Rare & BSM decays of Higgs boson at CMS

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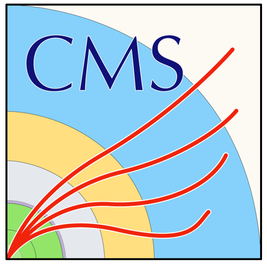
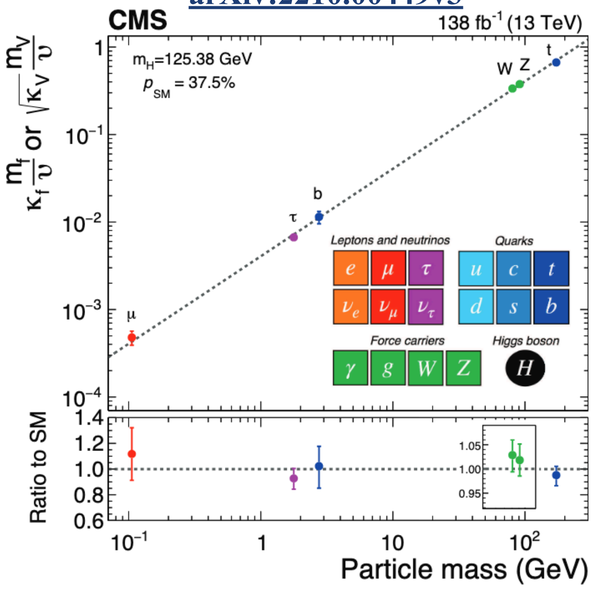


Introduction

- Standard Model (SM) accurately describes fundamental particles and interactions (except gravity).
- A significant triumph of the SM: **Discovery of the Higgs boson** in 2012 at the LHC

arXiv:2210.00449v3



Why look Beyond the Standard Model (BSM)??

- Despite its success, SM fails to explain:
  - gravity, dark matter and dark energy, account for neutrino masses, provide sufficient CP violation for matter-antimatter asymmetry etc.

How to search for BSM ??

- Search for new BSM particle directly
- Investigate rare and exotic decay that are either not predicted or highly suppressed in the SM.

This talk explores rare and exotic decays of Higgs boson as a search for potential signal of BSM physics….

Outline

Selected analysis results for the talk

1. Higgs to pseudoscalar decays
   - H → aa → $\mu\mu$ bb / $\tau\tau$ bb *EPJC 84 (2024) 712*
   - H → aa → 4b *CMS-PAS-HIG-18-026*

2. Higgs decays to axion like particle (H → Z a) *CMS-HIG-22-003*

3. Higgs decays to invisible particles *EPJC 83 (2023) 933*

4. LFV decays of Higgs boson (H → $e^{\pm}\mu^{\mp}$) *CMS-HIG-22-002*

5. Higgs decays to Mγ (M = $\rho^0/\phi/K^{*0}$) *CMS-PAS-HIG-23-005*

6. Higgs decays to μμ *CMS-HIG-19-006*

7. Higgs decays to Zγ *CMS-HIG-19-014*

Higgs decays to light pseudoscalar particles

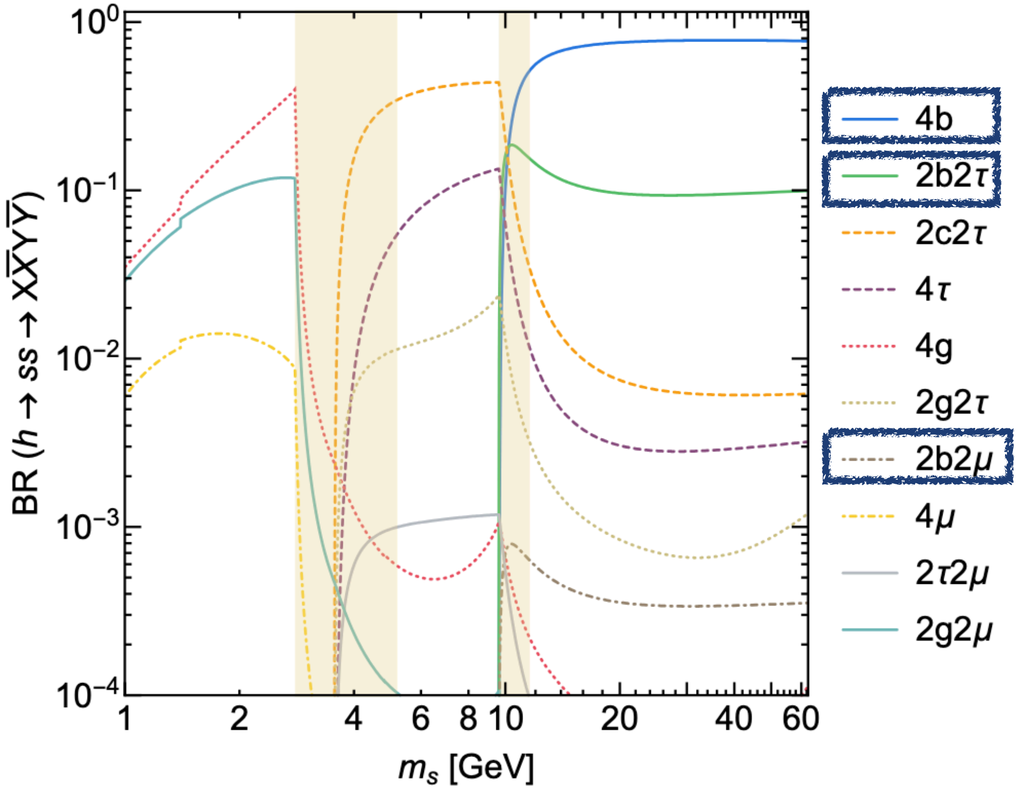
- **2HDM+S model**: BSM framework with two Higgs doublets (ϕ_1,ϕ_2) and a singlet scalar (s).

- Types of 2HDM + S model:
  - four types: **type I, type II, type III and type IV**, which forbids flavour changing neutral currents.

  - classified by coupling structure of two Higgs doublets with SM fermions

- Tan β is the ratio of vacuum expectation values of Higgs doublets.

- LHC data are used to search for this exotic decay and set limit on Br (H → a a → f f).



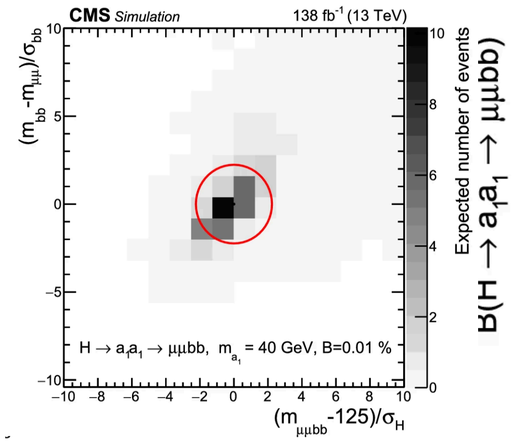
Predicted decay branching ratios of H to a decoupled singlet state (s) in 2HDM+S
https://arxiv.org/pdf/1312.4992

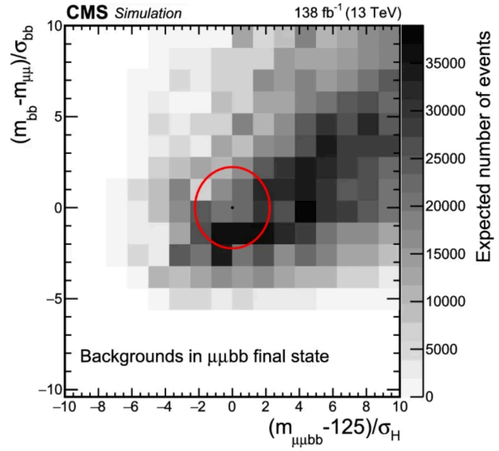
$H \rightarrow aa \rightarrow \mu\mu bb$ / $\tau\tau bb$

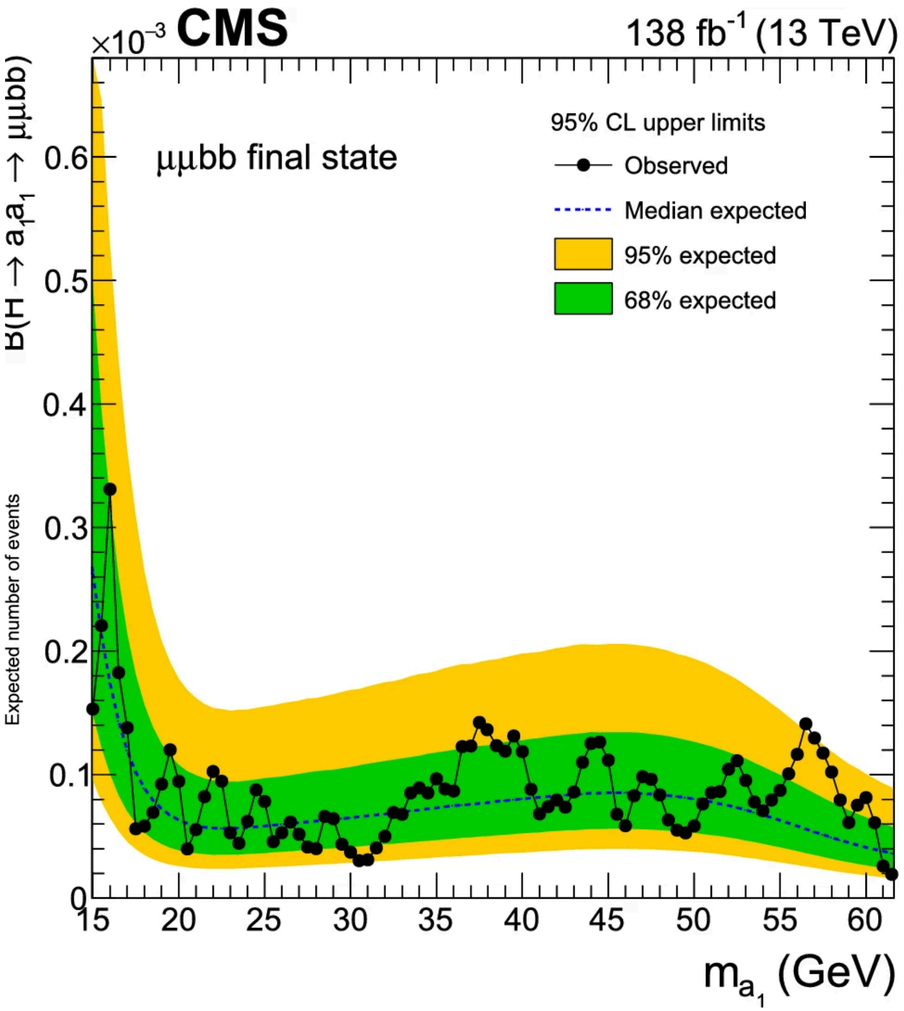
$H \rightarrow aa \rightarrow \mu\mu bb$

- Search for mass range: 15 GeV to 62.5 GeV
- Dominant background: Drellyan and $t\bar{t}$ + jets
- Strategy
  - model dependent selection
  - exploit two features in signal selection:
    $\mathbf{m_{\mu\mu} = m_{bb}}$ and $\mathbf{m_{\mu\mu bb} = 125}$ GeV
- Events are categorised based on b-jet properties.
- 95% CL upper limit set on $\mathbf{Br(H \rightarrow aa \rightarrow \mu\mu bb)}$
  - Observed: $(0.17 - 3.3) \times 10^{-4}$
  - Expected: $(0.35 - 2.6) \times 10^{-4}$

No excess found over SM backgrounds





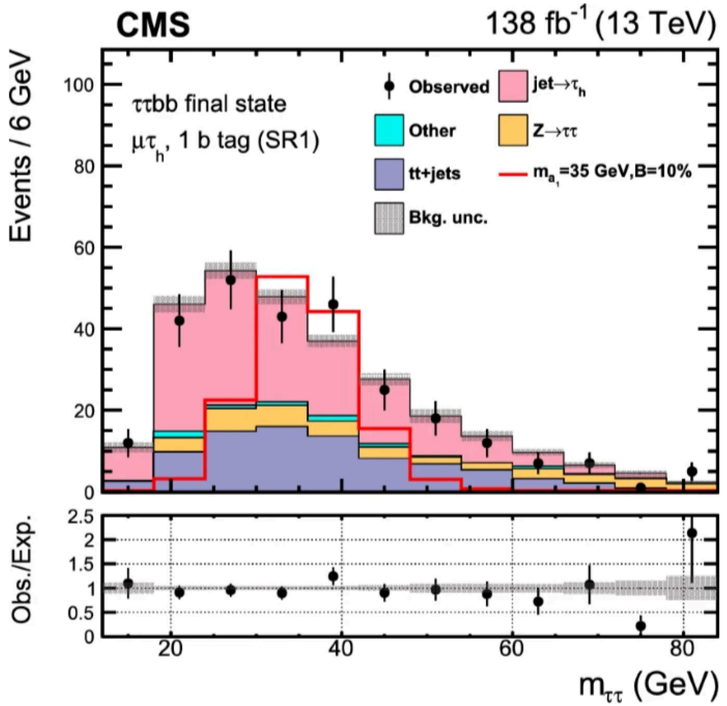


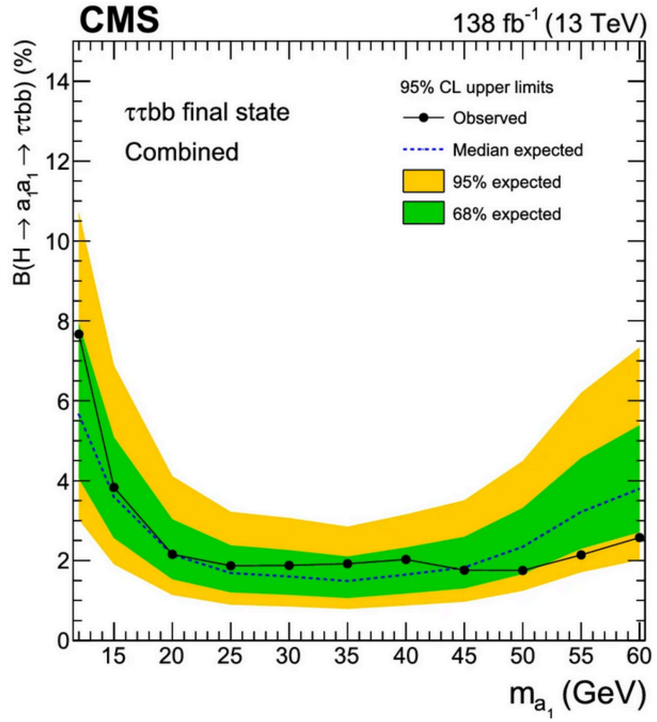
EPJC 84 (2024) 712

H → aa → $\mu\mu$bb / $\tau\tau$bb

H → aa → $\tau\tau$bb

- mass range: $12 < m_a < 60$.
- $\tau\tau$ final states: $e\mu$, $e\tau_h$, $\mu\tau_h$
- dominant backgrounds: $\mathbf{t\bar{t}}$, $\mathbf{Z} \rightarrow \tau\tau$, reducible processes with $jet \rightarrow \tau_h$ fakes (W+jets, QCD …)
- $m_{\tau\tau}$ is reconstructed including neutrino energies.
- categorization based on b-tag jet multiplicity (1 b-tag jet or ≥ 2 b-tag jets) and DNN score.





Combining all final $\tau\tau$bb final states;

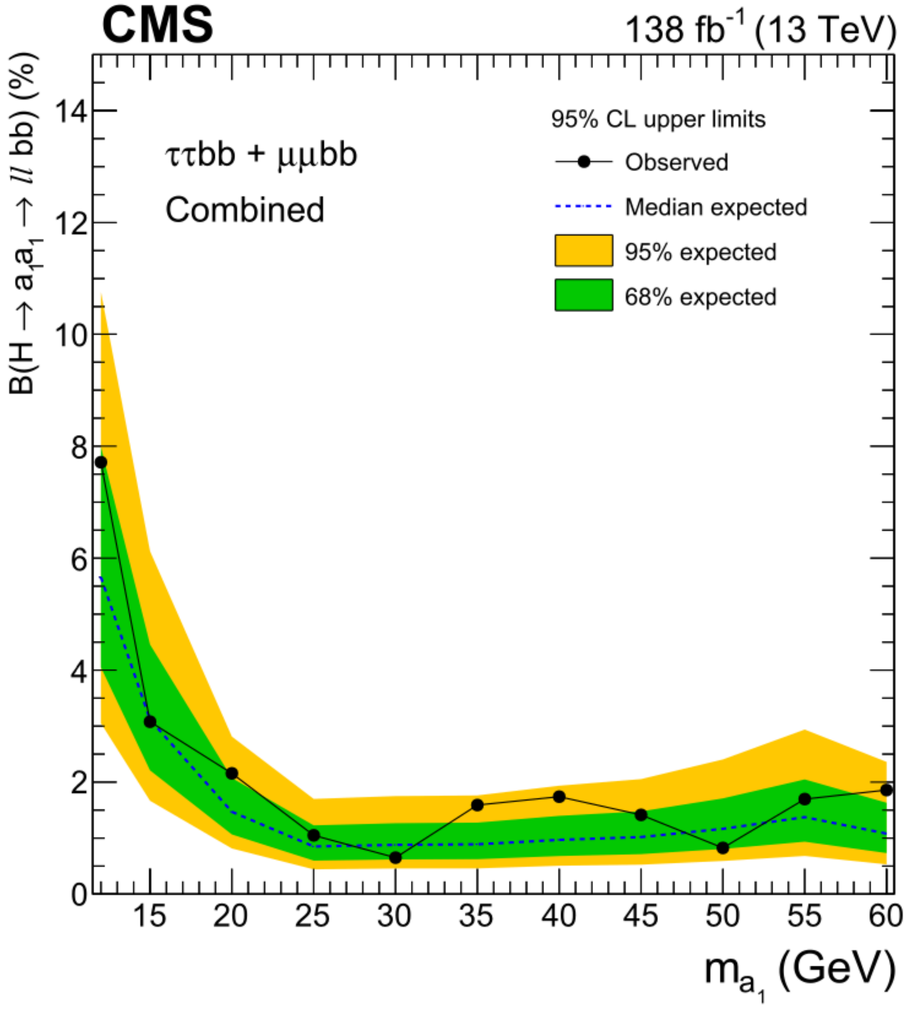
- expected limit on branching fraction:(1.5–5.6) %
- observed limit on branching fraction: (1.8 - 7.7)% at 95% CL

EPJC 84 (2024) 712

H → aa → $\mu\mu$bb / $\tau\tau$bb

No significant excess over SM background is observed

- The results are obtained as functions of m_{a1} for 2HDM+S models.
- B(H → a_1a_1) above 23% are excluded, at 95% CL for $15 < m_{a1} < 60$ in most of Type II models.
- In Type III and IV, upper limits as low as about 1% and 3% are obtained respectively, for tan β = 2.0 and 0.5.

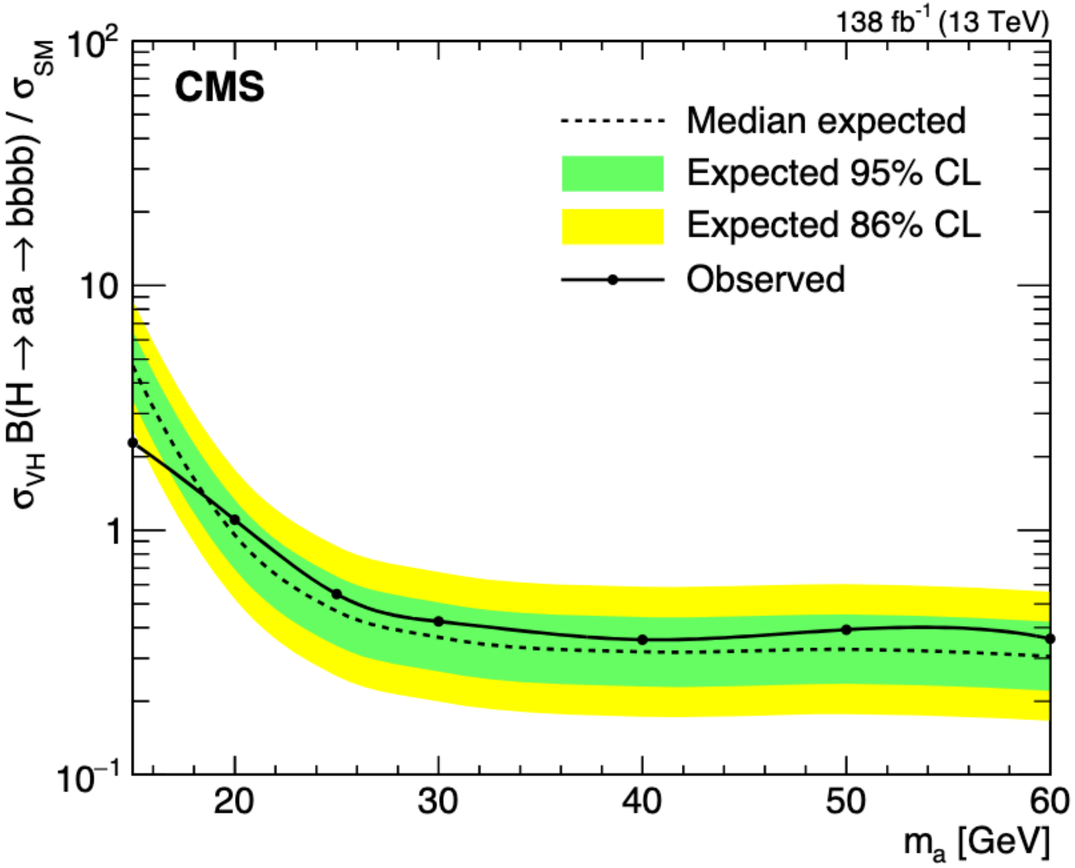


EPJC 84 (2024) 712

H → aa → bbbb

- Only feasible with VH production with V (W or Z) decayed leptonically.
- Dominant backgrounds: $t\bar{t}$ + jets, Z + jets, W+jets and QCD.
- Events are categorized interms of number of b-jets and number of AK4 jets.
- Best fitted signal strength value for the combined WH and ZH channels is 0.360(1.103)[expected: 0.305(0.957)] for m_a = 60 (20) GeV.

No evidence for the targeted decay mode is observed



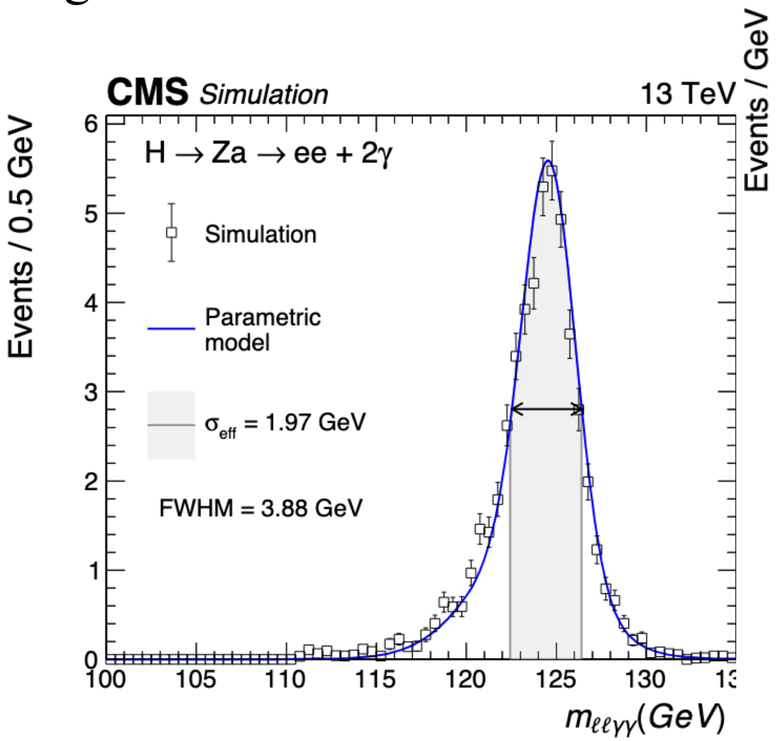
CMS-PAS-HIG-18-026

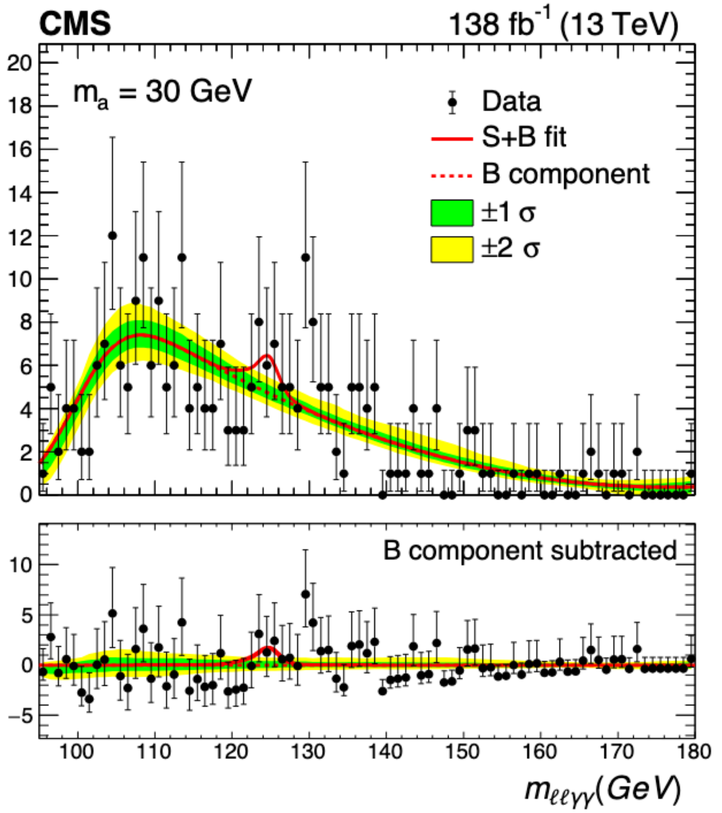
$H \rightarrow Za \rightarrow ll\gamma\gamma$

- **Motivation:** First search for axion like particles.
  - addresses strong CP problem and a potential dark matter candidate.
  - possible explanation for anomaly in the magnetic moment of the muon.

- Strategy;
  - Mass range of search: $1 < m_a < 30$ GeV.
  - Dominant background: SM Drell yan
  - Events are categorized according to BDT score.
  - m($ll\gamma\gamma$) shape is modeled using a sum of n gaussians.

[CMS-HIG-22-003]



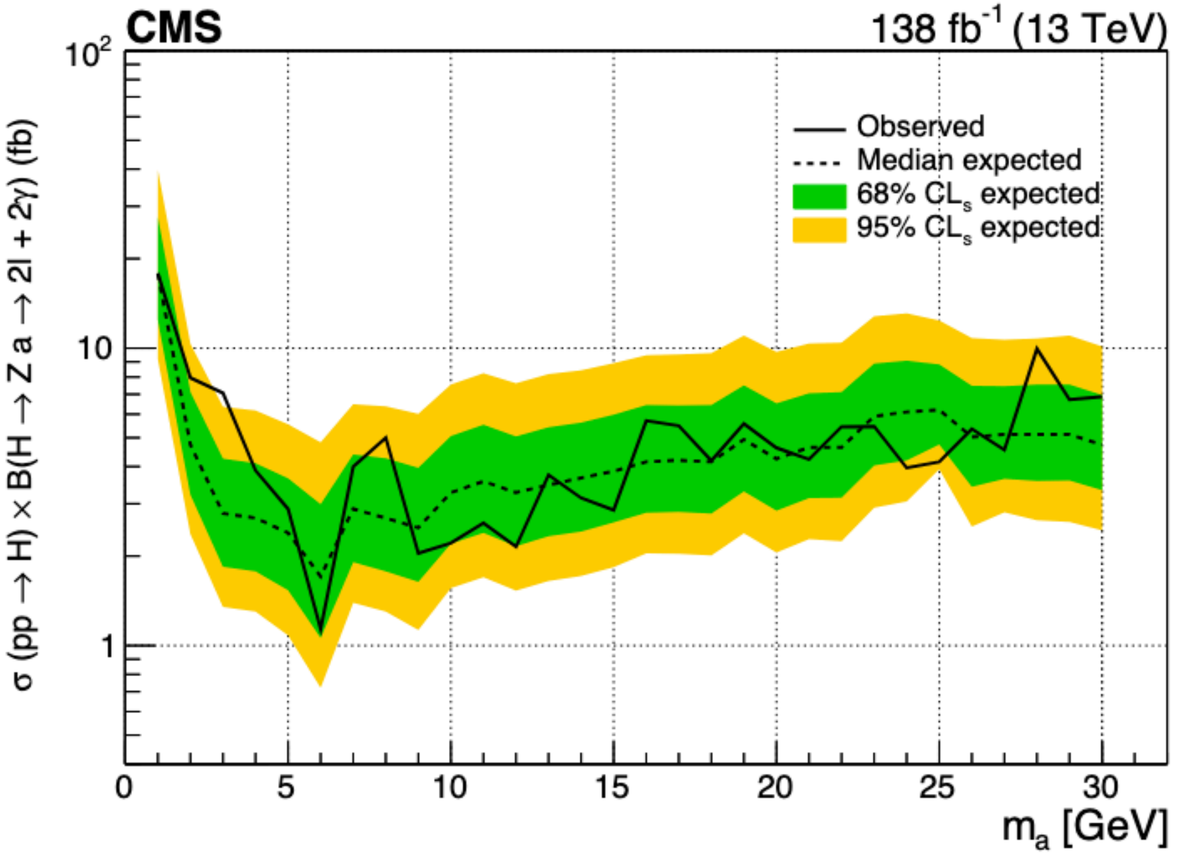


H → Za → ll$\gamma\gamma$

Excess of data above SM background is observed with 2.6(1.3) σ local (global) significance at m_a = 3 GeV

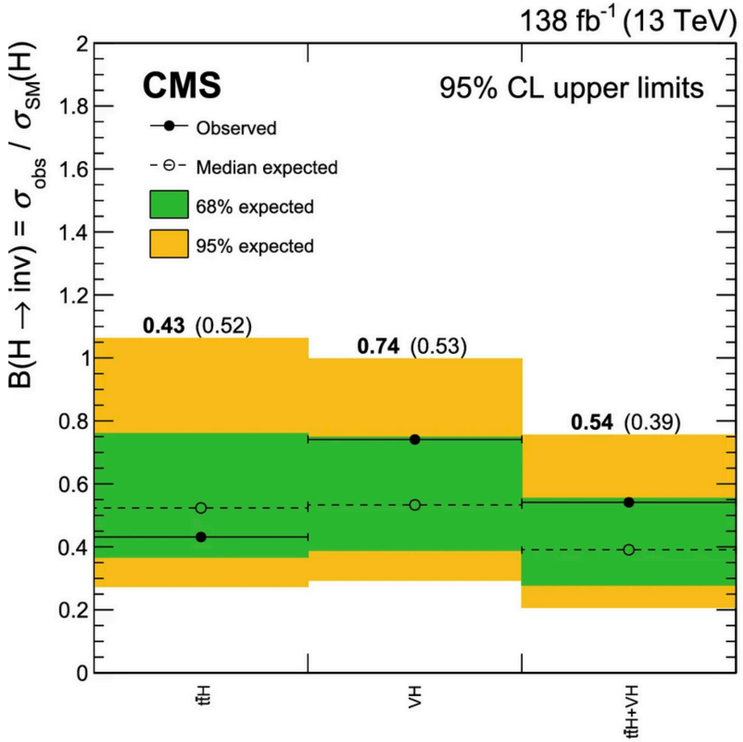
- Upper limits at 95% confidence level are set on $\sigma(pp \rightarrow H) \times Br(Za \rightarrow ll\gamma\gamma)$.
- Observed (expected) limits are in the range of 1.1–17.8 (1.7–17.9) fb within the probed m_a range.

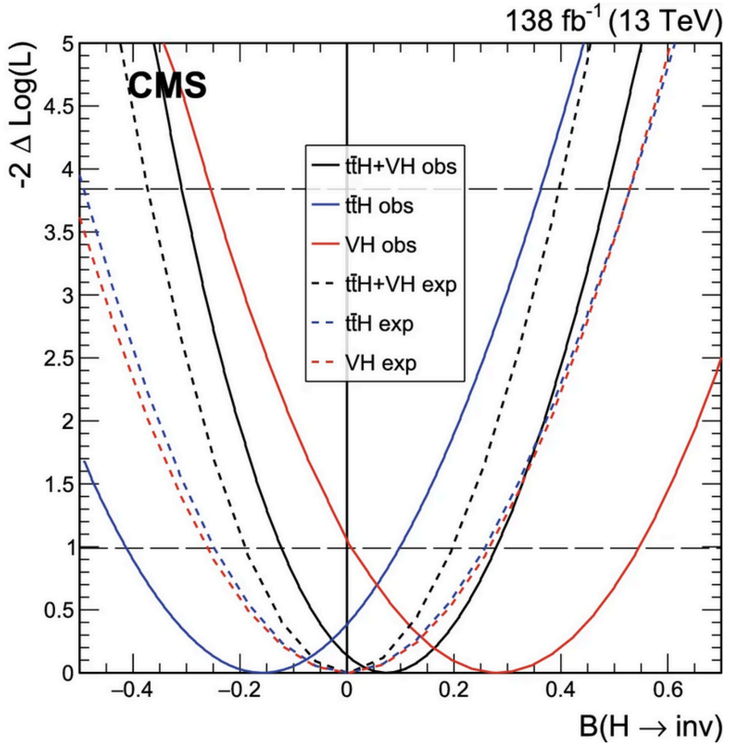
[CMS-HIG-22-003]

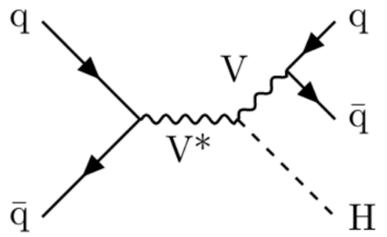


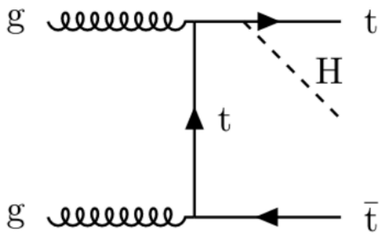
Higgs decays to invisible particles

- Branching fraction of Higgs to invisible states is ~0.1% according to SM, but BSM theories predict larger values.
- In the Higgs portal model, the Higgs mediates interactions between Standard Model particles and dark matter.
- The search include Higgs decays in **ttH** and **VH** modes with fully hadronic final states.







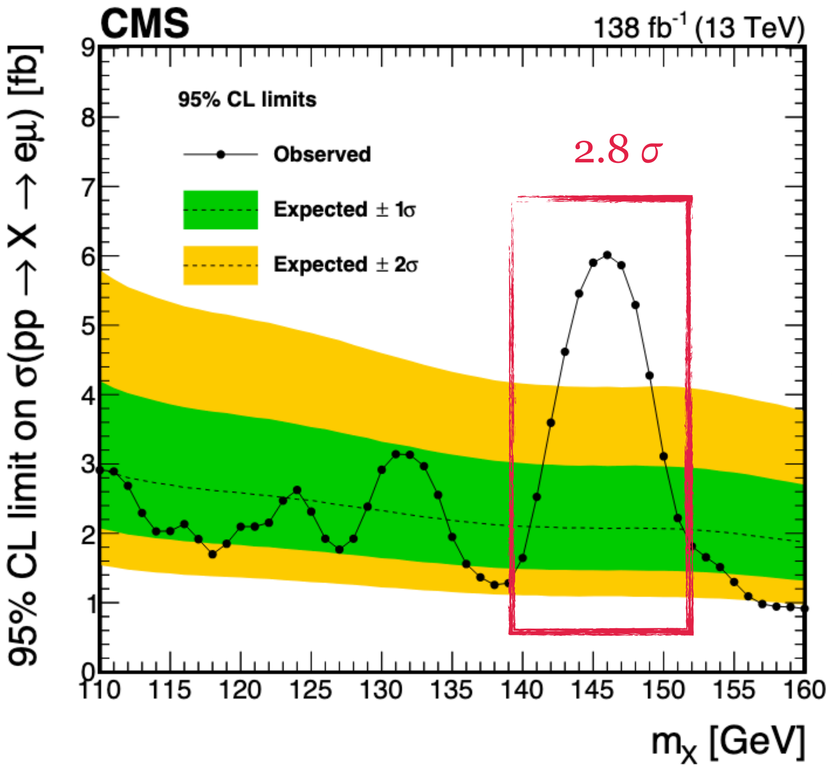


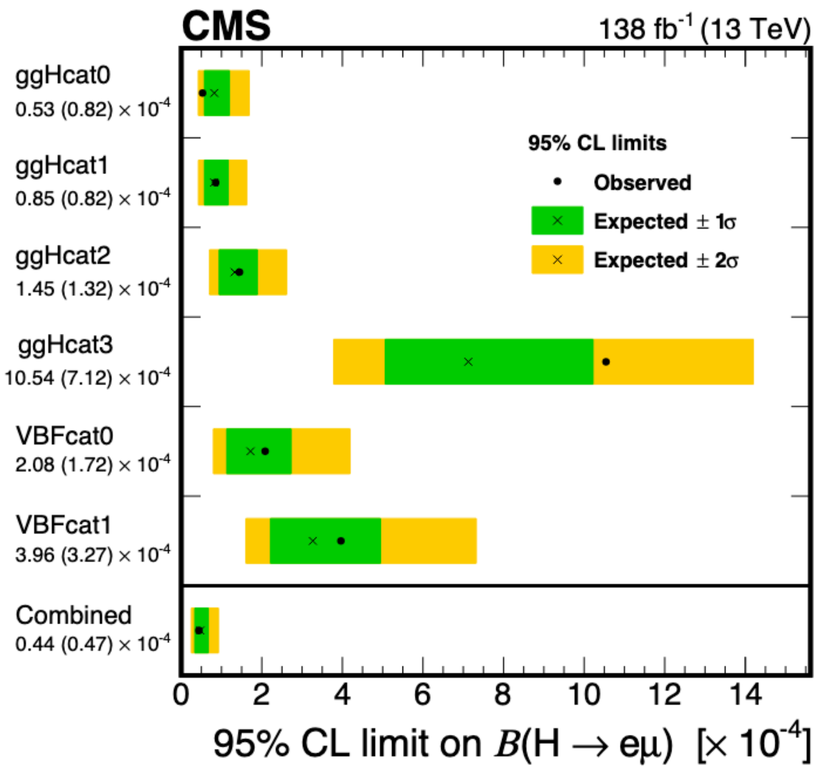
The combined (Run 1 + Run 2) upper limit on the branching fraction is 15 % at 95 % CL.

[EPJC 83 (2023) 933]

$H \rightarrow e^{\pm}\mu^{\mp}$

- The **LFV decays** are forbidden in SM, however arise in BSM theories.
- Search for the H(125) and extra Higgs bosons X decaying to $e^{\pm}\mu^{\mp}$ (110 GeV < m_X < 160 Gev).
- Event categorisation: ggH and VBF, further split based on BDT discriminants





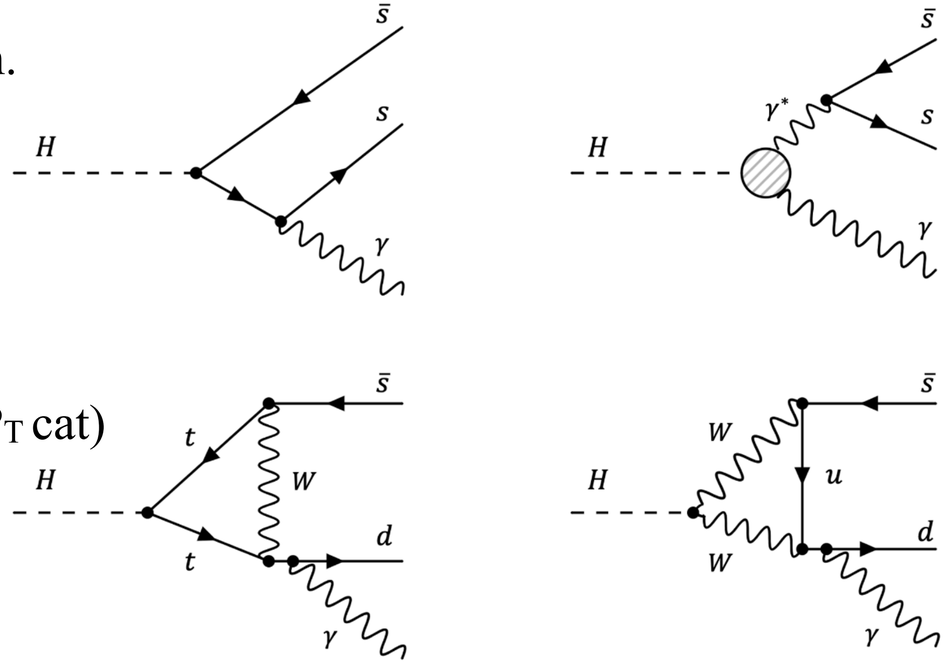
Observed (expected) upper limit on Br(H(125) → $e\mu$): **4.4 (4.7) × 10^{-5}**

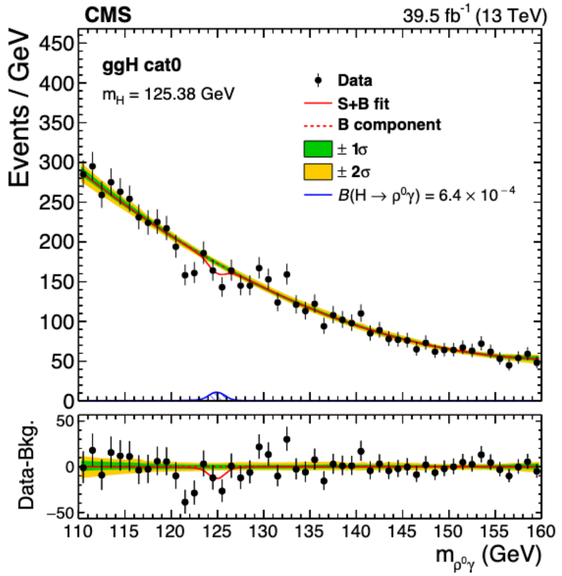
CMS-HIG-22-002

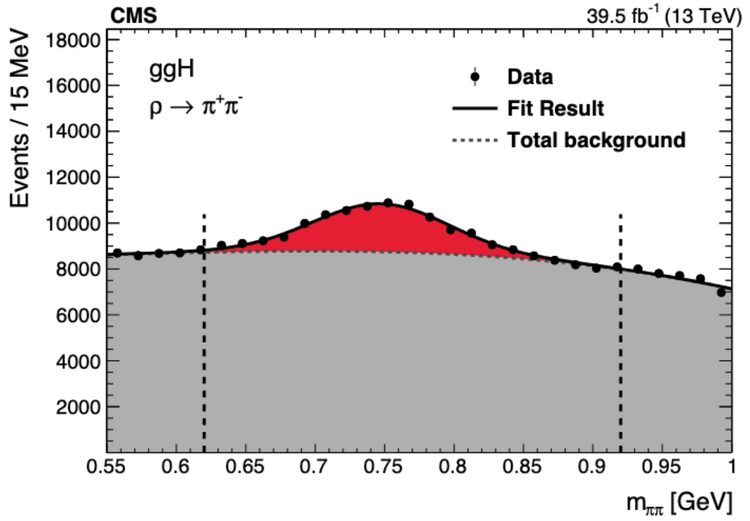
$H \to \rho^0/\phi/K^{*0}\gamma$

- **Motivation:** To confirm the interaction of higgs boson with first generation of fermions (u, d, s).
- Final states are high energy photon and high energy di-tracks from meson.
- Trigger selection;
  (i) single (double) lepton trigger
  - electron: $P_T > 27$ GeV (23 and 12 GeV)
  - muon: $P_T > 24$ GeV (17 and 8 GeV)

  (ii)photon trigger with $P_T > 75$ GeV (high P_T cat) and $P_T > 35$ GeV (low P_T cat)







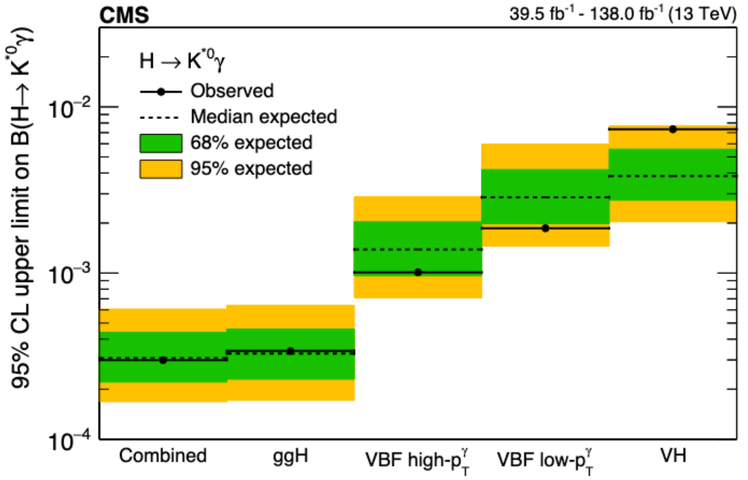
[CMS-PAS-HIG-23-005]

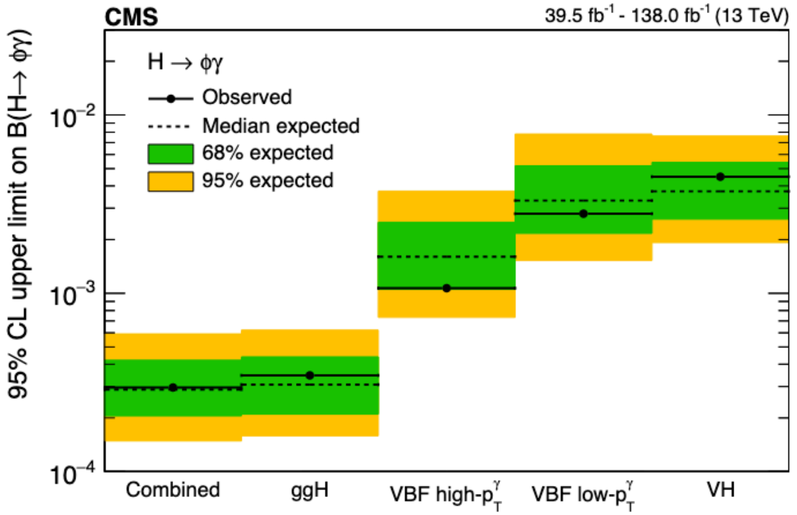
Channel	Coupling	SM Br($H \to M\gamma$)
$H \to \phi\gamma$	S	$(1.68 \pm 0.08) \times 10^{-5}$
$H \to \rho^0\gamma$	u,d	$(2.31 \pm 0.11) \times 10^{-6}$
$H \to K^{*0}\gamma$	d&s (flavor-changing)	*only available for* $H \to \bar{d}s + \bar{s}d$ 1.19×10^{-11}

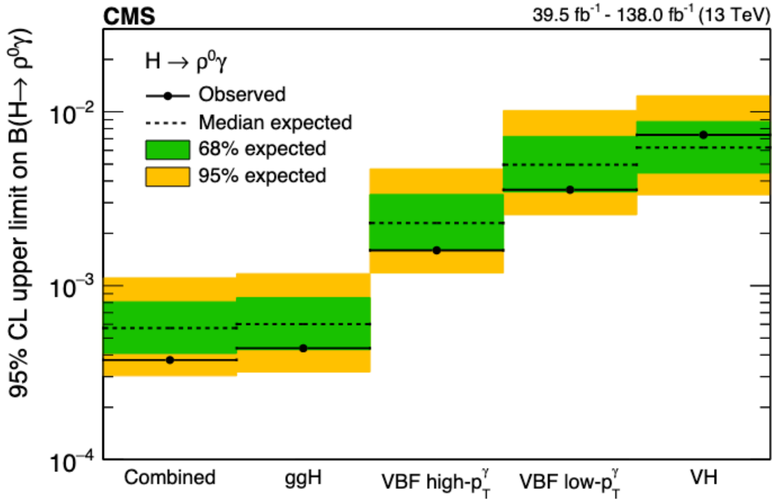
$H \to \rho^0/\phi/K^{*0}\gamma$

- **Observed** (expected) Upper limit on;
  - Br($H \to \rho^0\gamma$): **3.74 × 10⁻⁴**(5.7 × 10⁻⁴)
  - Br($H \to \phi\gamma$) : **2.97 × 10⁻⁴**(2.9 × 10⁻⁴)
  - Br($H \to K^{*0}\gamma$) :**1.71 × 10⁻⁴** (3.1 × 10⁻⁴)

no significant excess above the background expectations is observed.



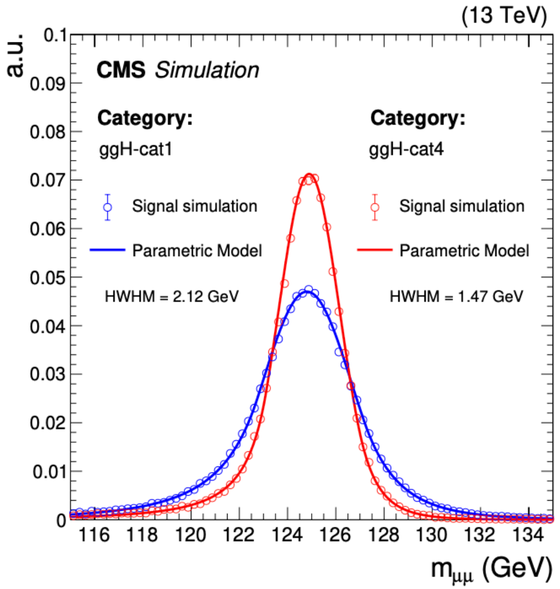




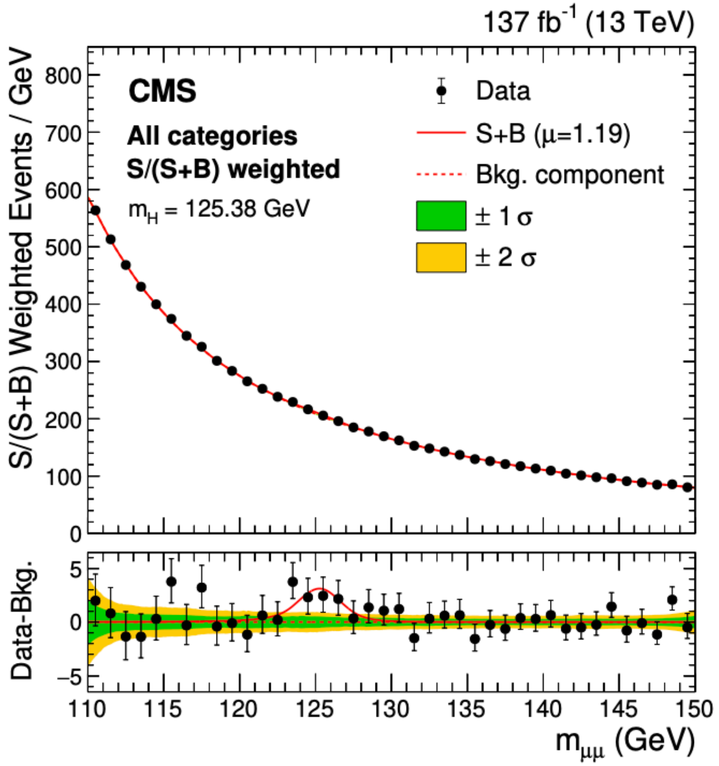
[CMS-PAS-HIG-23-005]

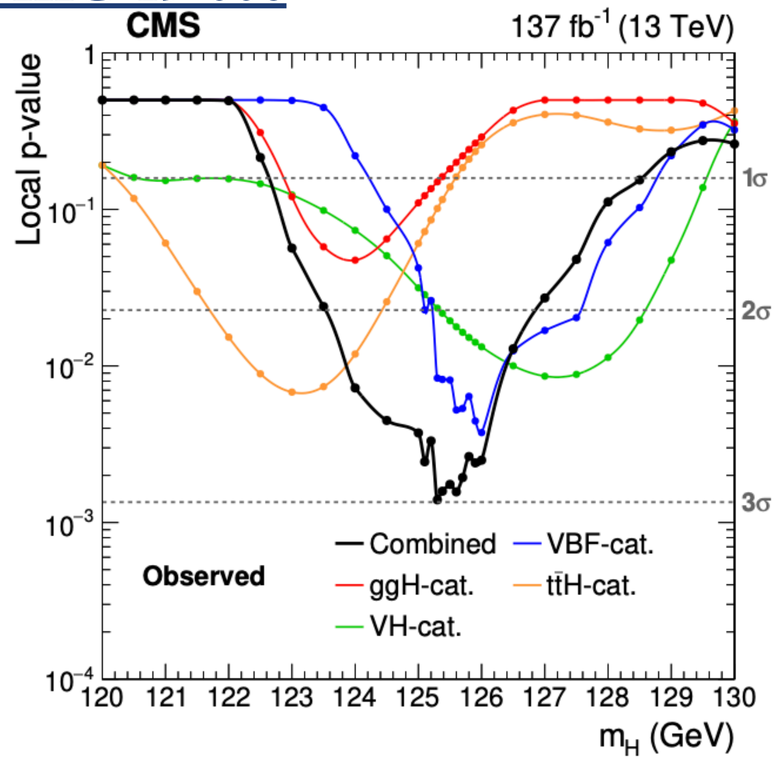
$H \rightarrow \mu\mu$

- First evidence for the SM Higgs decay to fermions of the second generation
- Events separated into ggH, VBF, VH and ttH production modes.
- Run I + Run II combination results;
  - **observed** (expected) excess in data over background prediction of **3**σ (2.5σ) at $m_H = 125.38$ GeV.



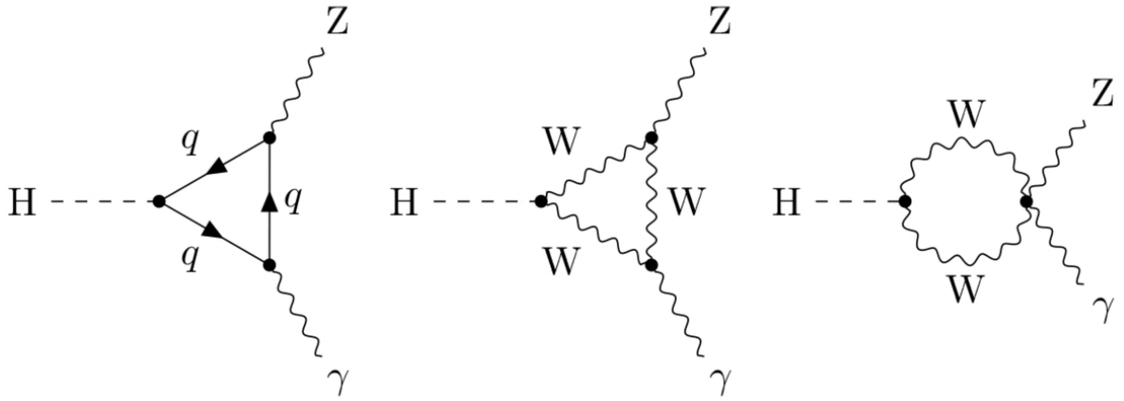
[CMS-HIG-19-006]

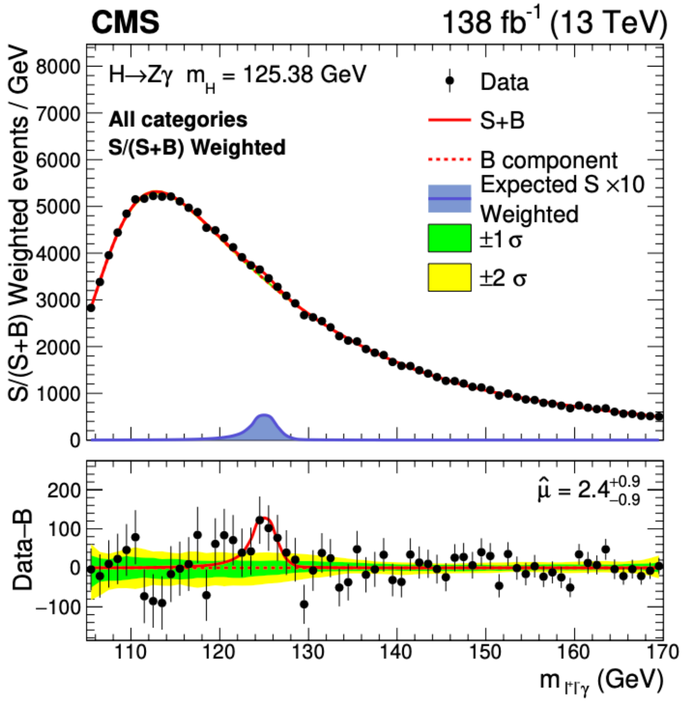




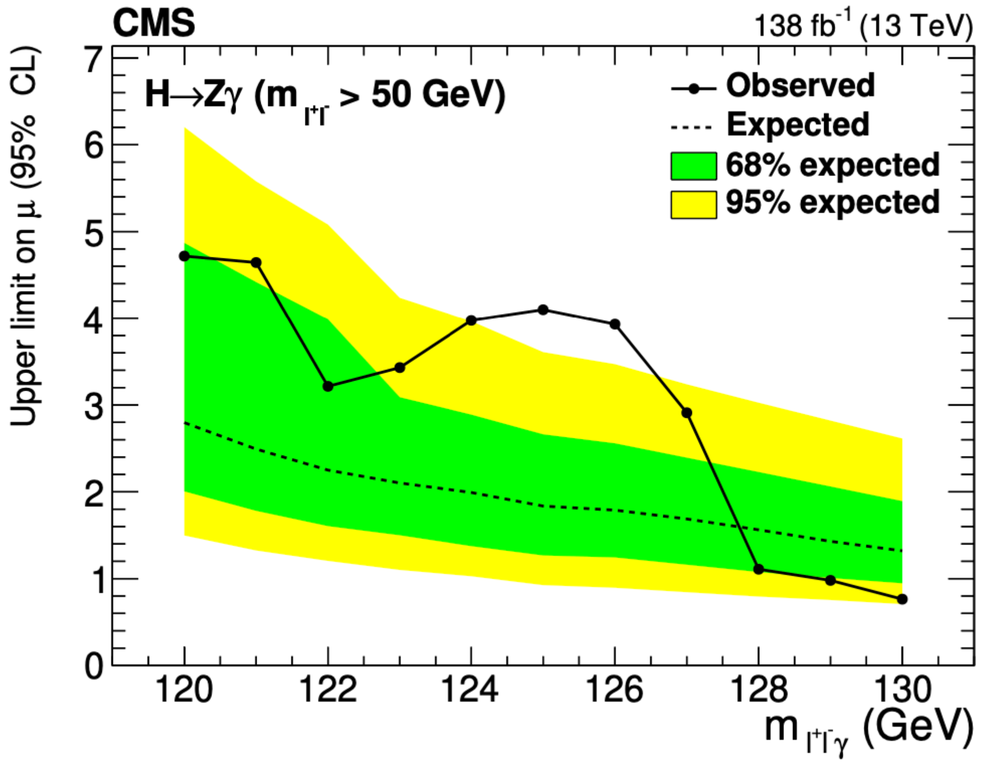
$H \to Z\gamma$

- Rare radiative decay of Higgs boson.
- Measured $\sigma(pp \to H).\mathrm{Br}(H \to Z\gamma) = 0.21 \pm 0.8$ pb
  - consistent with SM prediction at 1.6σ level.
- Best fit signal strength: 2.4 ± 0.9.
- Excess events are observed with a significance of 2.7σ.
- Measured $\mathrm{Br}(H \to Z\gamma)/\mathrm{Br}(H \to \gamma\gamma) = 1.5^{+0.7}_{-0.6}$
  - consistent with SM prediction at 1.5σ level.





CMS-HIG-19-014



Summary

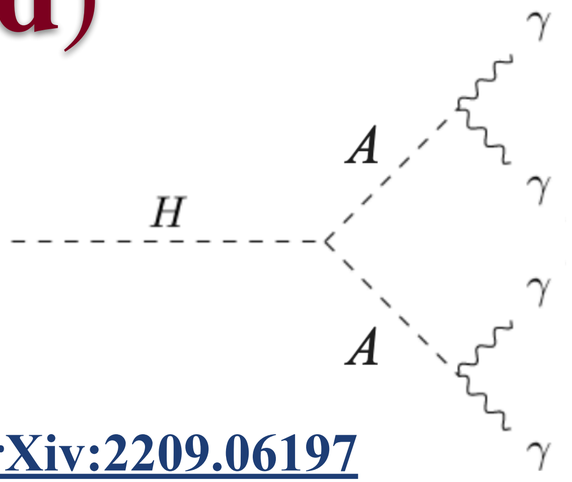
- No Excess was observed in H → pseudoscalars, invisible particles, eμ and meson + γ decays.
- **H → Za → llγγ:** excess of data over SM background with **2.6** σ significance at m_a = 3 GeV**.**
- For **H → μμ** and **H → Zγ,** excess events were observed with significance **3**σ and **2.7**σ respectively.
- Overall results align with the SM prediction and no signs of BSM yet.
- **Looking Ahead to Run 3**: higher luminosity and energy promise greater sensitivity and new physics discovery potential.

BACK UP

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

- Search for exotic decay of Higgs boson to light pseudo scalars, where $\mathbf{A} \rightarrow \gamma\gamma$.
  - a is a low-mass, **boosted scalar** decaying promptly to two highly merged photons.

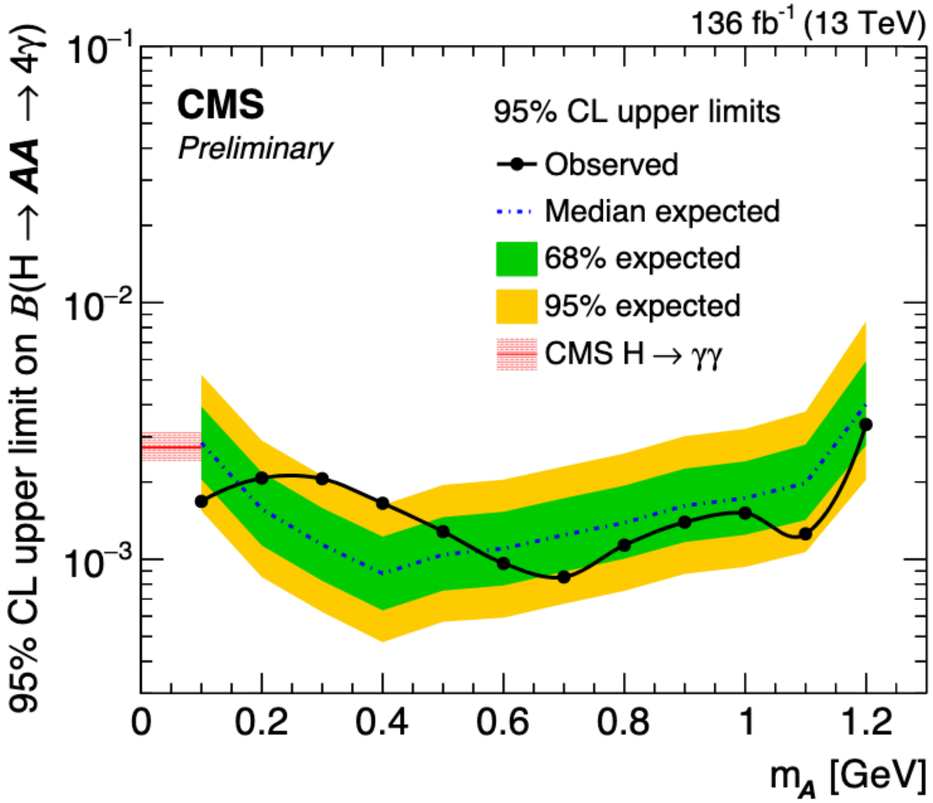
  - well motivated in BSM extension of Higgs sector (2HDM, NMSSM, ALP).



- Search performed in the mass range 0.1 to 1.2 GeV
- Each $\mathbf{A} \rightarrow \gamma\gamma$ leg reconstructed as 1 merged photon object "Γ"
- Probe invariant mass spectrum of Γ reconstructed in events resembling a SM $H \rightarrow \gamma\gamma$ final state, using the end-to-end deep learning reconstruction technique.
- Upper limits on the $Br(H \rightarrow AA \rightarrow 4\gamma)$ of $(0.9–3.3) \times 10^{-3}$ are set at the 95% CL for masses of a in the range $0.1 < m_a < 1.2$ GeV.

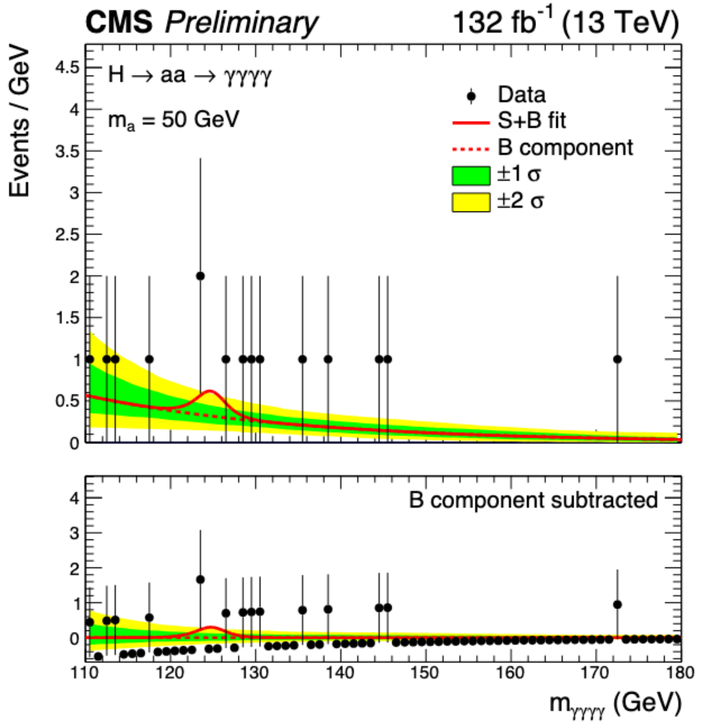
No excess of events above the estimated background is found.

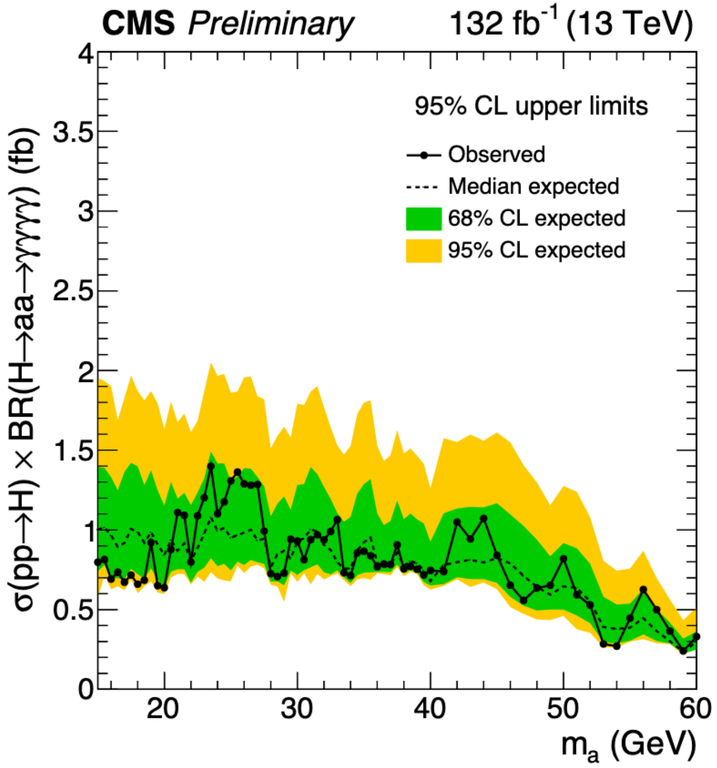
arXiv:2209.06197



$H \rightarrow AA \rightarrow 4\gamma$(resolved)

- **Fully resolved final states**: Both photon pairs have wide opening angles, with each photon reconstructed separately.
- Mass range : 15 GeV < m_a < 60 GeV.
- Improved **vertex selection** enhances Higgs candidate mass resolution by ~3%.
- Primary vertex identified using a BDT-based multivariate (MVA) technique.





- The observed (expected) limit ranges from 0.80 (1.00) fb for m_a = 15 GeV to 0.33 (0.30) fb for m_a = 60 GeV.

No significant deviation from the background-only hypothesis is observed

arXiv:2208.01469