Searches for exotic decays of the 125 GeV Higgs boson in the CMS experiment

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20 December 2024

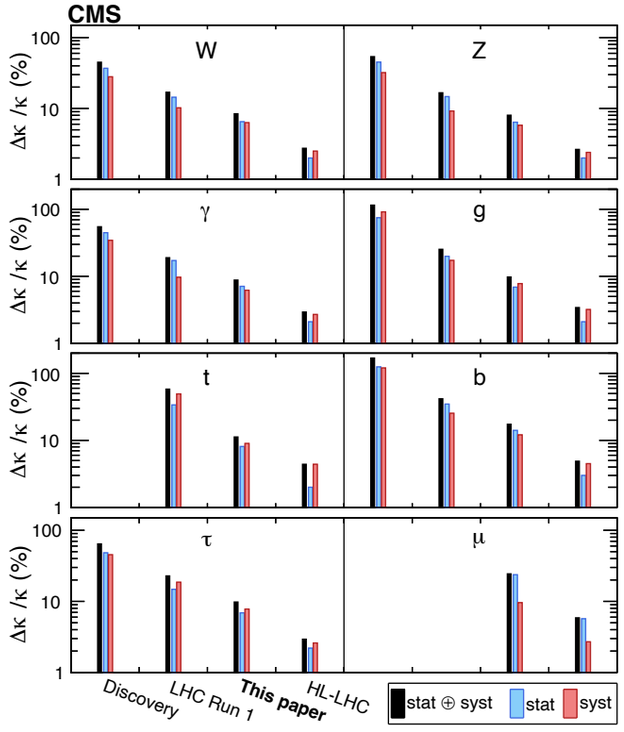
XXVI DAE-BRNS High Energy Physics Symposium
BHU, Varanasi, India, 2024

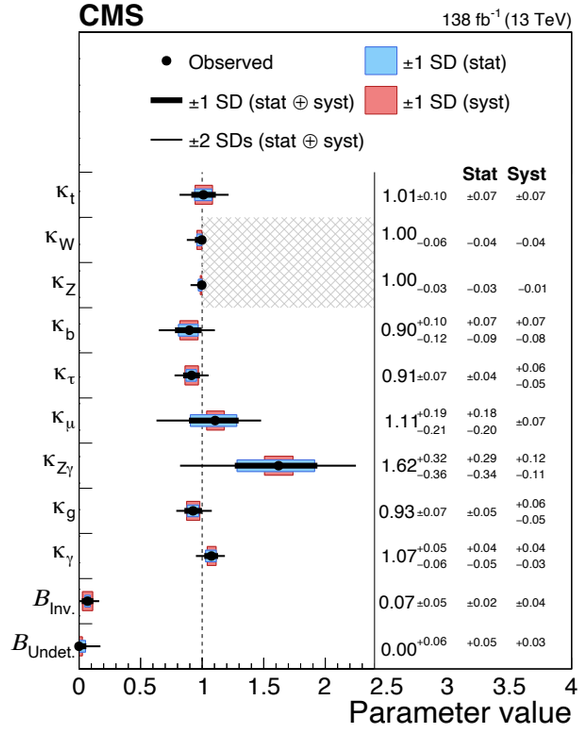
Introduction

12 years since the Higgs boson discovery: has LHC really entered the "precision era"?

- Important characterisation of the Higgs boson still remaining: first-generation Yukawa couplings, self-coupling, quartic coupling, differential cross-section measurements…
- Limited sensitivity to new physics interactions through SM Higgs coupling measurements
- Improvement of analysis techniques and trigger strategies enabling experiments to probe rare event signatures with available data

Nature 607, 60–68 (2022)





- LHC experiments focus on measuring the Higgs properties, including probes to BSM physics
- Direct search for exotic particles able to probe several TeV energy scales
- This talk: reviewing results from various Higgs boson exotic decay signatures using Run 2 data collected by CMS experiment

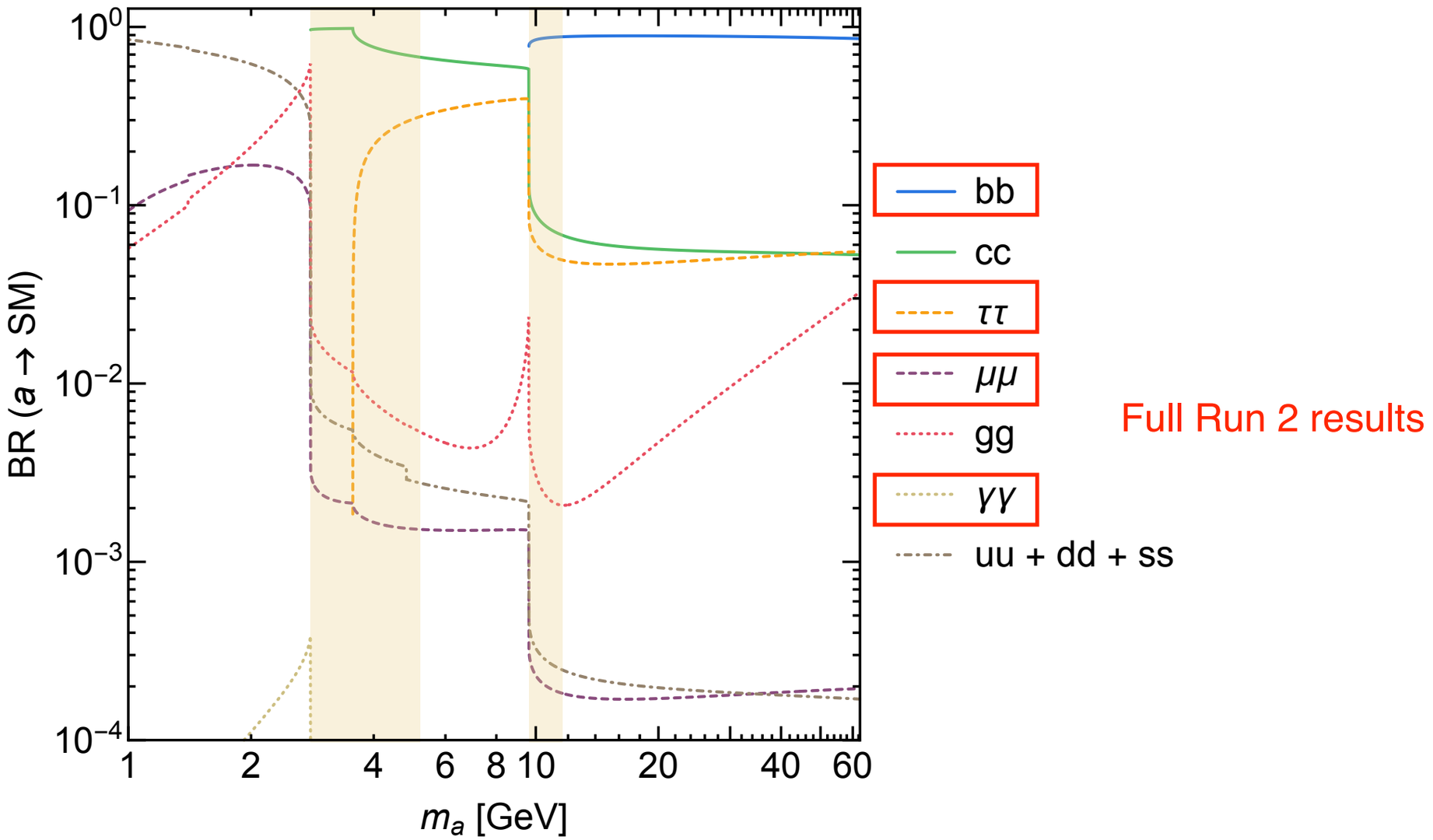
Higgs to pseudoscalar decays

- Simplest extension of Higgs sector: two Higgs doublets model (2HDM), however available parameter space of 2HDM at the LHC is already much constrained
- By adding an extra singlet, a wide range of possible exotic Higgs decays are possible: 2HDM+S
- The additional singlet has no direct Yukawa coupling, only couples to the two Higgs fields

Predicted decay branching ratios of pseudoscalar to SM particles in Type I 2HDM+S

arxiv:1312.4992

Type II couplings → NMSSM



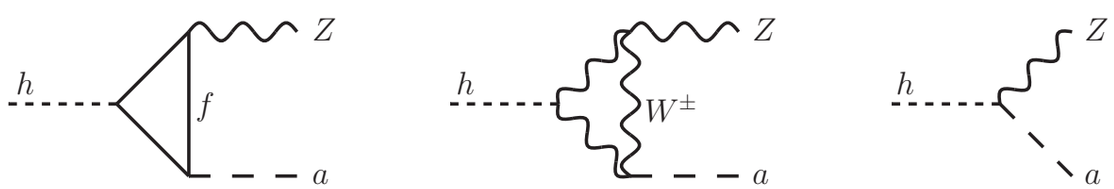
Full Run 2 results

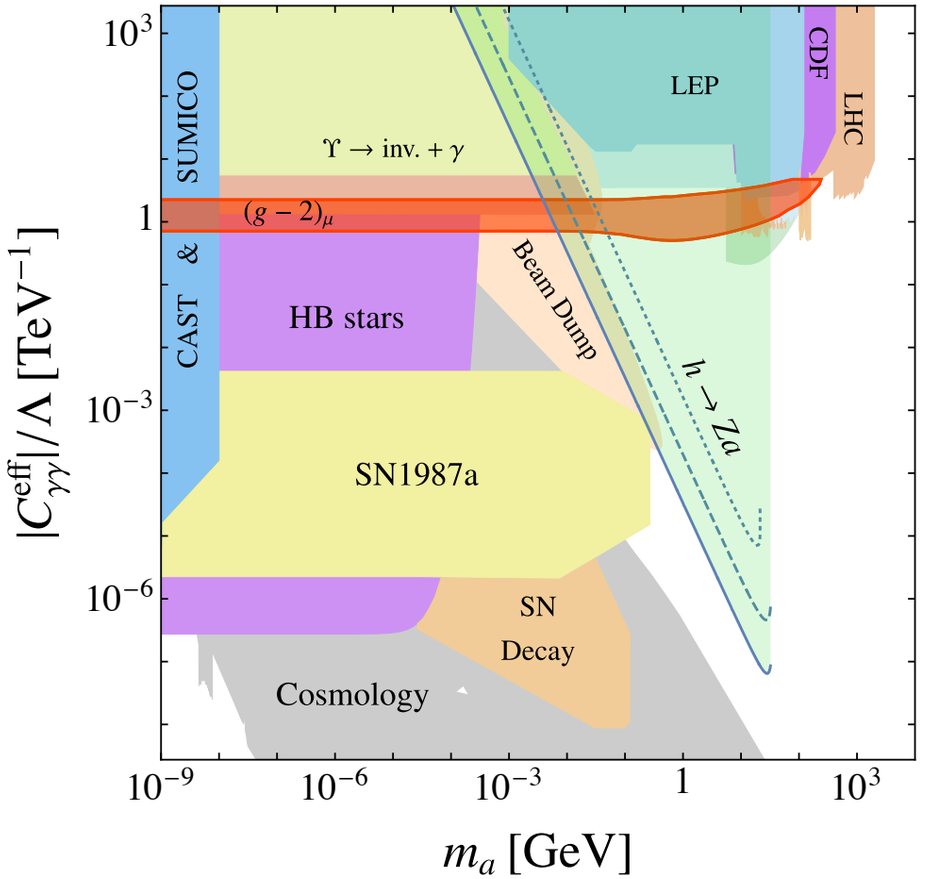
Higgs decays to Axion-Like-Particles

- Axions: pseudoscalar particles, originally proposed to answer strong CP problem in QCD
  - Extension of the SM with an additional, spontaneously broken, global chiral symmetry
- ALPs are gauge singlets under SM, coupling to SM fermions
  - Enhanced coupling to photons can contribute to anomalous muon magnetic moment
  - Constraints on the ALP mass and coupling to photons derived from various experiments

JHEP 12 (2017) 044

- Search channels: h→aa and h→Za
  - Effective couplings: C_{Zh}^{eff}/Λ and $C_{\gamma\gamma}^{eff}/\Lambda$
- For strongly boosted ALPs, a→γγ will appear as a single photon jet and contribute to h→Zγ measurement





H→aa→4γ (boosted)

Search for very low mass pseudoscalars (0.1 < m_a < 1.2 GeV) in the diphoton decay mode

- Boosted diphoton decay is reconstructed as a single photon-like object "Γ" using end-to-end deep learning PRD 108 (2023) 052002

Fit 2D distribution of invariant masses $m_{\Gamma 1}$ and $m_{\Gamma 2}$

PRL 131 (2023) 101801

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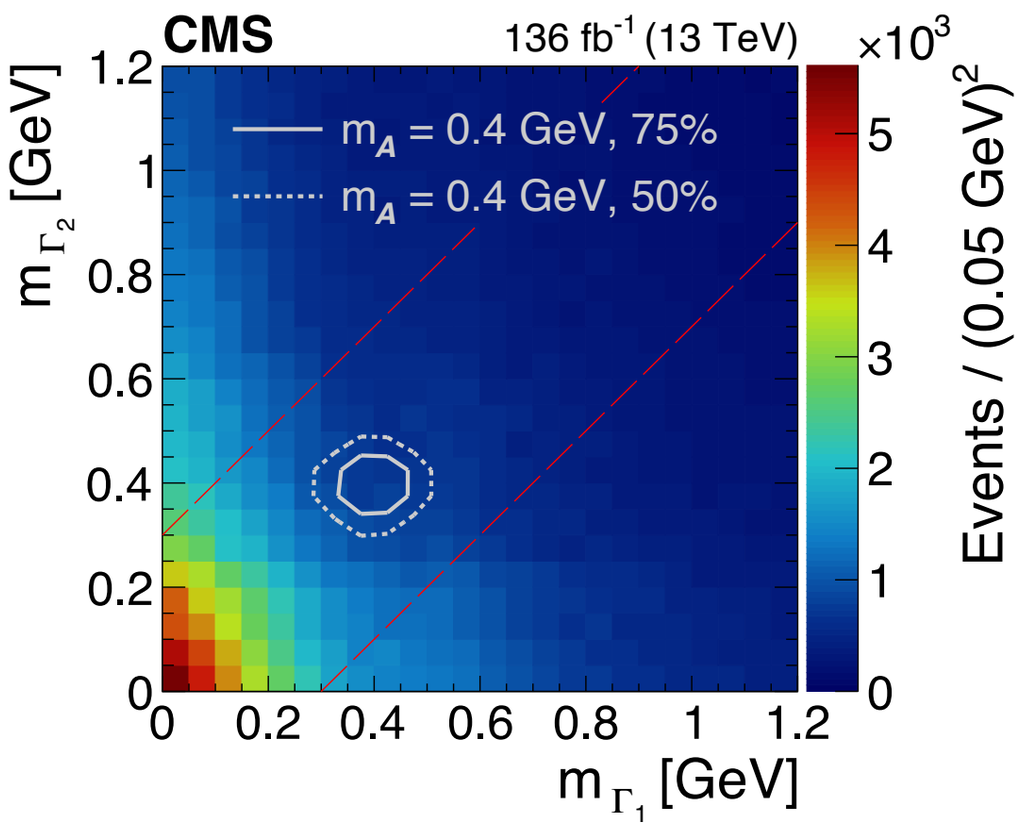
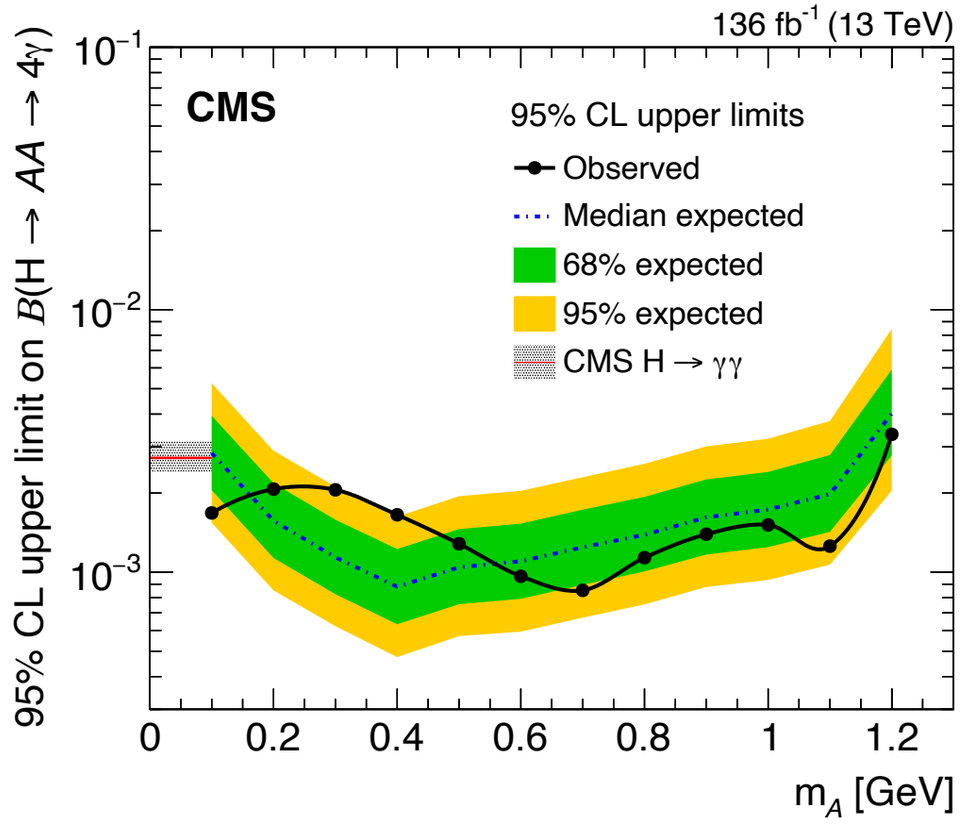
- **Signal region:** 110 < $m_{\Gamma\Gamma}$ < 140 GeV around Higgs resonance
- **Sideband regions:** 100 < $m_{\Gamma\Gamma}$ < 110 GeV and 140 < $m_{\Gamma\Gamma}$ < 180 GeV used to estimate non-resonant background





Search is also sensitive to long-lived decays: For m_a = 0.1 (0.4) GeV, upper limits are 1.6 (0.9) times larger for cτ = 1 mm and 30 (3) times larger for cτ = 10 mm

H→aa→4γ (resolved)

Search for SM-like H→aa→4γ where the four photons are well isolated:

JHEP 07 (2023) 148

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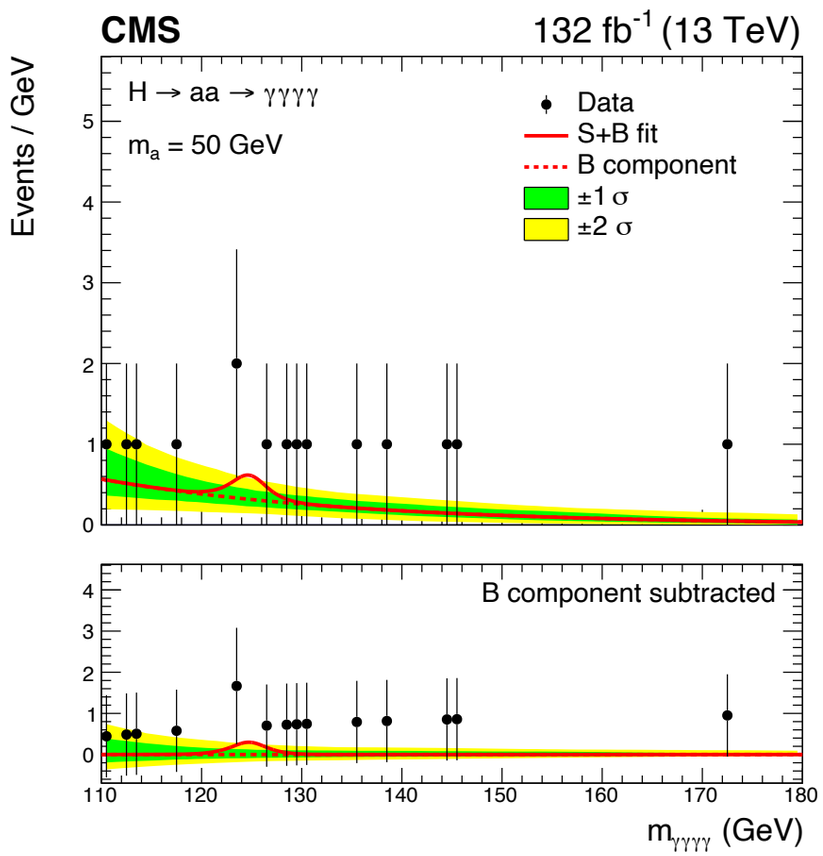
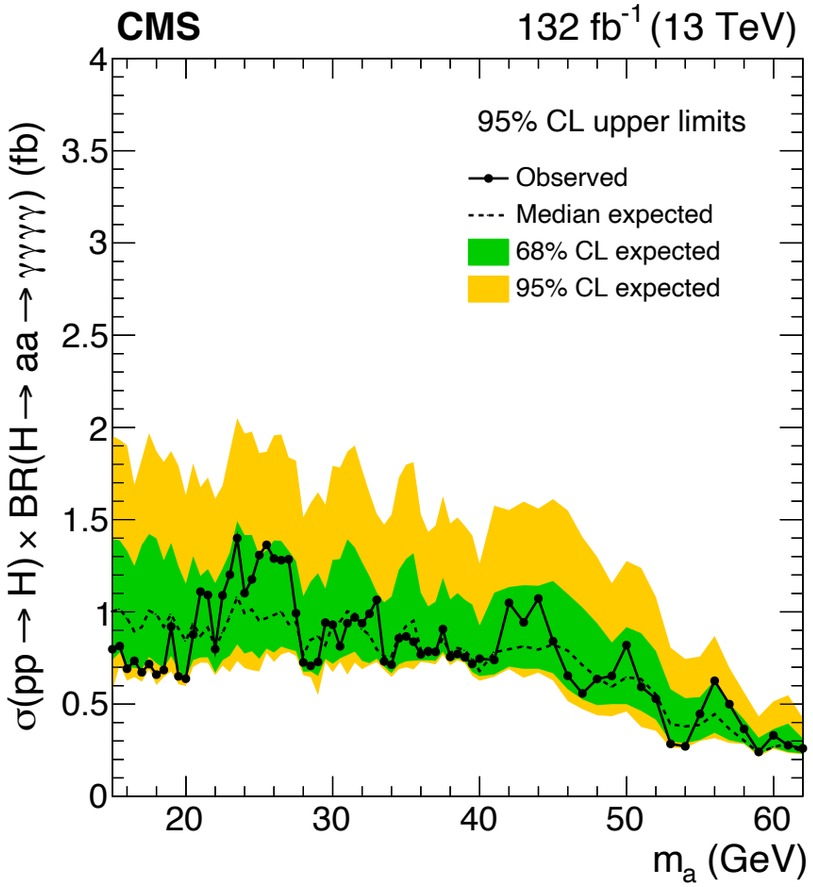
- Probes the mass range $15 < m_a < 62$ GeV
- Train a event classifier using variables uncorrelated to $m_{\gamma\gamma\gamma\gamma}$ and look for a 125 GeV resonance in the $m_{\gamma\gamma\gamma\gamma}$ spectrum of the signal-like events





Observed upper limits on cross section range between 0.80-0.26 fb, compared to Higgs production cross section of 52 pb

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

H→aa→2μ2b

Clean signature with a precise mass resolution from $m_{\mu\mu}$ and large BR from bb

- Search for a masses within $15 < m_a < 60$ GeV
- Bump hunt analysis using the dimuon invariant mass $m_{\mu\mu}$
- Completely data-driven background estimation

EPJC 84 (2024) 493
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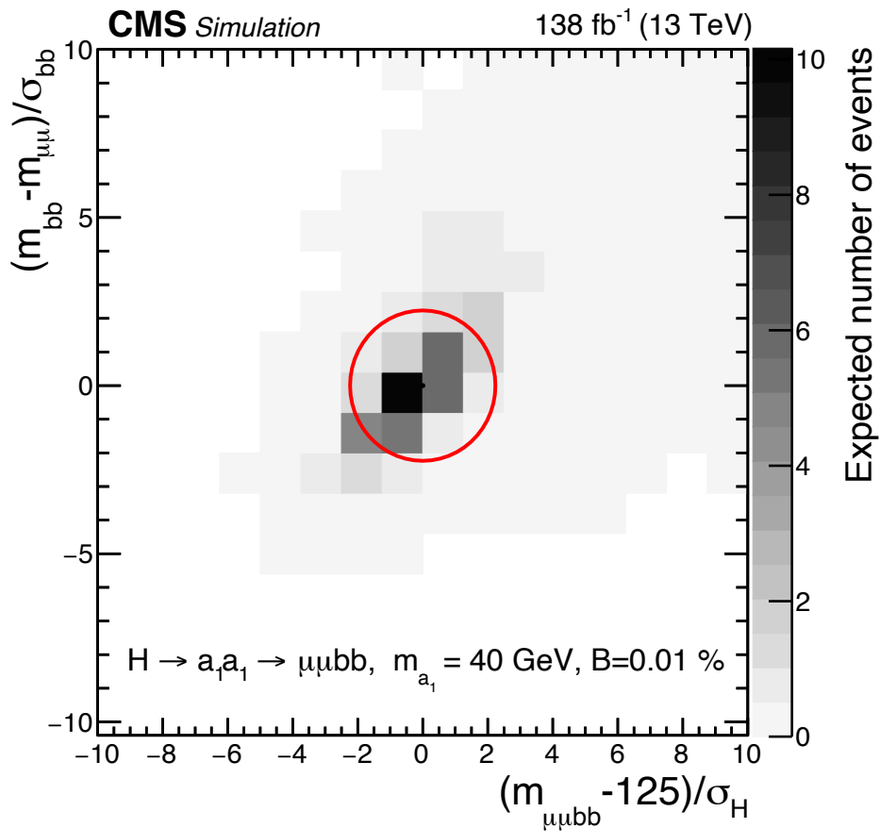
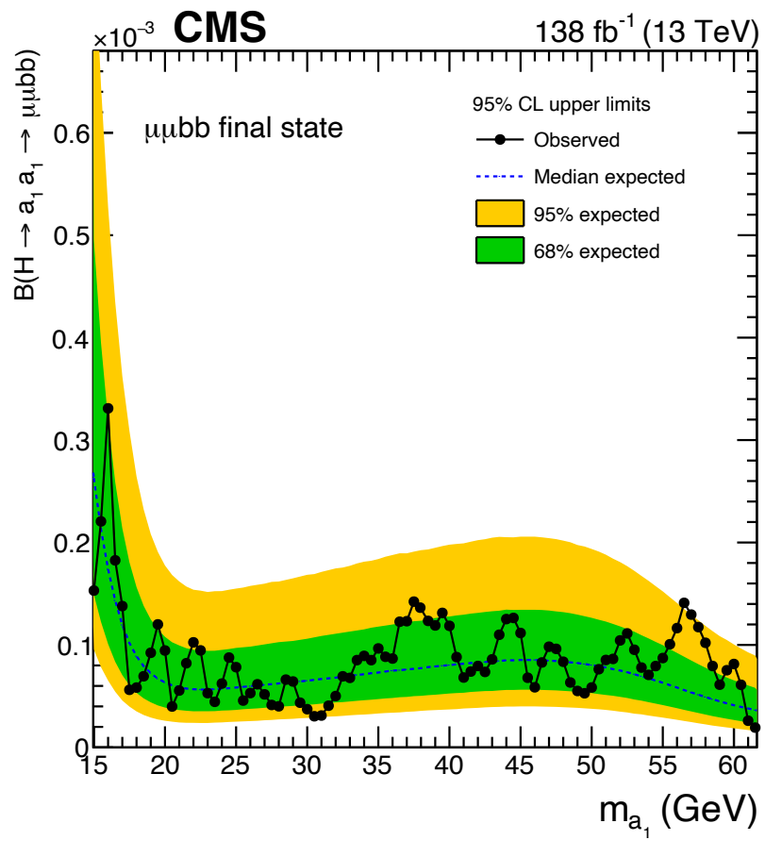
Most stringent observed upper limit till date in this final state, slightly better than ATLAS results





No significant deviations from SM prediction, analysis is limited by statistics

H→aa→2τ2b

Relatively larger BR to bb and ττ, improved τ lepton reconstruction techniques

- Search for a masses within $12 < m_a < 60$ GeV
- Three final states explored: $\mu\tau_h$, $e\tau_h$, $e\mu$
- SVfit algorithm to reconstruct $m_{\tau\tau}$ including neutrino energies

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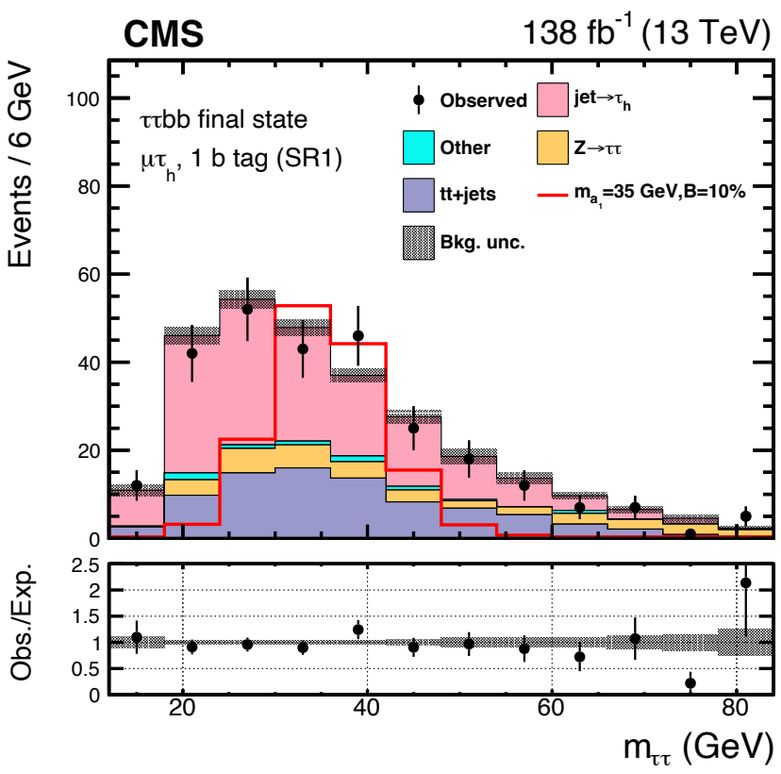
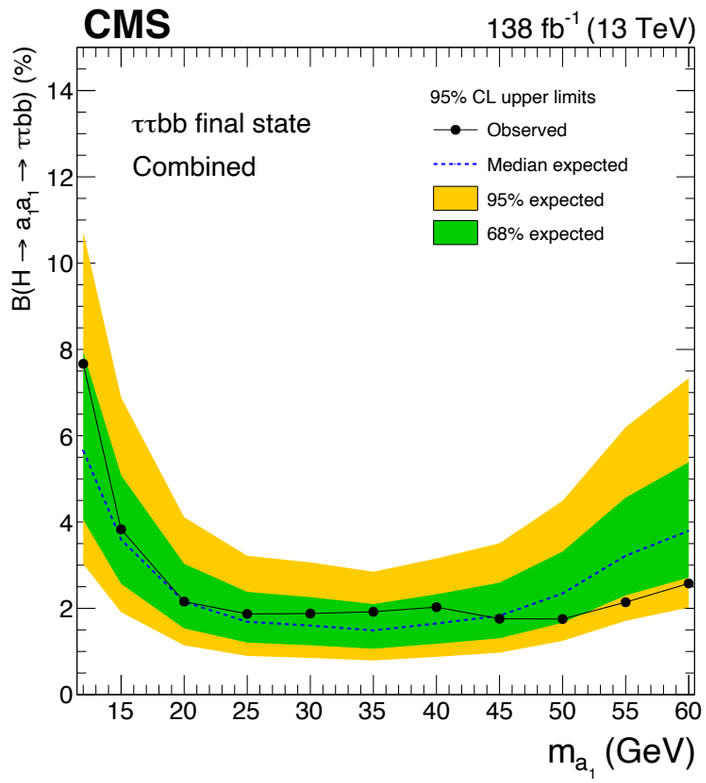
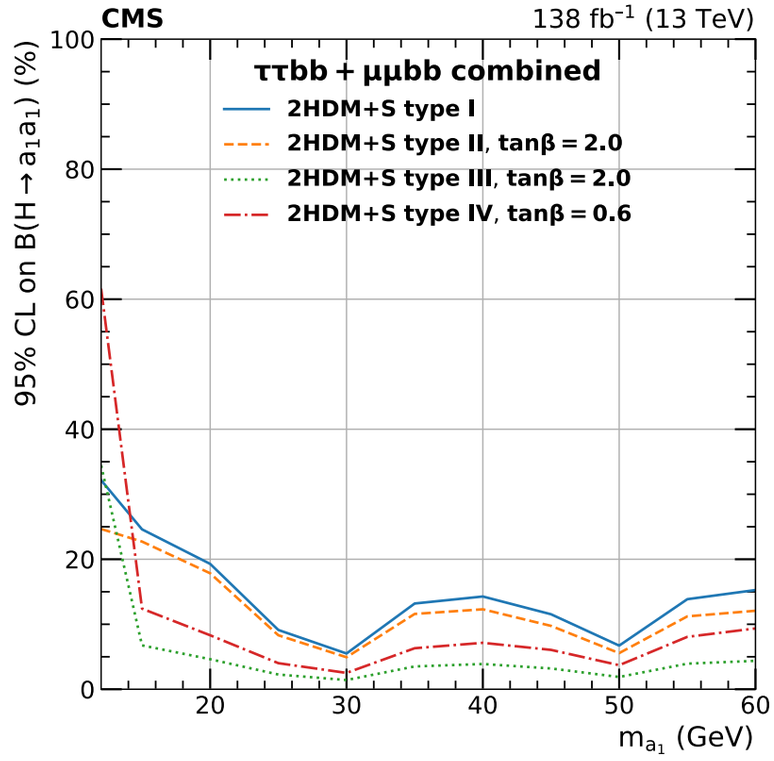
Type-independent upper limits on BR(H→aa→llbb) in the context of 2HDM+S are derived combining with 2μ2b as a function of m_a







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, consider mass range $12 < m_a < 60$ GeV

- 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

JHEP 06 (2024) 097
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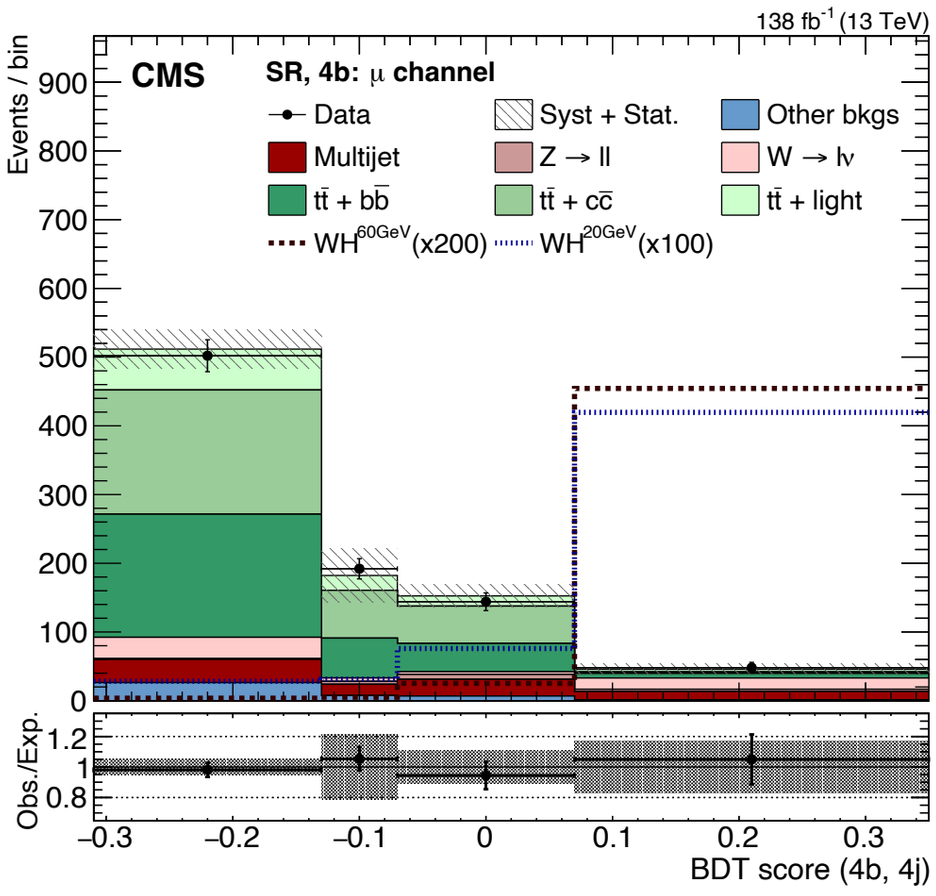
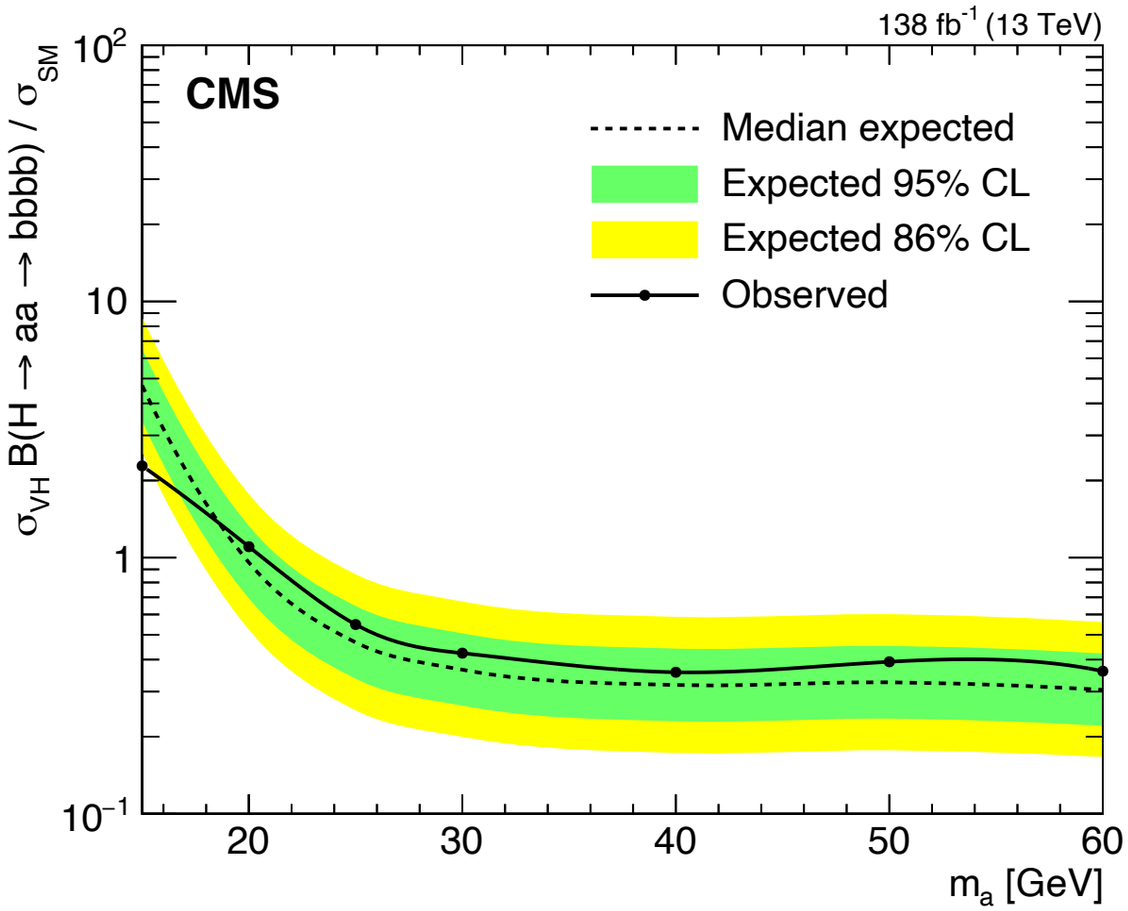




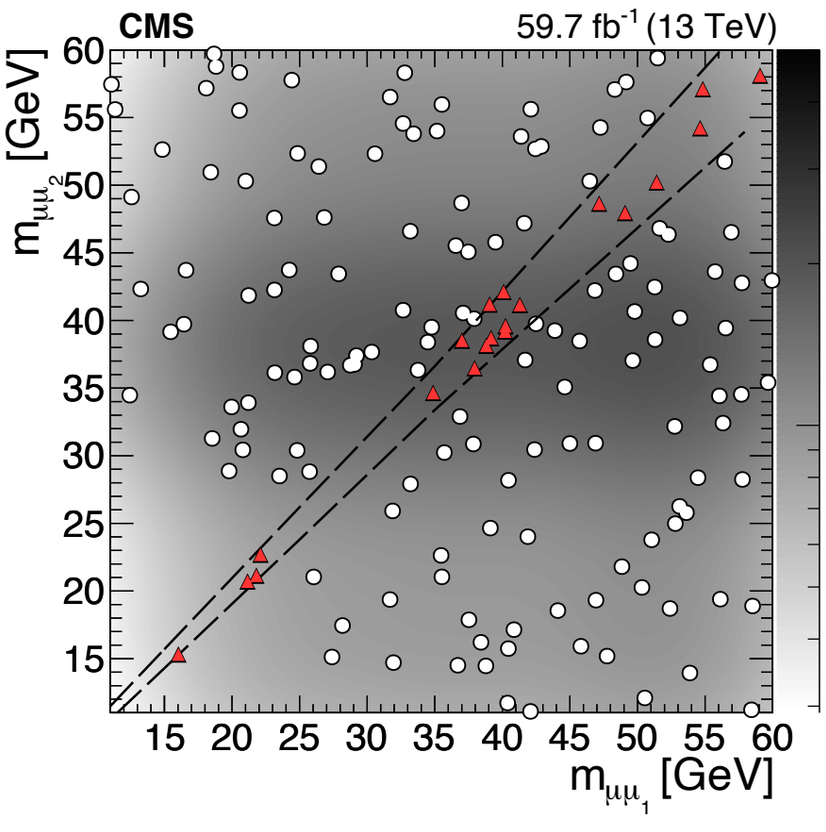
Assuming B(H→aa→4b) = 100%, m_a values between 21-60 GeV are excluded at 95% CL

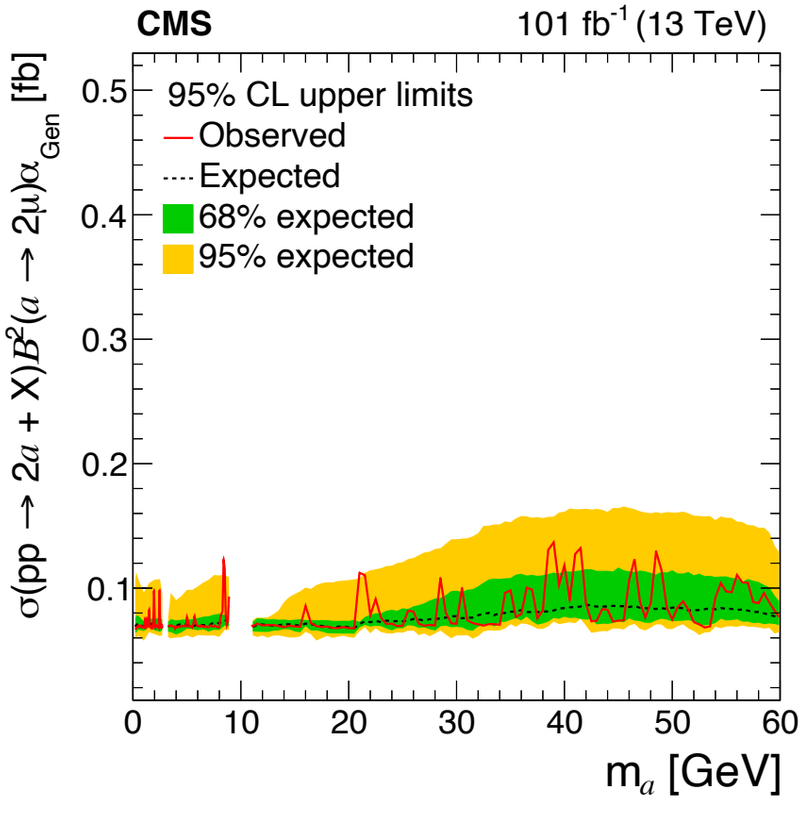
H→aa→4μ

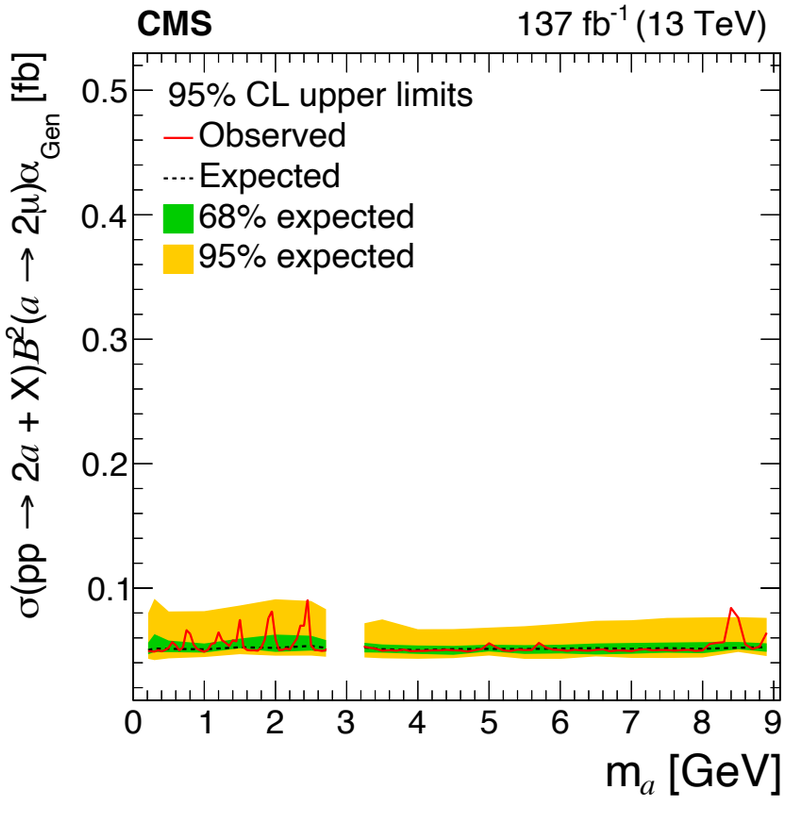
Excellent muon reconstruction, can target very low mass $0.21 < m_a < 60$ GeV

- Two dimuon pairs per event are chosen, where $|m_{(\mu\mu)1} - m_{(\mu\mu)2}| < W[(m_{(\mu\mu)1} + m_{(\mu\mu)2})/2]$, satisfying stringent reconstruction requirements that eliminate most of the background
- Displaced signature considered for 2018 data using new displaced muon trigger
- Model independent observed upper limits on cross section range between 0.049-0.247 fb for the entire mass range

arxiv:2407.20425
public plots





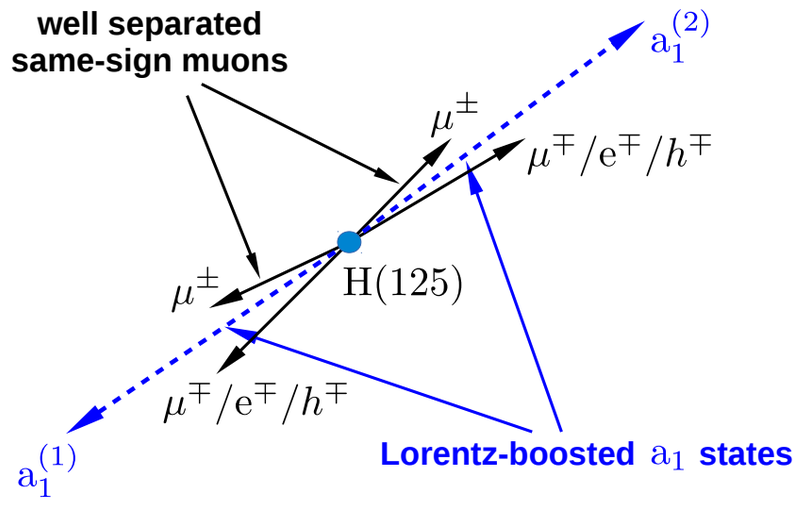


Results interpreted in NMSSM, ALP and Vector Portal models, 2018 result used to constrain long-lived signature from dark-SUSY model

H→aa→4τ

Analysis targets $4 < m_a < 15$ GeV where $a \to \tau_\mu \tau_{1\text{-prong}}$, also sensitive to $H \to aa \to 2\mu 2\tau$

- Same sign muons with large angular separation are selected
- Muons are non-isolated: accompanied by a charged track
- 2D distribution of the two muon-track system is used to discriminate between signal and background



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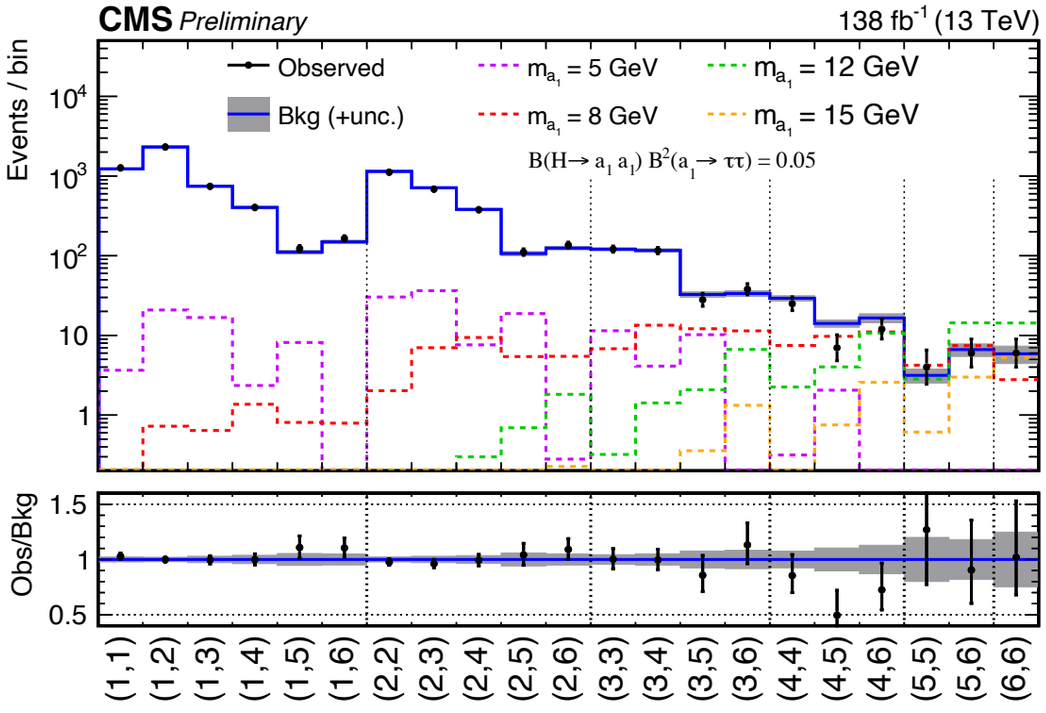
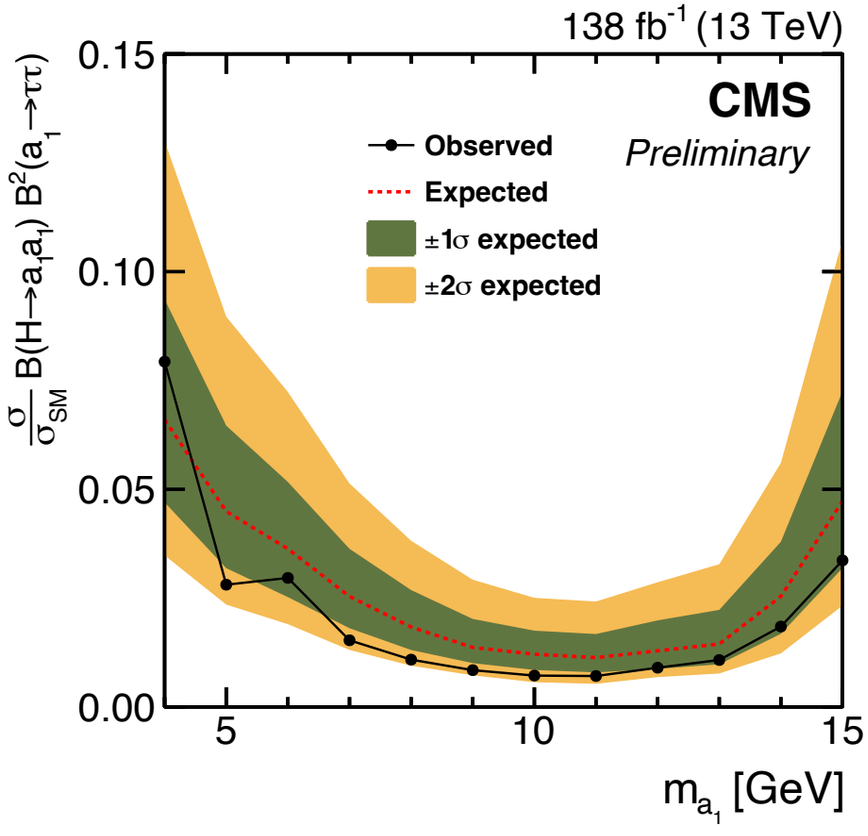




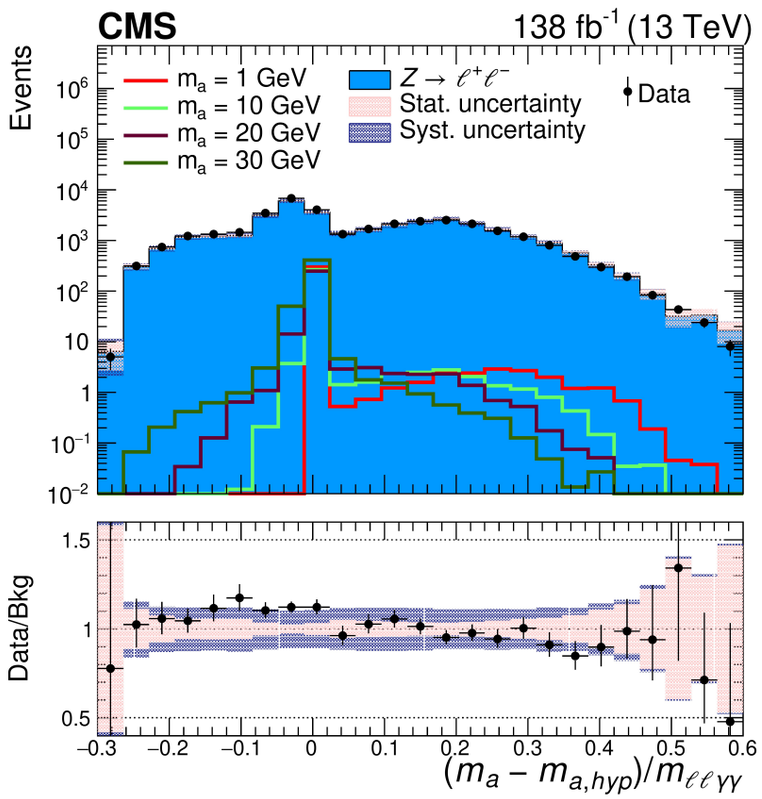
Most stringent upper limits to date for Type III 2HDM+S for all mass points for tanβ > 2

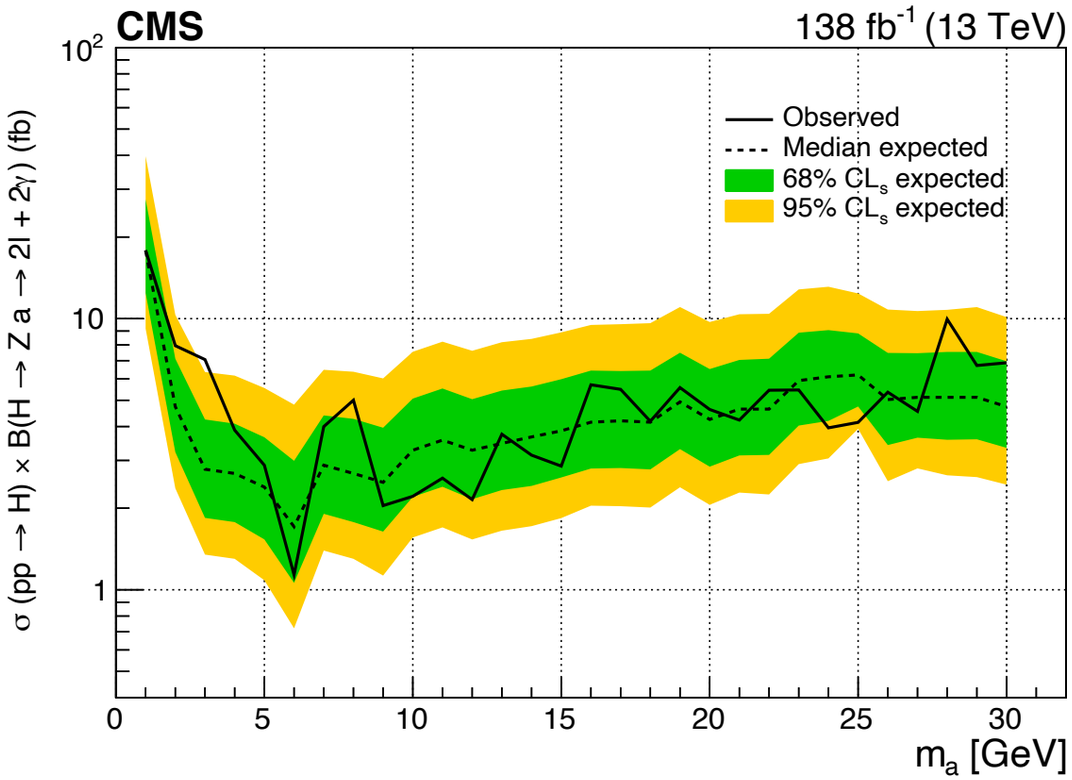
$H \rightarrow Za,\ a \rightarrow \gamma\gamma$

Consider ALP mass range $1 < m_a < 30$ GeV

PLB 852 (2024) 138582
public plots

- Use $m_{ll\gamma\gamma}$ distribution within 95 - 180 GeV to extract signal
- Completely data-driven background
- A BDT classifier is used to separate signal from background, threshold optimised per mass point





No significant deviation from SM background is observed, analysis limited by statistical uncertainty: $B(H \rightarrow Za)$ below $\sim 10^{-4}$ for $1 < m_a < 30$ GeV

Constrain effective coupling between H, Z and a within ~ 0.015 to 0.1 in this mass range, comparable to ATLAS results in the same mass range

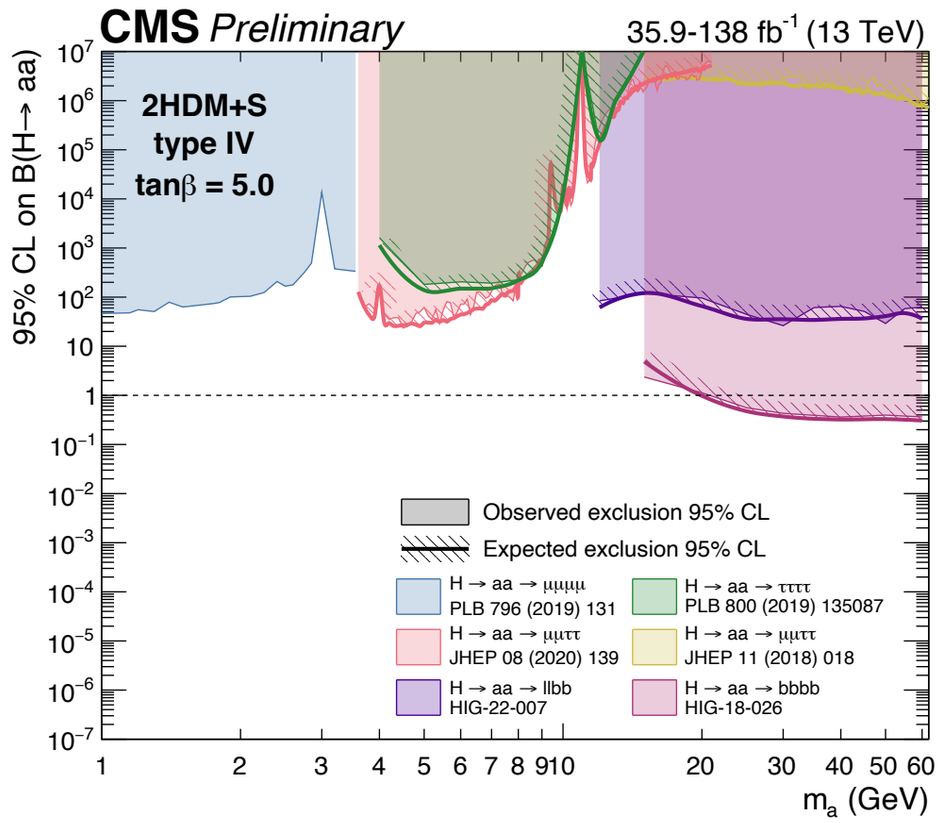
Summary

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

→ **Many full Run-2 results, some analyses ongoing**

- Improved sensitivity compared to previous searches using novel analysis techniques and machine learning
- Model independent searches can be interpreted in various theoretical models, including long-lived signatures
- Possibility to add h→Za search in a→ll/jj channels, even a→ττ
- For H→aa, no significant excess over SM prediction *just yet*, many other channels remain to be explored
  - Asymmetric pseudoscalar masses
  - Long-lived hadronic signatures
  - Boosted reconstruction for low pseudoscalar mass points

Present results are dominated by statistical uncertainties: looking forward to Run-3!



Thank You