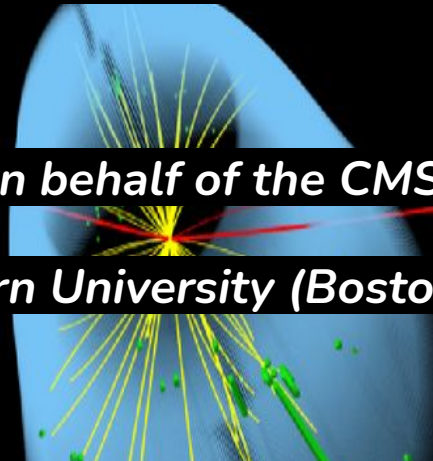


CMS rare H(125) and BSM decays

Badder Marzocchi¹, on behalf of the CMS Collaboration

¹Northeastern University (Boston, US)



Results and prospects in the electroweak symmetry breaking sector

Higgs Hunting

September 20 - 22, 2021
Orsay-Paris, France

Bruno Mazoyer - ICLab 2021



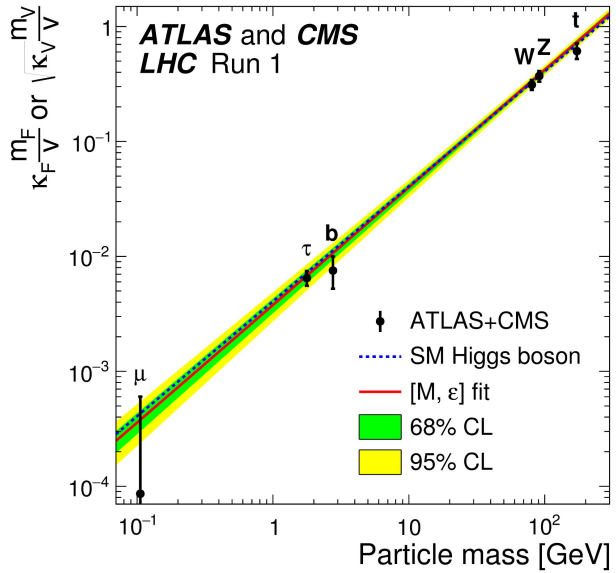
- The Higgs boson has been observed decaying to

- Massive vector bosons (Z, W) and photons
- Third generation charged fermions (b,τ)
- Coupling to top quarks observed (ttH)

- The interaction to the 1st and 2nd generation fermions not observed

- New physics can be probed from SM deviations:

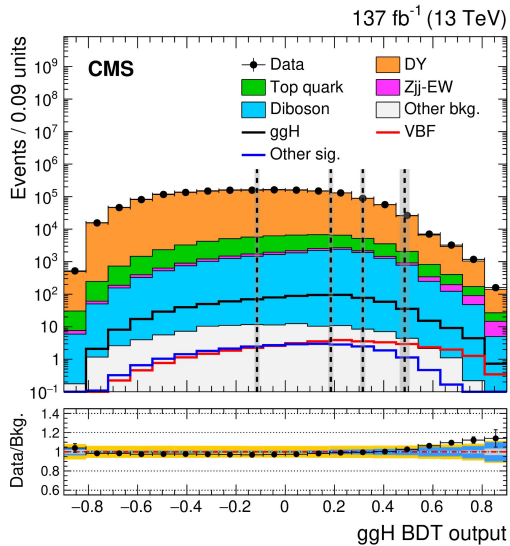
- In rare decay measurements
- In Higgs BSM decay modes



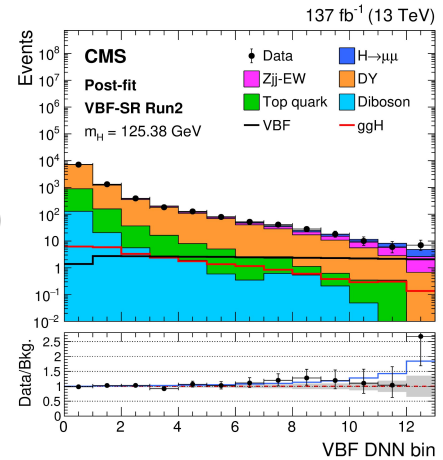
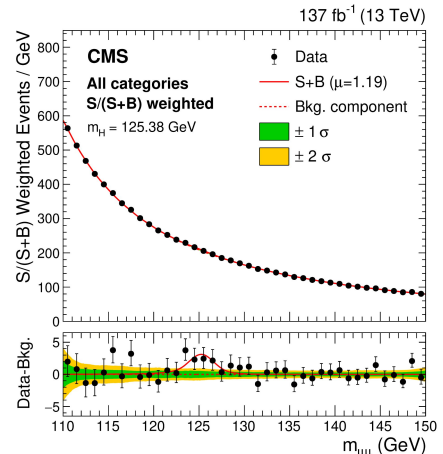
Decay	BR (%)
H → bb	58
H → WW	21.6
H → ττ	6.3
H → cc	2.9
H → ZZ	2.7
H → γγ	0.23
H → Zγ	0.115
H → μμ	0.022

- Most sensitive probe of H couplings to 2nd generation fermions
- Fit the Higgs boson peak dimuon mass:
 - Narrow resonant peak at 125 GeV (few percents resolution) from MC signal
 - SM smooth falling background from data
- Require at least 2 well isolated muons with opposite charges ($p_T > 20$ GeV, $|\eta| < 2.4$)
 - Muon tracks refitted using primary vertex information (3-10% improvement)
 - Final state radiation (FSR) energy recovered (3% improvement)

[\[JHEP 01 \(2021\) 148\]](#)



- The search is divided by the production modes, for which multivariate discriminators are trained:
 - Leptonic and Hadronic ttH
 - VBF (bkg estimated from MC, fit BDT score)
 - WH and ZH
 - ggH
- Categories with different signal purity chosen from MVA discriminator scores

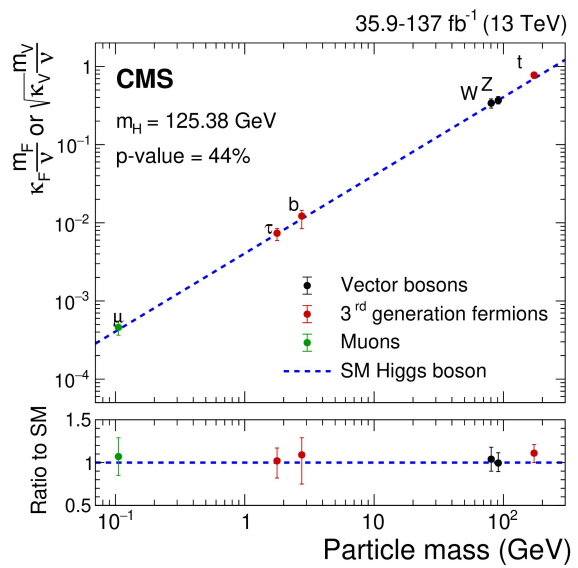
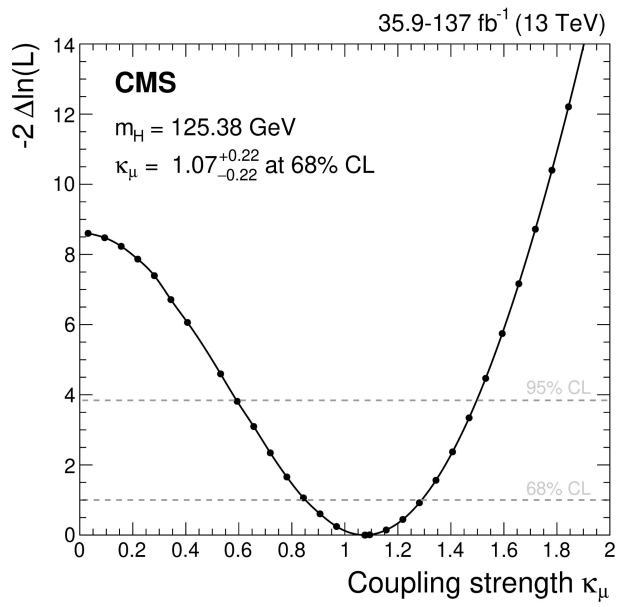
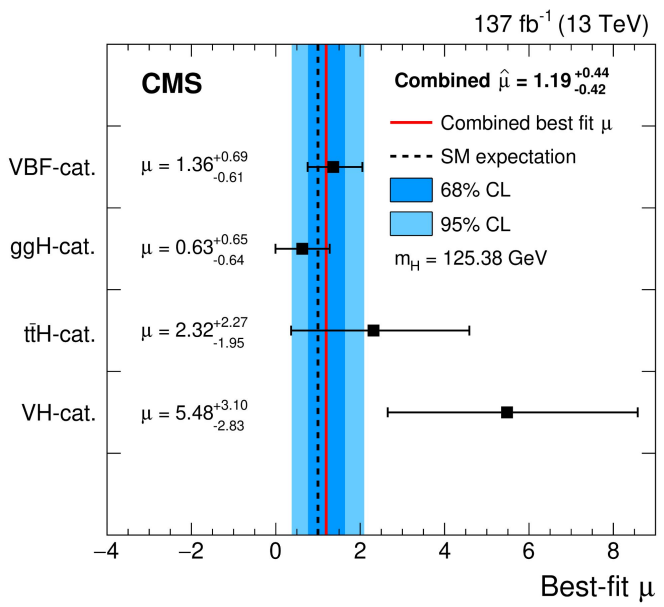


H → μμ

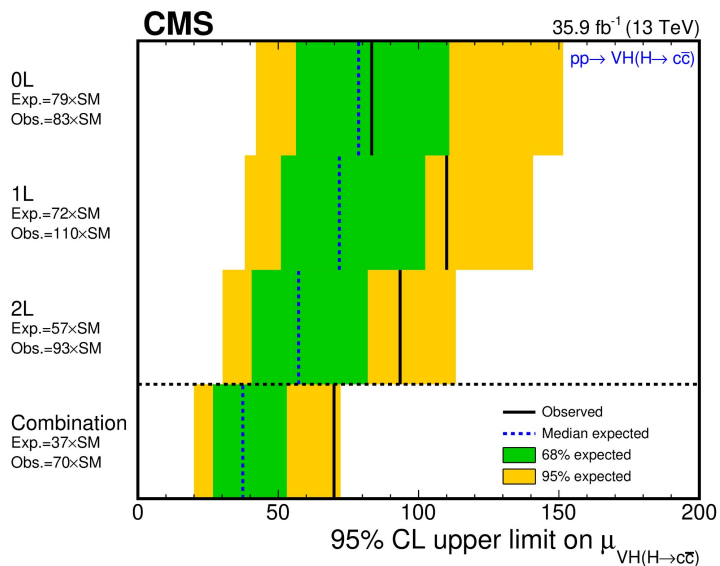


Results: evidence of H → μμ

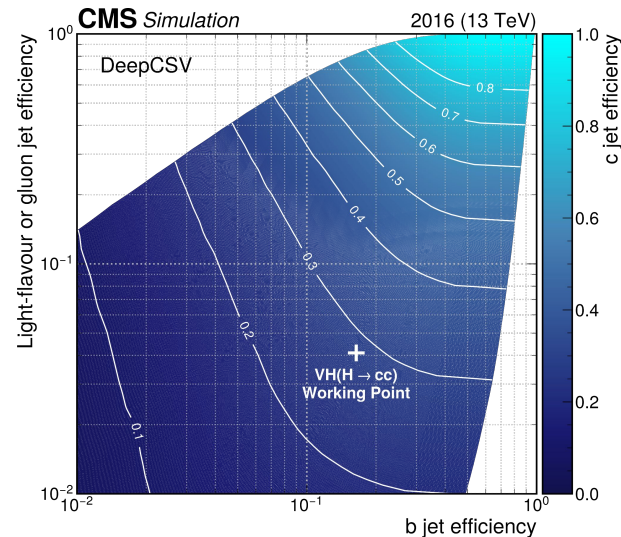
- p-value: 3.0σ (2.5σ exp.)
- μ = 1.19 ± 0.40 (stat) ± 0.15 (syst) → statistically limited
- No deviation from SM observed



- Most sensitive probe of H couplings to 2nd generation quarks
- VH (H → cc):
 - Heavily relying on charm-tagging [\[JINST 13 \(2018\) P05011\]](#)
 - Highly contaminated with hadronic backgrounds
 - VH production mode provides clean event signature (triggering and QCD suppression)



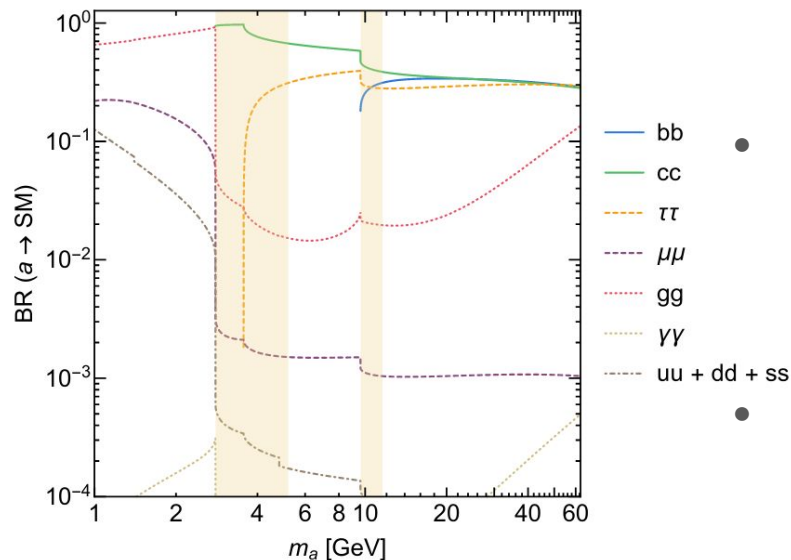
[\[JHEP 03 \(2020\) 1311\]](#)



- **Analysis strategy:**
 - 3 decay channels: 0-lepton, 1-lepton, 2 lepton
 - 2 Higgs decay topologies:
 - 2 resolved jets: Signal extraction from BDT
 - 1 merged jet: Signal extraction from Higgs candidate mass, using additional kinematic BDT selection
- **Results with 2016 data:**
 - 70(37)xSM observed (expected)
 - Expect improvement with full Run 2 analysis

- Higgs decay to BSM particles is possible from Run2 results:
 - $B_{\text{BSM}} \lesssim 35\%$ (95% CL intervals)
 - Given the small $\Gamma_H = 4.1$ MeV, even small couplings with BSM particles, $\sim O(10^{-2})$, yield $\text{Br}(h \rightarrow \text{BSM}) = 10\%$

Type IV, $\tan \beta = 0.5$

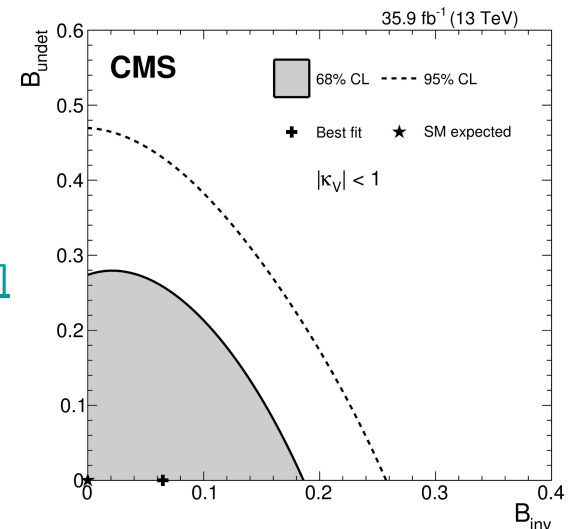


[[Eur. Phys. J. C 79 \(2019\) 421](#)]

- Many possible BSM models:
 - 2HDM+S: $H \rightarrow aa$
 - SUSY and Composite Higgs: LFV H decays
 - Higgs Portal: $H \rightarrow \text{invisible}$

- Many Higgs decay modes were tested with CMS data:
 - $H \rightarrow aa \rightarrow bbbb, H \rightarrow aa \rightarrow \mu\mu bb, H \rightarrow aa \rightarrow bb\tau\tau, H \rightarrow aa \rightarrow \tau\tau\tau\tau, H \rightarrow aa \rightarrow \mu\mu\tau\tau, H \rightarrow aa \rightarrow \mu\mu\mu\mu$
 - $H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$ (full Run2 data)
 - $H \rightarrow \mu\tau/e\tau$ (full Run2 data)
 - $H \rightarrow \text{invisible}$: Jets+MET (2017-2018 data)

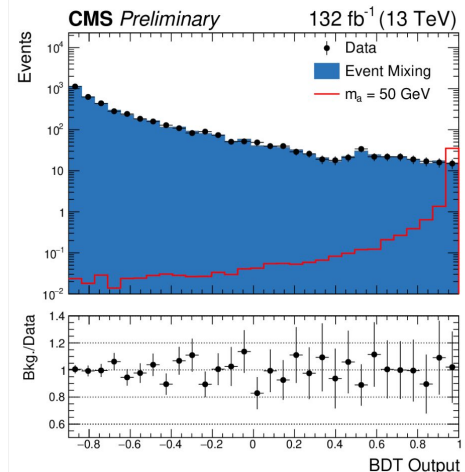
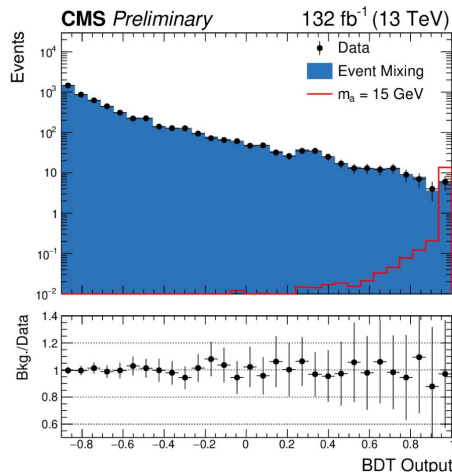
[[Phys. Rev. D 90, 075004 \(2014\)](#)]



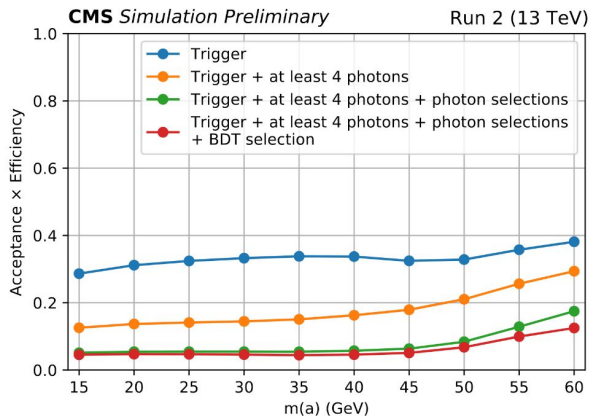
H \rightarrow aa \rightarrow YYY



- First search of this type for CMS
 - ATLAS Run1: [\[EPJC 76 \(2016\) 210\]](#)
- Model independent analysis with 4 fully resolved γ 's, $m_a \in [15, 60]$ GeV
 - photon pairs have wide opening angle
 - photons reconstructed separately
- In theoretical models:
 - Coupling of 'a' to fermions can lower BR($a \rightarrow \gamma\gamma$)
 - Low background in 4γ 's



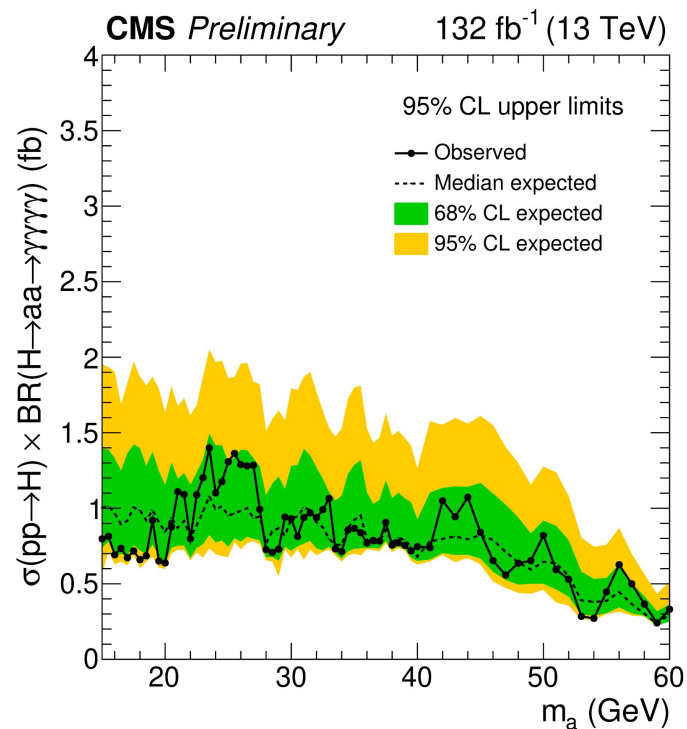
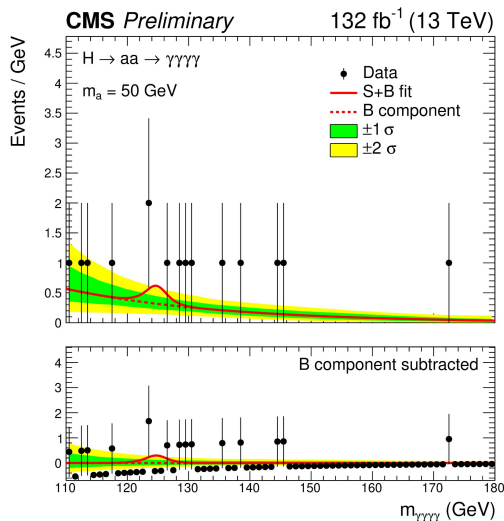
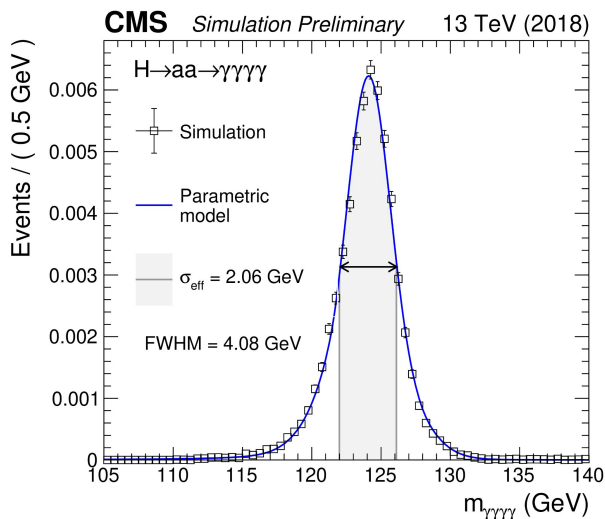
[\[CMS-PAS-HIG-21-003\]](#)



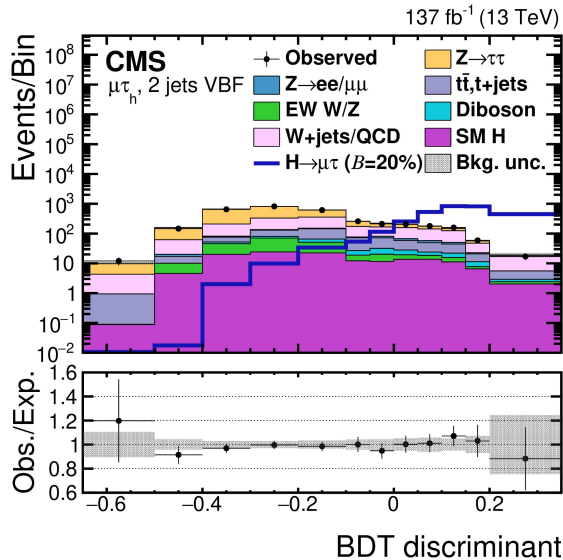
- Categorization BDT, after base selections on 4γ 's:
 - Exploits the identification and kinematic information of γ and 'a'
 - Data driven description of background obtained by mixing photons between events (only used for training)
 - Parametric training: output uniform and sensitive to full m_a range
- BDT selection:
 - Optimized by maximizing s/\sqrt{B} for all the possible categories
 - For each m_a only the best category is chosen

H → aa → γγγγ

- **Signal model:**
 - Built from MC for each nominal m_a
 - Modelled using double sided crystal ball function
- **Background model:**
 - Built from selected data (3 years merged) for each nominal m_a
 - Modelled using Envelope method



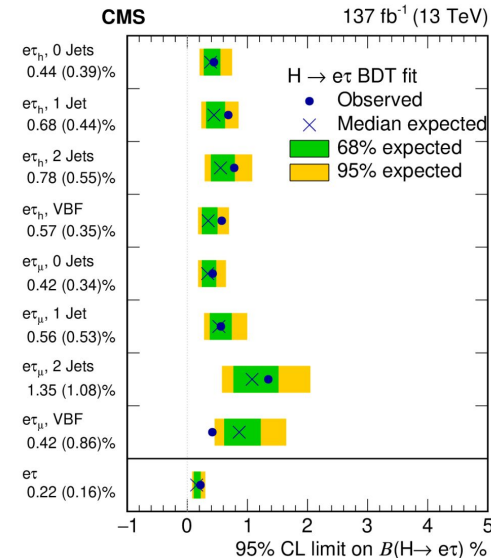
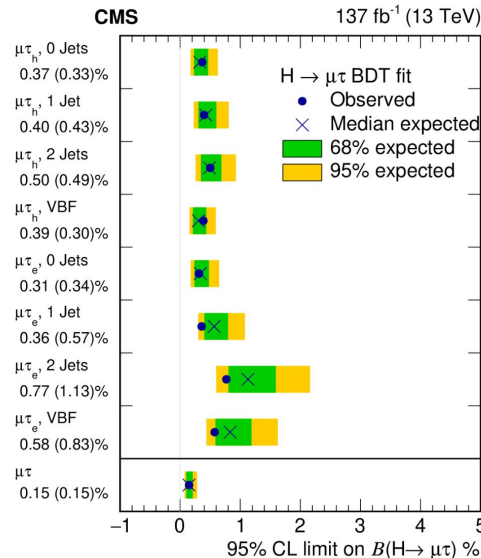
- **Results:**
No excess and observed limits are in agreement with the expected limits



- **Lepton Flavor Violation (LFV):**
 - $Y_{e\mu}, Y_{\mu\tau}, Y_{e\tau}$ Yukawa couplings in SUSY and Composite Higgs models
 - From electron and muon magnetic moments: $B(H \rightarrow \mu\tau) \approx 10\%$ and $B(H \rightarrow e\tau) \approx 10\%$
- **Results with full Run2:** No deviation from SM
 $B(H \rightarrow \mu\tau) < 0.15\%$ and $B(H \rightarrow e\tau) < 0.22\%$

- **Analysis strategy:**
 - Decay channels: $\mu\tau_h, \mu\tau_e, e\tau_h,$ and $e\tau_\mu$
 - Categories: 0 jets, 1 jet, 2 jets ggH and 2 jets VBF (m_{jj} discriminant)
 - Backgrounds estimated from data and simulation
 - A BDT is trained for each final state and category and fit BDT distributions

[[Phys. Rev. D 104 \(2021\) 032013](#)]



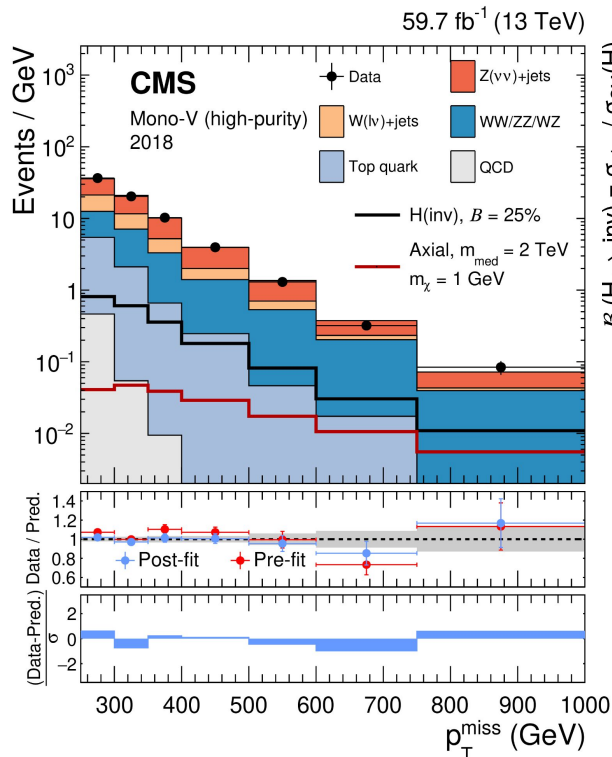
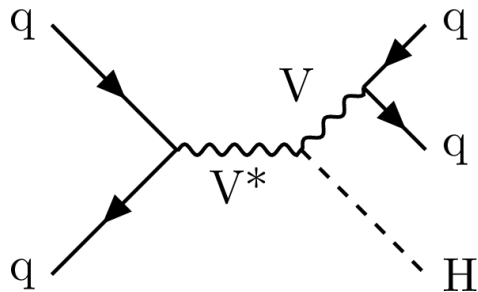
Jets+MET in $H \rightarrow \text{inv}$

Higgs portal scenario:

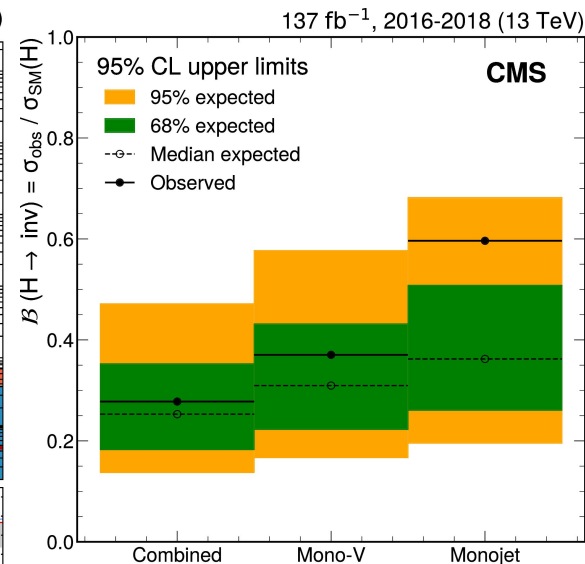
- DM particles are produced in decays of the Higgs
- From other measurements: $B(H \rightarrow \text{inv}) < 25\%$

Analysis strategy:

- Channel: $V \rightarrow qq$ (boosted regime)
- Categories: Low purity and high purity (on DEEPAK8 score) Mono-V and Mono-Jet (AK4 jets)
- Simultaneous fit of MET distribution in data/MC SR and CRs

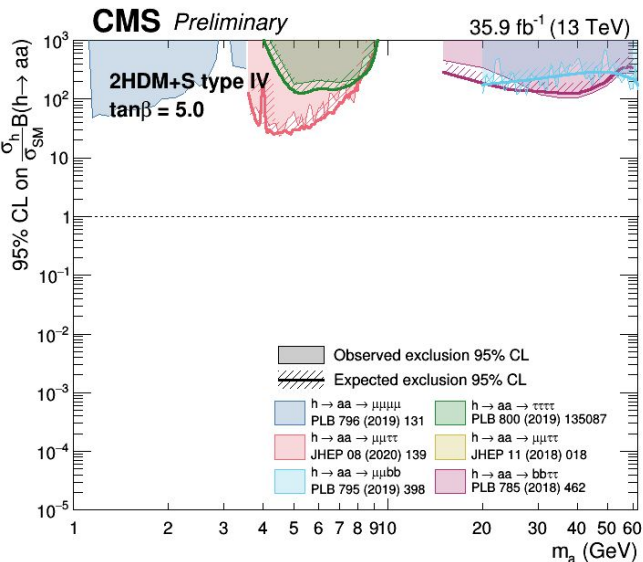
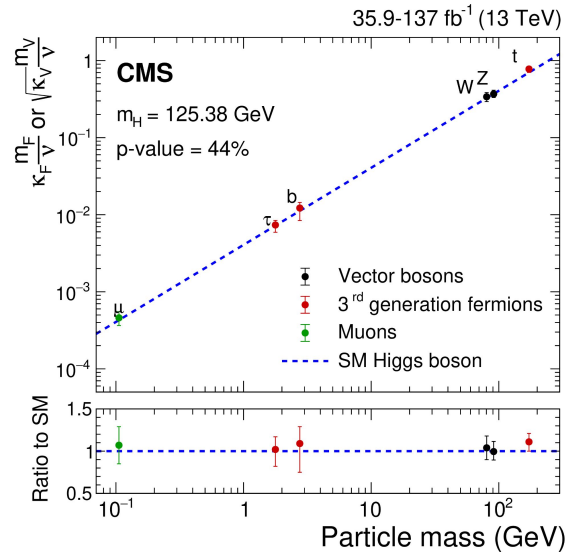


[CMS-EXO-20-004]



- Results: $B(H \rightarrow \text{inv}) < 27.8\%$

- The Higgs boson has been observed decaying to W,Z, photons, b and τ
- New physics can be probed from SM deviations:
 - In rare decays measurements: $H \rightarrow \mu\mu$, $H \rightarrow c\bar{c}$
 - First evidence of $H \rightarrow \mu\mu$
 - No deviation from SM was found

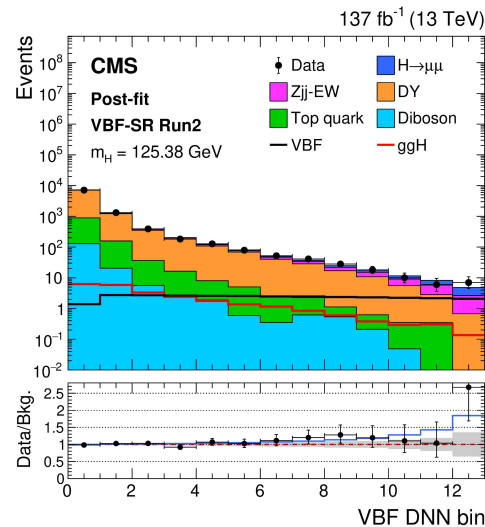
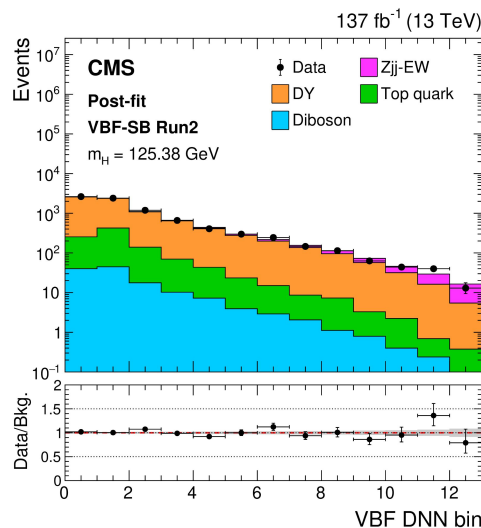
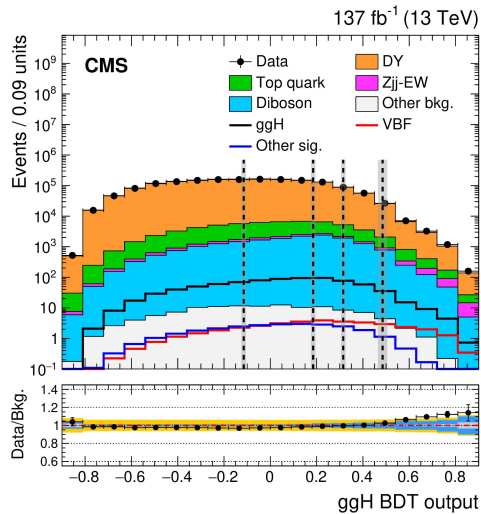


- In BSM H decays:
 - 2HDM+S : $H \rightarrow a\bar{a}$ in many final states
 - SUSY and Composite Higgs: LFV H decays
 - Higgs Portal: $H \rightarrow$ invisible
 - No significant deviation or excess has been found, many scenarios were excluded, but some phase spaces are still uncovered
- Further improvements will be obtained with full Run2 data analyses, Run3 data, and finally with HL-LHC data

BACKUP

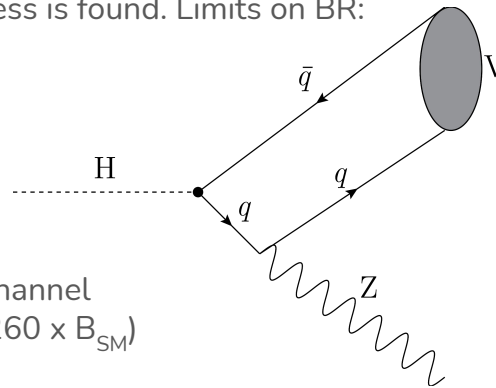
H → μμ: Analysis strategy

- The search is divided by the production modes, for which multivariate discriminators are trained:
 - **Leptonic (Hadronic) ttH**: ≥1 b jets, 1 (2) add. leptons (dominated by tt and ttZ backgrounds)
 - **VBF**: no b jets, no additional leptons, VBF selection
 - **WH (ZH)**: no b jets, 1 (2) additional leptons (dominated by WZ/ZZ background)
 - **ggH**: no b jets, no additional leptons, VBF veto (dominated by DY background)



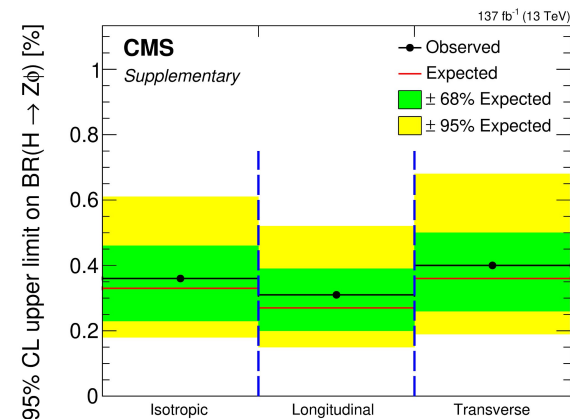
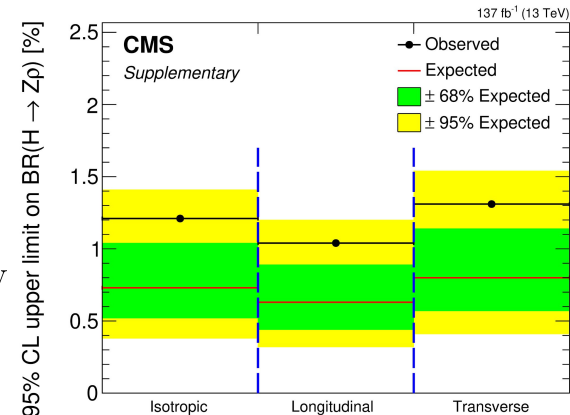
- Categories with different signal purity chosen from MVA discriminator scores:
 - Signal extracted from MC simulation
 - Background categories estimated from data (non-VBF categories)
- Simulation-based analysis in VBF category:
 - background estimated using MC templates
 - +20% improvement in expected sensitivity

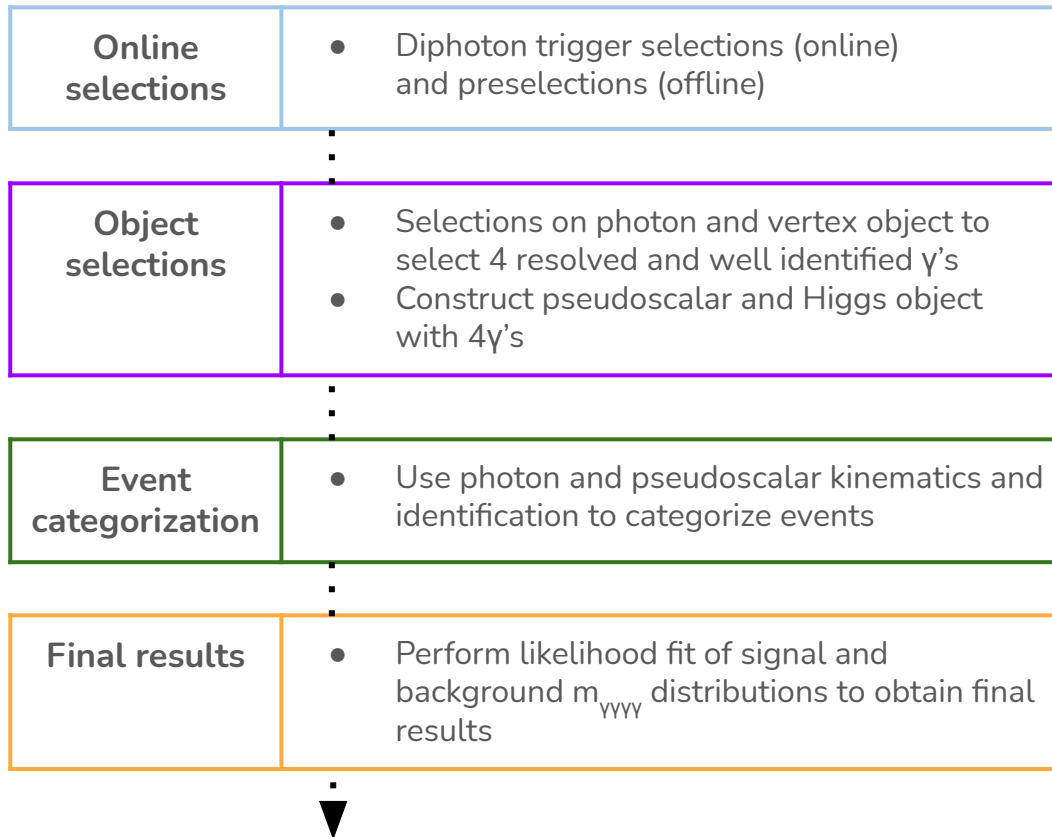
- H → Z ρ/φ:** [\[JHEP 11 \(2020\) 039\]](#)
 - $B(H \rightarrow Z\rho) = (1.4 \pm 0.1) \times 10^{-5}$ and $B(H \rightarrow Z\phi) = (4.2 \pm 0.3) \times 10^{-6}$
 - $Z \rightarrow ee/\mu\mu$, $\rho \rightarrow \pi\pi$ and $\phi \rightarrow KK$ decay channels
 - 2HDM with SFV predicts enhancement of the Yukawa coupling up to 30, 500, and 2000 for s, d, and u quarks
 - Analysis performed on Run2 data and no excess is found. Limits on BR:
 - $B(H \rightarrow Z\rho)$: $740\text{-}940 \times B_{SM}$
 - $B(H \rightarrow Z\phi)$: $730\text{-}950 \times B_{SM}$

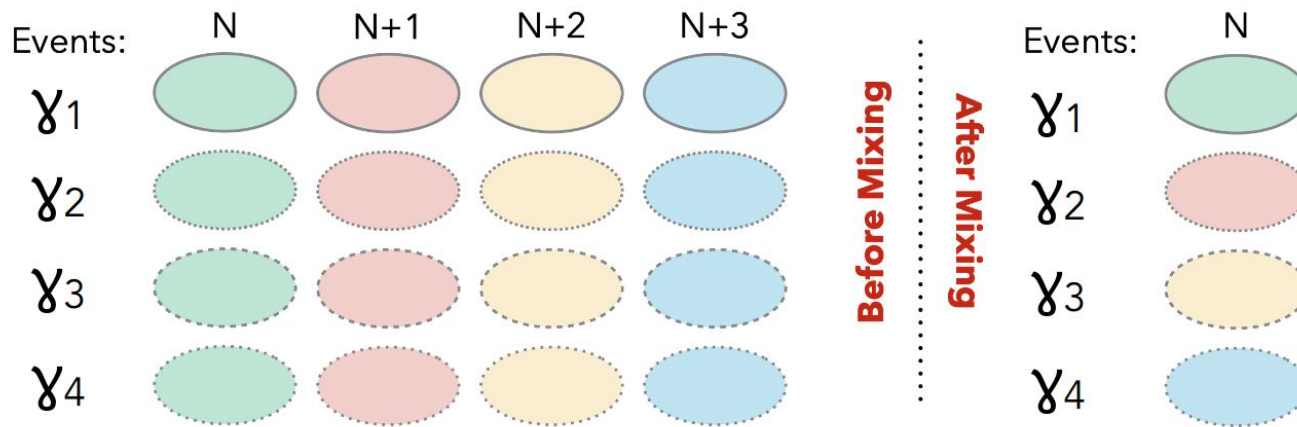


- H → J/ψ γ → μμγ:** [\[Eur. Phys. J. C 79 \(2019\)94\]](#)
 - $B_{SM}(H \rightarrow J/\psi\gamma) = (3.0 \pm 0.2) \times 10^{-6}$
 - Analysis performed on 2016 data, $J/\psi \rightarrow \mu\mu$ channel
 - Obtained 95% CL upper limit: $BR < 7.6 \times 10^{-4}$ ($260 \times B_{SM}$)

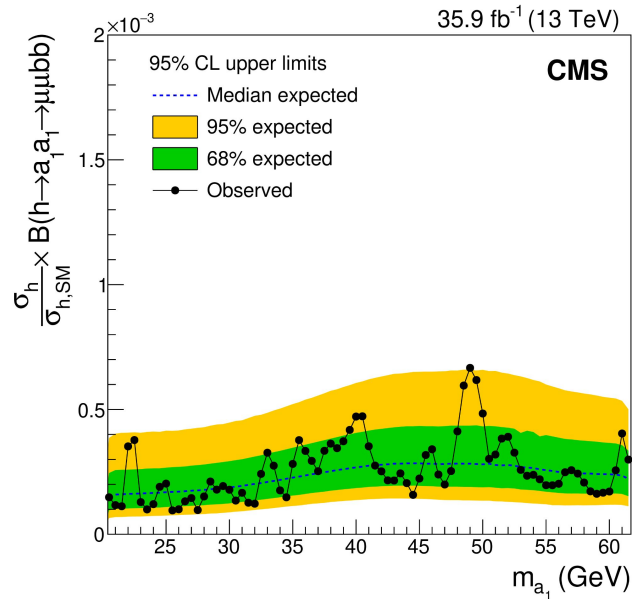
- H → ℓ ℓ γ:** [\[JHEP 11 \(2018\) 152\]](#)
 - Search performed in two channels:
 - $H \rightarrow \gamma^*(\mu\mu)\gamma$ ($m_{\mu\mu} < 50$ GeV) [$BR_{SM} = 3.8 \times 10^{-5}$]
 - $H \rightarrow Z(\ell\ell)\gamma$ ($m_{\mu\mu} > 50$ GeV) [$BR_{SM} = 5.1 \times 10^{-5}$]
 - 95% CL upper limit: $\mu < 3.9$ ($\mu < 2.0$ exp.)



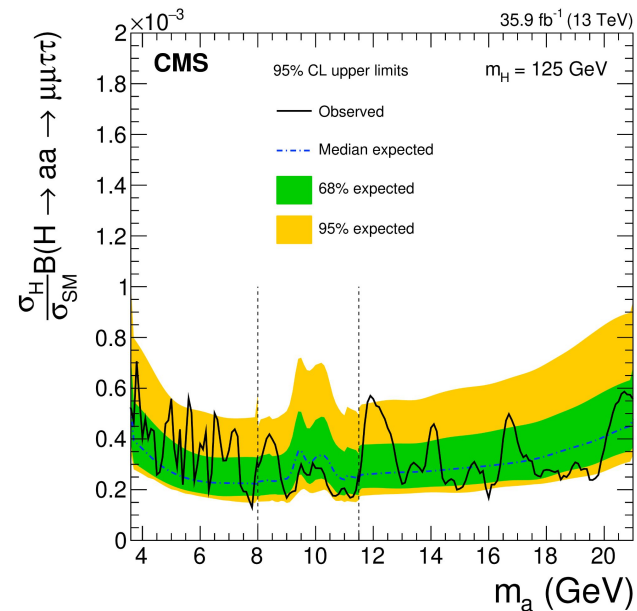
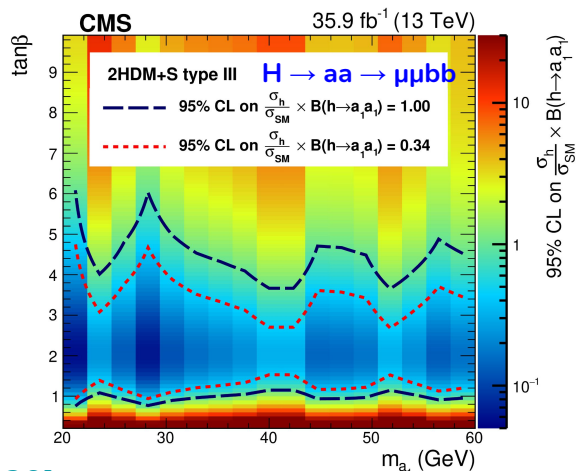




- Artificially create background shape by shuffling photons between events
- Idea: after full event selection, replace 3 of the 4 selected photons by photons in other events
- The procedure can be repeated multiple times: covers full phase space of the background
- Results in good description of background shape



- **H → aa → μμbb:** [\[PLB 795 \(2019\) 398\]](#)
 - Uses double muon trigger paths, and a → bb has a large BR
 - Exclusive categorization based on the b-tagging to improve sensitivity
 - Background modelled on data via the envelope method
 - No excess and observed limits are in agreement with the expected limits



- **H → aa → μμττ:** [\[JHEP 08 \(2020\) 139\]](#)
 - Boosted regime $m_a \in [3.6, 21]$ GeV as BR(a → ττ) dominates if $m_a < 2m_b$
 - Background modelled on data, taking into account J/Ψ, Ψ' and Y resonances for $m_{\mu\mu}$
 - No excess and observed limits are in agreement with the expected limits

2HDM+S: $H \rightarrow aa$

