
  - Search for new resonances with leptonic Z decay





- **Analysis strategy:**
  - Split into two regimes, based on the angular separation of the photons

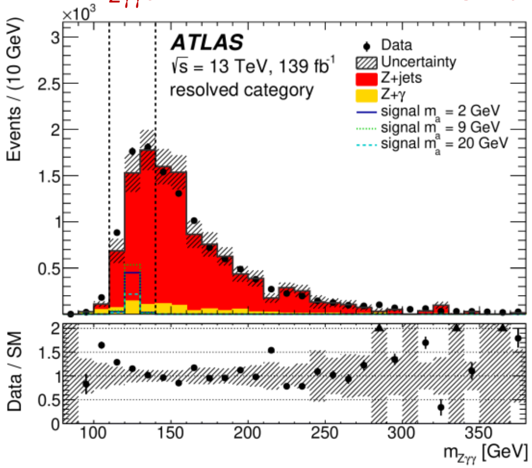


$$\Delta R(\gamma\gamma) = \frac{2m(\gamma\gamma)}{p_T(\gamma\gamma)}$$

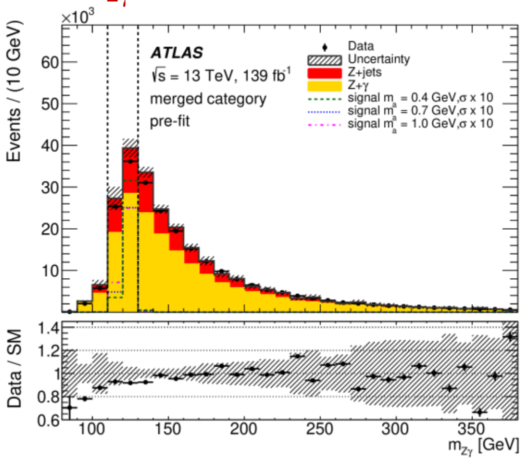
- **Resolved category – m(a) > 2 GeV:**
  - $\geq 2\gamma$
  - $0.96 < \Delta R(\gamma\gamma)\, p_T^{\gamma\gamma} / (2m^{\gamma\gamma}) < 1.2$
  - 90% Z+jets, 10% Z+γ

- **Merged category – m(a) < 2 GeV:**
  - Showers reconstructed as a single γ
  - $110 < m(Z\gamma) < 130$ GeV
  - $E_{ratio} > 0.8$ (discriminates γ and jets)
  - 25% Z+jets, 75% Z+γ

$m_{Z\gamma\gamma}$ for the resolved category



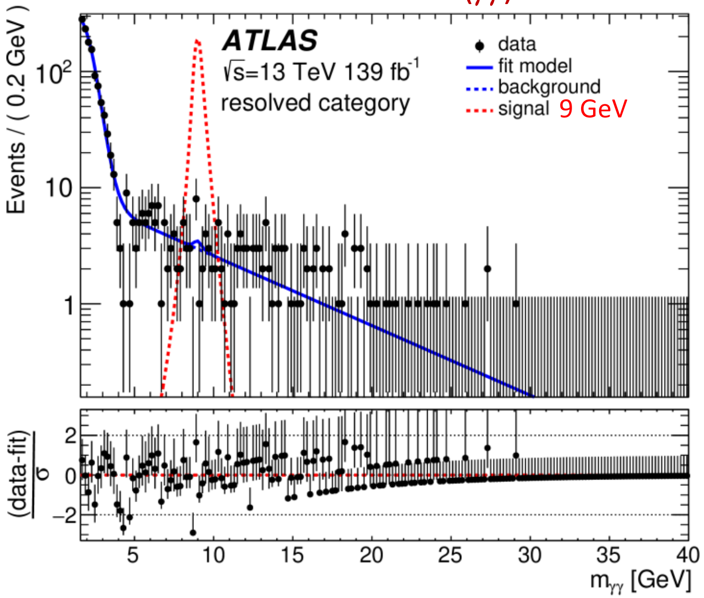
$m_{Z\gamma}$ for the merged category



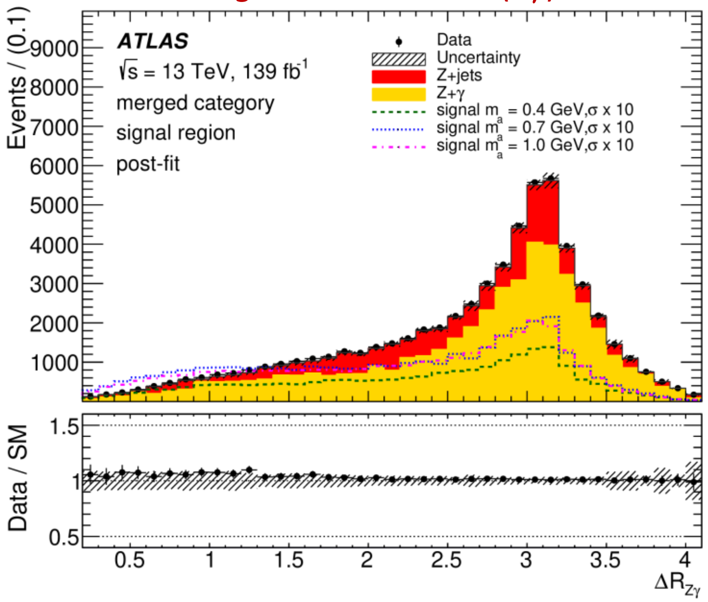
Search for H→Za, a→γγ – analysis

- **Resolved category:**
  - Data-driven background parameterized with an analytic function derived in a CR
  - Fit of the m(γγ) invariant mass distribution
- **Merged category:**
  - Background estimated from simulation with shapes corrections derived from a CR
  - Fit of the ΔR(Zγ) in the SR

Invariant mass m(γγ)



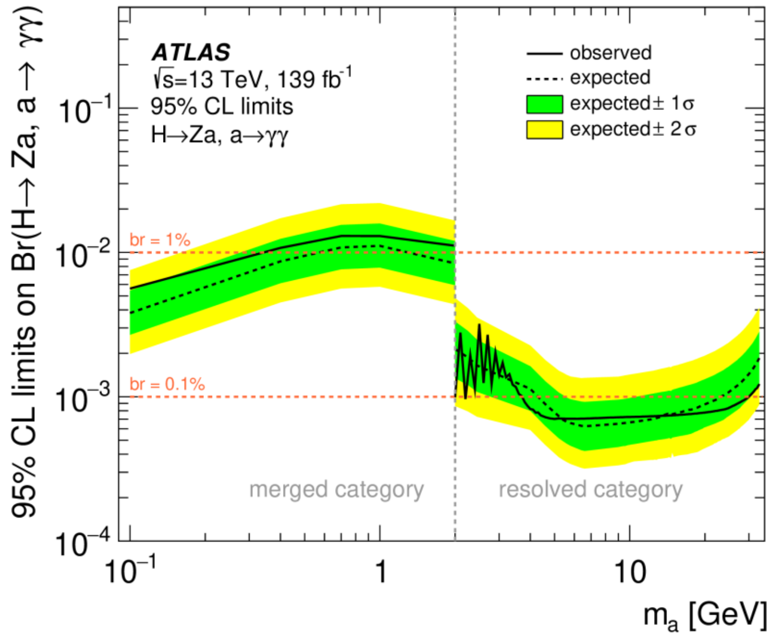
Angular distance ΔR(Zγ)



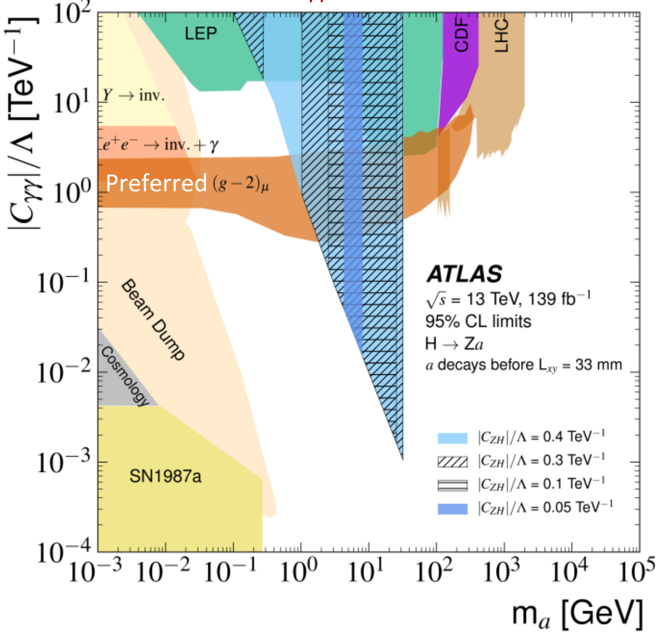
Search for H→Za, a→γγ – results

- **Results:**
  - Broad range of m(a) covered: from 0.1 to 33 GeV
  - Upper Limits on BR(H→Za, a→γγ) : ~1%/<0.1%
- **Interpretation in the context of Axion-Like Particles:**
  - Sensitivity to short-lived axions
  - Very complementary to existing bounds

Upper limits BR(H→Za, a→γγ) *versus* m(a)



m(a) *versus* $C_{\gamma\gamma}$ *exclusion contours*

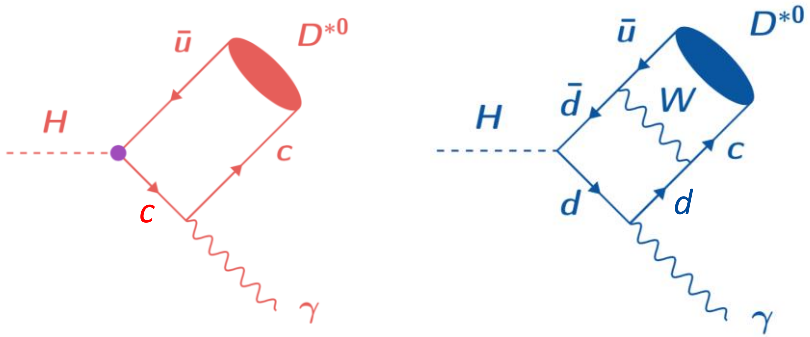


Higgs decays to flavoured mesons – introduction

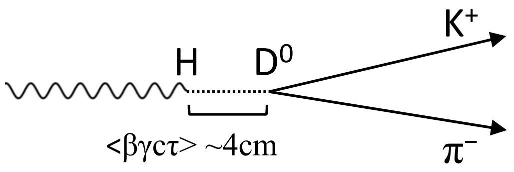
arXiv:2402.18731 (Feb 2024)

- **Introduction:**
  - Radiative Higgs decays to flavoured mesons can probe flavor changing Yukawa interactions
  - Examples are $H \to (K^{*0}, D^{*0}, B^{*0}, B_S{}^{*0})\ \gamma$
  - $H \to D^{*0}\gamma$ is interesting as BR $\sim O(10^{-27})$ in the SM
  - Almost all D^{*0} decay to $D^0\pi$ or $D^0\gamma$
    - Target the decay $D^0 \to K^+\pi^-$ (BR ~4%)

Flavour-changing $H \to c\bar{u}$ decay   *SM decay*



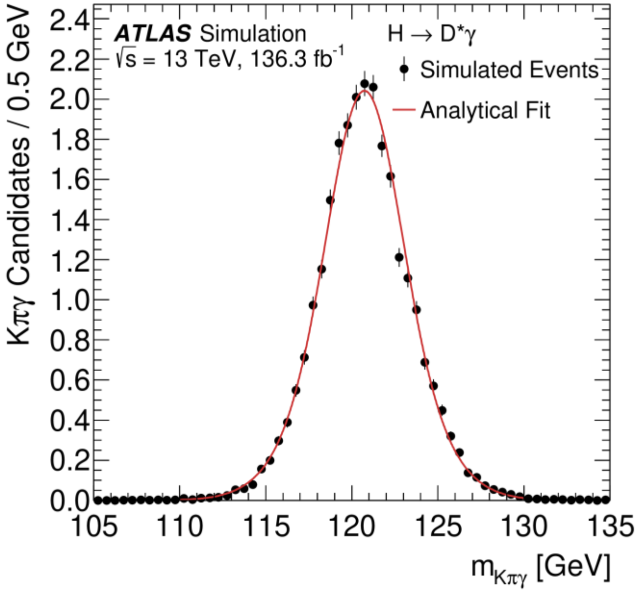
- **Analysis:**
  - Full decay chain: $H \to D^{*0}\gamma \to D^0\gamma\ \gamma \to K^+\pi^-\ \gamma\ \gamma$
  - Two isolated tracks recoiling against an isolation photon
    - No attempt to reconstruct the soft photon
  - Used dedicated triggers requiring two tracks and a specific range of its invariant mass
  - Exploited displaced meson decay vertex to reduce backgrounds



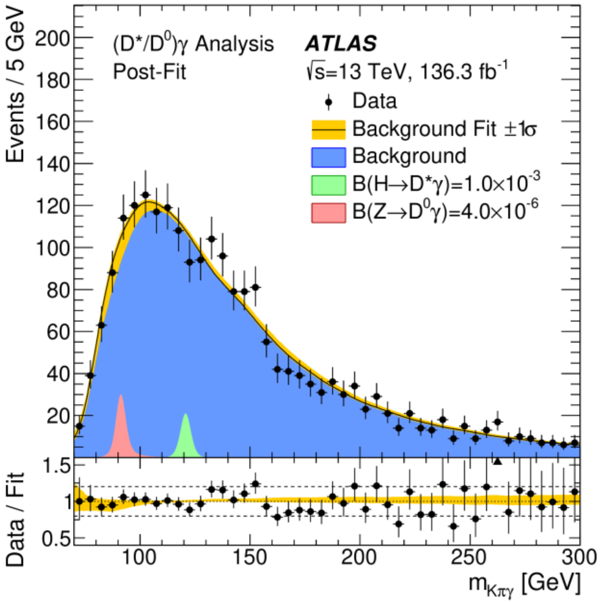
H→D^{*0}γ analysis – results

- **Background:**
  - Dominated by γ+jet and multi-jet processes
  - Used data-driven finely binned Higgs mass templates
- **Fit:**
  - Signal extracted with a likelihood fit to $m_{K\pi\gamma}$
  - Background modelling uncertainties dominant

Invariant mass of the Higgs, m(Kπγ), for signal



Post-fit invariant mass of the Higgs



H→D^{*0}γ analysis – limits

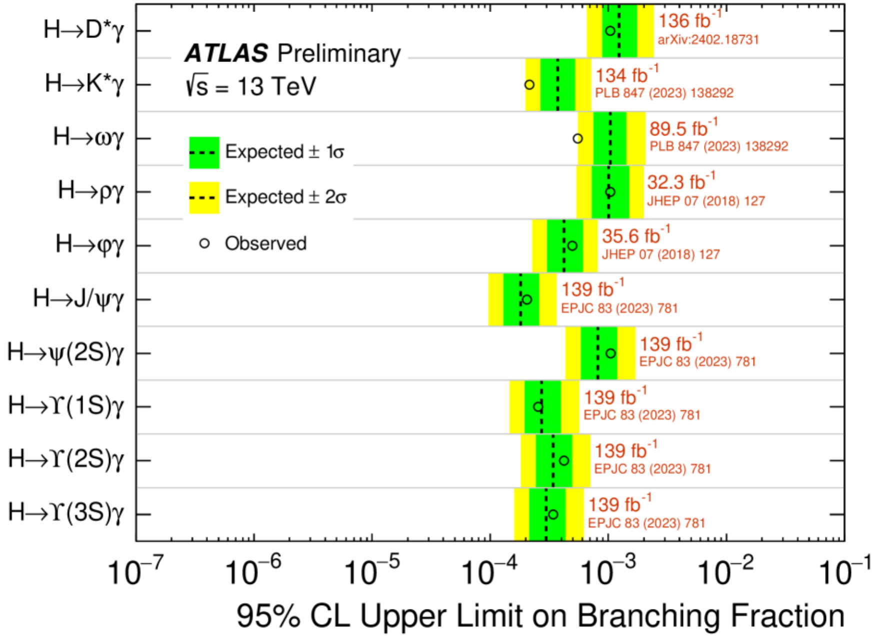
ATL-PHYS-PUB-2023-004

Search limited by statistics

Channel	Mass range [GeV]	Observed (Expected) background	H signal $\mathcal{B} = 10^{-3}$
$H \rightarrow D^{*}\gamma$	116–126	203 (214.8 ± 5.5)	25.4 ± 2.0

	95% CL upper limit	
	Expected	**Observed**
$\mathcal{B}\left(H \rightarrow D^{*0}\gamma\right)$	$\left(1.2^{+0.5}_{-0.3}\right) \times 10^{-3}$	$\mathbf{1.0 \times 10^{-3}}$
$\mathcal{B}\left(Z \rightarrow D^{0}\gamma\right)$	$\left(3.4^{+1.4}_{-1.0}\right) \times 10^{-6}$	$\mathbf{4.0 \times 10^{-6}}$
$\mathcal{B}\left(Z \rightarrow K^{0}_{S}\gamma\right)$	$\left(3.0^{+1.3}_{-0.8}\right) \times 10^{-6}$	$\mathbf{3.1 \times 10^{-6}}$

Upper limits on BR(H→meson + γ)



The analysis includes a search for Z→D^{0}γ and Z→K$^{0}_{S}$γ decays, improving the LHC-b limit

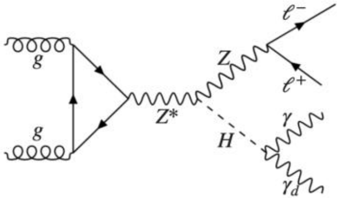
Complementary to an extensive programme of H and W/Z boson exclusive decays in ATLAS

Search for dark photons : $H \to \gamma\gamma_d$

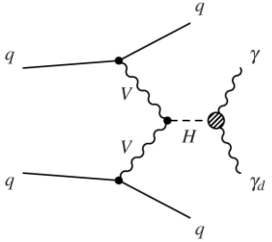
- **Introduction:**
  - **Dark Higgs Vector Portal:**
    - U(1) gauge boson: visible photon, γ
    - $U(1)_D$ gauge boson: massive (or massless) dark photon, γ_d
  - Search for dark photons γ_d from Higgs boson decays in various production modes

- **Analyses:**
  - **ZH production** (*JHEP 07 (2023) 133*)
    - ee or μμ, one isolated γ and E_T^{miss}
    - Fake E_T^{miss} (from data)
    - Top, $e \to \gamma$, $VV\gamma$ (from CRs in the fit)
    - BDT response as discriminant
  - **VBF production** (*EPJ. C 82 (2022) 105)*
    - E_T^{miss}, 2 VBF jets, one isolated γ
    - $W\gamma$+jets, $Z\gamma$+jets (from CRs in the fit)
    - Fit of $m_T(\gamma, E_T^{miss})$ as discriminant

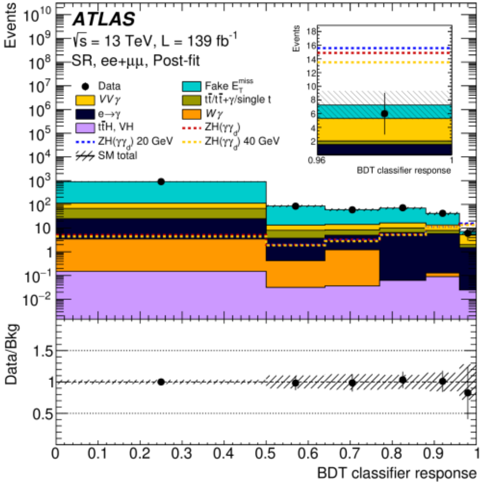
ZH production



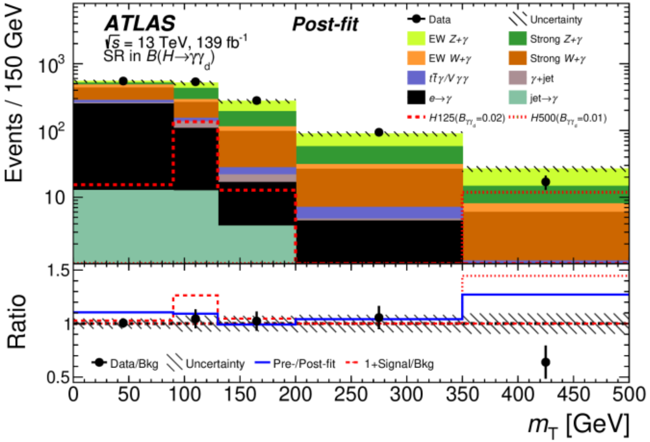
VBF production



Post-fit BDT distribution for the SR



Post-fit $m_T(\gamma, E_T^{miss})$ distr. for the SR



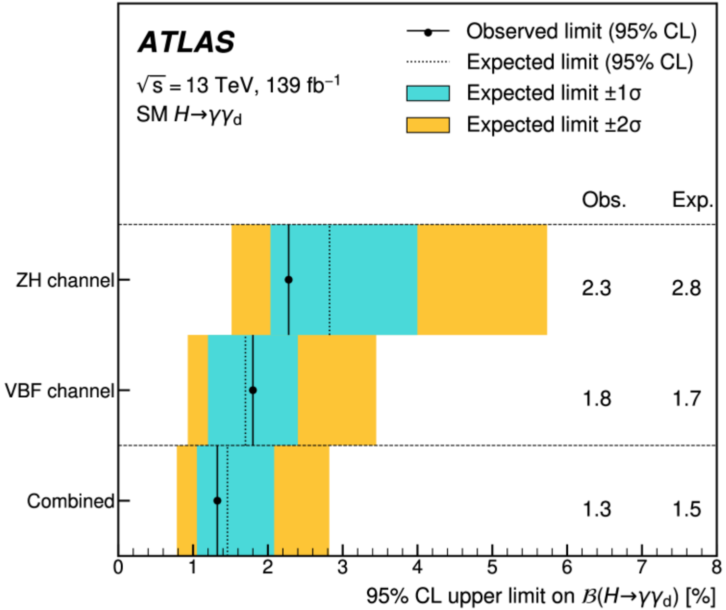
Combination of ZH and VBF $H \rightarrow \gamma\gamma_d$

NEW

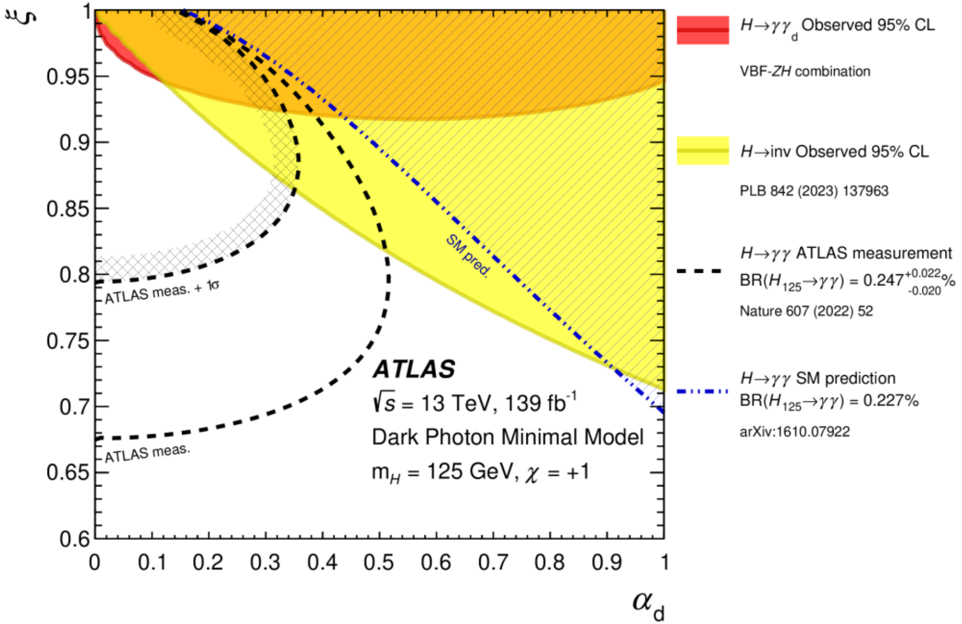
arXiv:2406.01656 (Jun 2024)

Combination of the ZH and VBF channels has been performed and is shown at LHCP for the first time

BR$(H \rightarrow \gamma\gamma_d)$ *upper limits per channel & combined*



α_d versus ξ exclusion contours



Interpretation in a minimal simplified model consisting of one left-doublet and one right-singlet of the $SU(2)_L$
Partly excluding phase space in the 2D Plane of the mixing parameter ξ versus the fine structure constant α_d

Summary and conclusions

- **Using the full Run 2 data, we continue exploring exotic decays of the Higgs boson probing new phase spaces**
- **Shown in this talk:**
  - **Recent searches for Axion-Like-Particles including long-lived decays**
  - **Recent searches for flavour-changing decays of the Higgs boson**
  - **Combination of searches for dark photons**
- **More analyses using the full Run 2 data together with Run 3 data are to be expected in the near future**
  - **New production and decay channels will become available**
- **Stay tuned!**

THANK YOU!

BACKUP

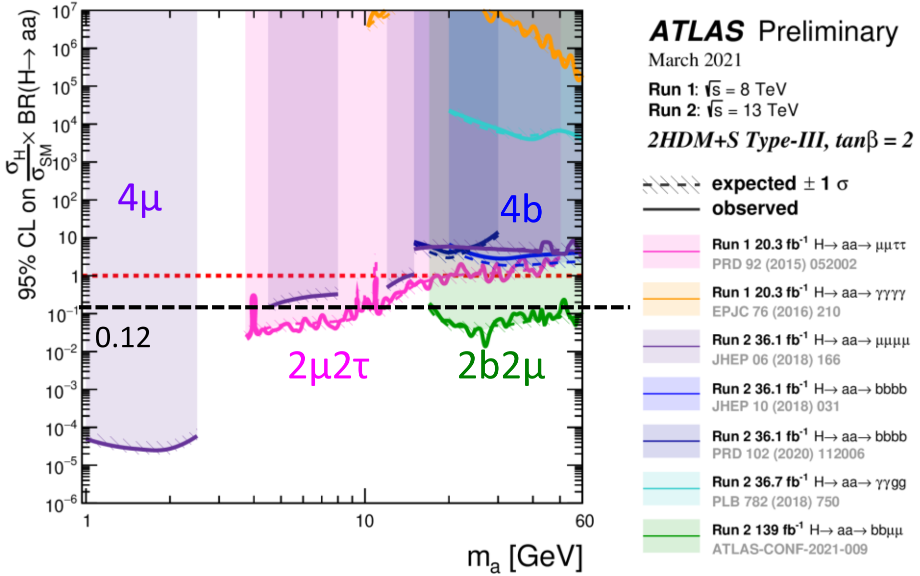
H→aa searches – summary plots

ATL-PHYS-PUB-2021-008 (Mar 2021)

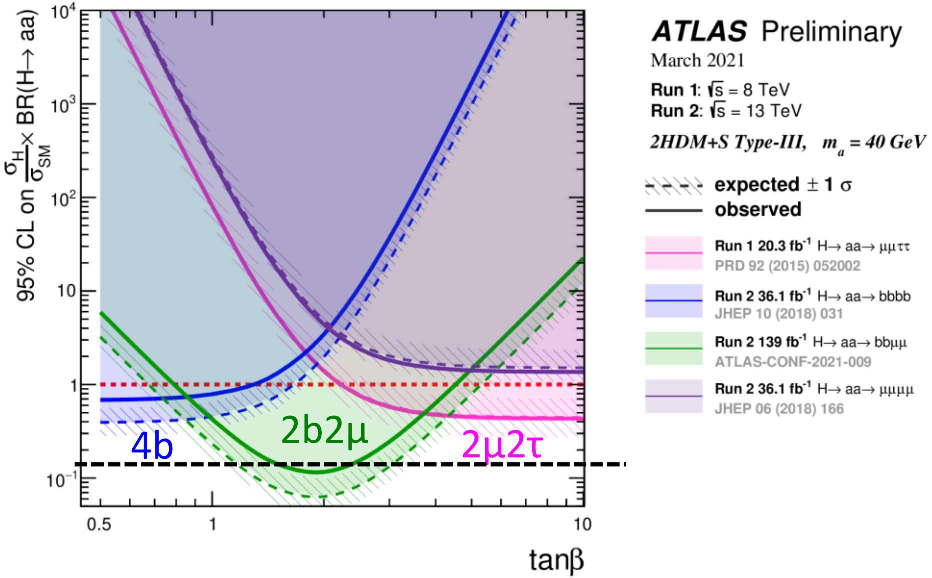
arXiv:1312.4992
arXiv:1802.02156

Limits on BR(H→aa) assuming a particular 2HDM+S model predicting BR(aa→xx yy)

Limits on BR(H→aa) versus m(a)



Limits on BR(H→aa) as a function of tanβ



Nice complementarity of searches, probing different tanβ phase space