Light Higgs Bosons in ATLAS and CMS experiments

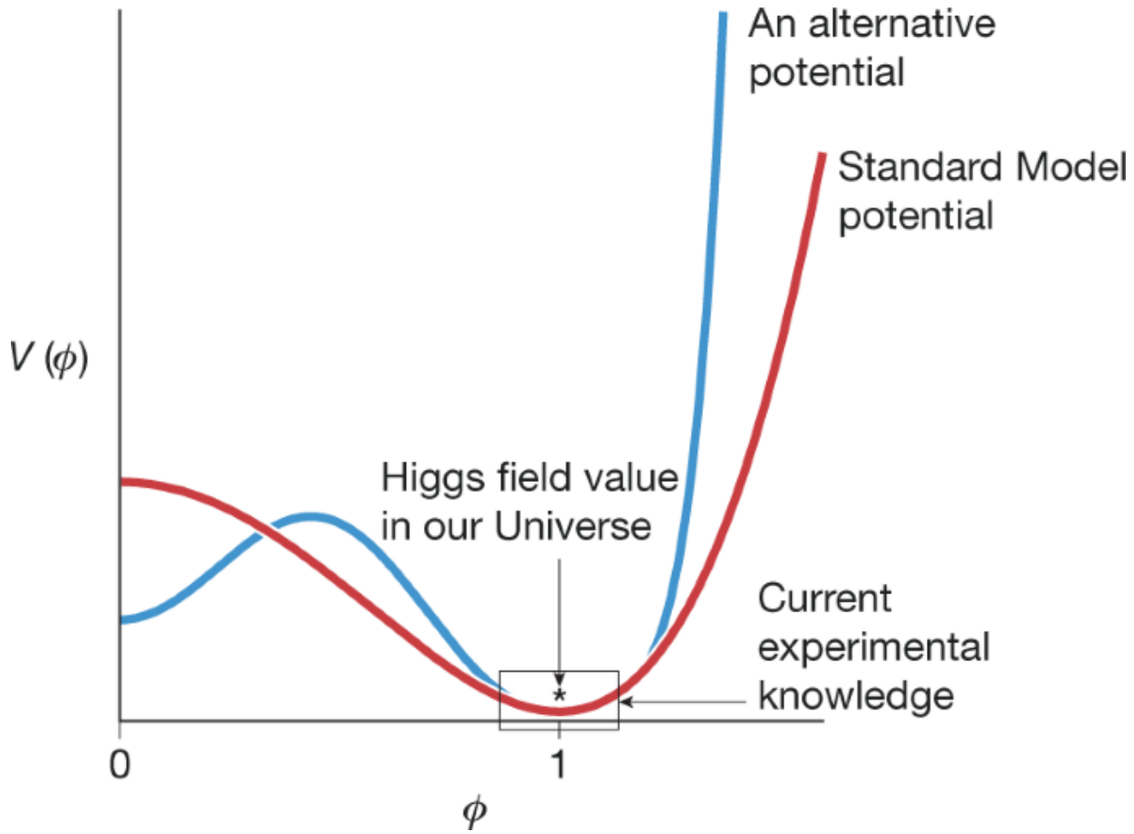
Pallabi Das
on behalf of the ATLAS and CMS Collaborations

Roadmap of Dark Matter models for Run 3
CERN, Geneva
16th May, 2024

Introduction

- So far the Standard Model (SM) is consistent with LHC data
  - No evidence of new particles from supersymmetry
  - Unsolved questions: matter antimatter asymmetry, dark matter in the universe…
- Several extended scalar sector models accommodate the SM Higgs boson + EW baryogengesis
  - Result in different symmetry breaking patterns because of the extra scalars
  - These scalars couple preferentially to the Higgs boson: “portal” to new physics interactions

Nature, 607, 41-47 (2022)



Width of the observed resonance is very narrow→ small coupling to BSM particles can lead to observable exotic decays of the Higgs boson at the LHC

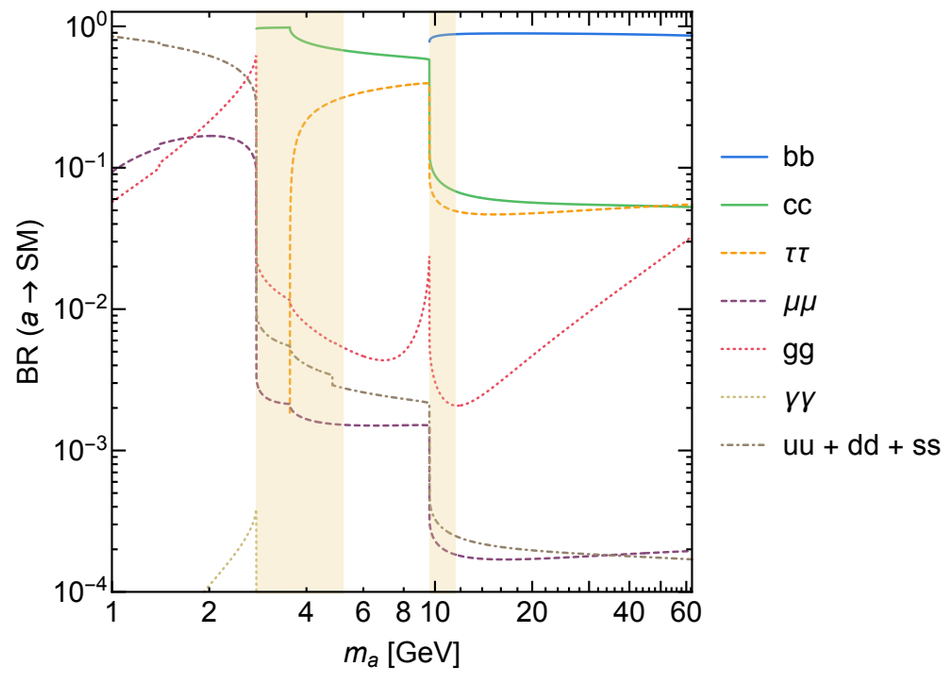
Direct searches of exotic Higgs boson decays in the ATLAS and CMS experiments

This talk: Higgs decays to light pseudoscalars

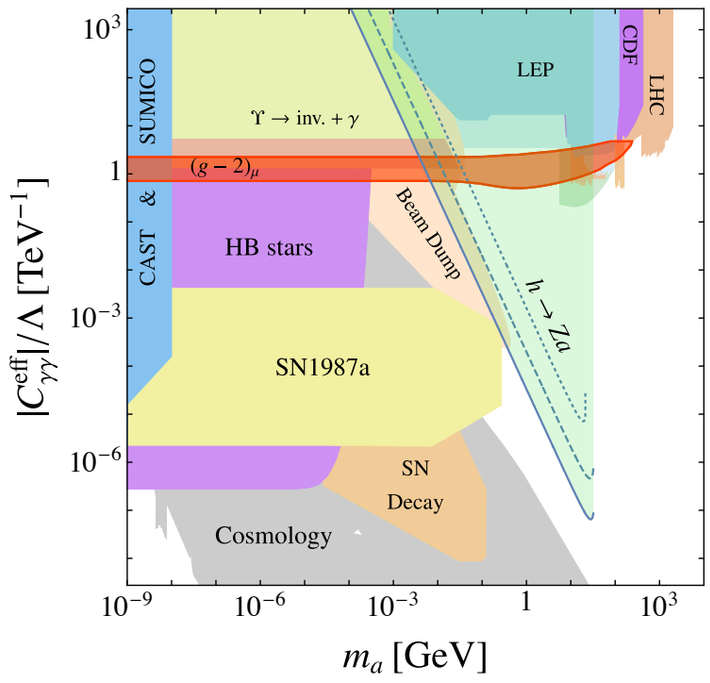
Higgs decays to pseudoscalars

- Two-Higgs-doublet model + singlet (2HDM+S):
  - Wide range of possible exotic Higgs decays, while much of the parameter space of 2HDM is constrained by LHC experiments
  - The additional singlet has no direct Yukawa coupling, only couples to the two Higgs fields
  - Small mixing with Higgs field: H→aa→SM particles
- Axion-like particles (ALPs):
  - Gauge singlets under SM, coupling to SM fermions
  - Enhanced coupling to photons can contribute to anomalous muon magnetic moment
  - Search channels: H→aa and H→Za, effective couplings: C_{ZH}^{eff}/Λ and $C_{\gamma\gamma}^{eff}/\Lambda$

arxiv:1312.4992 Type I



JHEP12(2017)044

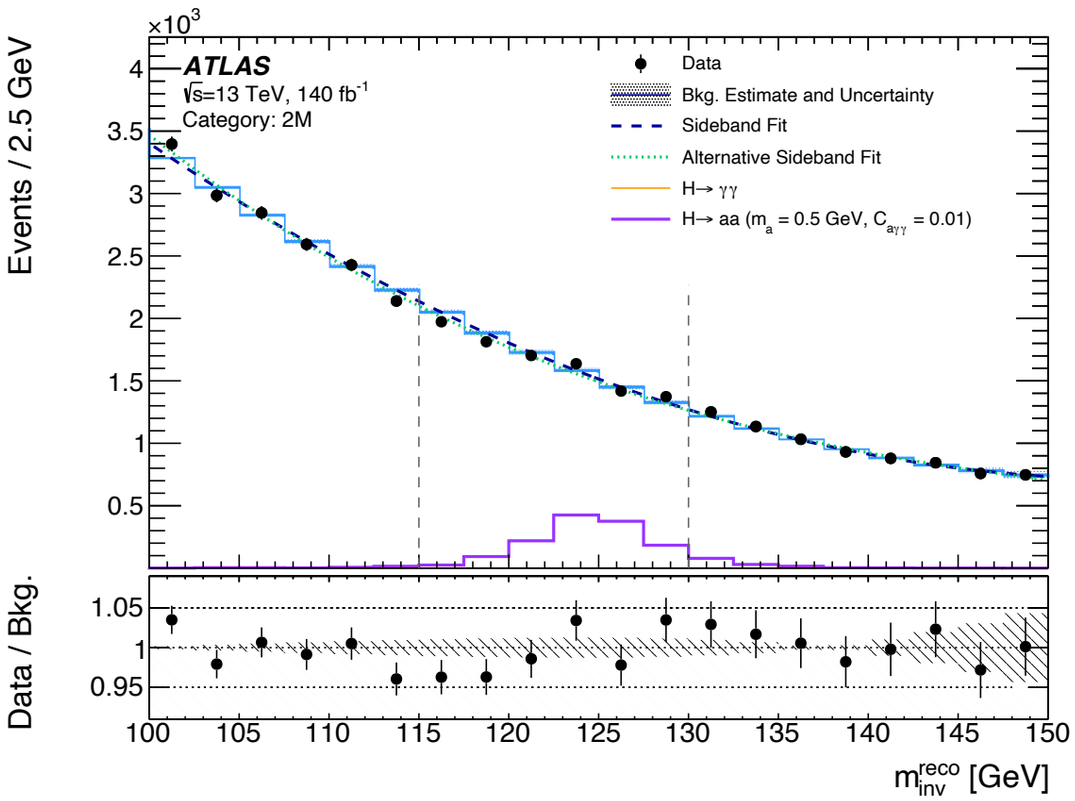


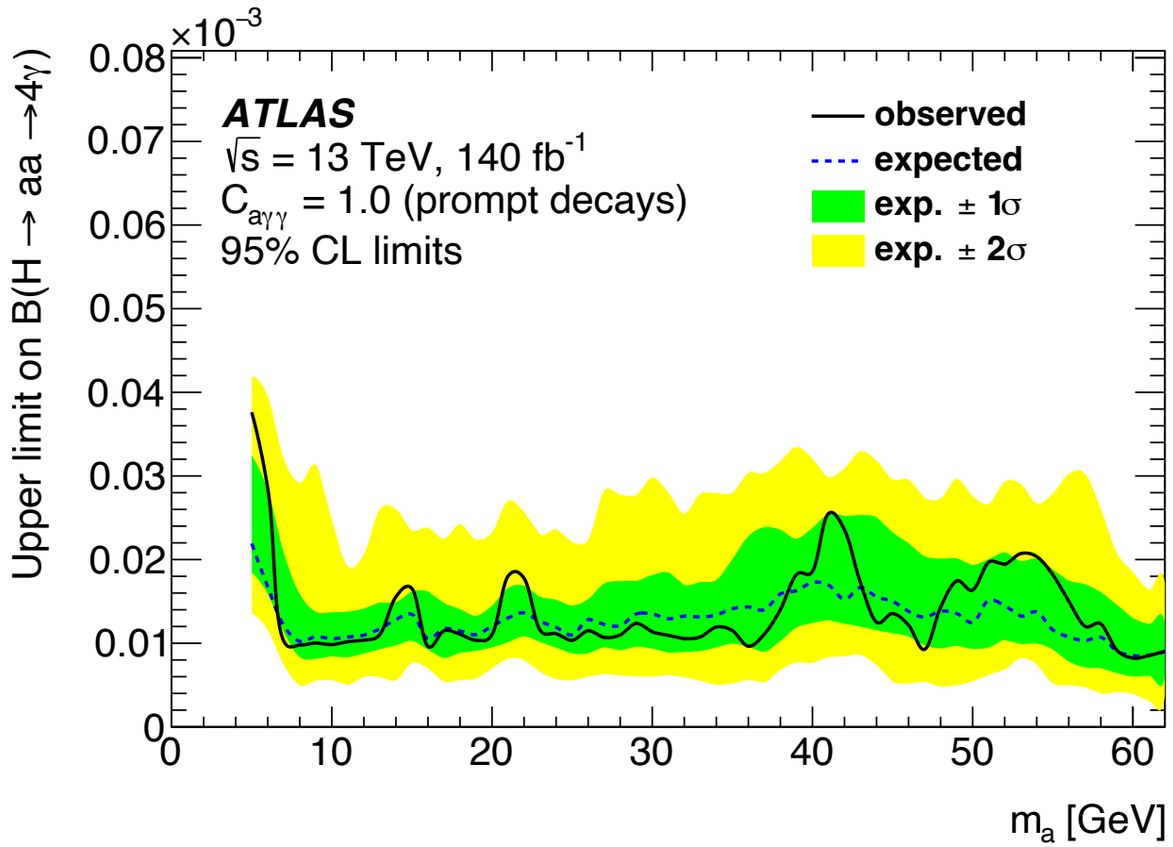
$H \to aa \to 4\gamma$

Consider ALP mass range $0.1 < m_a < 60$ GeV

HDBS-2019-19

- Collimated photon signatures below $m_a < 3.5$ GeV identified as single object
- Two types of signal: prompt and long-lived
- Reconstruct invariant mass of the Higgs boson in signal region categories based on merged or resolved photons in the events





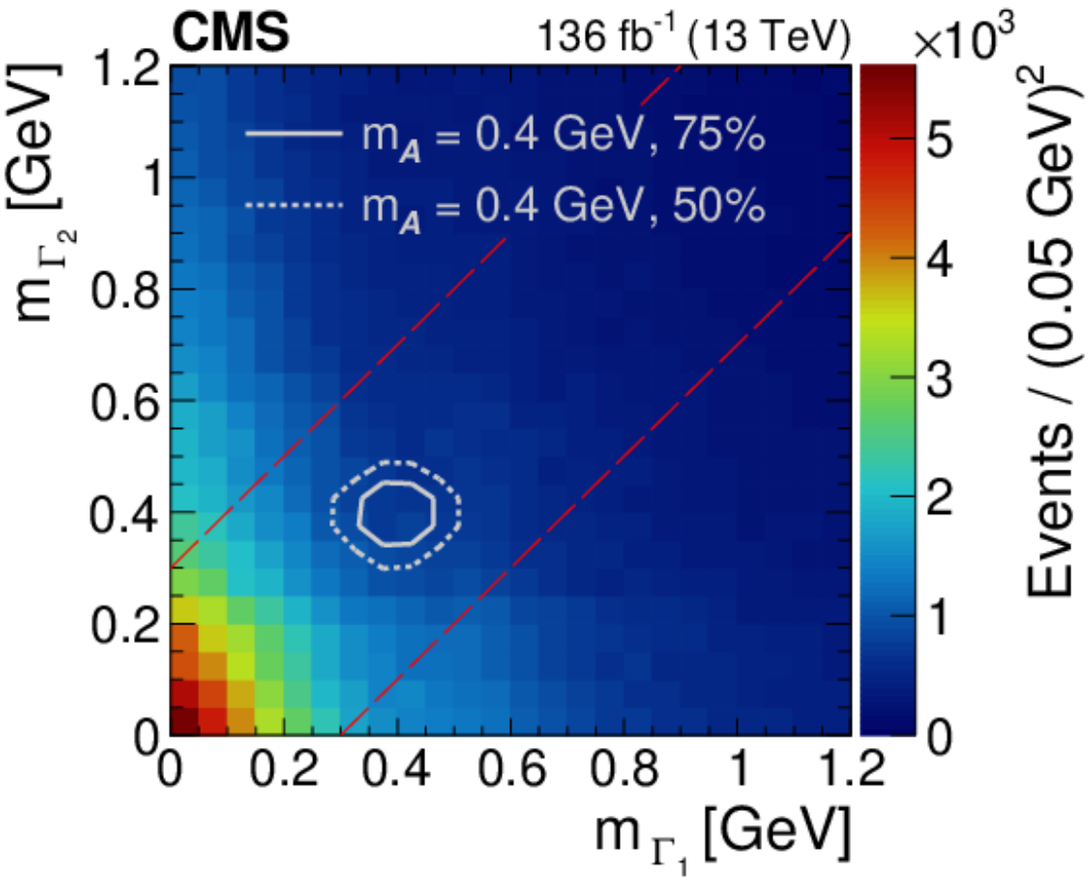
Most stringent limits till date on long-lived ALPs ($z_0 > 500$ mm): $B(H \to aa \to 4\gamma) < 2 - 6 \times 10^{-5}$ for $m_a > 10$ GeV and $< 10^{-5} - 3 \times 10^{-2}$ for $m_a < 10$ GeV

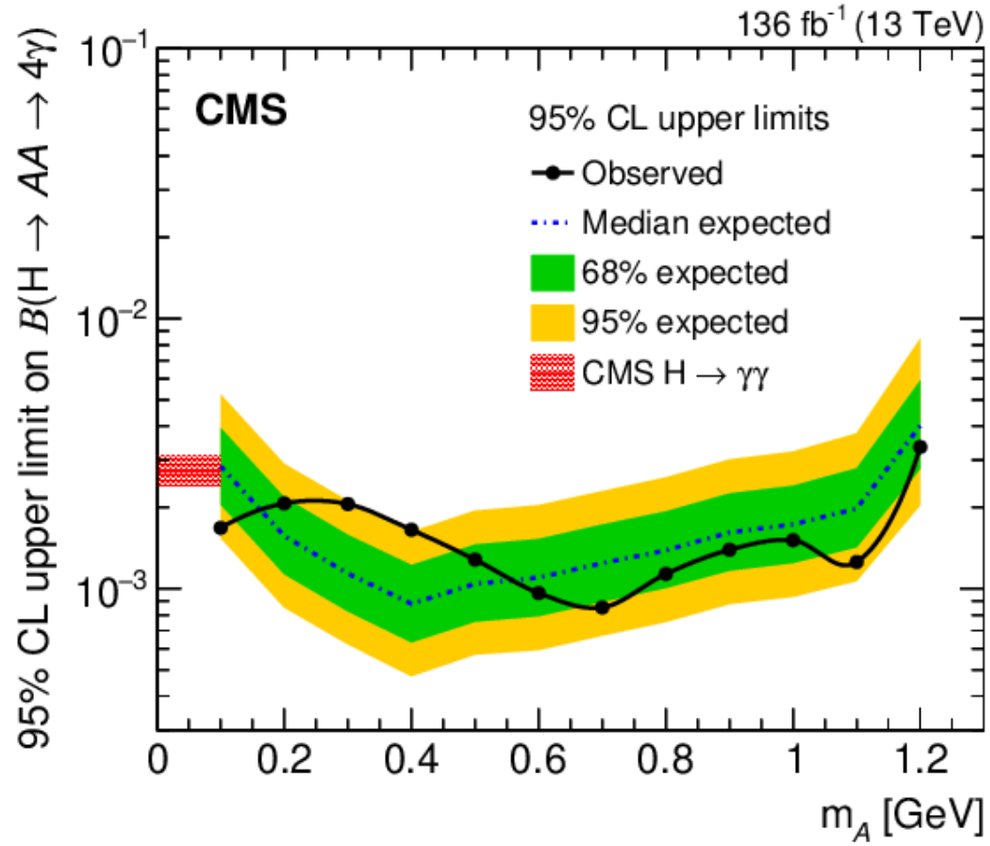
H→aa→4γ (boosted)

Search for very low mass pseudoscalars $0.1 < m_a < 1.2$ GeV

PRL 131 (2023) 101801

- Diphoton decay is boosted and reconstructed as a single photon-like object "Γ"
- Using novel merged diphoton reconstruction technique of end-to-end deep learning
- Fit 2D distribution of invariant masses $m_{\Gamma 1}$ and $m_{\Gamma 2}$





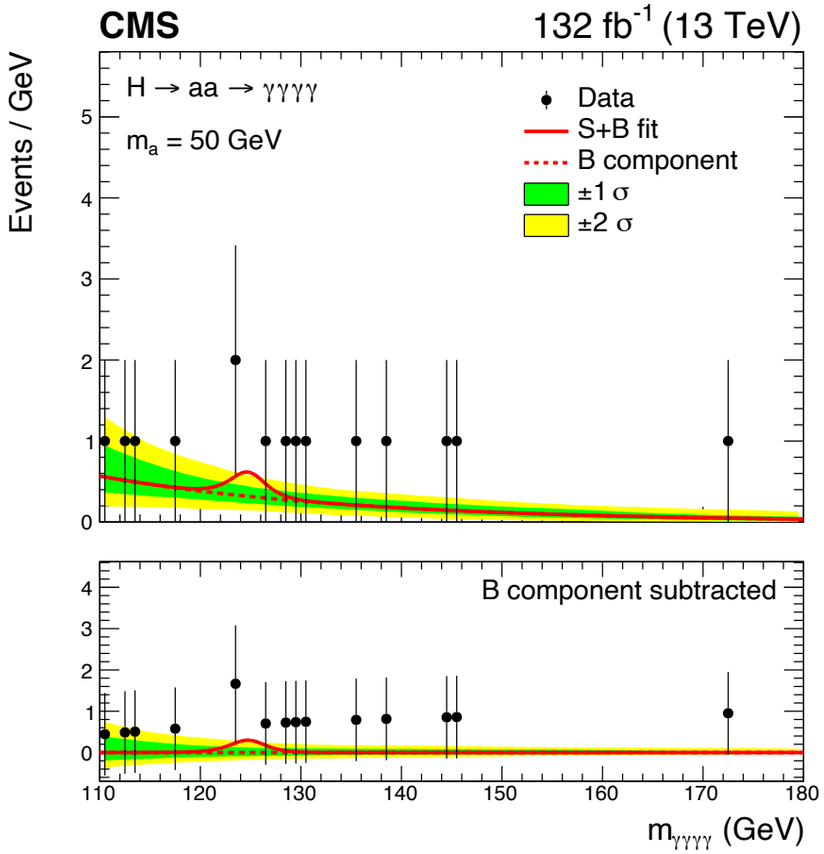
B(H→aa→4γ) below 0.9 – 3.3 x 10^{-3} for $0.1 < m_a < 1.2$ GeV

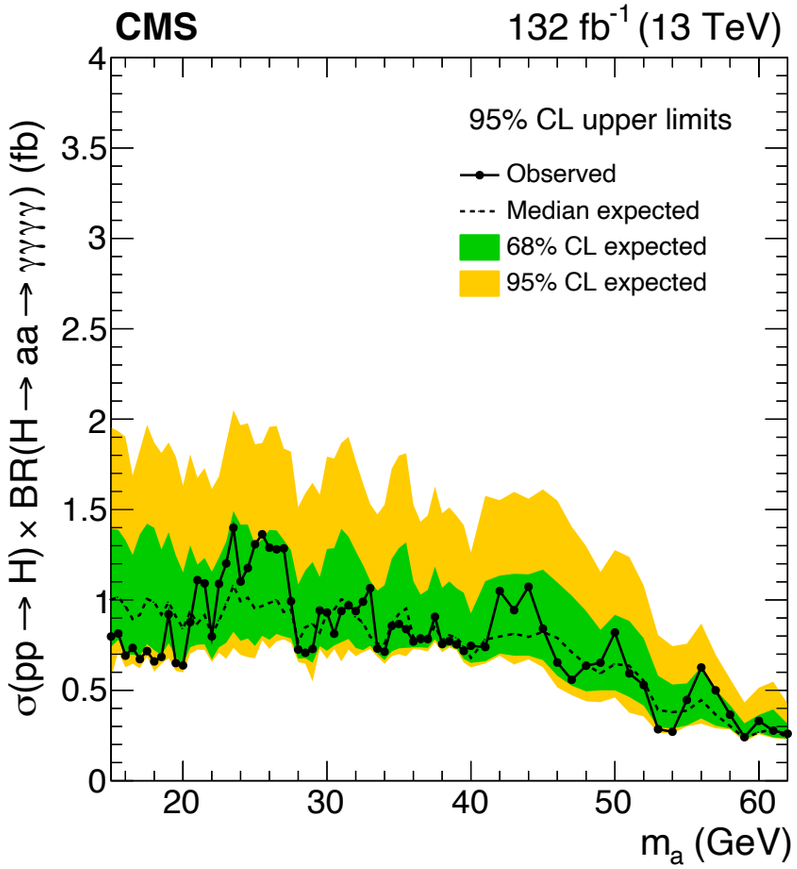
Search is also sensitive to long-lived decays: For $0.1 < m_a < 0.4$, upper limits are 0.9 to 1.8 times larger for cτ = 1 mm and 3 to 30 times larger for cτ = 10 mm

H→aa→4γ (resolved)

Search for SM-like H→aa→4γ in the mass range 15 < m_a < 62 GeV: JHEP 07 (2023) 148

- Four photons are well isolated
- Identifies the primary vertex using a BDT trained using variables related to tracks recoiling against the well reconstructed four-photon system → improves Higgs mass resolution
- Train event classifier using variables uncorrelated to $m_{\gamma\gamma\gamma\gamma}$ and look for a 125 GeV resonance





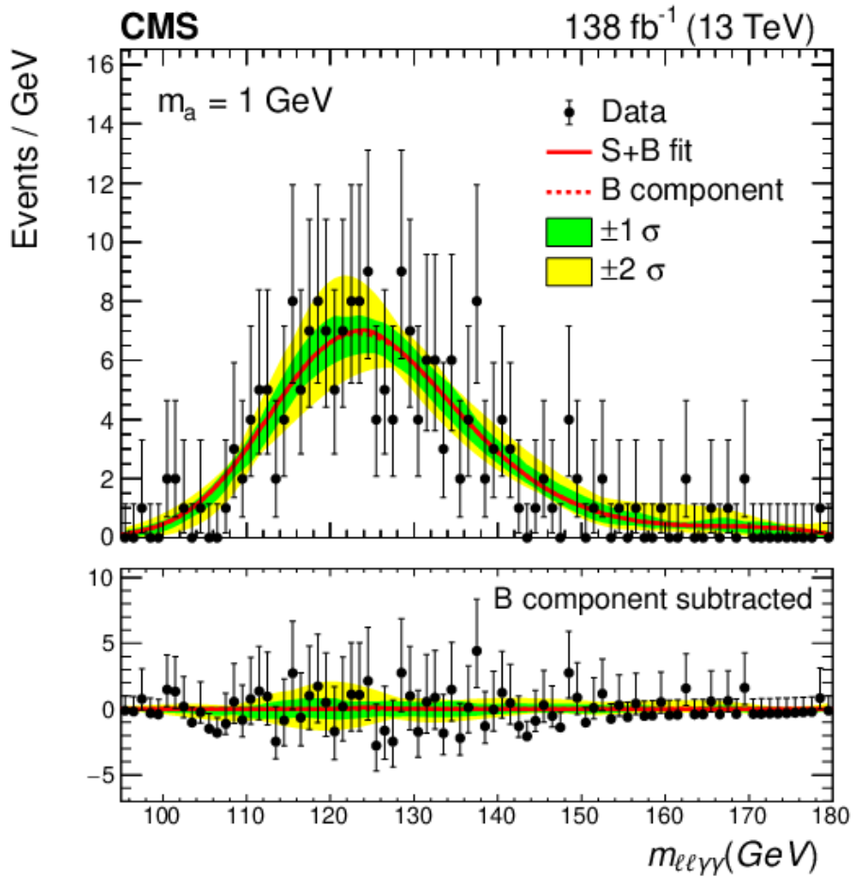
Observed 95% CL upper limits on cross section between 0.80-0.26 fb → B(H→aa→4γ) below ~ 10^{-6}

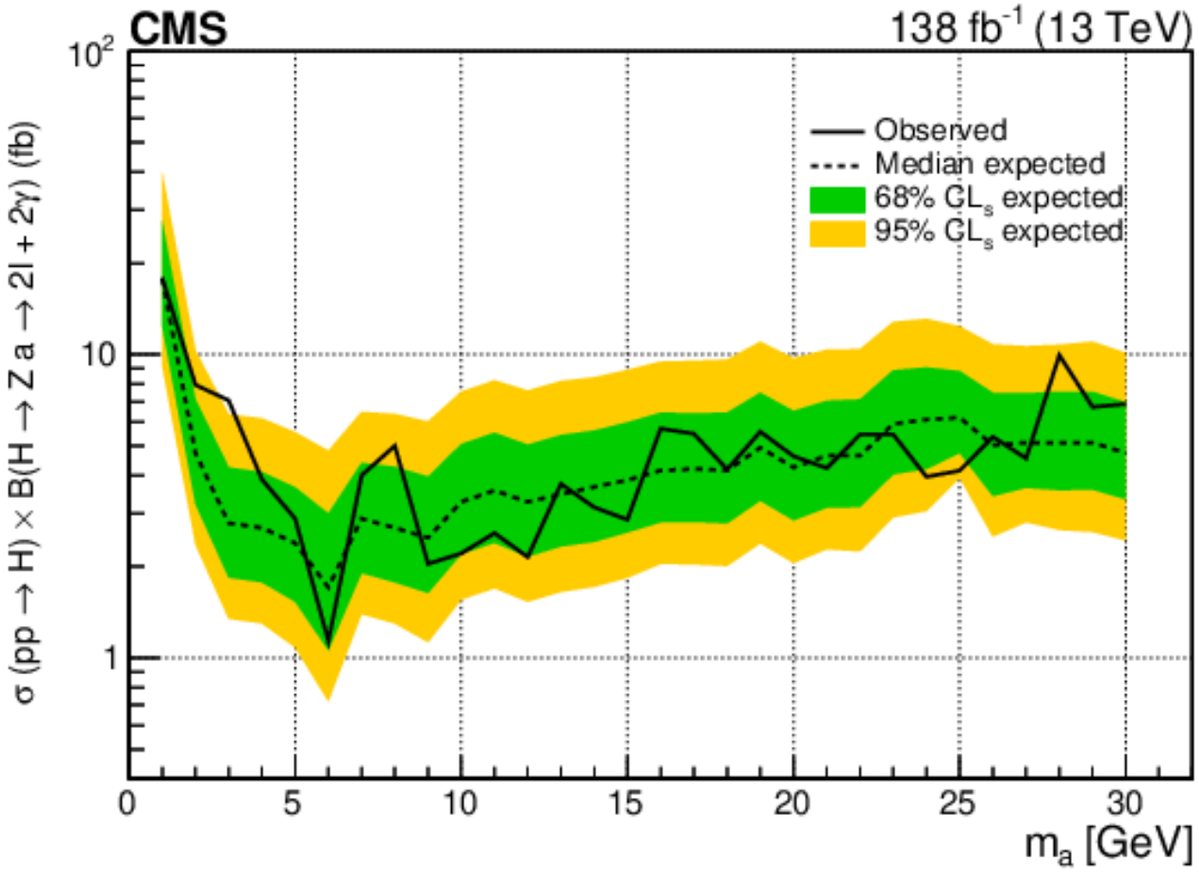
Both H→aa→4γ analyses are statistically limited and no significant deviation from SM background is observed

H→Za, a→γγ

First search at LHC for H→Za in the mass range $1 < m_a < 30$ GeV PLB 852 (2024) 138582

- Using merged photon reconstruction technique to identify boosted diphoton candidate from a
- Reject FSR photons from leptons to improve Higgs mass resolution
- BDT event classifier used to select the signal region maximising significance across $m_{llγγ}$ distribution





B(H→Za) below ~0.1 for $1 < m_a < 30$ GeV, no significant deviation from SM background observed

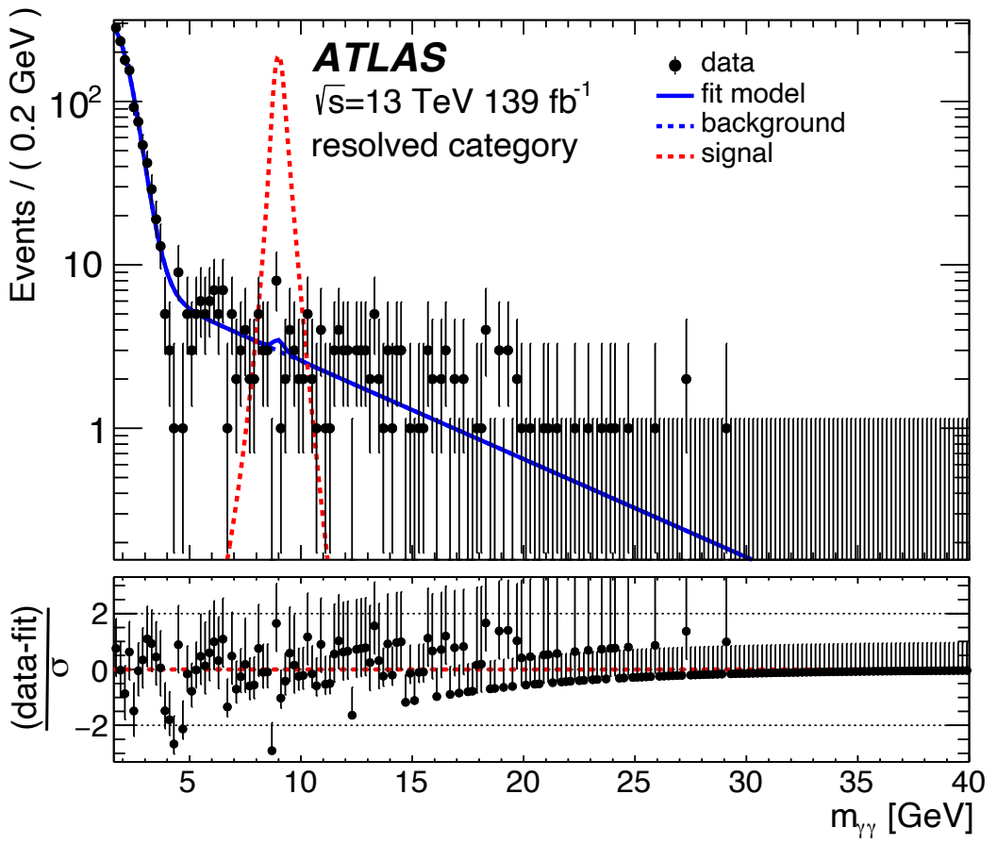
Also constrain effective coupling between H, Z and a within ~ 0.015 to 0.1 in this mass range

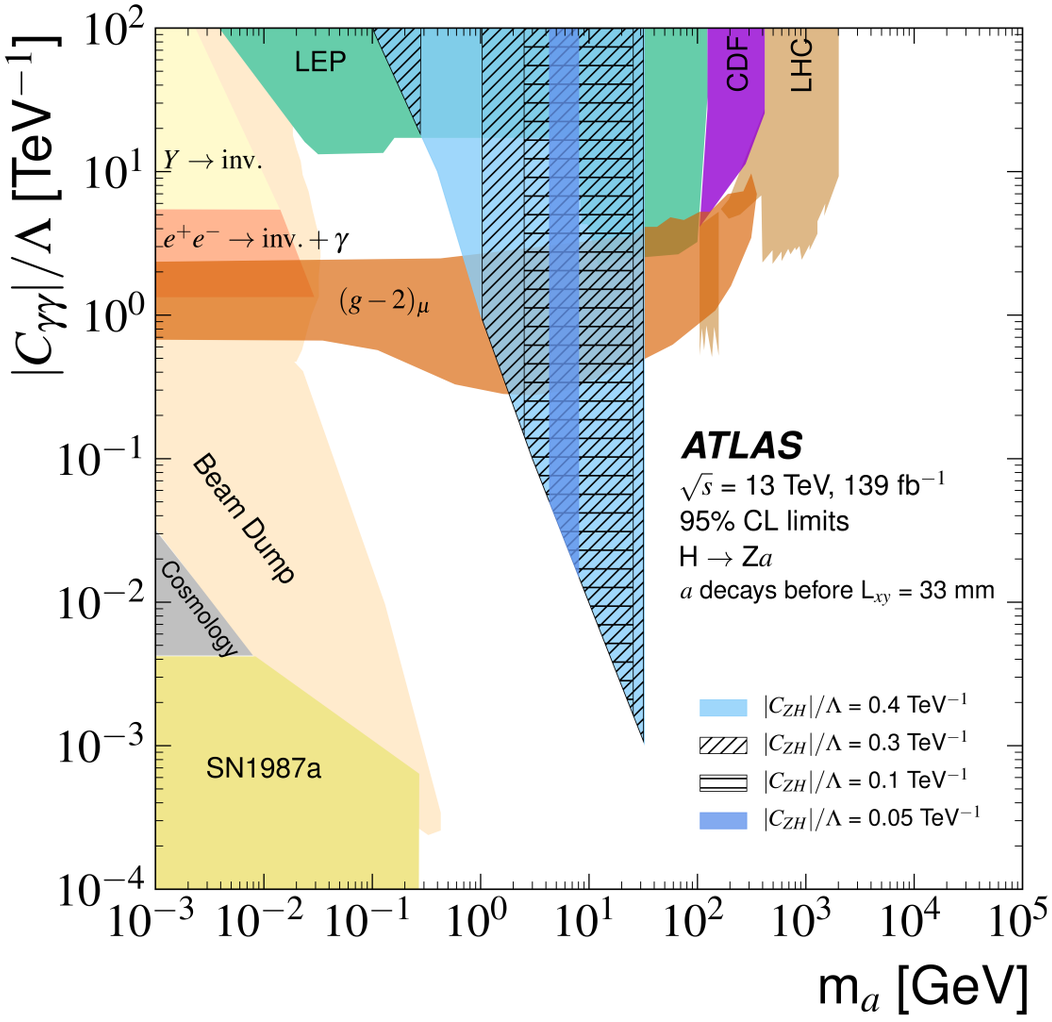
$H \to Za,\ a \to \gamma\gamma$

Consider ALP mass range $0.1 < m_a < 33$ GeV

PLB 848 (2024) 138536

- Merged photon reconstruction below $m_a < 2$ GeV identified as single object
- Final state contains a lepton pair from Z decay and one (merged) or two (resolved) photons from a
- Compare expected to observation: ΔR(Z,γ) (merged) and diphoton invariant mass (resolved)





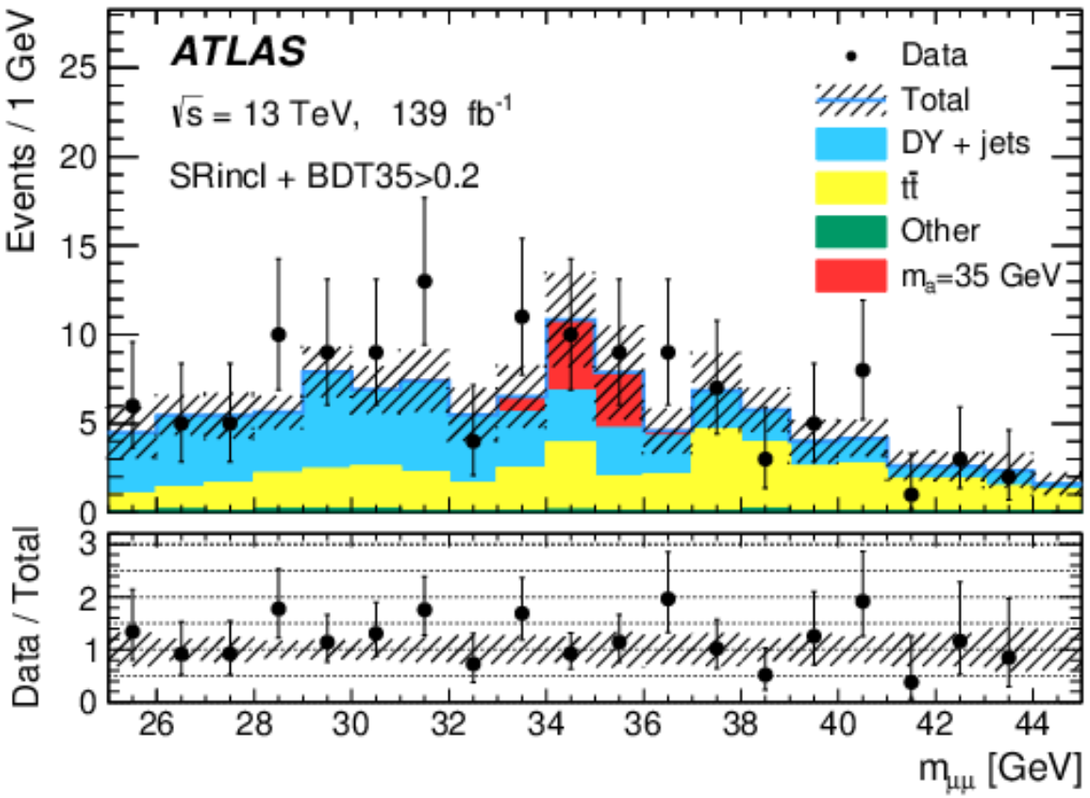
95% CL upper limit on B(H→Za) : 0.08 - 2 x 10^{-2} for the considered mass range

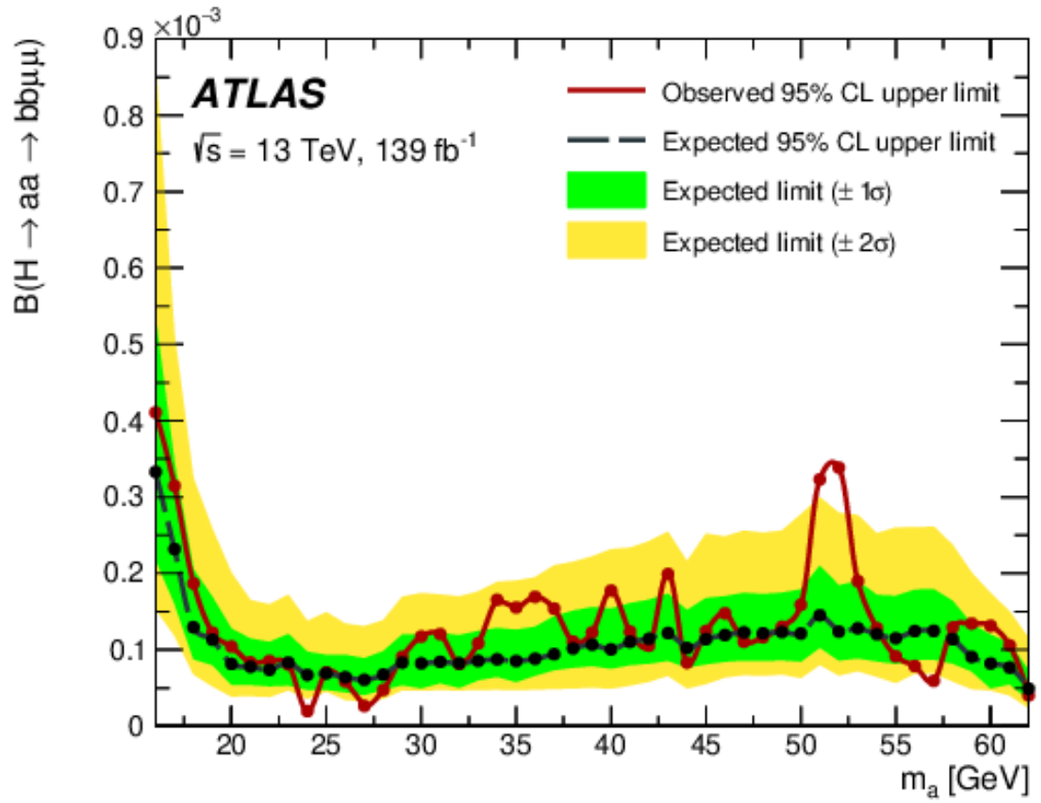
H→aa→2μ2b

Search for a masses within $16 < m_a < 62$ GeV

PRD 105 (2022) 012006

- A kinematic likelihood (KL) fit exploits $m_{\mu\mu} \sim m_{bb} \sim m_a$ to improve the reconstruction of $m_{\mu\mu bb}$
- The output of the fit, $\ln(L^{Max})$, and $m_{\mu\mu bb}$ is used for categorisation of signal and control regions
- A BDT classifier, trained per mass point, is used to further reduce SM backgrounds in SR





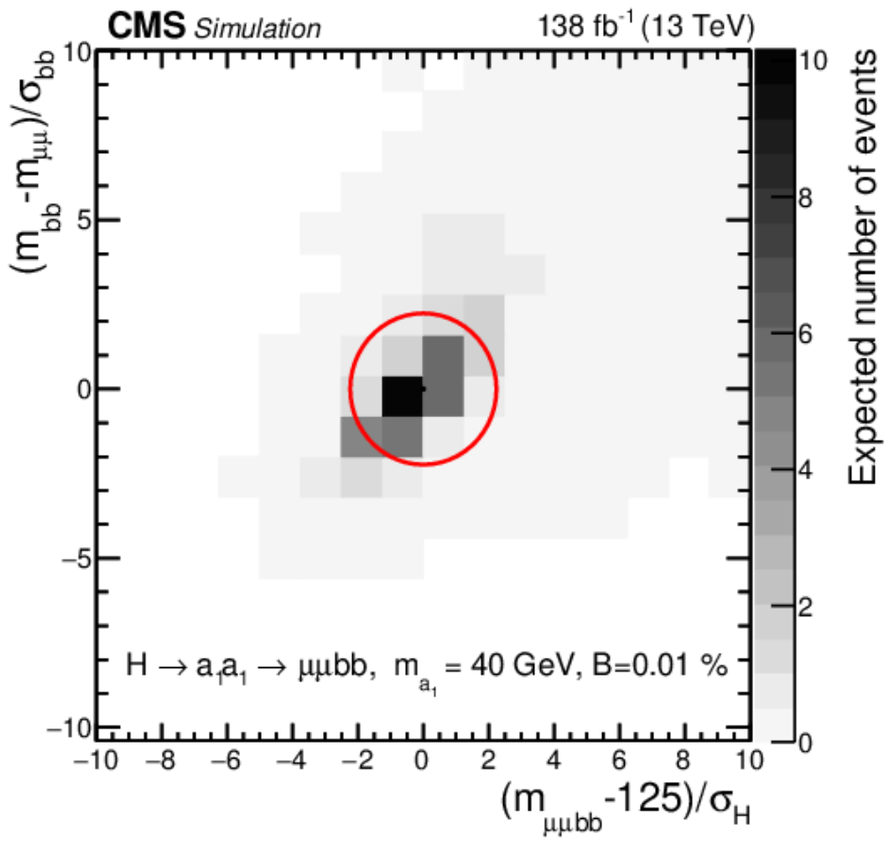
95% CL observed upper limits on $B(H \to aa \to 2\mu 2b) < 0.2\text{–}4.0 \times 10^{-4}$ with the largest excess observed near $m_a \sim 52$ GeV at 3.3σ local significance

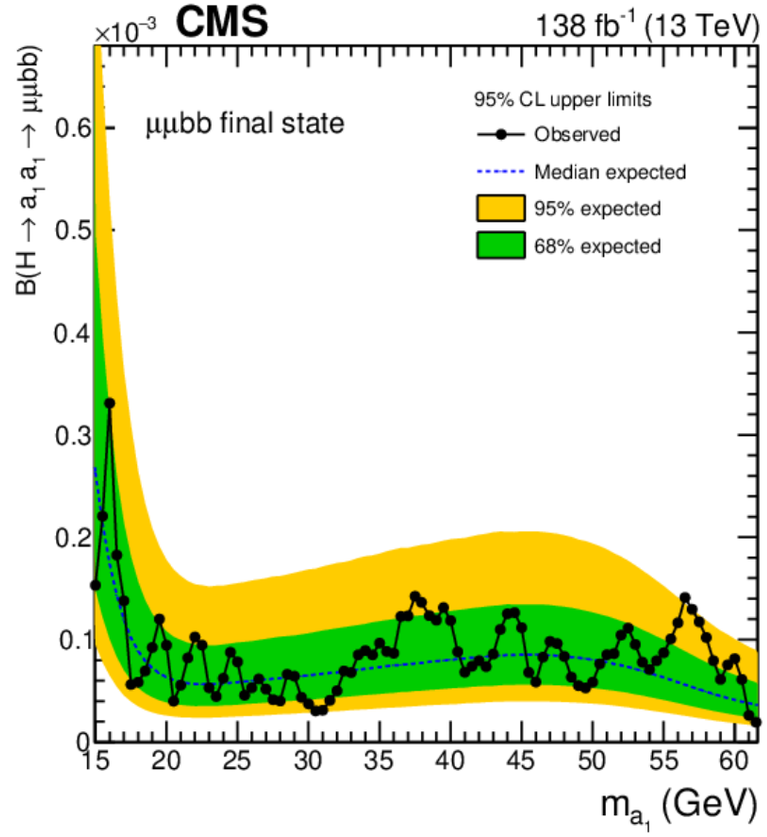
H→aa→2μ2b

Search for a masses within $15 < m_a < 60$ GeV

EPJC 84, 493 (2024)

- Bump hunt analysis using the dimuon invariant mass $m_{\mu\mu}$
- Completely data-driven background estimation, use mass constraints $m_{\mu\mu} \sim m_{bb} \sim m_a$ and $m_{\mu\mu bb} \sim m_H$ to reject background
- Parametric fit of the signal model in different categories based on b-jet properties





95% CL observed upper limits on $B(H \to aa \to 2\mu 2b) < (0.17\text{–}3.3) \times 10^{-4}$

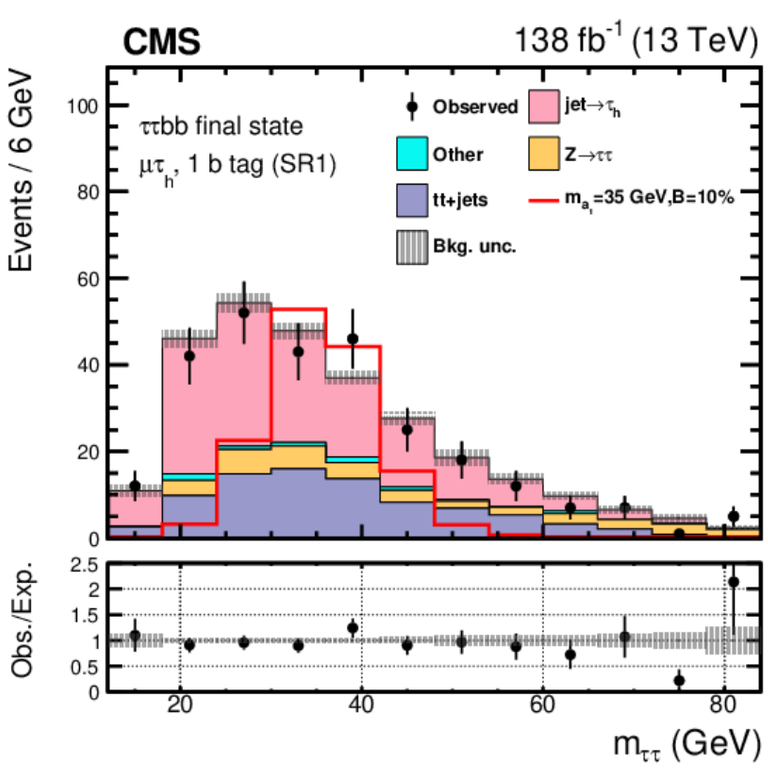
Most stringent observed upper limit till date in this final state, slightly better than ATLAS results

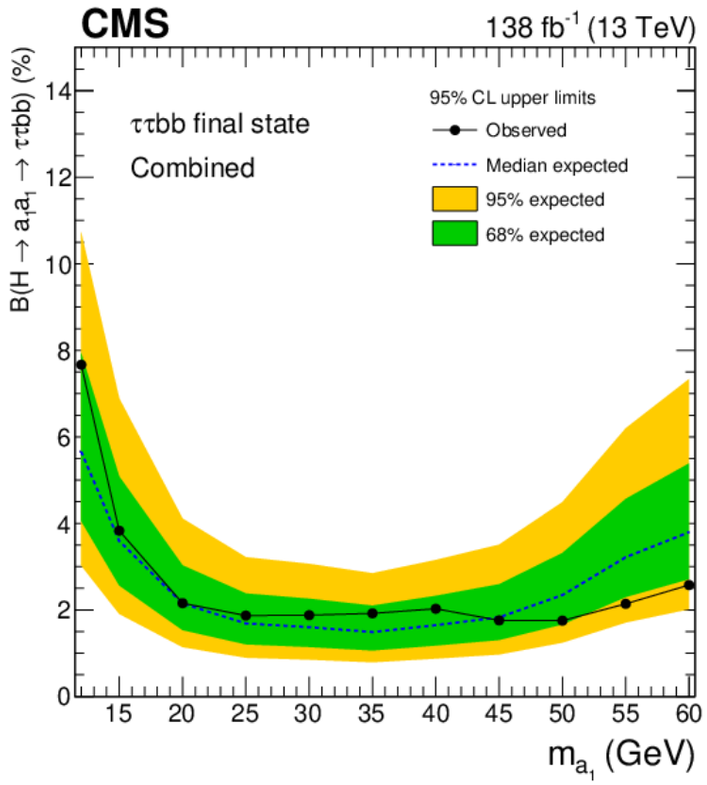
H→aa→2τ2b

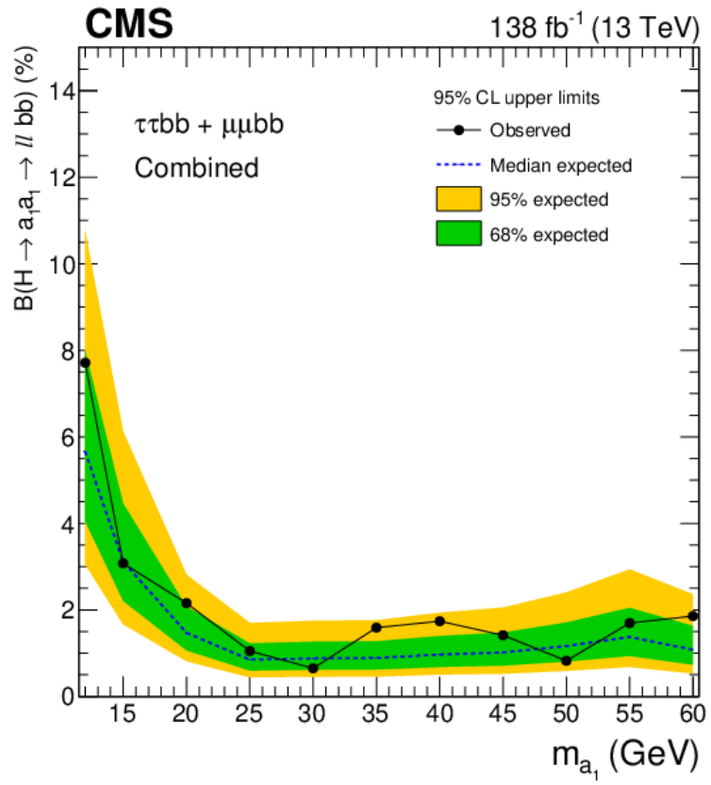
Search for a masses within $12 < m_a < 60$ GeV

EPJC 84, 493 (2024)

- Final state with relatively larger BR to bb and ττ, reconstruct $m_{\tau\tau}$ including neutrino energies
- Three final states explored: $\mu\tau_h$, $e\tau_h$, $e\mu$
- Deep neural network training in final states with 1 b-jet and 2 b-jets separately for three channels: used in event categorization to improve signal sensitivity







95% CL observed upper limits on $B(H\to aa\to 2\mu 2b) < 1.7\text{–}7.7 \times 10^{-2}$

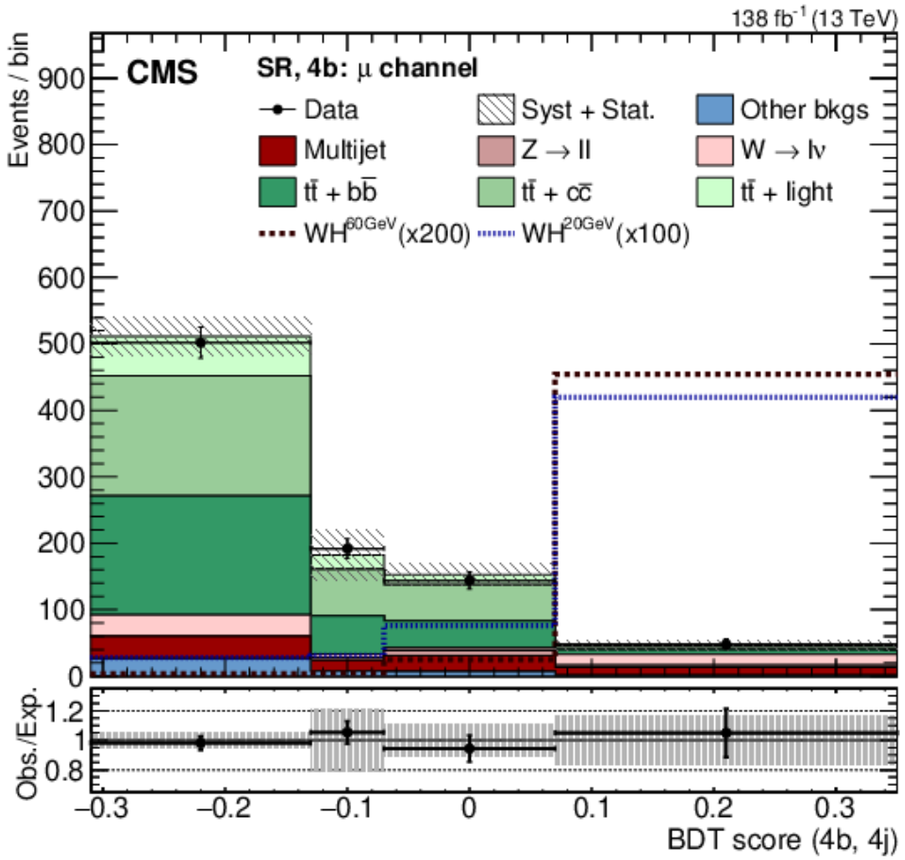
2μ2b and 2τ2b combination: BR(H→aa) values excluded above 23% (Type II tanβ > 1), 7% (Type III tanβ = 2.0) and 15% (Type IV tanβ = 0.5)

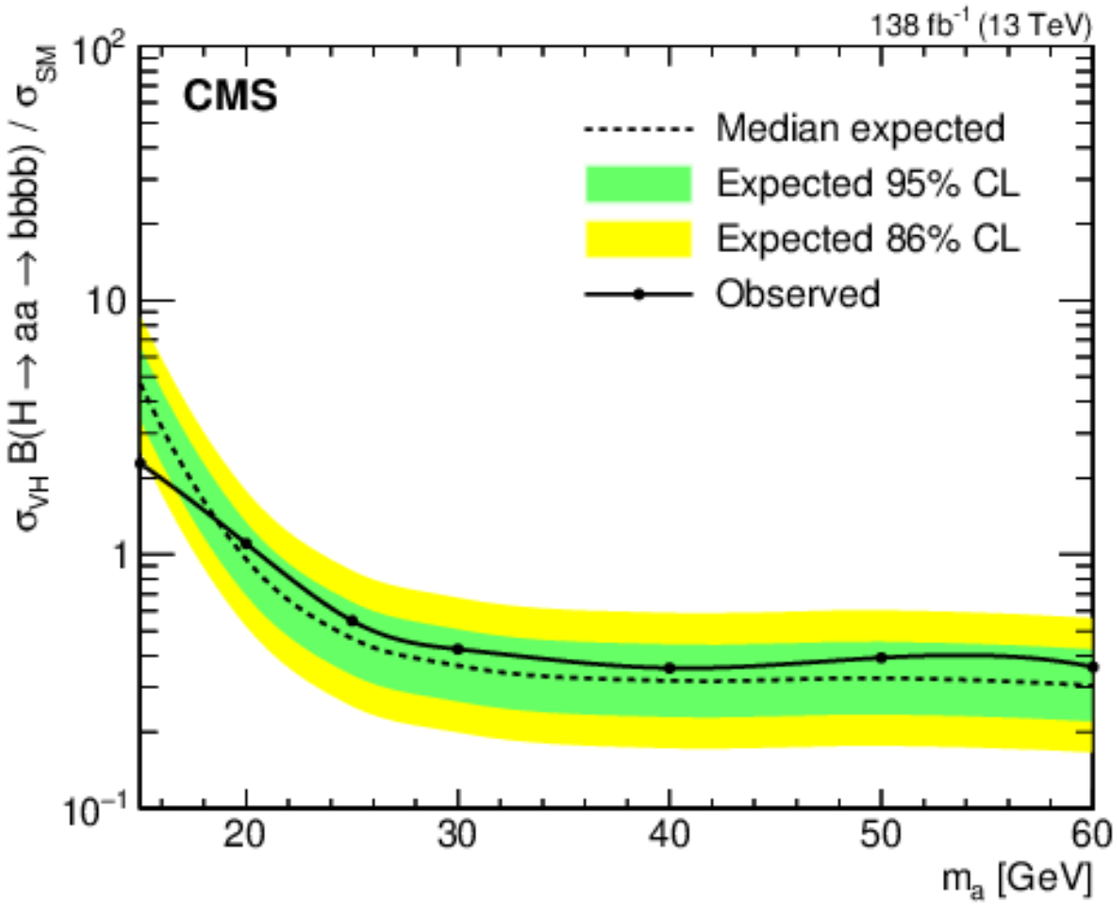
H→aa→4b

Challenging fully hadronic final state search within $12 < m_a < 60$ GeV

accepted by JHEP

- Feasible reconstruction in VH production mode, events selected using single or double-lepton trigger
- Resolved analysis: at least 3 jets in the selected events, categorised based on number of jets and b-jets
- Signal-to-background discrimination using a BDT, score distribution compared to data



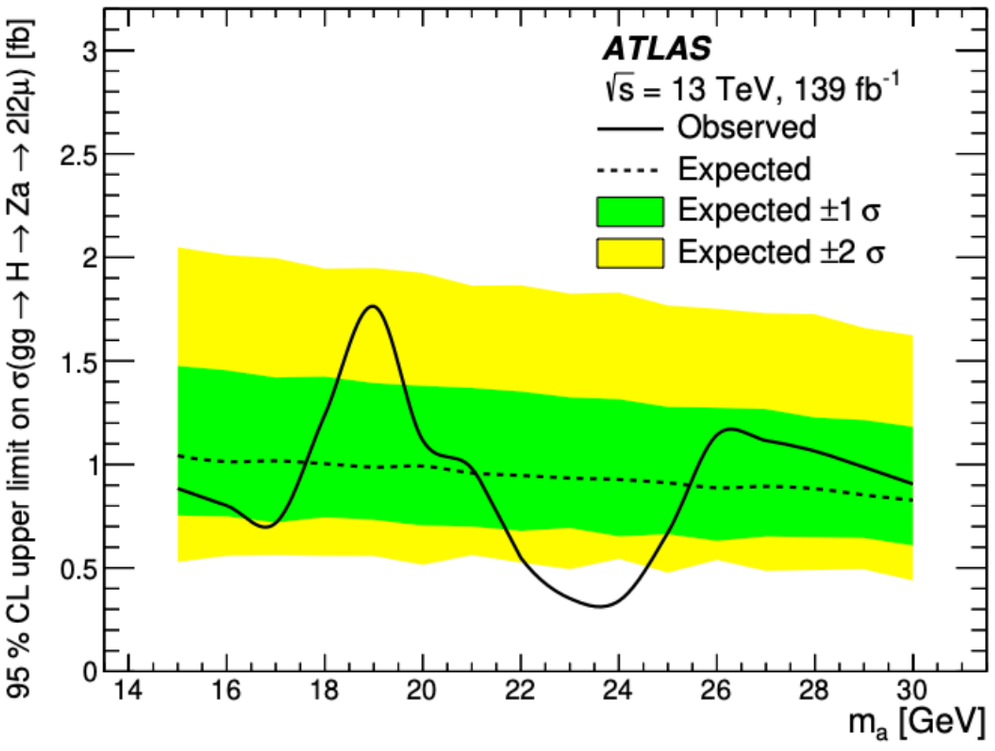


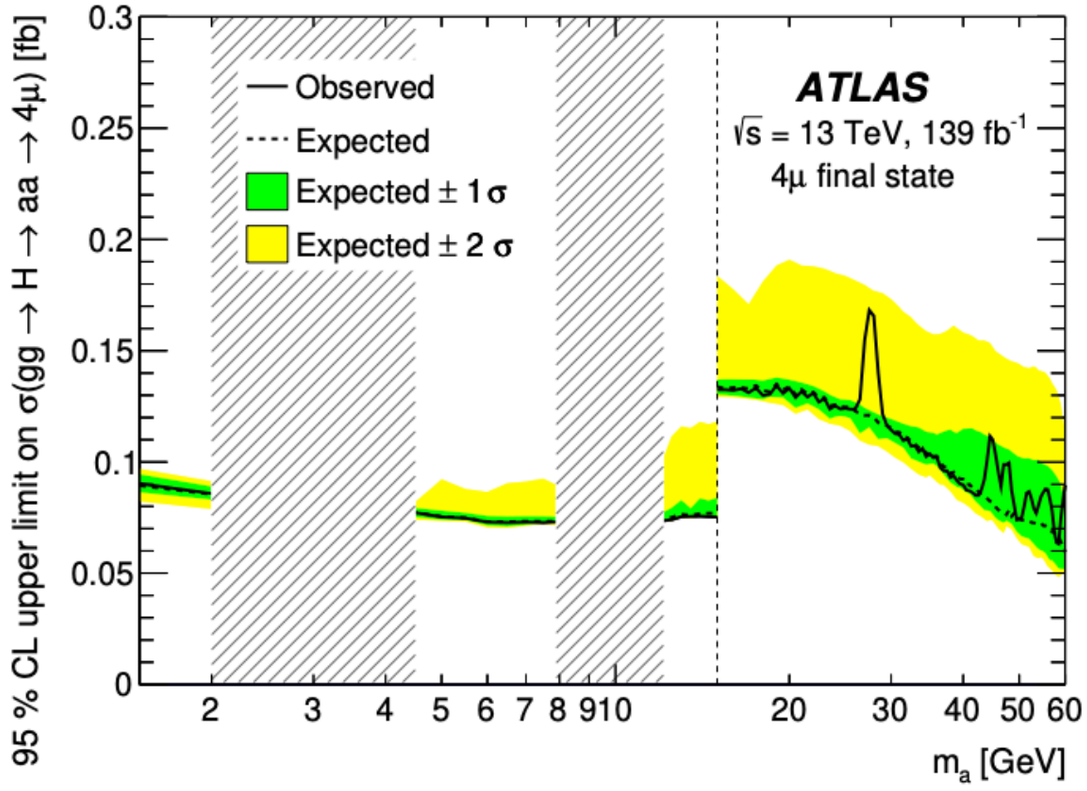
Assuming B(H→aa→4b) = 100%, m_a values between 21-60 GeV are excluded at 95% CL

H→aa/Za→4μ/4e

Higgs boson decays to spin-0 or spin-1 particles $1 < m_a < 60$ GeV JHEP 03 (2022) 041

- Reconstruct two same flavour opposite sign dilepton pairs per event
- For H→aa choose quadruplet with smallest $|m_{(ll)1}-m_{(ll)2}|$, for H→Za choose smallest $|m_Z-m_{(ll)1/2}|$
- Using $m_{(ll)1} \sim m_{(ll)2}$, maximum likelihood fit is performed on $\langle m_{ll} \rangle$ distribution





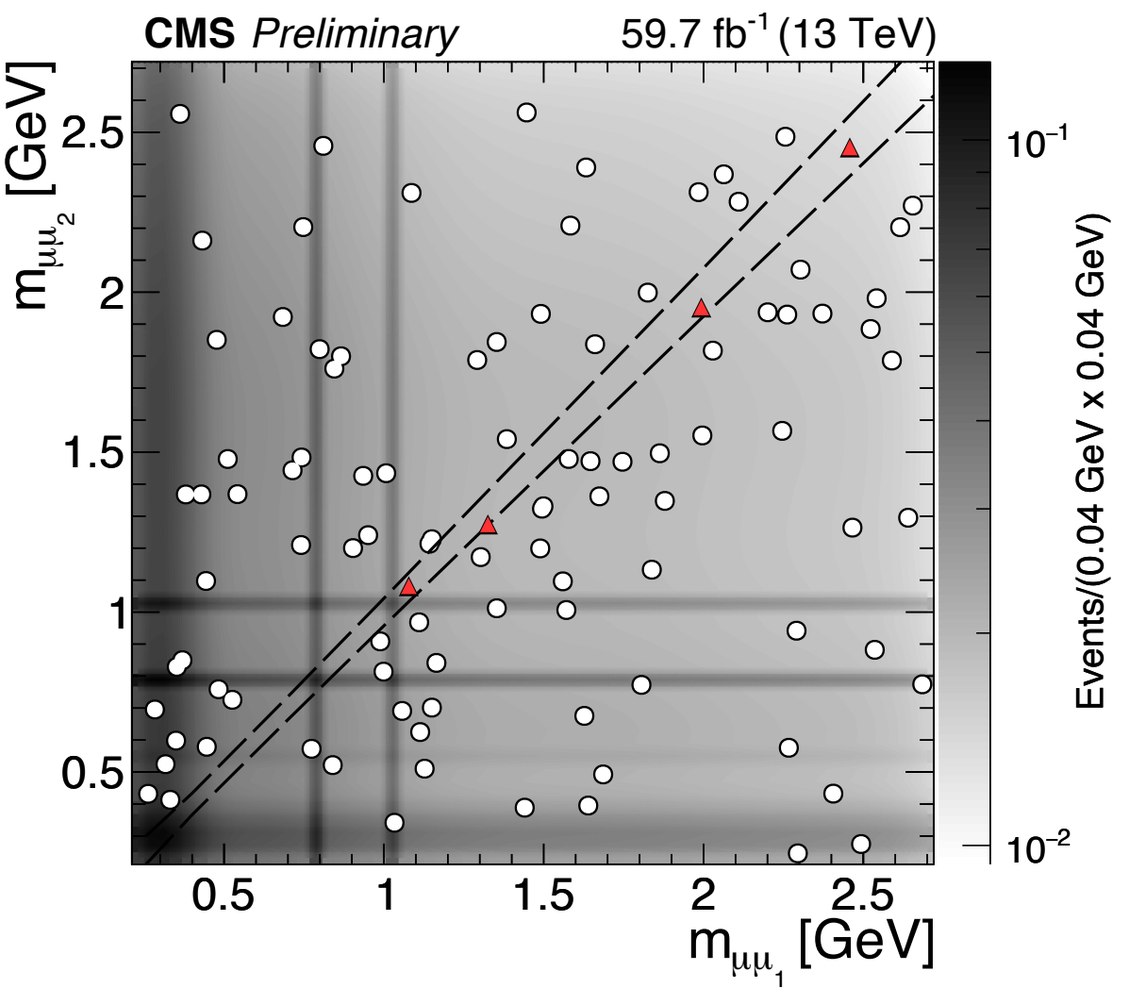
Limits are also set on the Higgs boson kinetic mixing parameter with a dark Higgs sector:

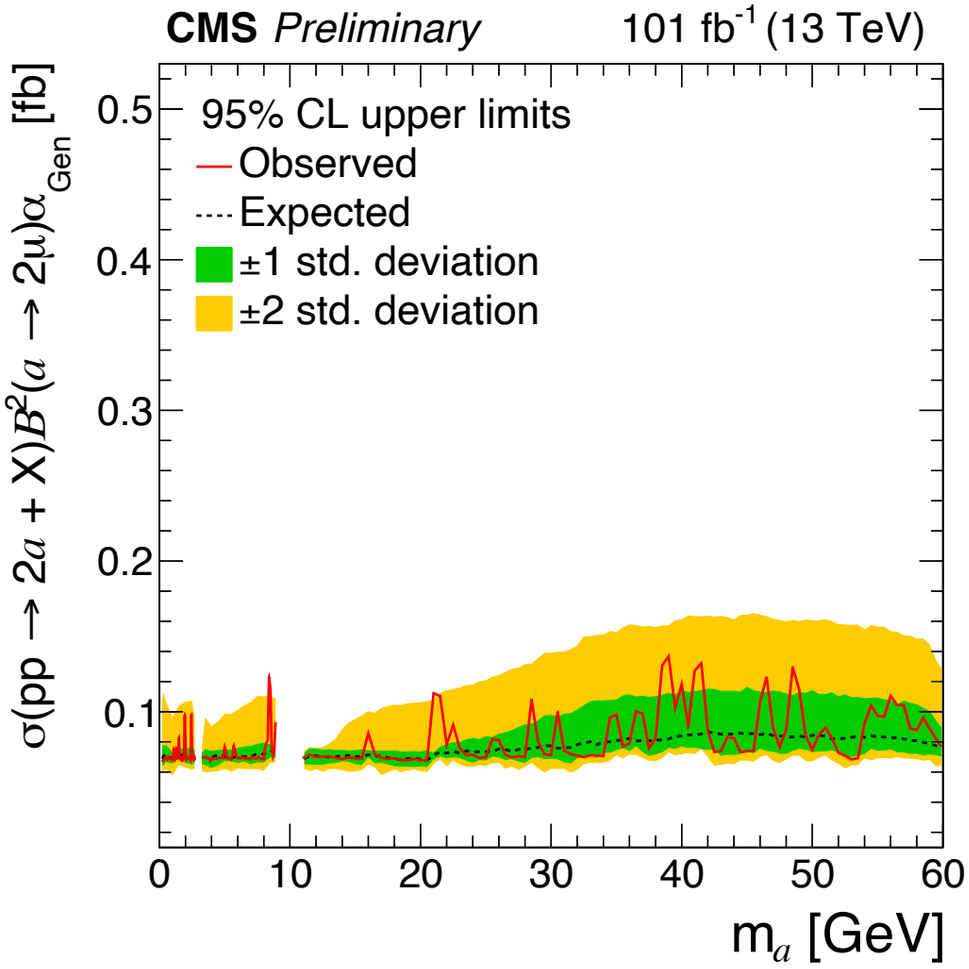
Observed values are constrained below 1-6 x 10^{-4} for the considered mass range, assuming kinetic mixing of the dark photon with the SM photon is 10^{-4}

H→aa→4μ

Model-independent search considering $0.21 < m_a < 60$ GeV and $0 < c\tau < 100$ mm HIG-21-004

- Interpreted in terms of vector-portal, ALPs, NMSSM, dark-SUSY models
- Long-lived muon trigger utilised for 2018 data
- Reconstruct two dimuon pairs per event where $|m_{(\mu\mu)1} - m_{(\mu\mu)2}| < f\,(m_{(\mu\mu)1} + m_{(\mu\mu)2})/2$)





95% CL upper limit on $\sigma(H\rightarrow 2a+X)\times BR^2(a\rightarrow 2\mu)$, constrained within 0.049 and 0.247 fb

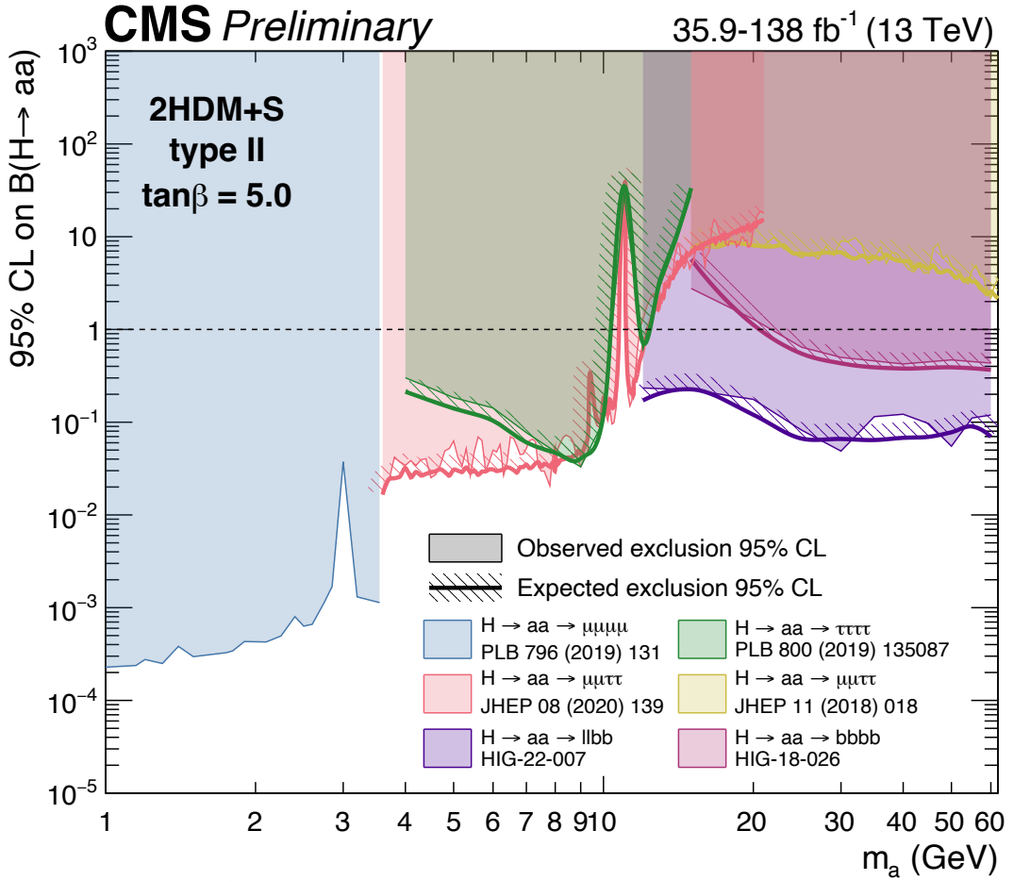
Summary

Higgs portal to hidden BSM sector being explored by CMS analyses in different final states

→ **Many full Run-2 results published, some are work in progress**

- Improved sensitivity compared to previous searches due to changes in analysis strategy rather than the increase in data statistics alone
- No significant excess over SM prediction *just yet*, many other possibilities remain to be explored
  - Possibility to add h→Za search in a→ll/jj channels, even a→ττ
  - Addition of long-lived signatures for low pseudoscalar masses
  - Results are dominated by statistical uncertainties
- Improve search strategies using new tools
  - Boosted reconstruction, triggers, adding new channels, combinations

Direct searches benefit the most with increase in luminosity: look forward to Run-3 results!



CMS Run-2 2HDM+S Summary

Thank You