Searches for light neutral bosons of an extended Higgs sector via decays of the SM-like Higgs boson at CMS

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Motivation

- Measurements of production and SM decays of H(125) are consistent with SM within their uncertainties so far
  - BR(H→invisible) < 16% [1]
    ⇒ BR(H→BSM) ≲ 20% if H is produced with SM strength [2]

- Many beyond SM (BSM) theories predict exotic decays of H
  - For e.g. H→*ss*, H→*aa*, H→*Za*, and *a*/*s*→SM
    where *s* (*a*): (pseudo-)scalar state

- Many well motivated candidates for light (pseudo-)scalar states [2]
  - Generic single scalar in SM+Singlet
  - Generic singlet (pseudo-)scalar in 2HDM+Singlet
  - Light (pseudo-)scalar of NMSSM
  - Pseudoscalar that mixes with the CP-odd Higgs of (N)MSSM

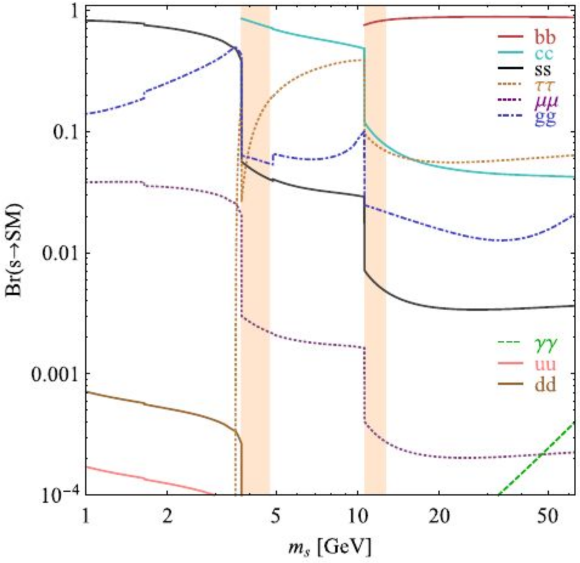

Fig: *s*⟶ SM branching fraction in SM+Singlet model [2]

[1] JHEP 08 (2022) 104
[2] *Phys. Rev. D* 90 (2014) 075004

Motivation (II)

- Searches for light bosons in H decays in CMS:
  - With data collected in 2016 (~36 fb^{-1}):
    - $H \to aa \to 4\tau$ [HIG-18-006]
    - $H \to aa \to 4\mu$ [HIG-18-003]
    - $H \to aa \to 2b\ 2\tau$ [HIG-17-024]
    - $H \to aa \to 2b\ 2\mu$ [HIG-18-011]
    - $H \to aa \to 2\mu\ 2\tau$ [HIG-17-029, HIG-18-024]
  - With data collected in 2016-2018 (~138 fb^{-1}):
    - **$H \to aa \to 4\gamma$ resolved ($m_a \in [15, 60]$ GeV)** [HIG-21-003] ★
    - **$H \to aa \to 4\gamma$ boosted ($m_a \in [0.1, 1.2]$ GeV)** [HIG-21-016] ★★
    - $H \to aa \to 2b\ 2\mu$ ($m_a \in [15, 62.5]$ GeV) [HIG-21-021] ★
    - Model independent searches
    - Searches in other final states are in pipeline

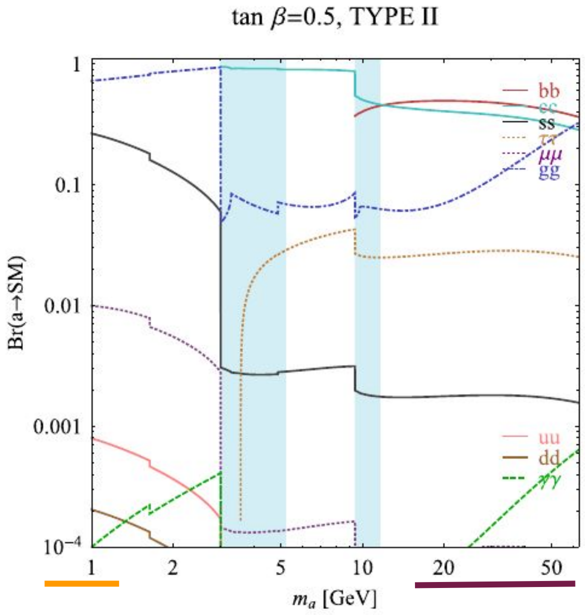

Fig: $a \to$ SM branching fraction in a specific scenario in 2HDM+Singlet model [1]

★ This presentation
★ Talk by Lakshmi [link]

[1] *Phys. Rev. D* 90 (2014) 075004

H→aa→4γ (resolved) HIG-21-003

Advantage of H→aa→4γ :

- Relatively low background contribution
- BR($a\to2\gamma$) ≈ 100% if a couples at renormalizable level only to Higgs and to heavy vector-like uncolored matter

Search for H→aa in resolved 4γ in final state for $15 \leq m_a \leq 60$ GeV

Selection conditions:

- Events with 4γ with $p_T > 30, 18, 15, 15$ GeV and $|\eta| < 2.4$
- MVA based γ-identification (ID).
  Also required electron veto based on tracker-calorimeter overlap.
- $110 < m_{\gamma\gamma\gamma\gamma} < 180$ GeV
- Used a dedicated BDT to select pp collision primary vertex (PV)
  ⇒ Improved $m_{\gamma\gamma\gamma\gamma}$ by 3% and PV identification efficiency by 10%

$a\to2\gamma$ tagging: Combination of 2γ pairs with the most similar $m_{\gamma\gamma}$ are selected as $a\to2\gamma$

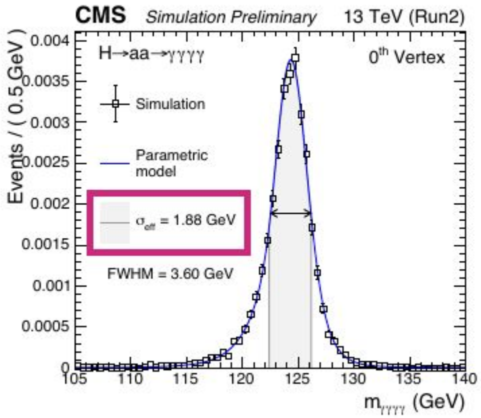

Fig: Standard PV selection (leading $\sum p_T^2$)

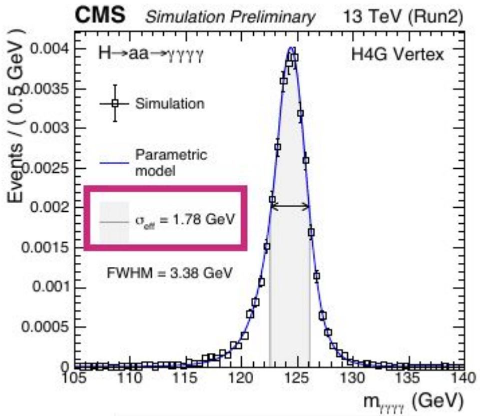

Fig: BDT based collision vertex selection

$H \rightarrow aa \rightarrow 4\gamma$ (resolved) (II)

Signal Region selection:

- BDT (mass-decorrelated) to discriminate signal over background
- Training sample: Signal from MC, background generated using data driven model through event mixing.
- Training variables: MVA based γ-ID score, $p_{T,a1}$, $p_{T,a2}$, $(m_{a1} - m_{a2})$, $(m_{a1} - m_{a,hyp})/m_{\gamma\gamma\gamma\gamma}$, $(m_{a2} - m_{a,hyp})/m_{\gamma\gamma\gamma\gamma}$ and $\cos\theta^*_{a\gamma}$.

Background:

- SM γγ + jets, γ + jets and multijet events, in which jets are misidentified as γ.
- Event mixing: 3 out of 4 γ are taken from the next consecutive events from data before preselection.
  - Those mixing γ are required to satisfy all γ selection criteria.
  - Per-event weight, calculated in $m_{\gamma\gamma\gamma\gamma}$ sideband, is applied to improve data - background agreement.

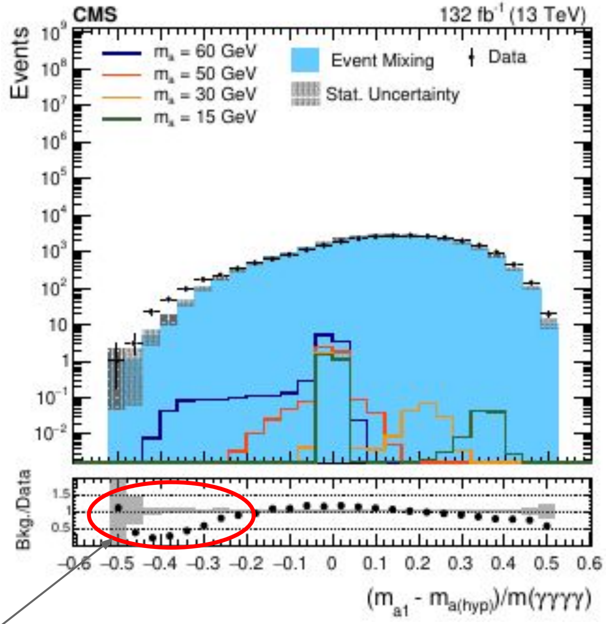

Fig: One of the top ranked variables in BDT training

$H \to aa \to 4\gamma$ (resolved) (III)

Signal Region (SR) selection (continue):

- Unique BDT output obtained for each m_a hypothesis
- BDT output threshold for SR is decided by maximizing approximate mean significance (AMS), separately for each m_a hypothesis

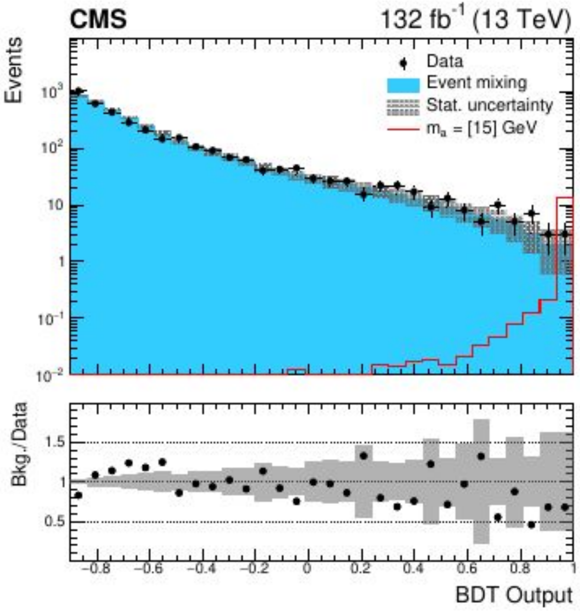

Fig: S vs B BDT for $m_{a,\,hyp}$ = 15 GeV

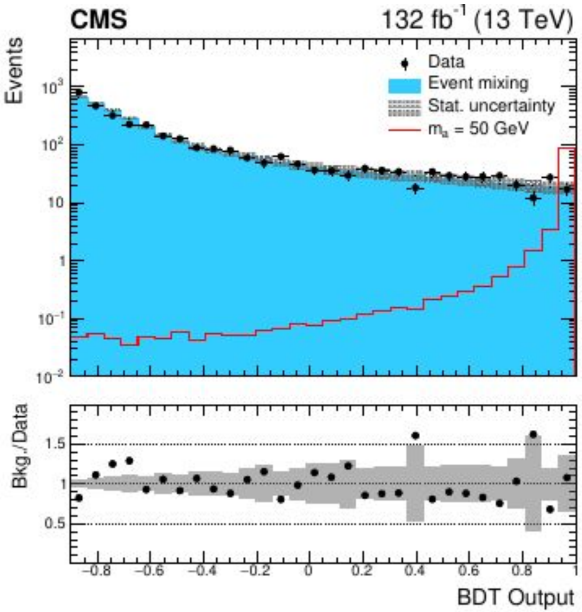

Fig: S vs B BDT for $m_{a,\,hyp}$ = 50 GeV

$H \to aa \to 4\gamma$ (resolved) (IV)

Signal estimation: Maximum likelihood fit of '$\mu S + B$' function to data in $m_{\gamma\gamma\gamma\gamma}$.

μ: signal strength parameter floating in the fit.

Signal modeling (S):

- Signal template is derived by fitting 'Double-sided Crystal Ball' function to $m_{\gamma\gamma\gamma\gamma}$ in signal MC,
- Separately for each m_a hypothesis and for each data taking year

Background modeling (B):

- Background functions: exponentials, Bernstein polynomials, Laurent series, and power law functions.
- Background modeling is performed by likelihood fit of background function to data. Choice of the background function is treated as a discrete nuisance parameter via discrete profiling method [1].

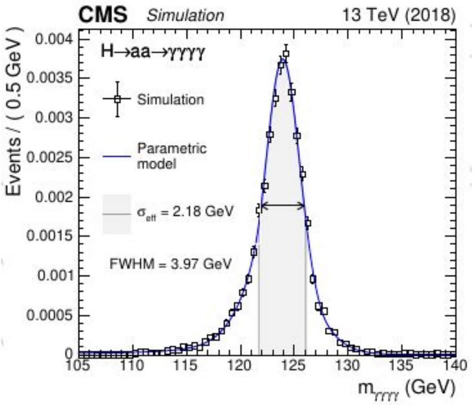

Fig: S profile for $m_{a,\,hyp}$ = 15 GeV

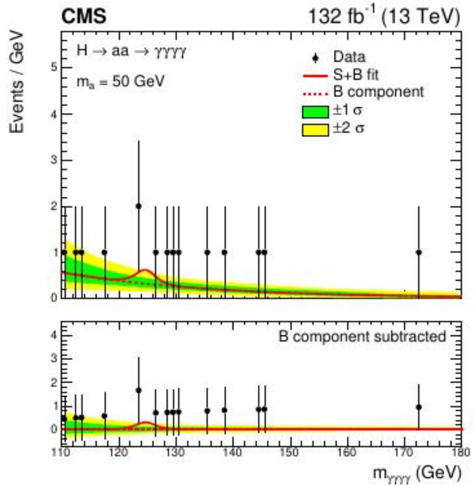

Fig: μS+B fit to data for $m_{a,\,hyp}$ = 50 GeV

[1] *JINST* 10 (2015) P04015

H→aa→4γ (resolved) (V)

- No significant deviation from background-only hypothesis.
- Observed (expected) upper limits at 95% CL on $\sigma_H \times$ BR(H→aa→4γ):
  0.80 (1.00) *fb* for m_a =15 GeV ⇔ BR(H→aa→4γ) = 1.5×10^{-5}
  0.26 (0.24) *fb* for m_a =50 GeV ⇔ BR(H→aa→4γ) = 0.5×10^{-5}

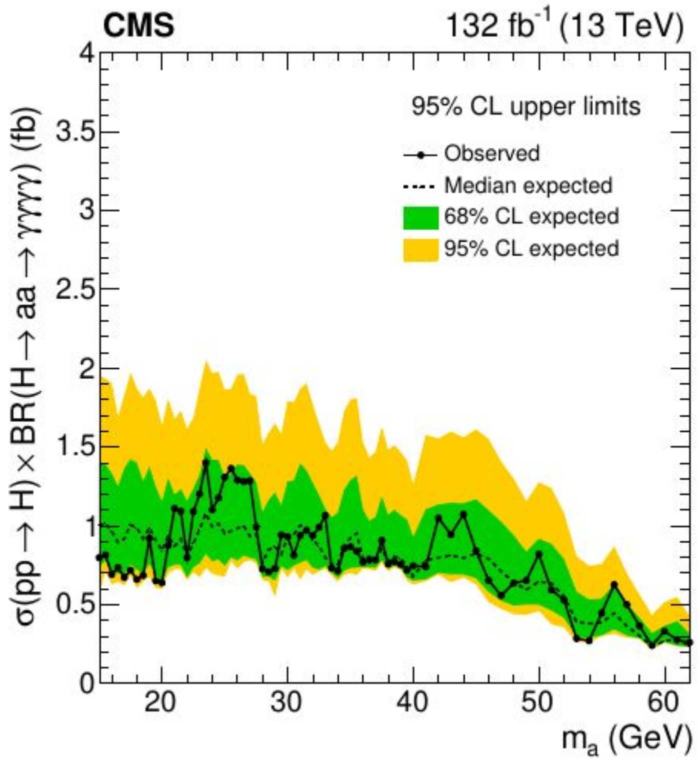

Fig: H→aa→4γ (resolved) upper limit

H→aa→4γ (boosted) HIG-21-016

Search for H→aa in 2 merged γ final for $0.1 \leq m_a \leq 1.2$ GeV

- BR(a→2γ) enhances for $m_a < m_{2\mu}, m_{2\pi}, m_{J/\psi}$ = 0.21, 0.28, 3.1 GeV [1]
- Smaller $m_a \Rightarrow$ larger Lorentz boost $\gamma_L = E_a/m_a$ for the same energy E_a
  $\Rightarrow a \to 2\gamma$ reconstructed as merged photon object (Γ)
- **End-to-end m_Γ regressor**: Dedicated convolutional neural network to estimate m_a from calorimeter deposits [2]

Selection conditions:

- Events with 2γ with $p_T > 33, 25$ GeV and $|\eta_\Gamma| < 1.4$
- MVA based γ-identification (ID).
  Also required electron veto based on tracker-calorimeter overlap.

[1] *Phys. Rev. D* 90 (2014) 075004
[2] arXiv:2204.12313

H→*aa*→4γ (boosted) (II)

Phase space is divided in different regions:

- m_H-SR: $110 < m_{\Gamma\Gamma} < 140$ GeV
- m_H-SB$_{low}$: $100 < m_{\Gamma\Gamma} < 110$ GeV; m_H-SB$_{high}$: $140 < m_{\Gamma\Gamma} < 180$ GeV
- m_A-SR: $|m_{\Gamma1}-m_{\Gamma2}| < 0.3$ GeV
- m_A-SB: $|m_{\Gamma1}-m_{\Gamma2}| > 0.3$ GeV

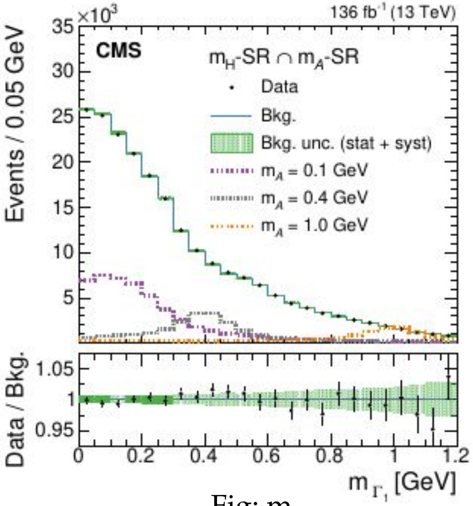

Fig: $m_{\Gamma1}$

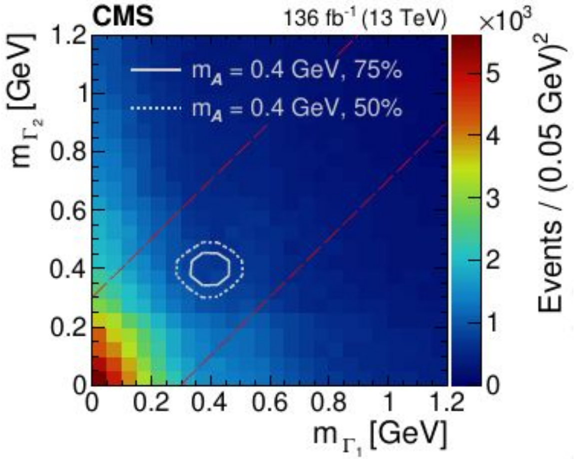

Fig: Observed 2D-m_Γ

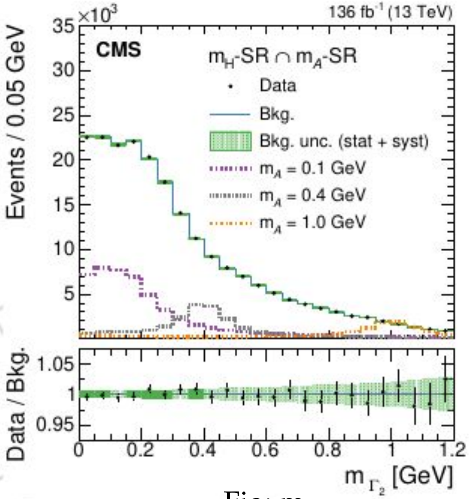

Fig: $m_{\Gamma2}$

H→*aa*→4γ (boosted) (III)

Signal estimation: Maximum likelihood fit of '$\mu S + B$' template to data in 2D-m_Γ in 'm_H-SR ∩ m_A-SR' region.

μ: signal strength parameter floating in the fit.

Signal model (S): Binned 2D-m_Γ template derived from signal MC

Background model (B):

- Components:
  - H→2γ background: 2D-m_Γ template derived from MC, normalize using BR(SM H→2γ)$_{theory}$
  - Non-resonant backgrounds:
    - Dijet, γ+jet, prompt $\gamma\gamma$
    - Data driven 2D-m_Γ template derived

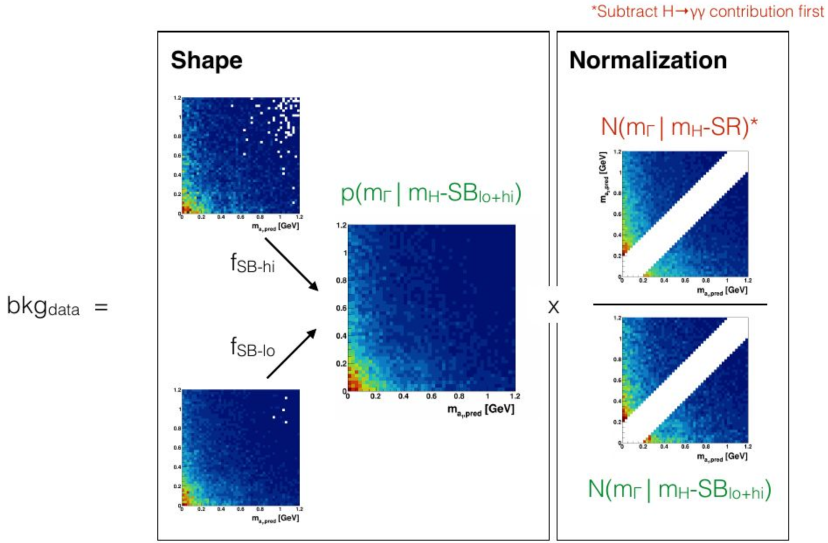

Fig: Data driven estimation of non-resonant background. Plots are for illustrative purpose only

H→aa→4γ (boosted) (IV)

- No significant excess observed over SM-only
- Observed (expected) upper limits at 95% CL on BR(H→aa→4γ): (0.9 - 3.3)×10^{-3} for m_a (0.1 - 1.2) GeV
- First CMS H→aa limits below a→2μ threshold (m_a< 0.210 GeV)

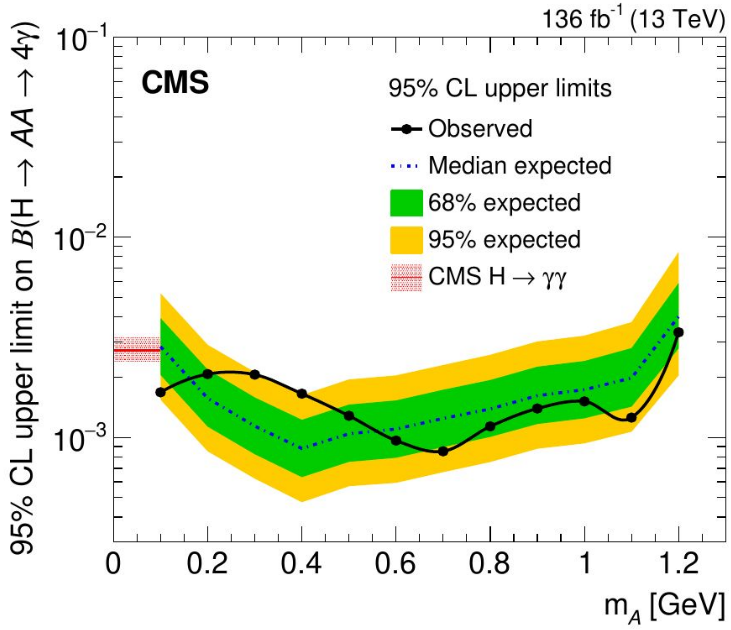

Fig: H→aa→4γ (boosted) upper limit

Summary

- Searches for H→*ss*, H→*aa*, H→*Za* exotic decays provide excellent probe to test many BSM scenarios
- The searches in CMS,
  - With data collected in 2016 (~36 fb^{-1}):
    - H→*aa*→4τ [HIG-18-006]
    - H→*aa*→4μ [HIG-18-003]
    - H→*aa*→2b 2τ [HIG-17-024]
    - H→*aa*→2b 2μ [HIG-18-011]
    - H→*aa*→2μ 2τ [HIG-17-029, HIG-18-024]
  - With data collected in 2016-2018 (~138 fb^{-1}):
    - H→*aa*→4γ resolved [HIG-21-003]
    - H→*aa*→4γ boosted [HIG-21-016]
    - H→*aa*→2*b* 2μ [HIG-21-021]
    - Model independent searches
    - The searches in few more final states are in pipeline. So stay tuned!

  - No signature of H→*aa* or H→*ss* found yet in the searches.
    However improvements from full Run 2 dataset and from state-of-art analysis techniques narrow down the search parameter space for future analyses.

Back up