Exotic production and decays of the 125 GeV Higgs in the CMS experiment

Pallabi Das on behalf of CMS Collaboration
Princeton University, USA

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Introduction

The discovery of the Higgs boson 10 years ago [1, 2] established the theory of the SM

→ ***But many questions remain!***

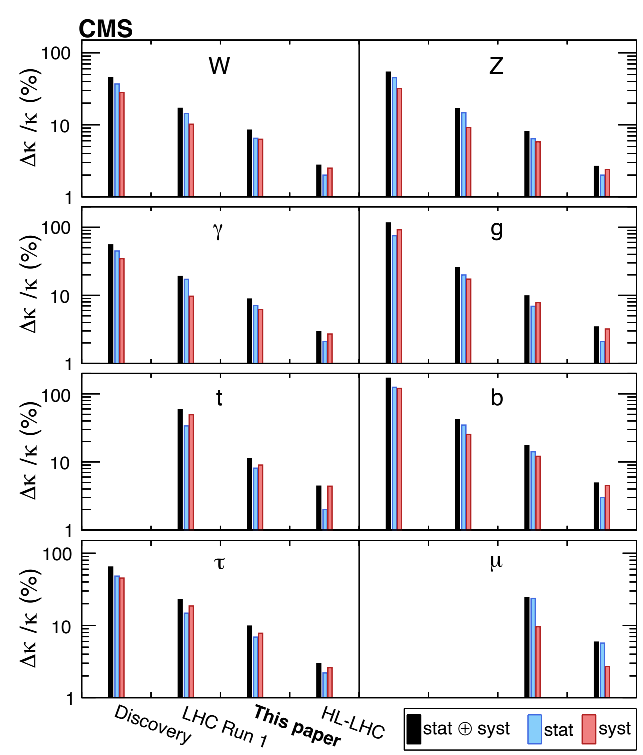
- Several BSM theories which can explain **Dark Matter** origin, **Hierarchy Problem**, etc. and also predict a **Higgs Resonance**
  → **New physics particles preferentially couple to the Higgs boson**

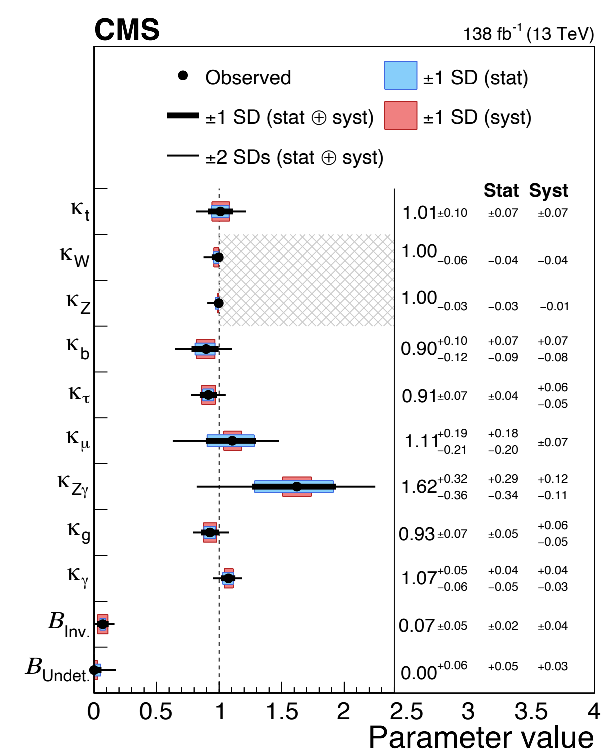
- Extended Higgs sector (MSSM, NMSSM etc.) allows the SM Higgs boson to act as a portal to a "hidden sector" of new physics interactions

- Run 2 focused on measuring the Higgs properties, including probes to BSM physics [3, 4]

New exotic phase space to be explored with additional data from Run 3

- Various SM Higgs couplings have only been constrained→new physics couplings may still be present





This talk: reviewing full Run-2 results from Phys. Rev. D 104 (2021) 032013, CMS-PAS-HIG-22-002, arXiv:2209.06197, arxiv:2208.01469, CMS-PAS-HIG-22-007, arxiv:2303.01214, HIG-PAS-22-003 and also JHEP 03 (2020) 025 using partial Run-2 data

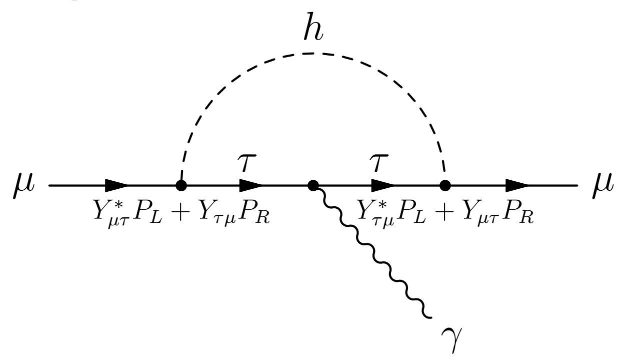
LFV decays of the Higgs boson

- SM forbids flavour violating Higgs couplings to leptons and quarks
  → Allowed in several new physics scenarios, e.g., 2HDM, extra dimensions, composite Higgs…

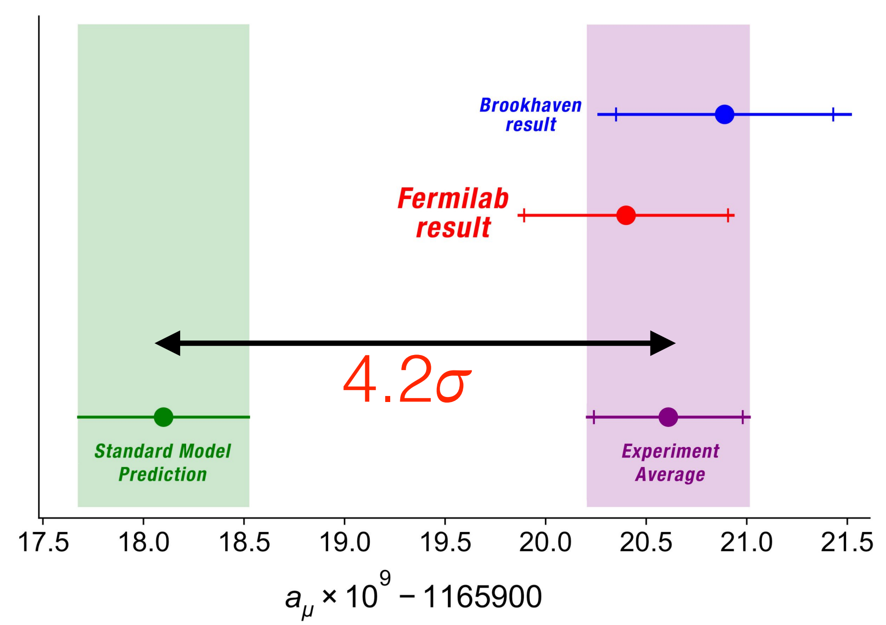
- Indirect limits:

  - BR(H→eμ): upper limit on μ→eγ at < 10^{-8}, albeit with several assumptions on Higgs couplings and FCNC interactions

  - BR(H→eτ/μτ): from rare τ decays and measurement of e and μ magnetic moments



$$Y = \begin{bmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau\tau} \end{bmatrix}$$



LFV Higgs couplings can contribute to anomalous muon magnetic moment g-2

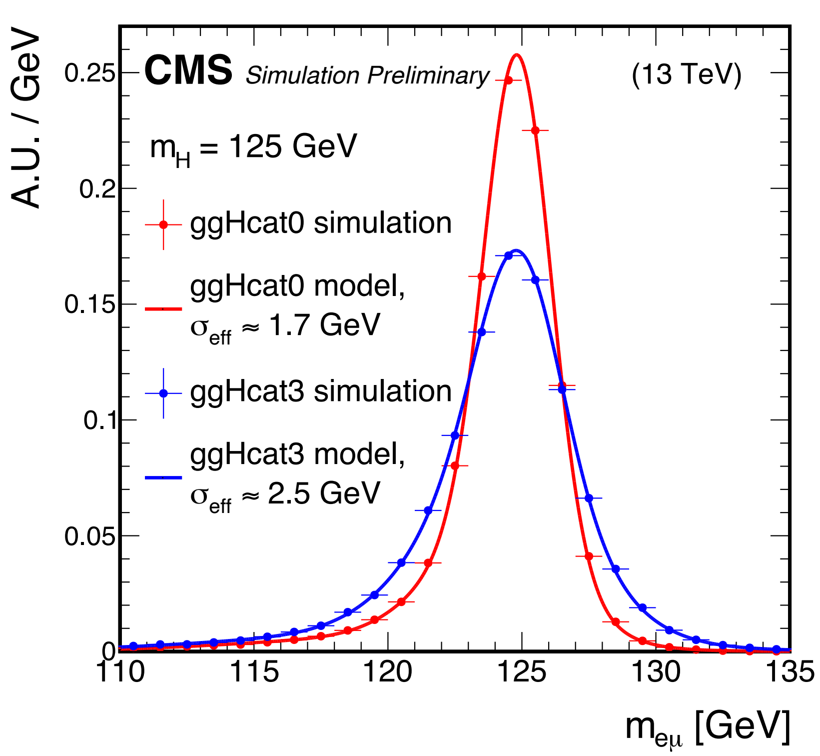
- Direct searches performed using full Run-2 luminosity

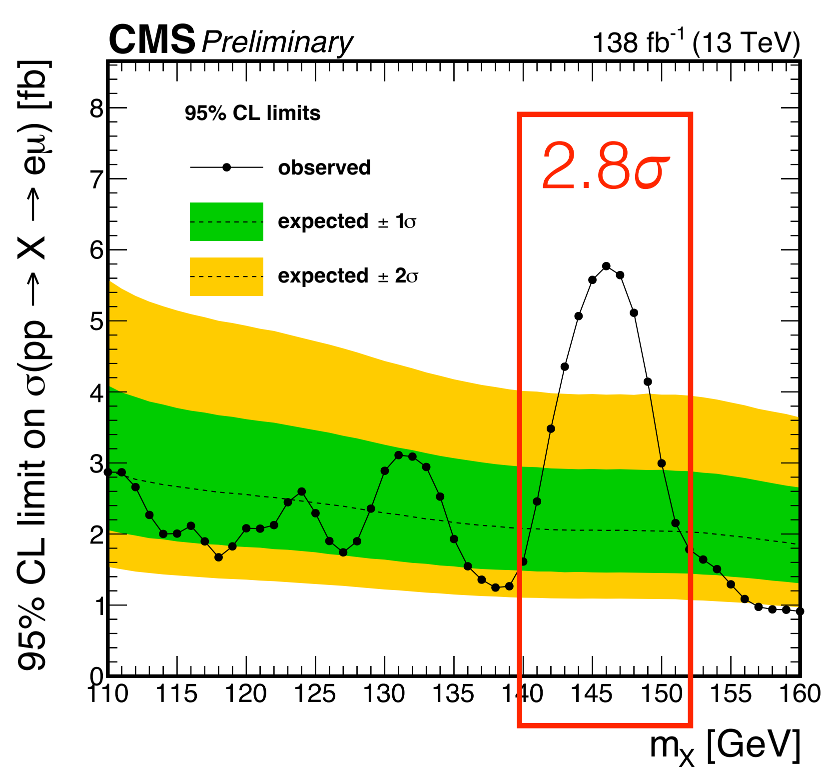
$H \to e\mu$

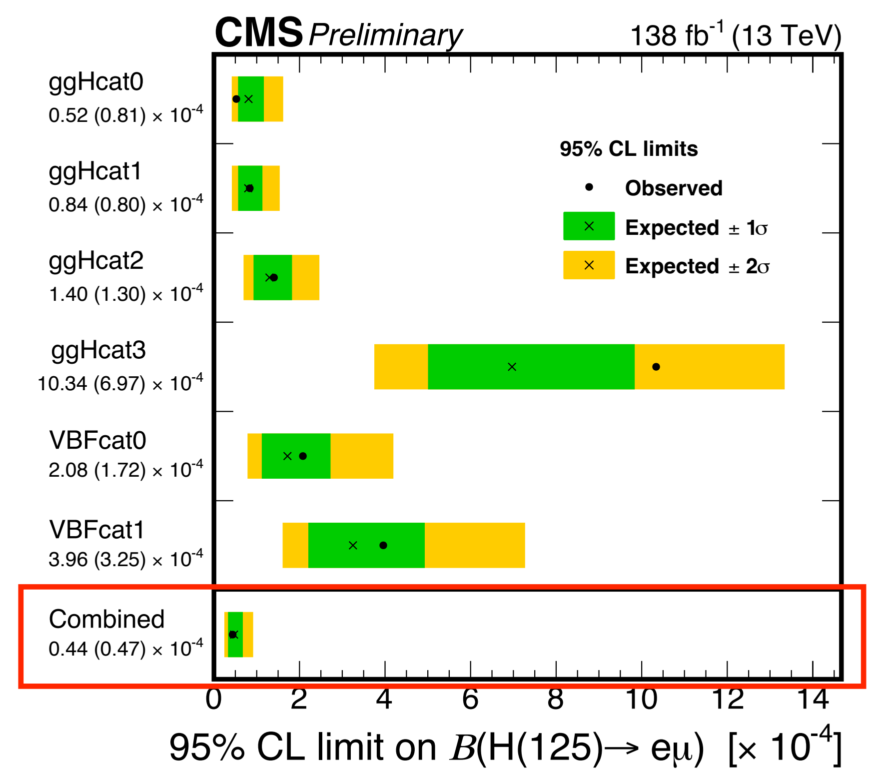
Search for both SM and BSM Higgs boson $X \to e\mu$, where 110 < m_X < 160, following a bump hunt strategy

- Categorised based on ggH and VBF Higgs production modes
- Completely data driven background estimation
- Signal $m_{e\mu}$ distributions fit with a parametric model and compared to background

The two signal categories further optimised using boosted decision tree (BDT) and split according to signal purity







Observed upper limit on the SM Higgs BR is determined to be 4.4 x 10^{-5} at 95% CL

The LFV Yukawa coupling is evaluated to be $\sqrt{|Y_{e\mu}|^2 + |Y_{\mu e}|^2} < 1.9 \times 10^{-4}$

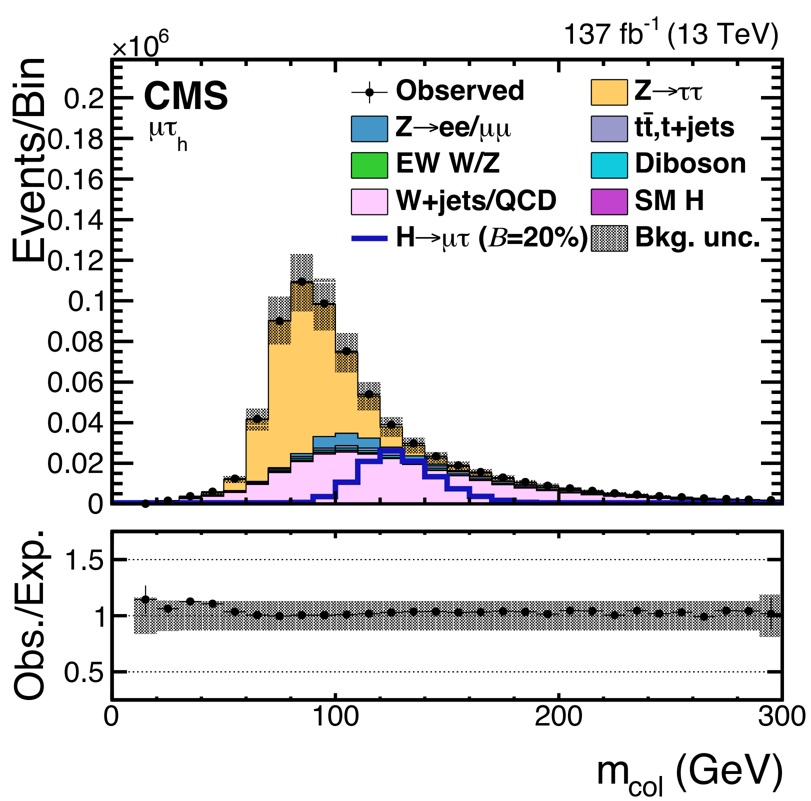
CMS-PAS-HIG-22-002

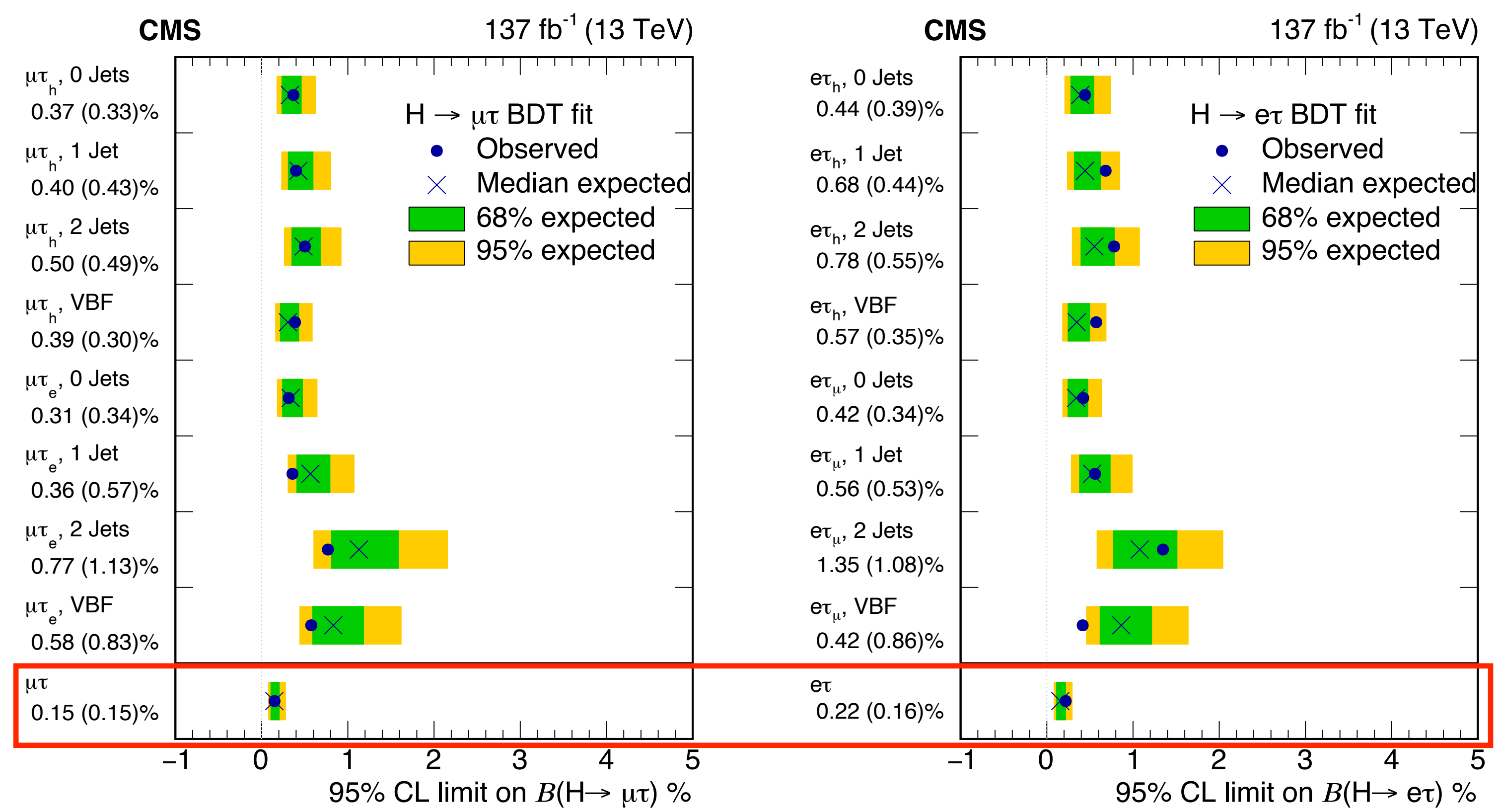
H→eτ/μτ

Overview:

- Multiple signal region categories based on τ decay and jet multiplicity to enhance sensitivity
- Construct collinear mass variable $m_{col} = m_{vis}/\sqrt{x_\tau^{vis}}$ to estimate m_H

A BDT is trained in each channel and the discriminant distribution is used in a maximum likelihood fit to extract the upper limits on the Higgs BR





Analysis constrains BR(H→μτ) < 0.15 and BR(H→eτ) < 0.16 at 95% CL

Also provides upper limits on LFV Yukawa couplings: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.11 \times 10^{-3}$ and $\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 1.35 \times 10^{-3}$

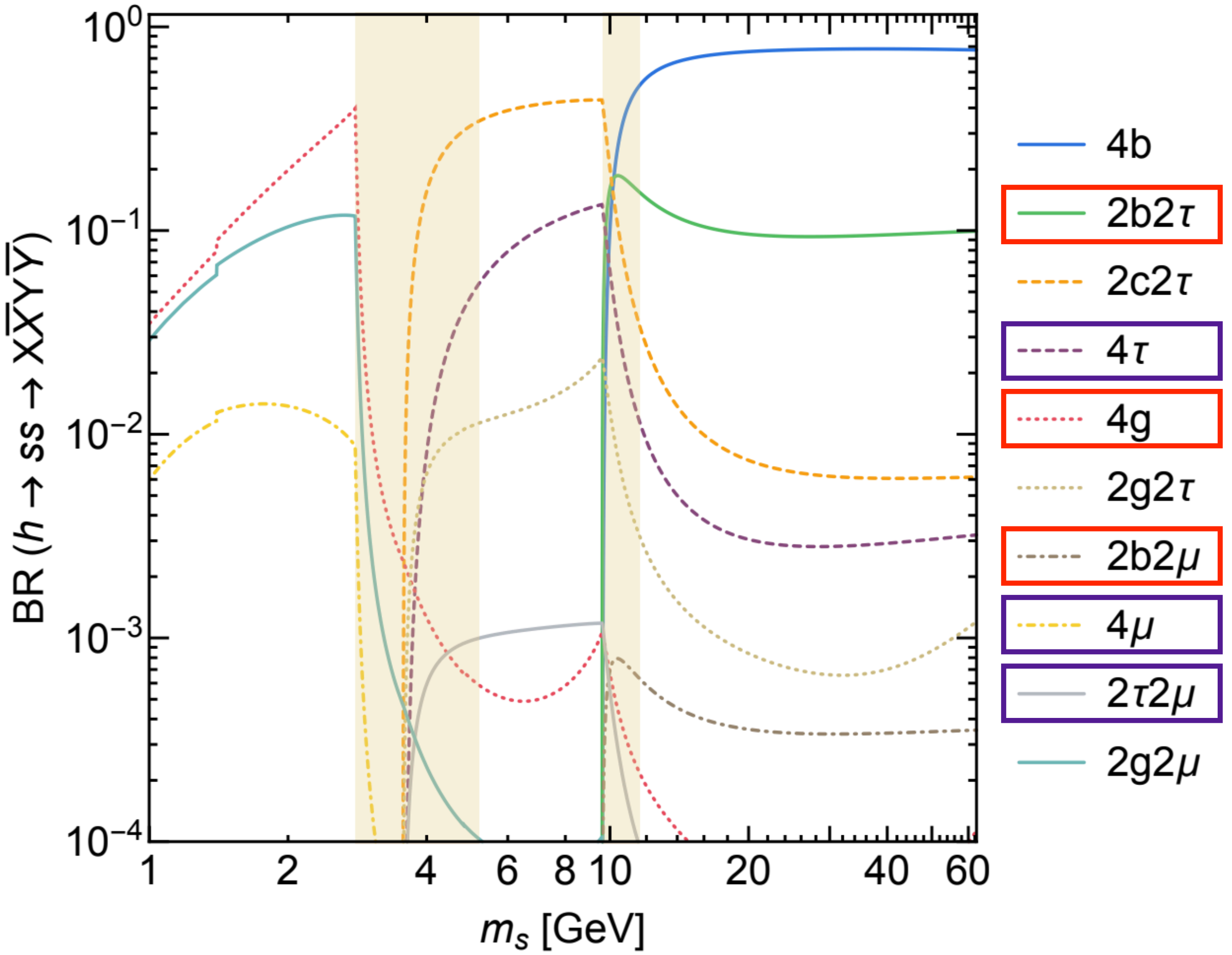
Phys. Rev. D 104 (2021) 032013

Higgs to pseudoscalar decays

- Viable decay in 2HDM+S: two scalar doublets and one scalar singlet, leading to seven scalars or pseudoscalars
- Assuming the singlet state has no direct Yukawa couplings, decays to fermions are a result of mixing with the Higgs sector
- Mixing is small enough to preserve the SM couplings of the Higgs, branching fractions of the pseudoscalars depend on the model and model parameters
  → Different BSM models can be tested considering H→aa but special interest is in constraining 2HDM+S that conserve observed features of the SM

Predicted decay branching ratios of H to a decoupled singlet state (s) in 2HDM+S

arxiv:1312.4992



Full Run-2 results

$H \rightarrow aa \rightarrow 4\gamma$ (boosted)

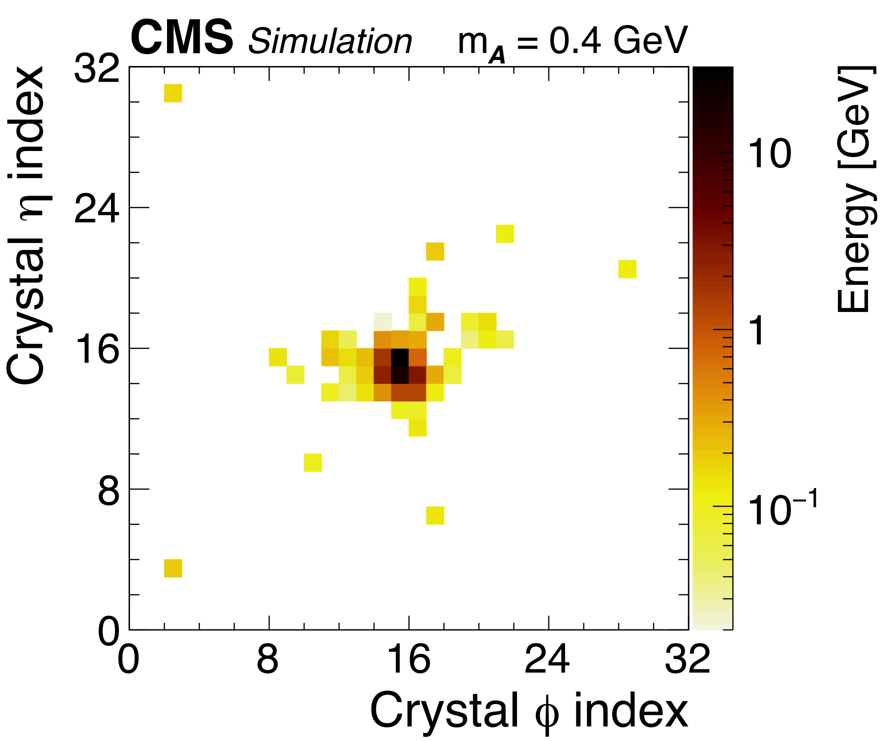
Search for very low mass pseudoscalars in the diphoton decay mode

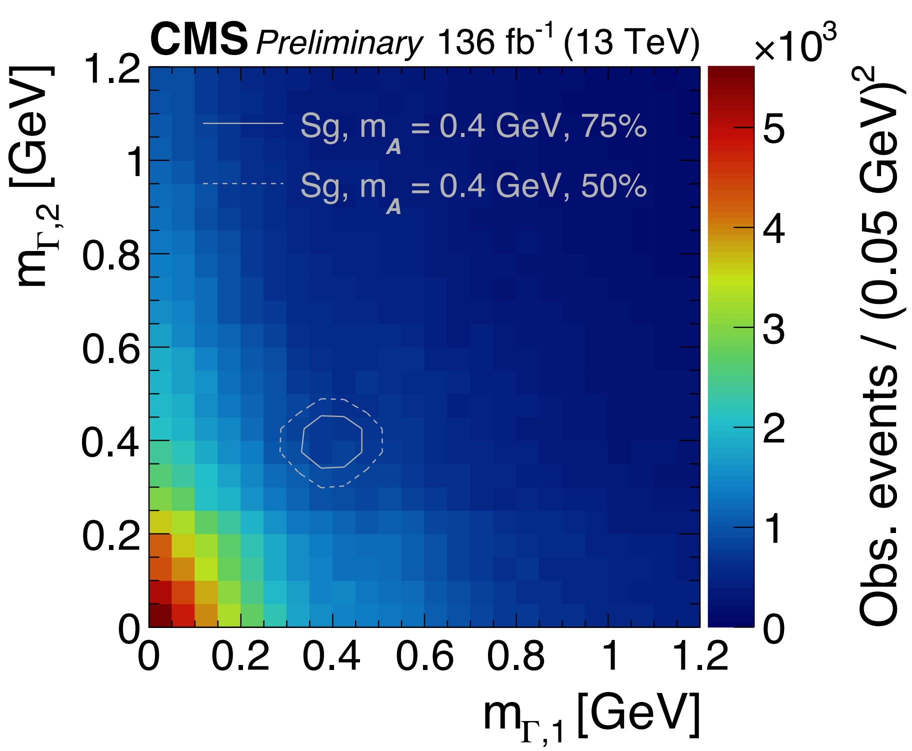
- Investigate $0.1 < m_a < 1.2$
- Diphoton decay is boosted and reconstructed as a single photon-like object “Γ”
- Probe merged Γ candidates in the SM $H \rightarrow \gamma\gamma$ final state using novel photon reconstruction technique of end-to-end deep learning [5]

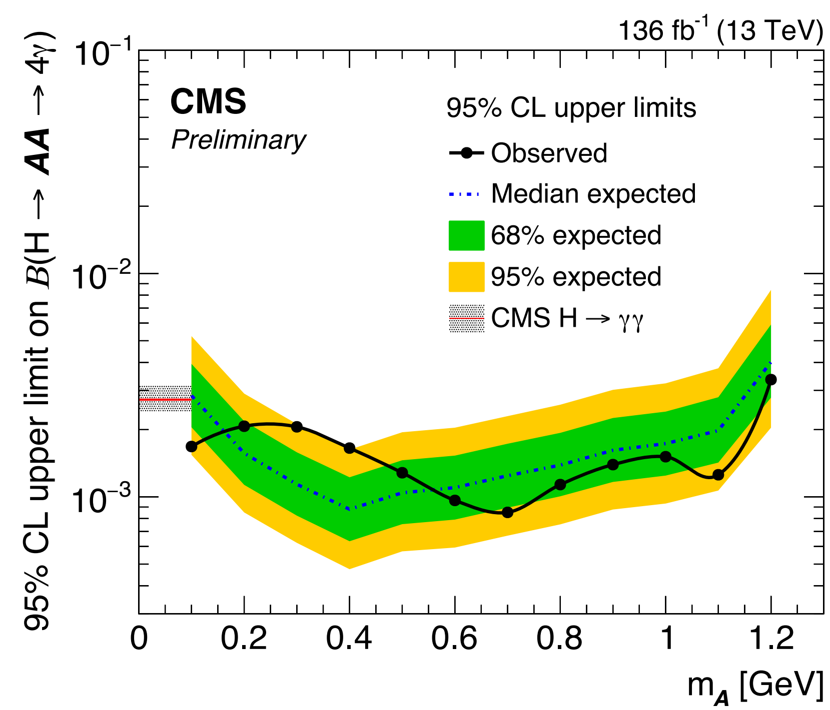
First search in this topology

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

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







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 $c\tau$ = 1 mm and 3 to 30 times larger for $c\tau$ = 10 mm

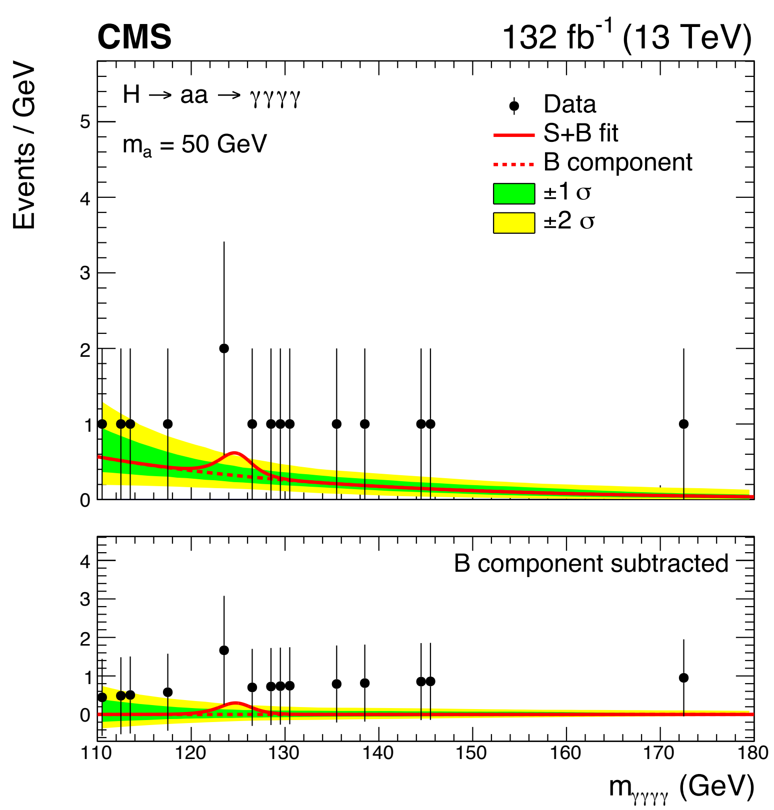
arxiv:2209.06197

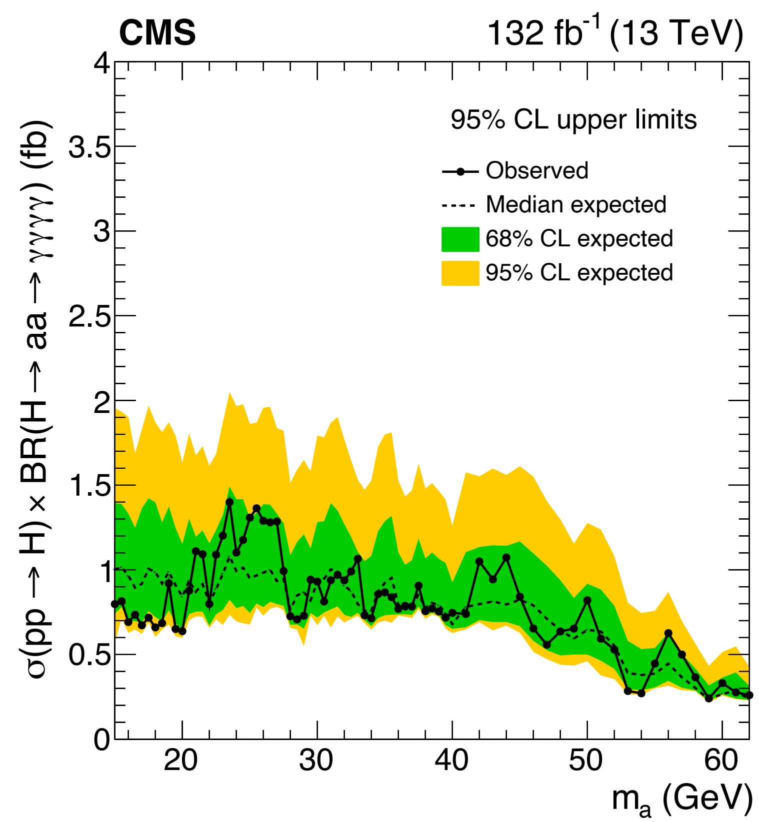
H→aa→4γ (resolved)

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

- Probes the mass range 15 < m_a < 62
- Identifies the primary vertex using a BDT is trained using variables related to tracks recoiling against the well reconstructed four-photon system → improves Higgs mass resolution

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





arxiv:2208.01469

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

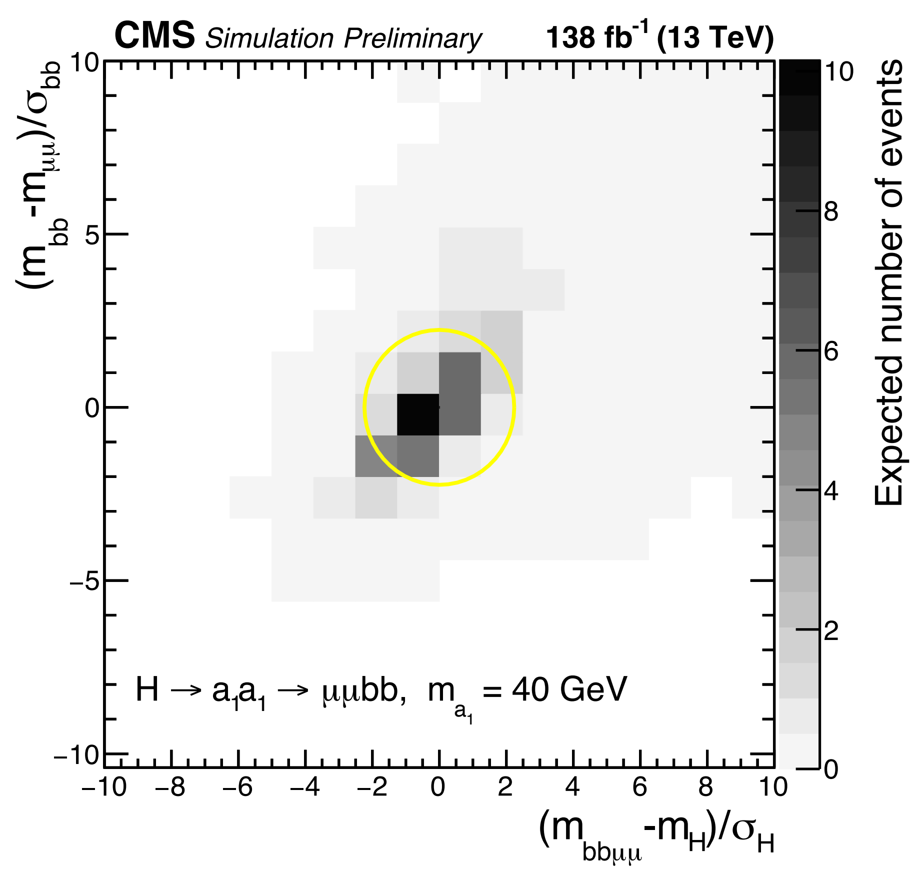
H→aa→2μ2b

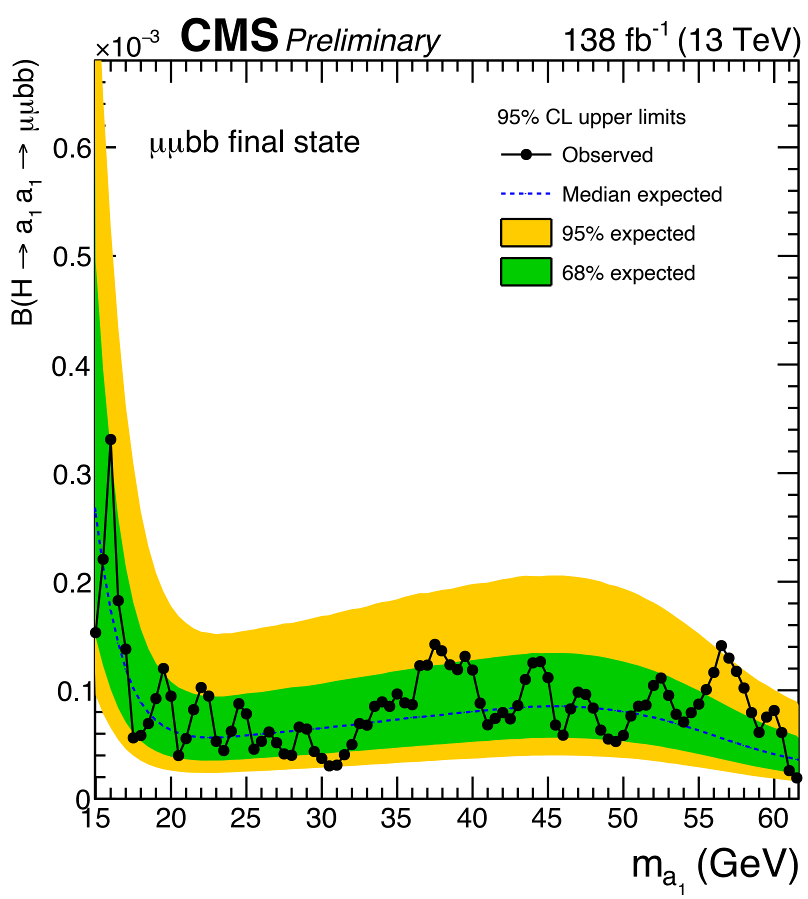
Clean signature with a precise mass resolution from $m_{\mu\mu}$ and large BR from bb

- Search for a masses within $15 < m_a < 60$
- Bump hunt analysis using the dimuon invariant mass $m_{\mu\mu}$
- Completely data-driven background estimation
- Thorough study of the signal to use a single discriminating variable to suppress background

Parametric fit of the signal model in different categories based on b-jet properties

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

CMS-PAS-HIG-22-007

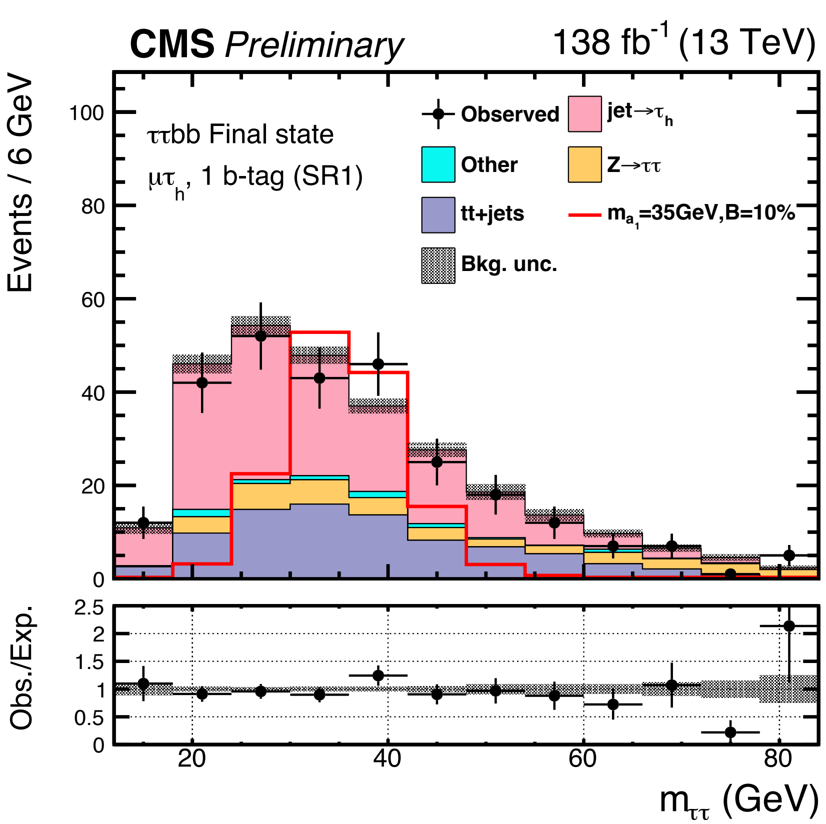
H→aa→2τ2b

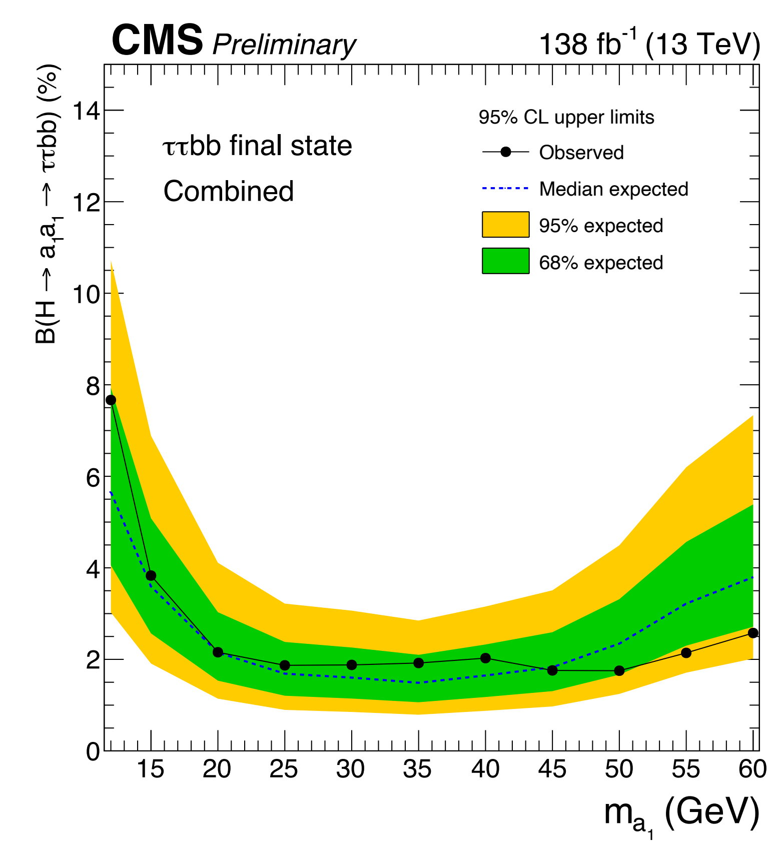
Relatively **larger BR** **to bb and ττ,** **improved τ lepton reconstruction techniques**

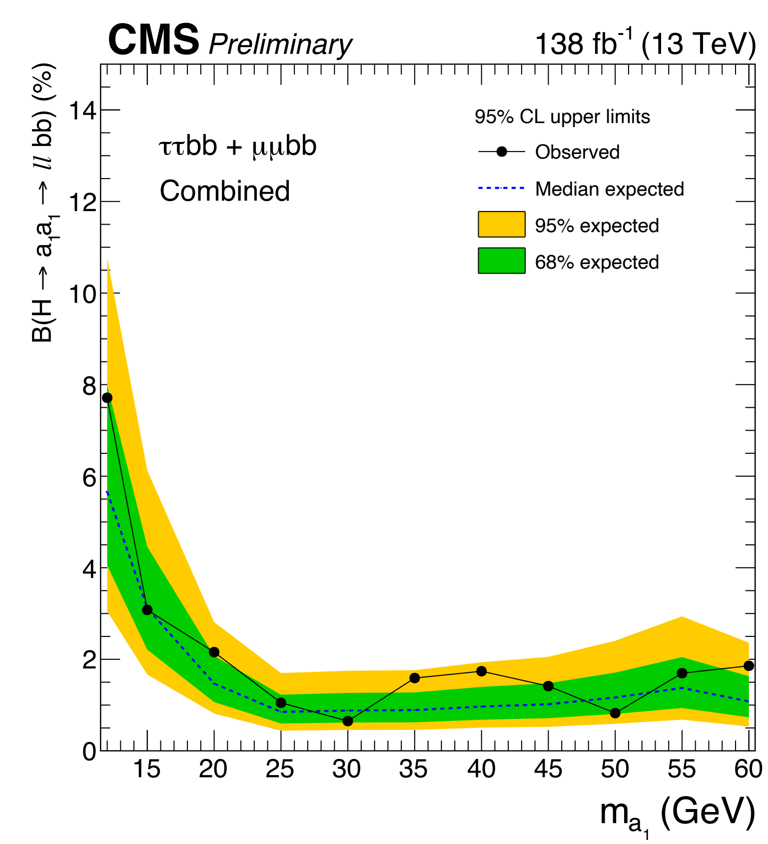
- Search for a masses within 12 < m_a < 60
- Three final states explored: $\mu\tau_h$, $e\tau_h$, $e\mu$
- SVfit algorithm to reconstruct $m_{\tau\tau}$ including neutrino energies

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

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)

CMS-PAS-HIG-22-007

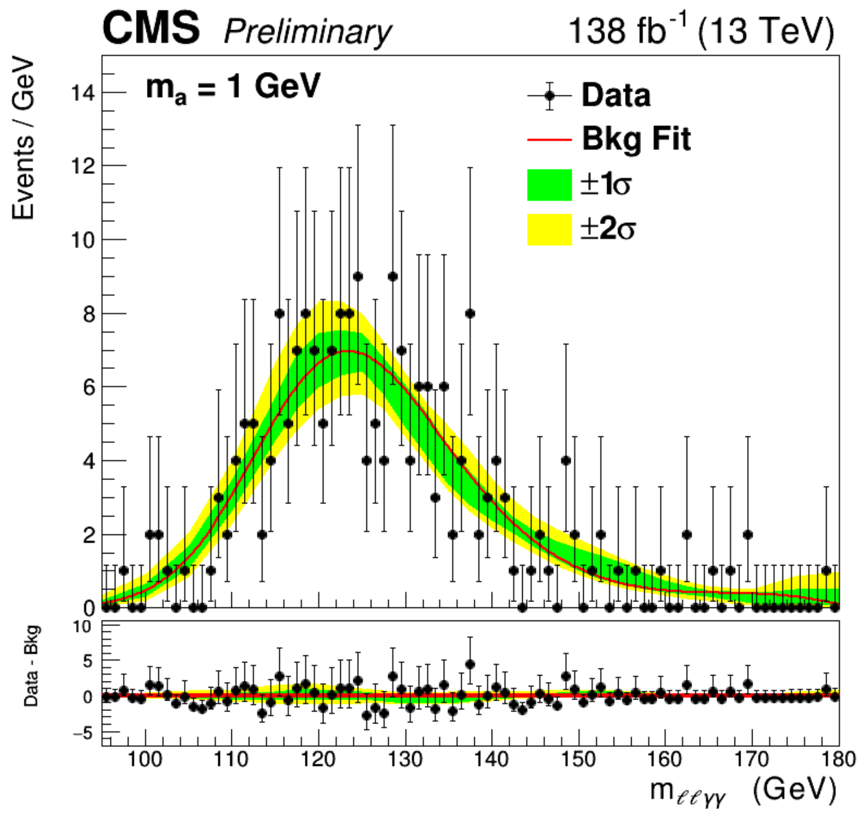
Higgs decay to Axion-like particle

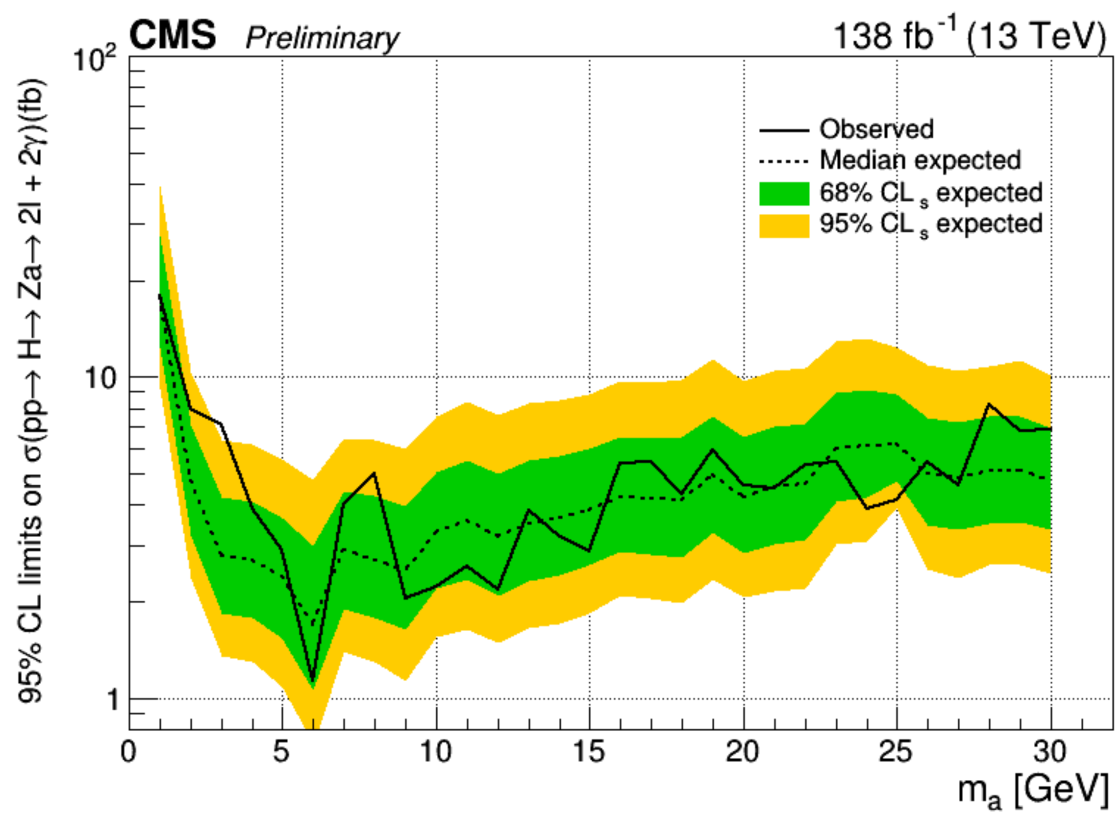
First search in LHC for Axion-like particles (ALPs) produced via H→Za

- ALPs are predicted in extended SM theories addressing strong CP problem
- They are dark matter candidates decaying into photons
- Exploit merged photon reconstruction technique [5] to explore the mass range 1 < m_a < 30

A BDT event classifier is used to select the signal region maximising significance across the invariant mass distribution $m_{ll\gamma\gamma}$

See poster by Zebing





No significant deviation from SM background is observed, analysis limited by statistical uncertainty

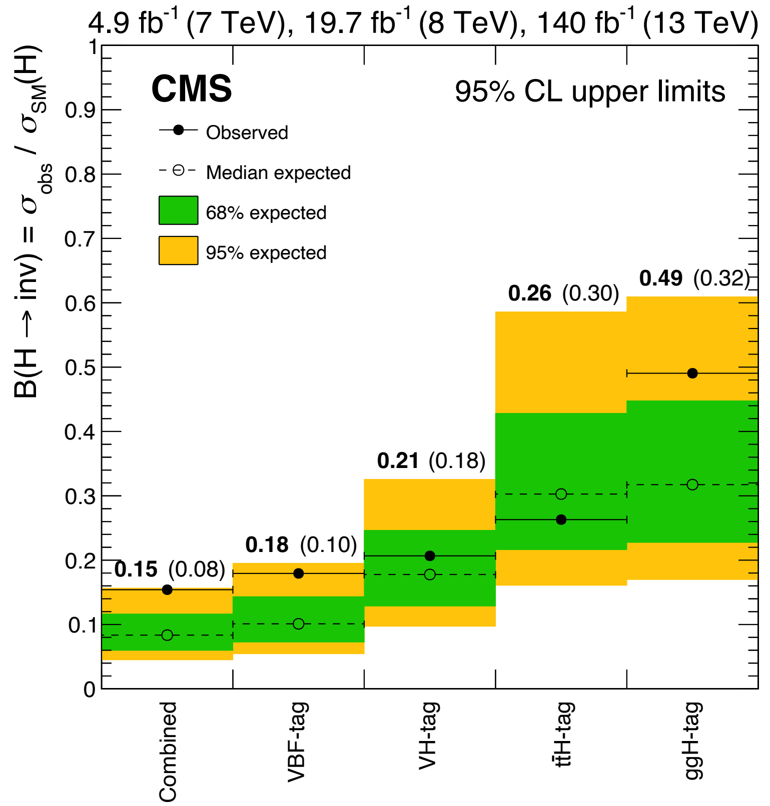
Also constrain effective coupling between H, Z and a within ~ 0.015 to 0.1 in this mass range

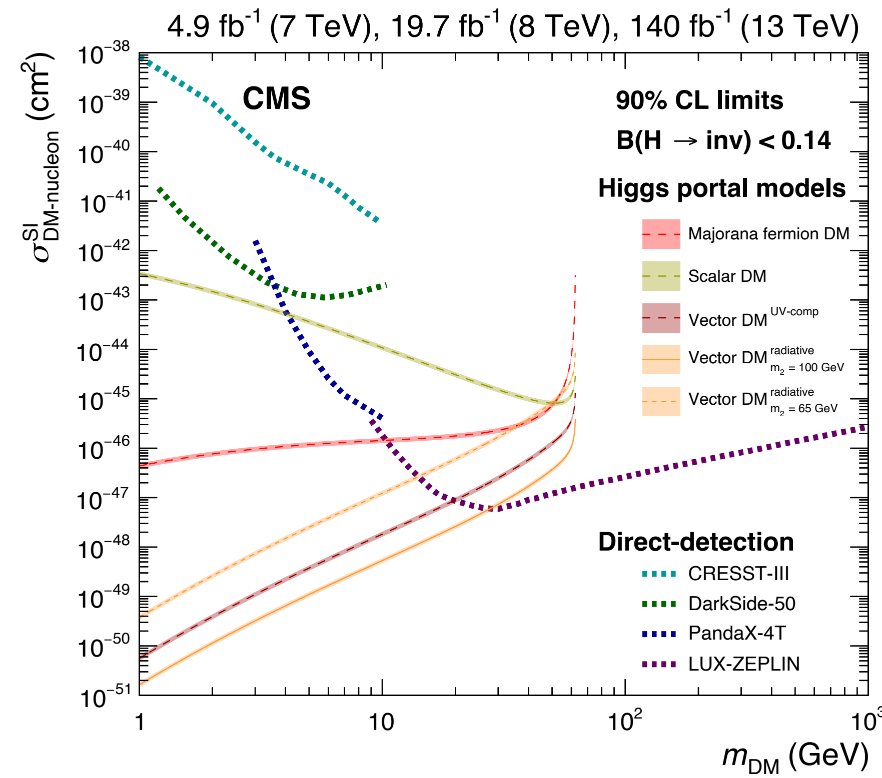
CMS-PAS-HIG-22-003

Invisible Higgs decays

- In the SM the H→invisible BR is ~ 0.1%, however much higher values are predicted by several BSM theories
  → Enhanced decay in Higgs portal models where dark matter particle mass $m_{DM} < m_H/2$
- VBF production mode is the most sensitive channel: allows suppression of SM backgrounds
- Recent search performed in ttH and VH production modes in hadronic final states

Signal is extracted from a fit to the hadron recoil distribution, equivalent to missing transverse momentum (p_T^{miss}), in ttH and VH channels





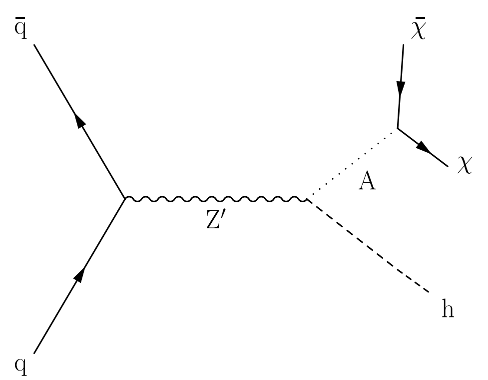
Results are combined with earlier searches for H→invisible decays yielding a combined upper limit of 15% on BR(H→invisible) at 95% CL

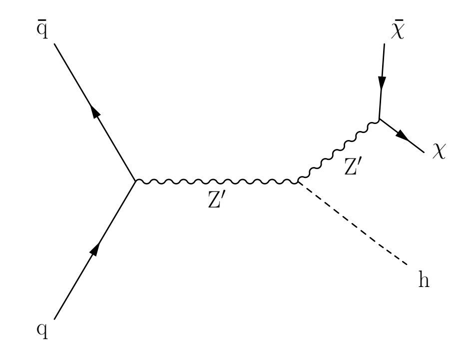
arxiv.org:2303.01214

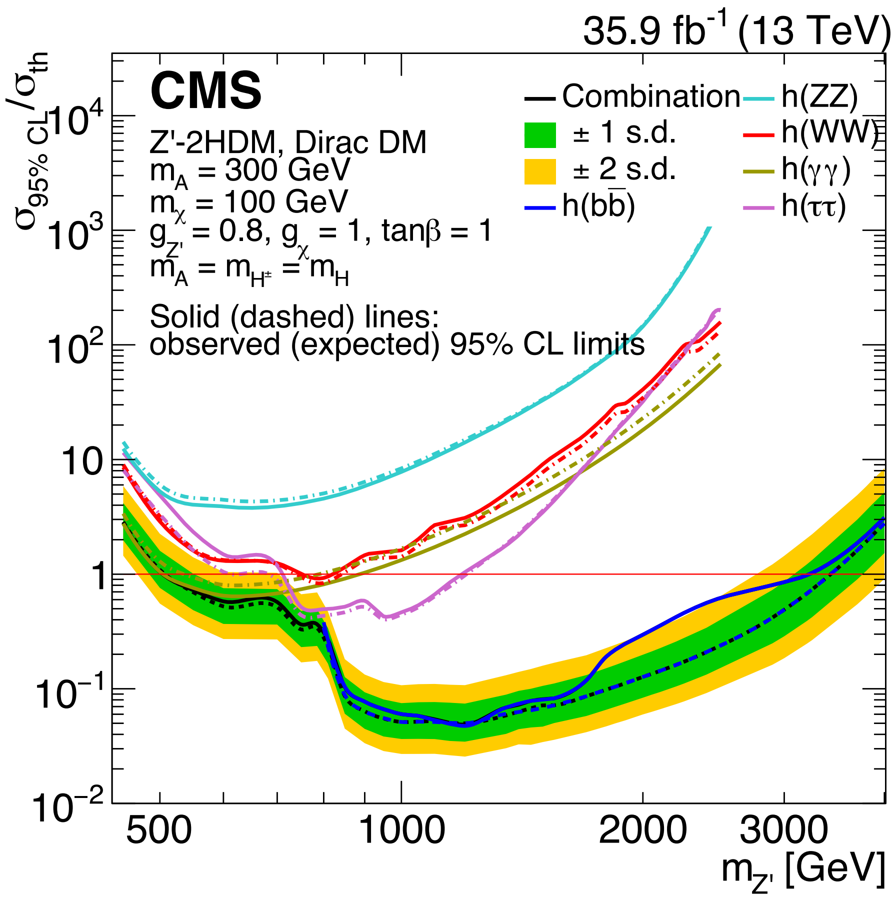
Exotic Higgs production

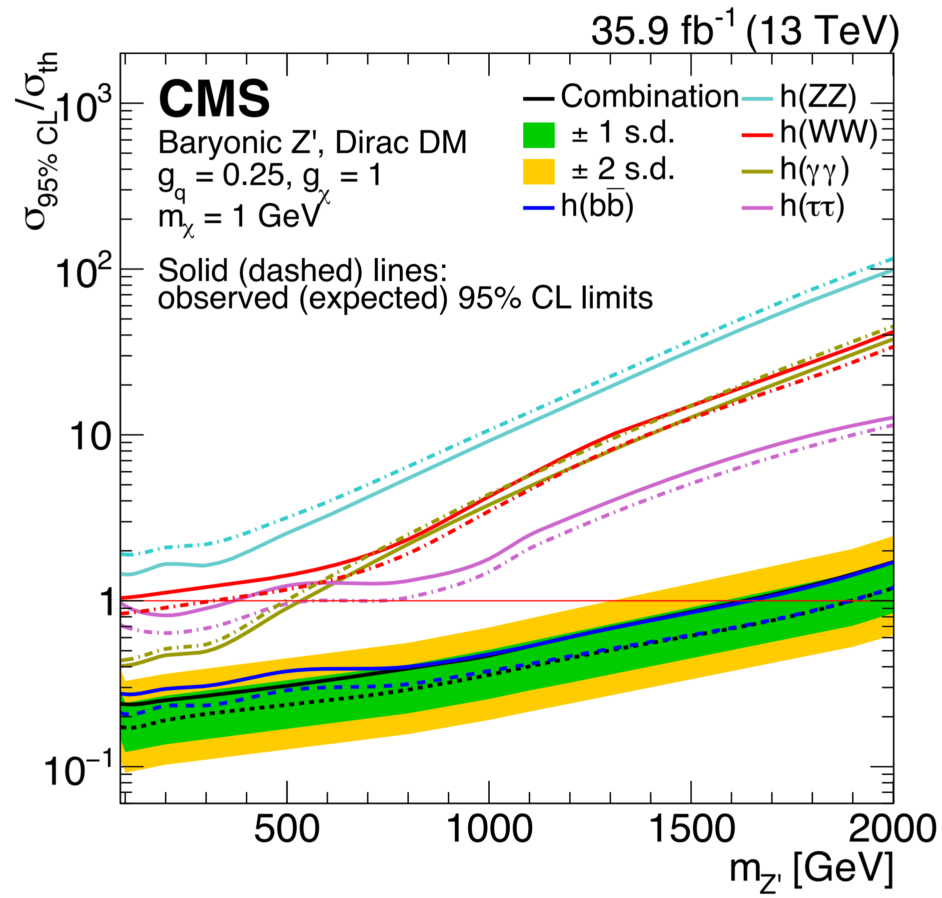
Dark matter at colliders: pairs of WIMPs resulting in p_T^{miss}

- Final state radiation of DM particle or a new physics interaction with the Higgs results in the final state H+p_T^{miss} or mono-Higgs events
  → Two main models: (1) Z'-2HDM (2) Baryonic-Z'
- Several Higgs decay channels are investigated: bb, ττ, γγ, WW and ZZ









All five decay modes are combined to place exclusion limits on the DM production cross section as a function of the Z' mass

JHEP 03 (2020) 025

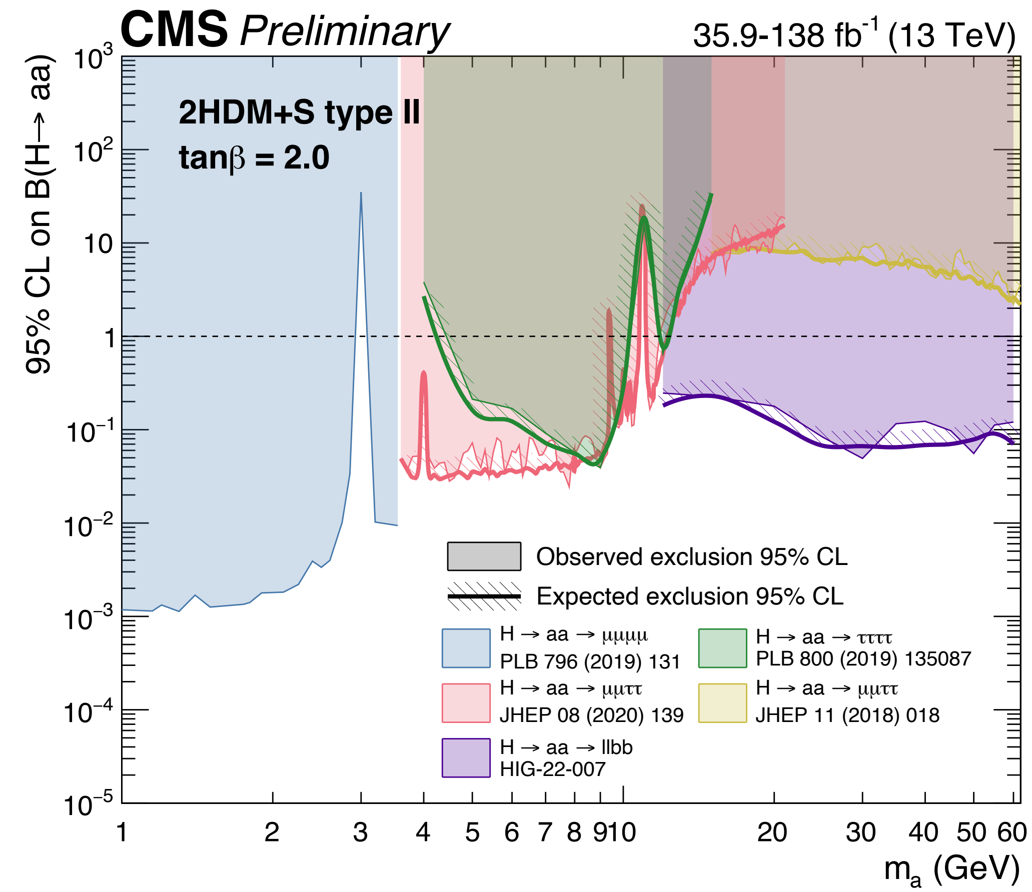
Summary

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

→ **First look at many full Run-2 results, some still to be updated**

- Improved sensitivity compared to previous searches using novel analysis techniques and machine learning
- Stringent upper limits placed on the explored phase spaces of mono-Higgs production, H→LFV decays and H→invisible final states
- For H→aa, no significant excess over SM prediction *just yet*, many other channels remain to be explored
  - Asymmetric pseudoscalar masses unexplored
  - Signals with low pseudoscalar mass to be analysed using boosted reconstruction techniques, similar to boosted H→aa→4γ and H→Za searches

Direct searches benefit the most with increase in luminosity: exciting times ahead with the onset of LHC Run-3!



Also tune in to talks by Ram and Toyoko for more BSM results! Summary is covered by Maxwell

Thank You

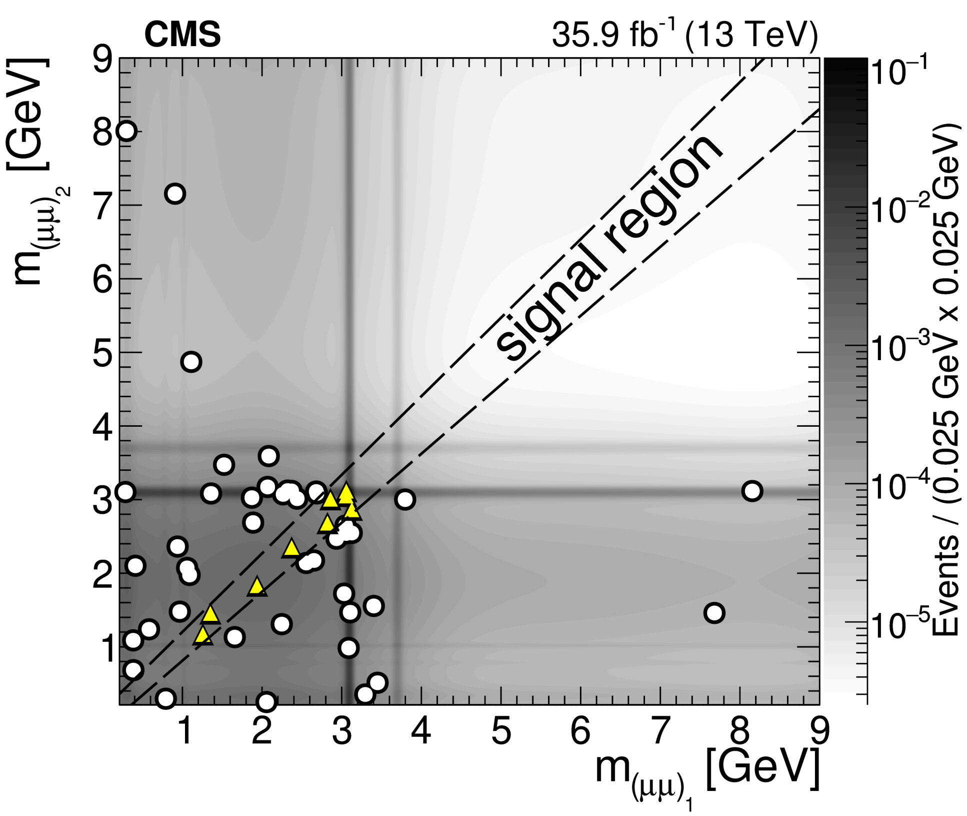
Backup

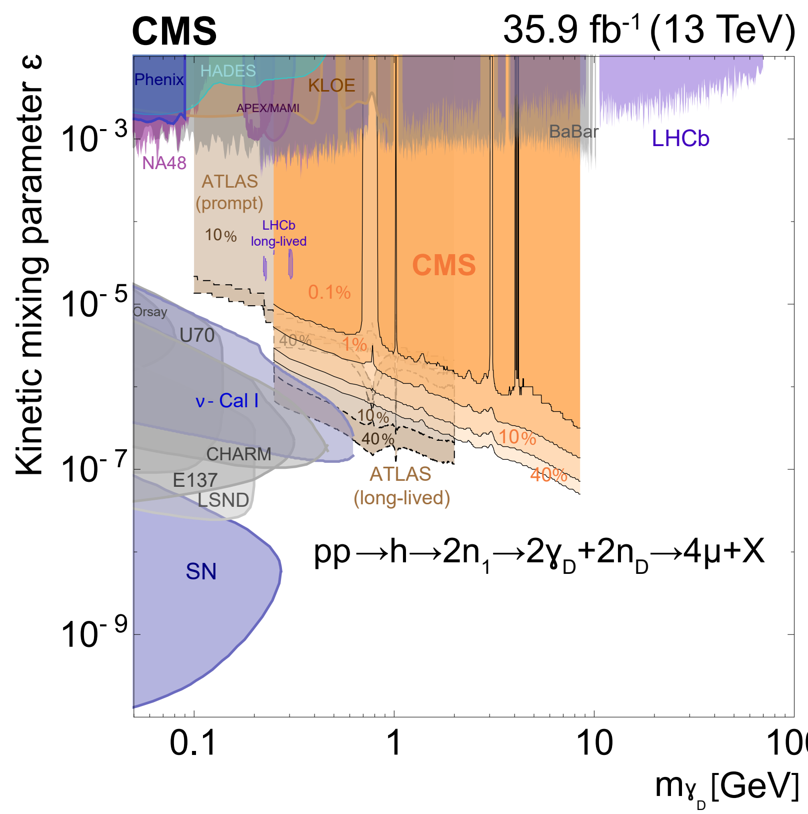
H→aa→4μ

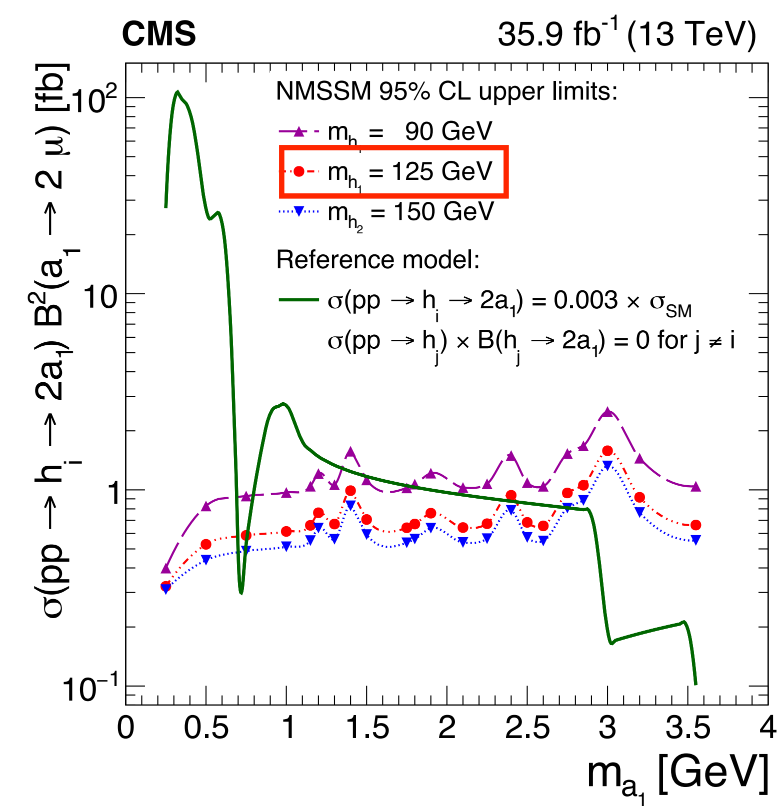
Analysis targets very low mass pseudoscalars:

- Interpreted in terms of **dark SUSY model** (0.25 < m_a < 8.5 GeV) and **NMSSM** (0.25 < m_a < 3.55 GeV)
- Limits derived as a function of dark photon mass and m_a respectively in the two scenarios

Two dimuon pairs per event are chosen, where $m_{(\mu\mu)1} \sim m_{(\mu\mu)2} < 9$ GeV, satisfying stringent reconstruction requirements that eliminate most of the background







In the context of **H→2a+X→4*μ*+X**, the search results in:

95% CL upper limit on σ(H→2a+X)xBR^2(a→2μ), constrained within 0.15 and 0.39 fb

90% CL upper limit on BR(H→2γ_D+X), constrained within 0.1 to 40%

Phys. Lett. B 796 (2019) 131

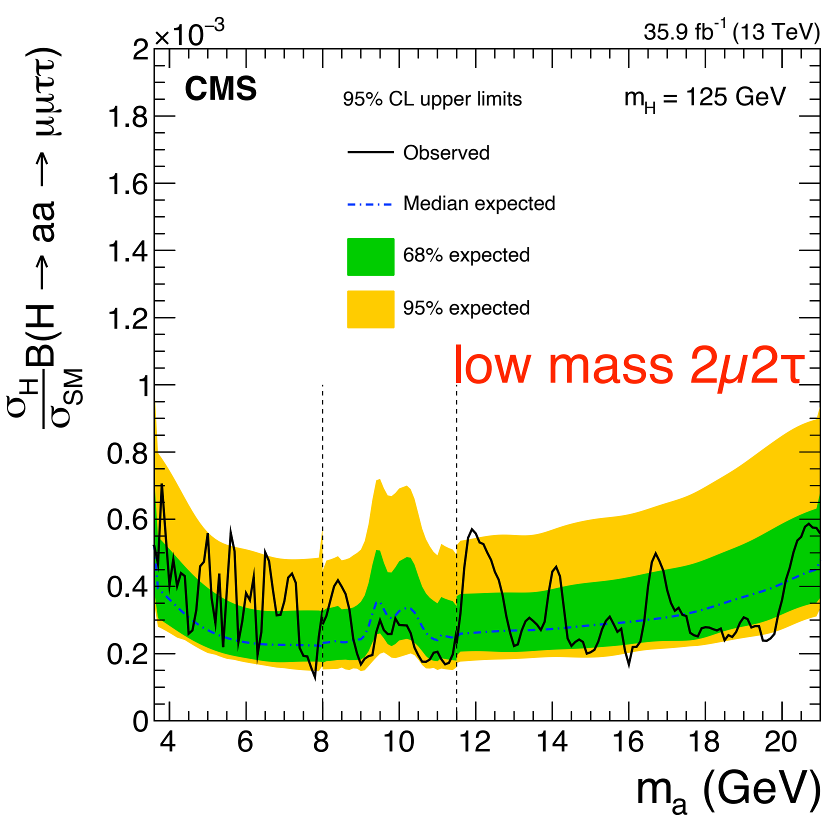
$H \to aa \to 2\mu 2\tau/4\tau$

Overview:

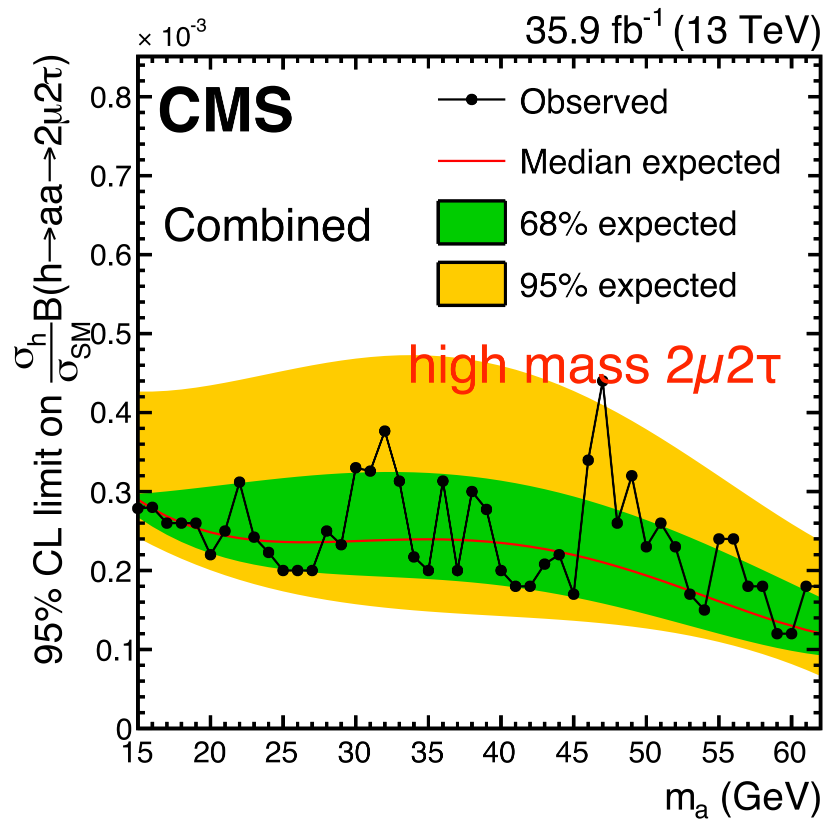
- $2\mu 2\tau$ final state: Target low mass ($3.6 < m_a < 21$) and high mass ($15 < m_a < 62.5$) pseudoscalars
- $2\mu 2\tau$ and 4τ final states: combined in the mass range $4 < m_a < 15$

Boosted τ pairs for very low m_a require specialized reconstruction and isolation algorithms to avoid overlap, standard μ identification algorithm used even in boosted topologies

A boosted topology with two well separated same-charged muons is also targeted, where one $a \to 2\mu$ and the other $a \to \tau_\mu \tau_{\text{one-prong}}$



JHEP 08 (2020) 139



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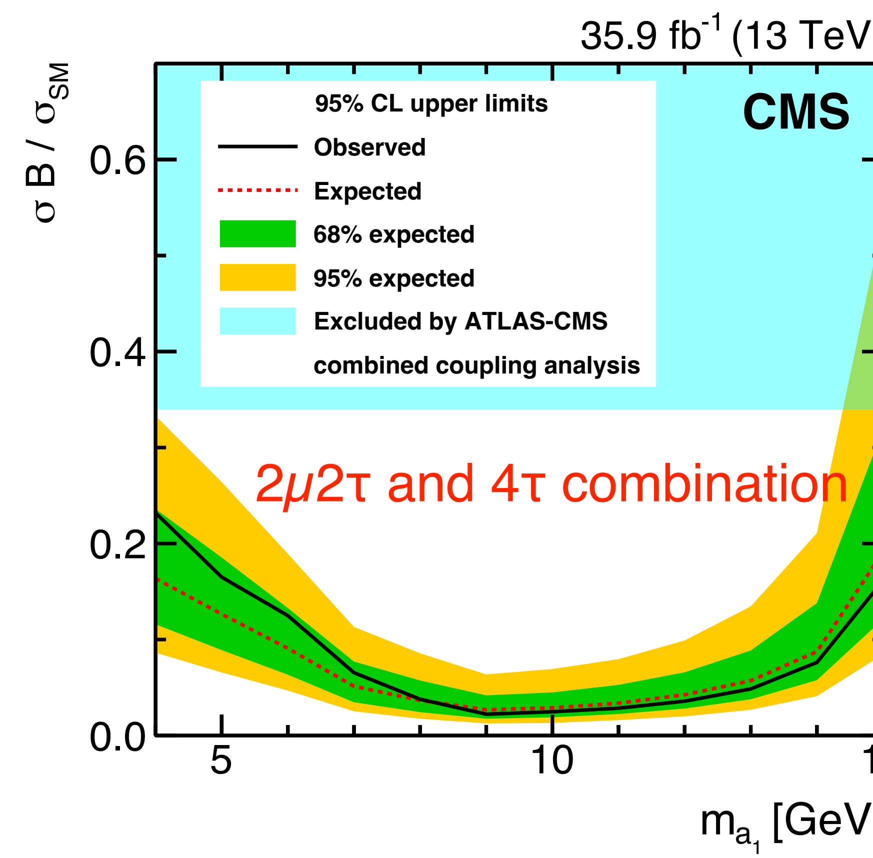

Phys. Lett. B 800 (2019) 135087