Search for Higgs boson decays to a pair of pseudoscalars in CMS

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Higgs Hunting 2023: 13th workshop of the Higgs Hunting series
Orsay-Paris, France
12 September 2023

Introduction

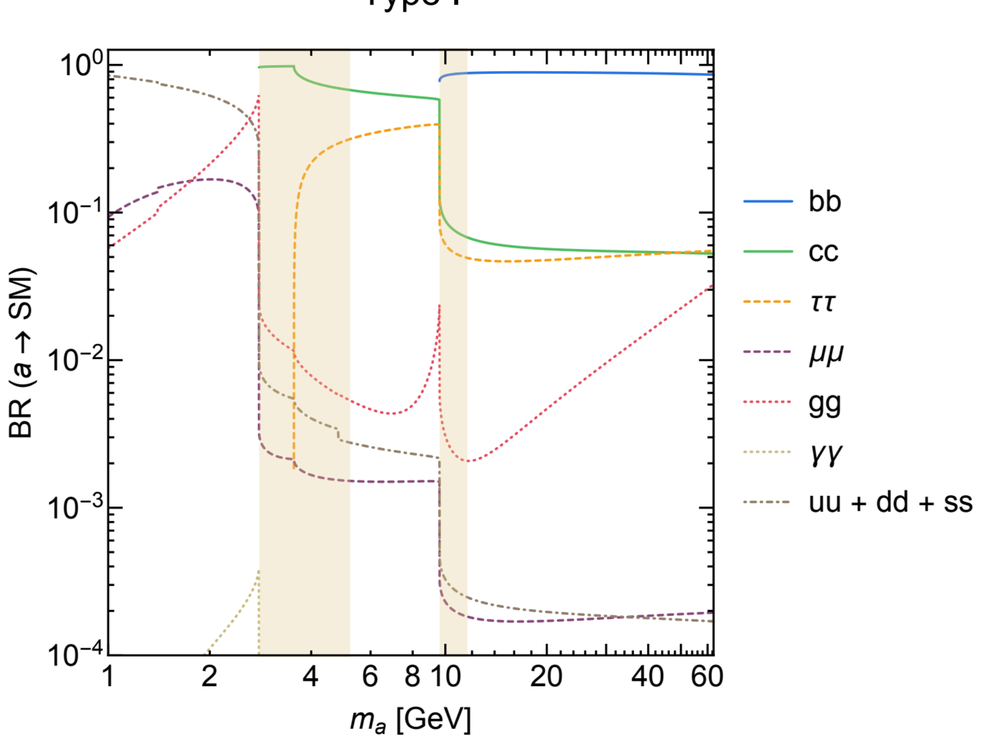
Direct searches for exotic Higgs decays to light states are an exciting potential window into BSM physics

2HDM+S (2 Higgs doublets models extended with one scalar) supports a large variety of Higgs decay phenomenologies:

- e.g. $H \to aa \to X\bar{X}Y\bar{Y}$ (pseudoscalar a, and X, Y are SM fermions and gauge bosons)
- Currently searching for four types of 2HDM+S that prevent large flavour-changing neutral currents
- The branching ratios $B(H \to aa \to X\bar{X}Y\bar{Y})$ depend on:
  - the model type (type I, II, III, or IV)
  - m_a (mass of the pseudoscalar)
  - $\tan\beta$ (ratio of the VEVs of the two doublets)

This talk: latest full Run-2 results for Higgs decays to pairs of pseudoscalars at CMS

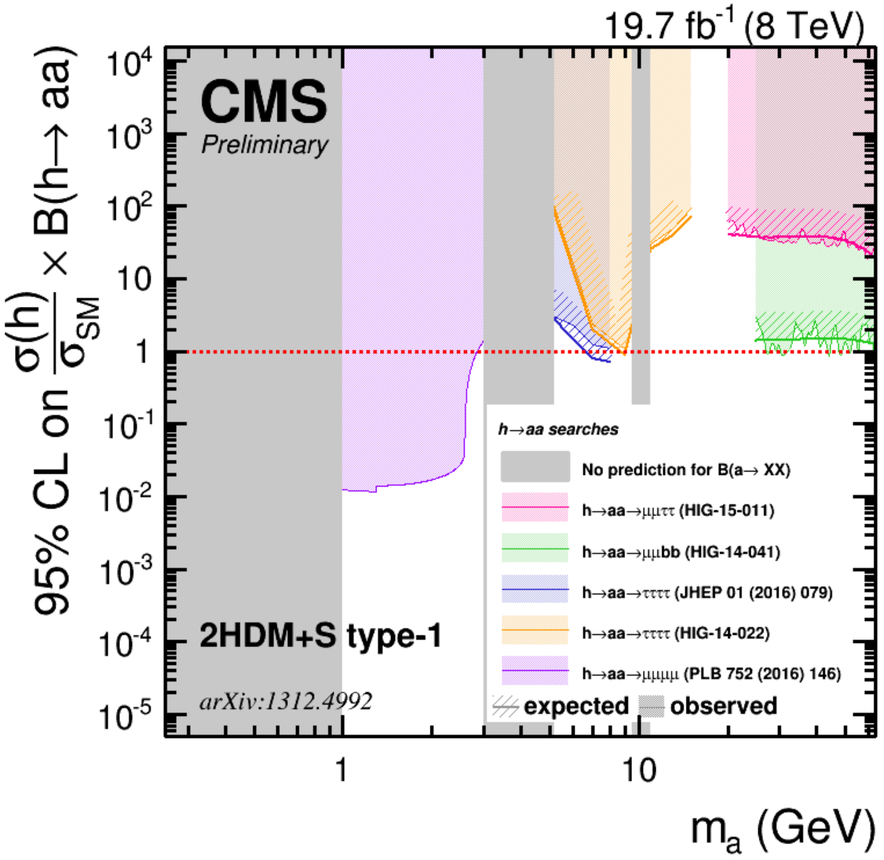
2HDM+S Type I branching ratios of the singlet-like pseudoscalar $B(a \to \text{SM})$



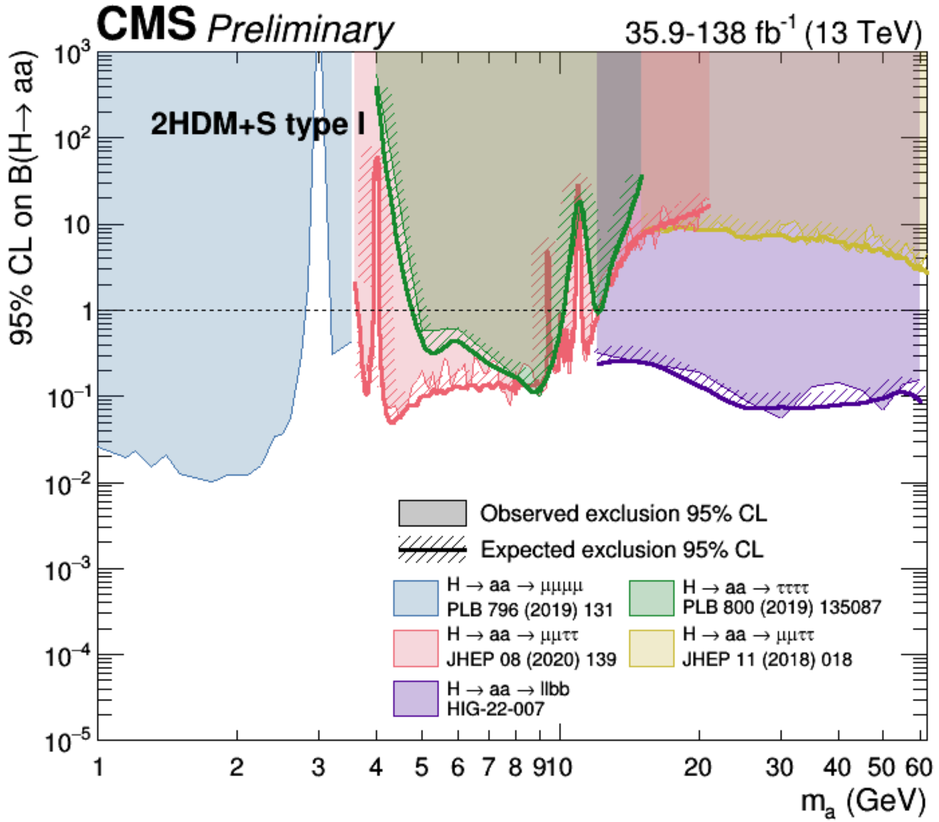
https://arxiv.org/pdf/1312.4992.pdf

Run-1 and Run-2 $H \to aa$ results at CMS

Run-1 (Type I 2HDM+S)



Run-2 (Type I 2HDM+S)



Full summary plots: https://twiki.cern.ch/twiki/bin/view/CMSPublic/Summary2HDMSRun2

From Run-1 to Run-2, large improvement in limits on $B(H \to aa)$

- e.g. almost x10 improvement in 2HDM+S Type I limits, for $m_a \in (5, 62)$ GeV
- Limits have improved from not just larger integrated luminosity, but also improved analysis techniques

Direct searches for $H \to aa$ at CMS

Final states searched for in Run-1, with Run-2 analyses ongoing:

$H \to aa \to 4\tau$ (JHEP 01 (2016) 079)

$H \to aa \to 4\mu$ (Phys. Lett. B 796 (2019) 131)

$H \to aa \to 2\tau 2\mu$: boosted (JHEP 08 (2020) 139)

resolved (JHEP 11 (2018) 018)

Final states with full Run-2 results- focus of this talk:

$H \to aa \to 4\gamma$: boosted (Phys. Rev. Lett. 131 (2023))

resolved (JHEP 07 (2023) 148)

$H \to aa \to 2b2\mu$

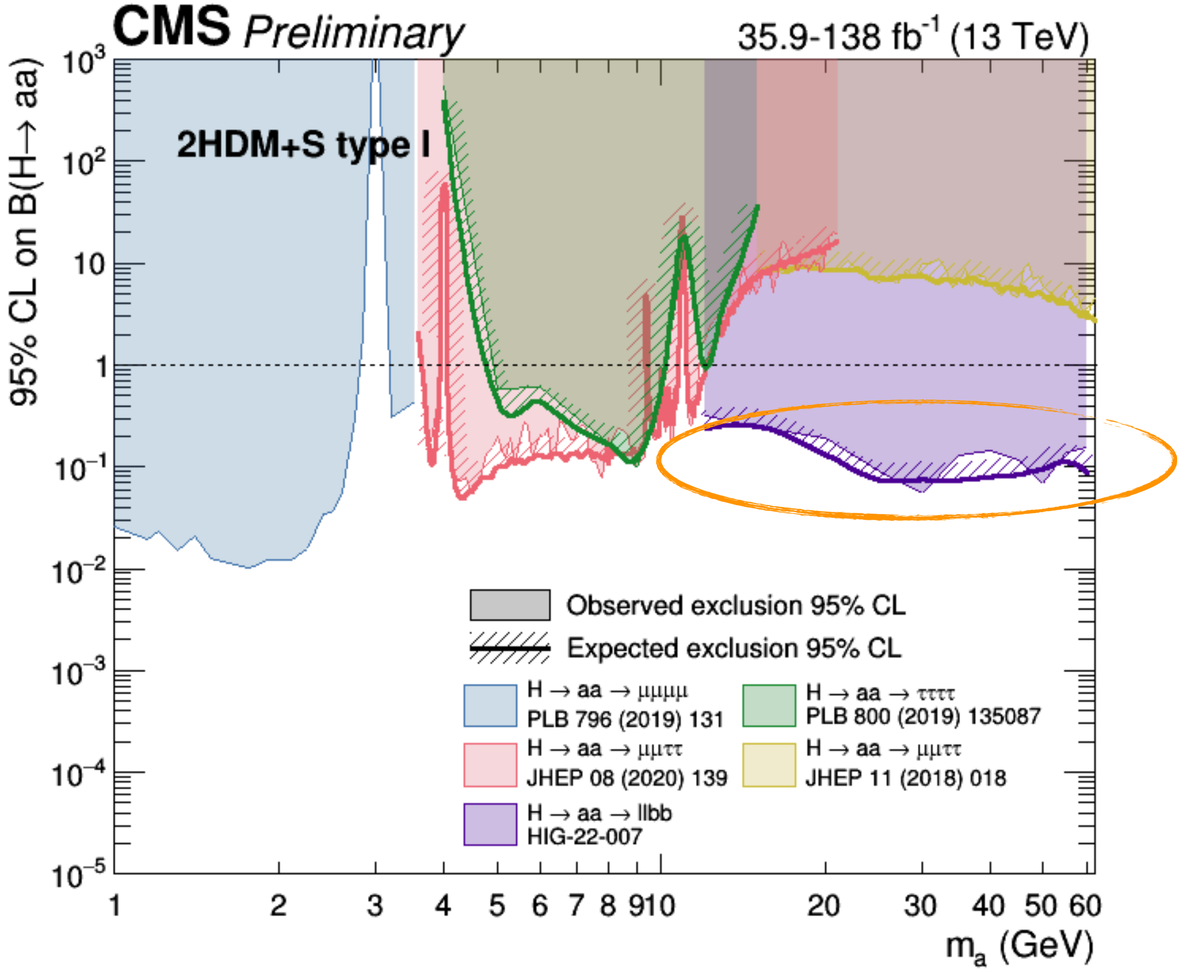
$H \to aa \to 2b2\tau$

} combined final states with improved limits:

$H \to aa \to llbb$

(PAS-HIG-22-007)

2HDM+S Type I: Current summary plot



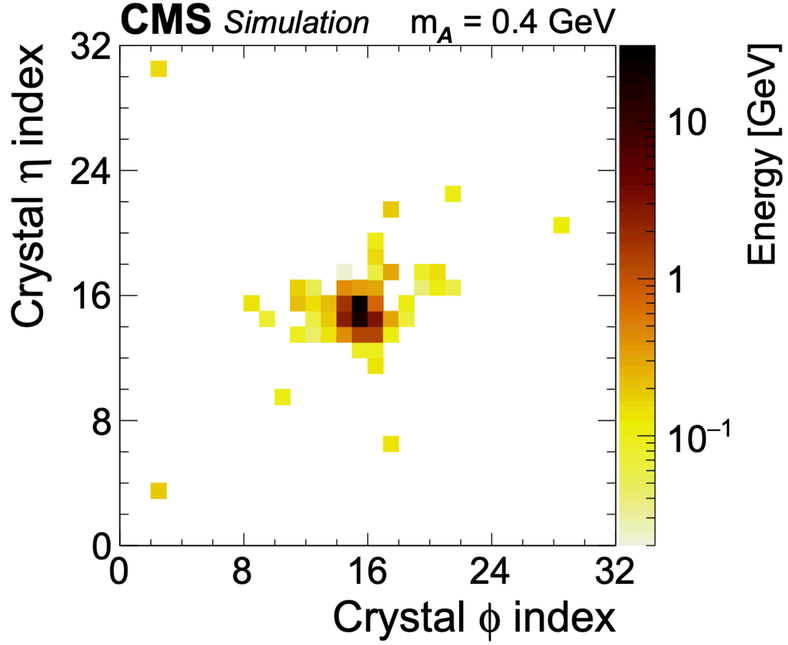
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Summary2HDMSRun2

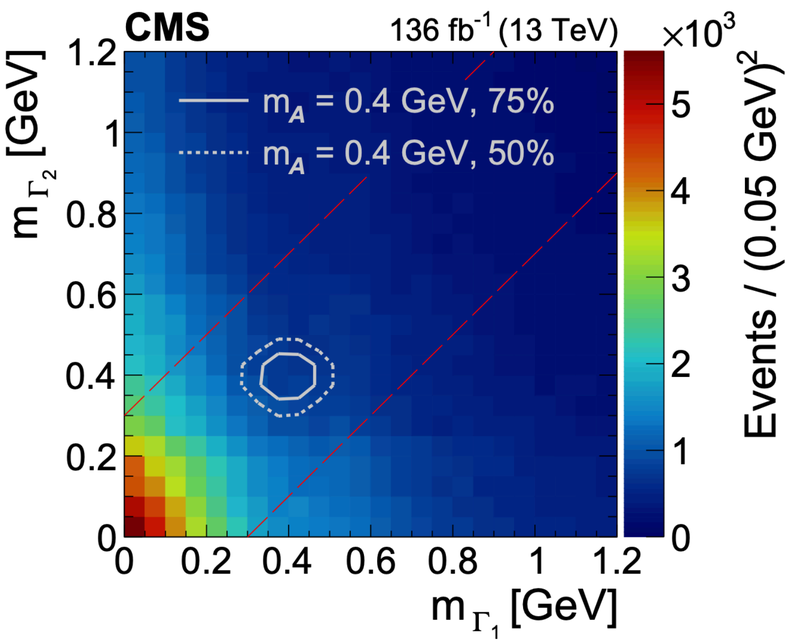
$H \to aa \to 4\gamma$ (boosted) (Phys. Rev. Lett. 131 (2023))

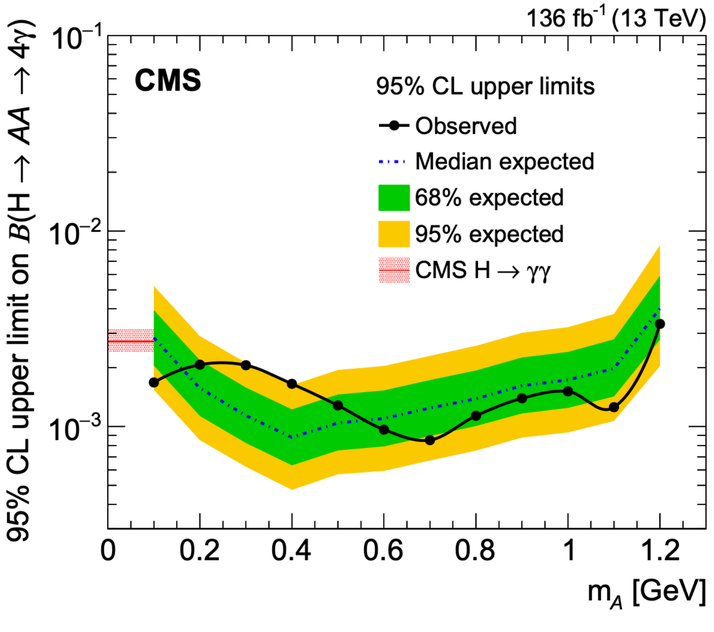
Search for very low pseudoscalar masses $m_a \in (0.1, 1.2)$ GeV, with boosted diphotons (first search in this topology!)

- Diphoton decays are reconstructed as two photon-like objects labeled $\Gamma_{1,2}$
- Novel end-to-end deep learning method for reconstructing highly boosted photons
- Final 2D fit to distribution of invariant masses $m_{\Gamma 1}$ and $m_{\Gamma 2}$;
- Upper limit on $B(H \to aa \to 4\gamma)$: $(0.9 - 3.3) \times 10^{-3}$ at 95% CL, for $m_a \in (0.1, 1.2)$ GeV, assuming SM Higgs production

Current best constraints in this pseudoscalar mass range





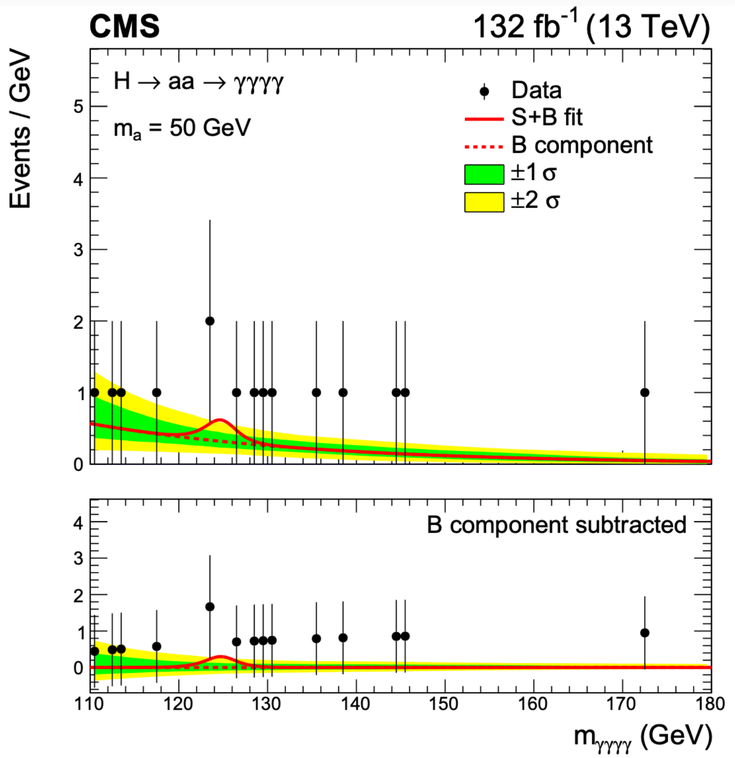


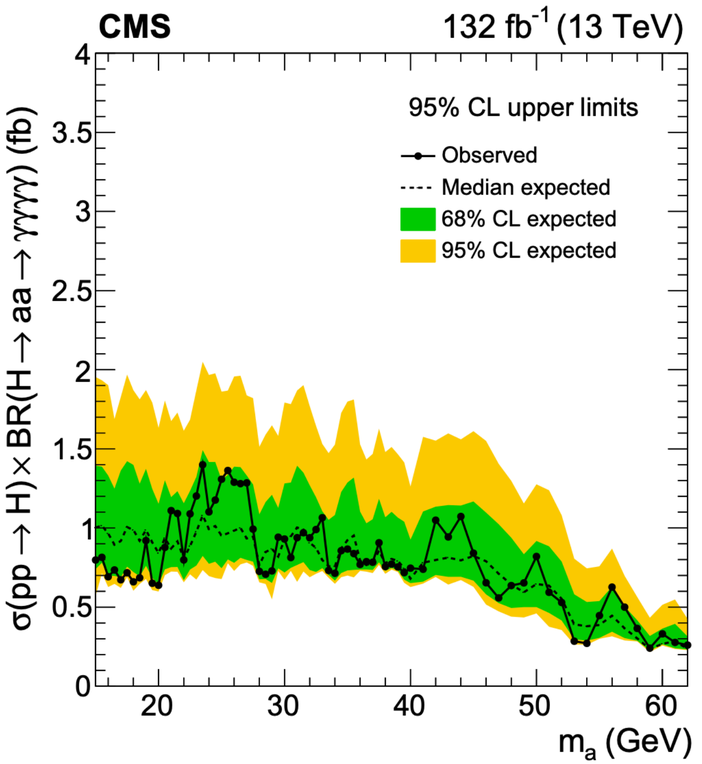
$H \to aa \to 4\gamma$ (resolved) (JHEP 2307 (2023) 148)

Search for pseudoscalar masses $m_a \in (15, 62)$ GeV, with four well-isolated photons

- Primary interaction vertex is identified with a BDT (one per year)
- Dedicated 4-photon BDT event classifier using ID and kinematic info of the photons and a candidates
- Final fit of $m_{\gamma\gamma\gamma\gamma}$ to 125 GeV resonance
- Observed limits $B(H \to aa \to 4\gamma)$: 1.5×10^{-5} at $m_a = 15$ GeV, 0.5×10^{-5} at $m_a = 62$ GeV (assuming SM Higgs production)

Low $a \to \gamma\gamma$ branching ratio (~10^{-4}), but 4γ channel has low Standard Model backgrounds and good photon reconstruction at CMS





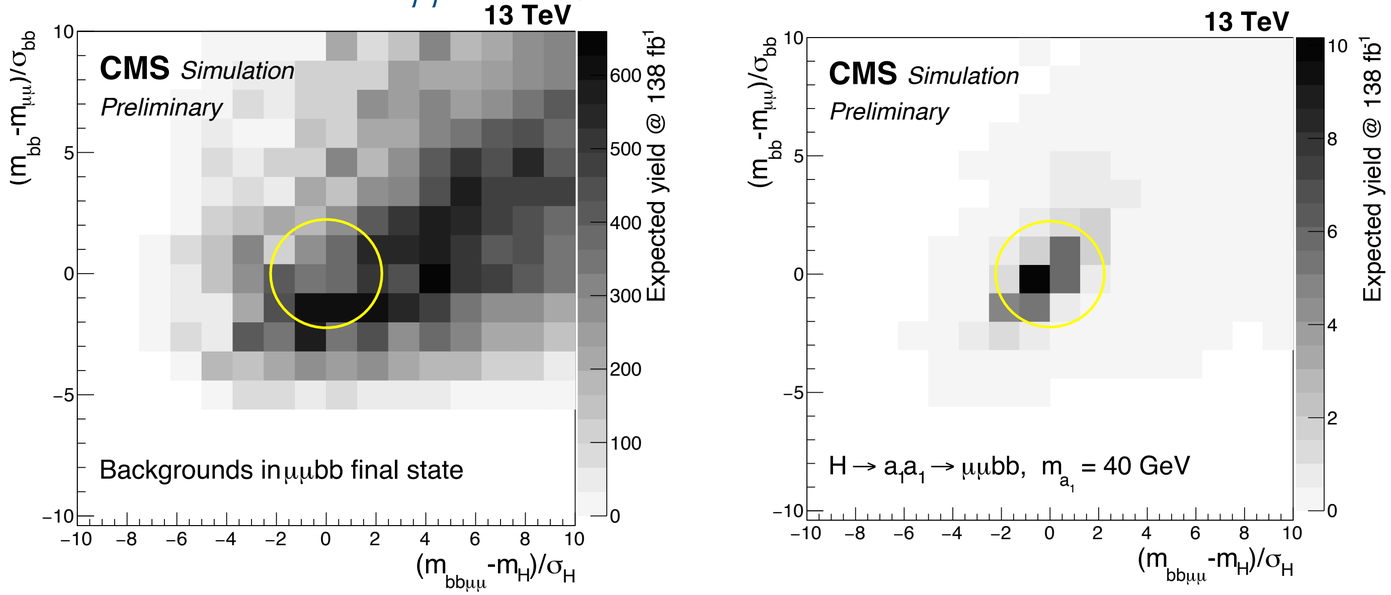
$H \to aa \to 2\mu 2b$ (CMS-PAS-HIG-22-007)

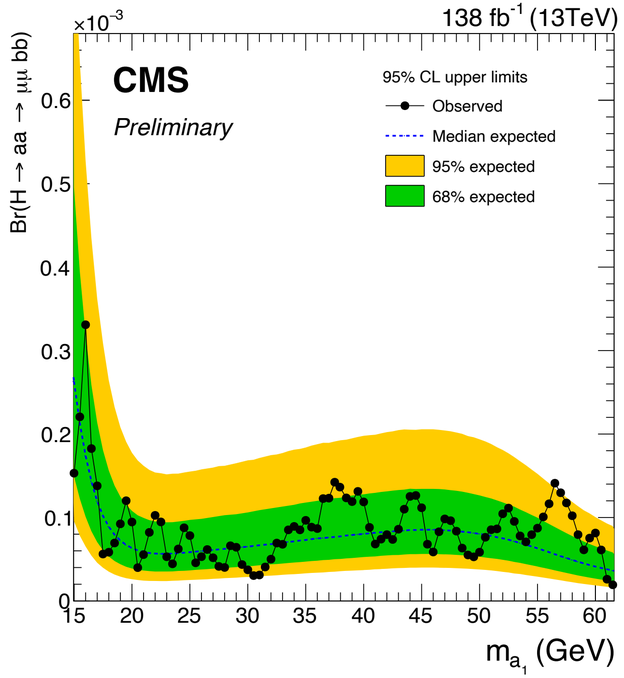
Search for $m_a \in (15, 60)$ GeV: clean signature with a precise di-muon mass resolution and large BR to bb

- Define two variables χ_{bb}, $\chi_{\mu\mu}$ to exploit $m_{\mu\mu} = m_{bb}$ and $m_{\mu\mu bb} = 125$ GeV, and de-correlate into one variable χ_d
- Cut on χ_d^2, and then further categorize events based on jet properties
- Unbinned maximum likelihood fit to $m_{\mu\mu}$, using parametric signal and background models
- Observed limit $B(H \to aa \to 2\mu 2b) < (0.17 - 3.3) \times 10^{-4}$ for this mass range

Most stringent observed upper limit to date in $2\mu 2b$ channel; slightly better than Run-2 ATLAS results

Below: distribution of $\chi_{\mu\mu}$ vs. χ_{bb} (before de-correlation) for bkg and signal



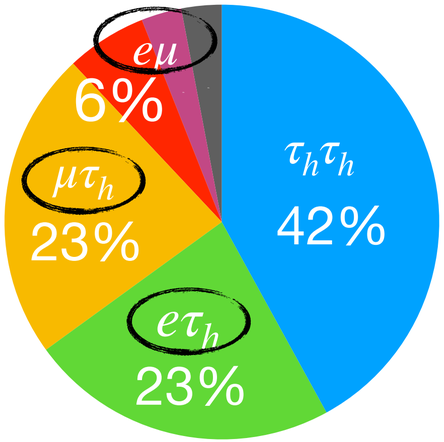


$H \to aa \to 2\tau 2b$ (CMS-PAS-HIG-22-007)

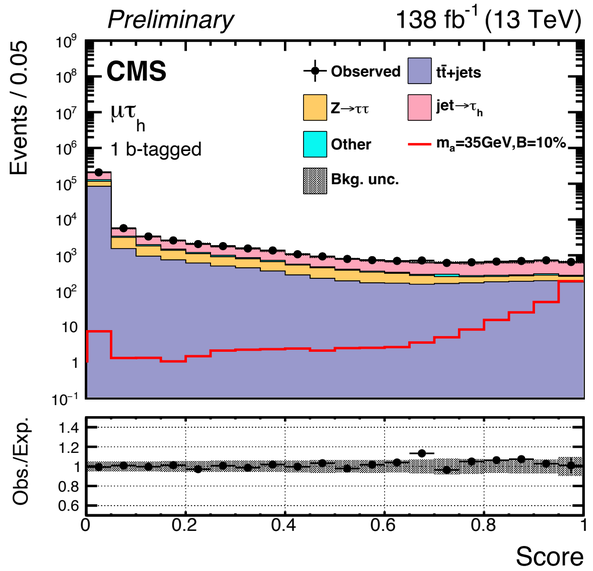
Search for $m_a \in (12, 60)$ GeV, large BR to bb and $\tau\tau$. Three $\tau\tau$ final states considered: $e\mu$, $\mu\tau_h$, $e\tau_h$

- Improved object selection: deep tau ID, deepJet b-tagging
- Full $m_{\tau\tau}$ instead of visible-only component $m_{\tau\tau}^{vis}$ (SVFit algorithm)
- $Z \to \tau\tau$ background estimation using Embedded samples (hybrid data/MC samples)
- DNN-based categorization: Events with exactly 1 b-tag jet and >1 b-tag jets are separated, and a DNN was trained for each case (three $\tau\tau$ final states * (1 or >1 b-tag jet)) = 6 distinct DNNs
- Maximum likelihood fit to $m_{\tau\tau}$

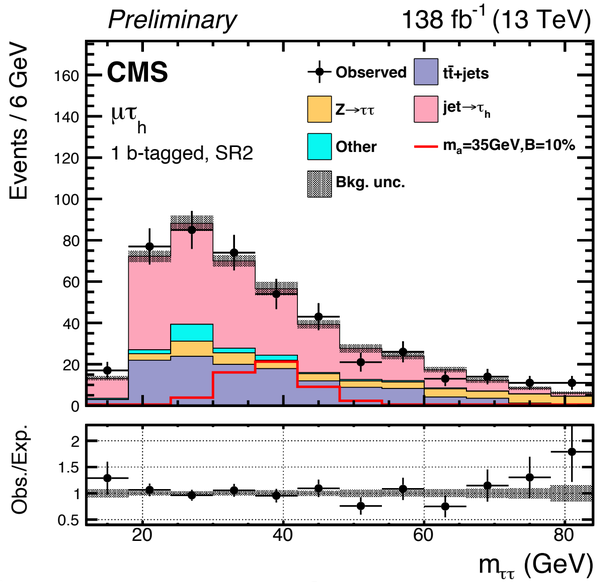
$\tau\tau$ final states

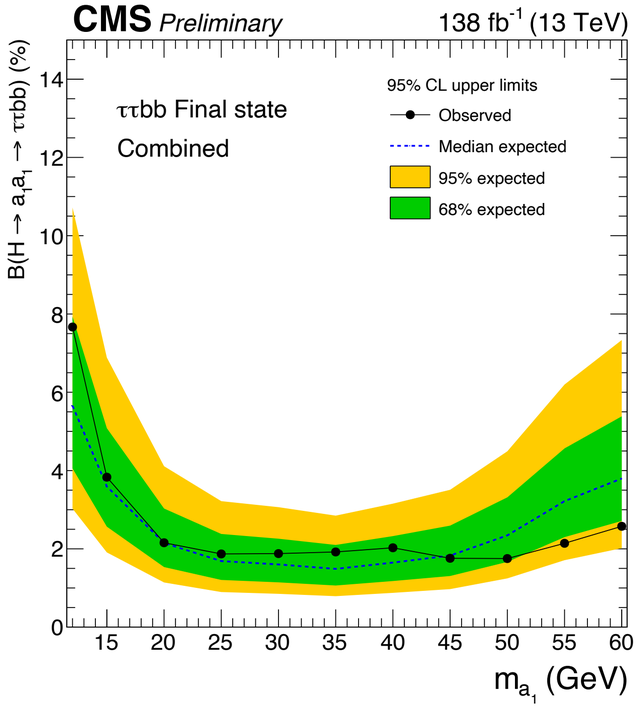


Pre-fit DNN score ($\mu\tau_h$ channel, 1 b-tag jet)



$m_{\tau\tau}$ ($\mu\tau_h$ channel, 1 b-tag, one of three signal regions)





Combination: $H \to aa \to \ell\ell bb$ (CMS-PAS-HIG-22-007)

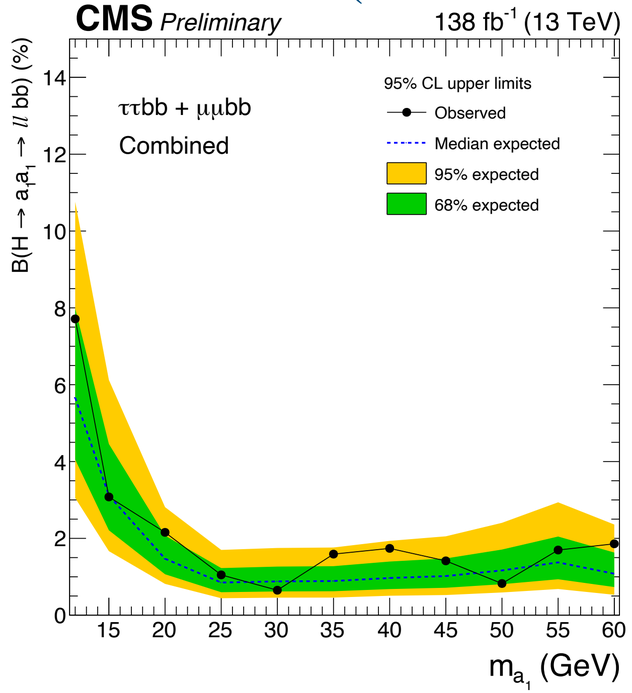
Combination of $2\mu 2b$ and $2\tau 2b$ possible since event selection is mutually exclusive

- $m_{\mu\mu}$ and $m_{\tau\tau}$ profiles are compared to data in a combined fit for $m_a \in (12, 60)$ GeV

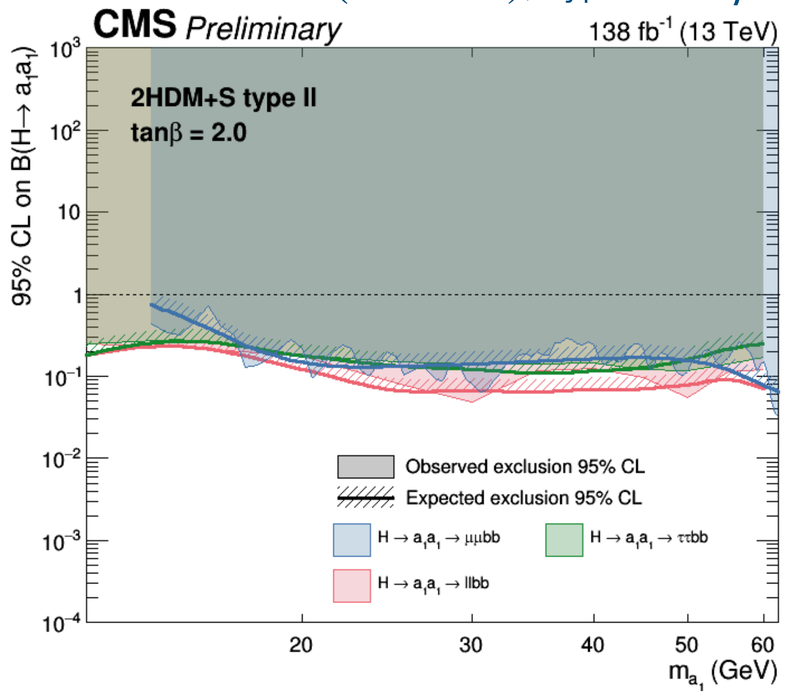
Combination yields more stringent limits on $B(H \to aa)$ and $B(H \to aa \to \ell\ell bb)$ than the individual analyses

- $B(H \to aa)$ values above 23% are excluded at 95% CL for most Type II 2HDM+S models, excluded at 7% for Type III $\tan\beta = 2.0$, and excluded at 15% for Type IV $\tan\beta = 0.5$

Combined limits on $B(H \to aa \to 2\ell 2b)$



Combined limits on $B(H \to aa)$, Type II $\tan\beta = 2.0$



Summary

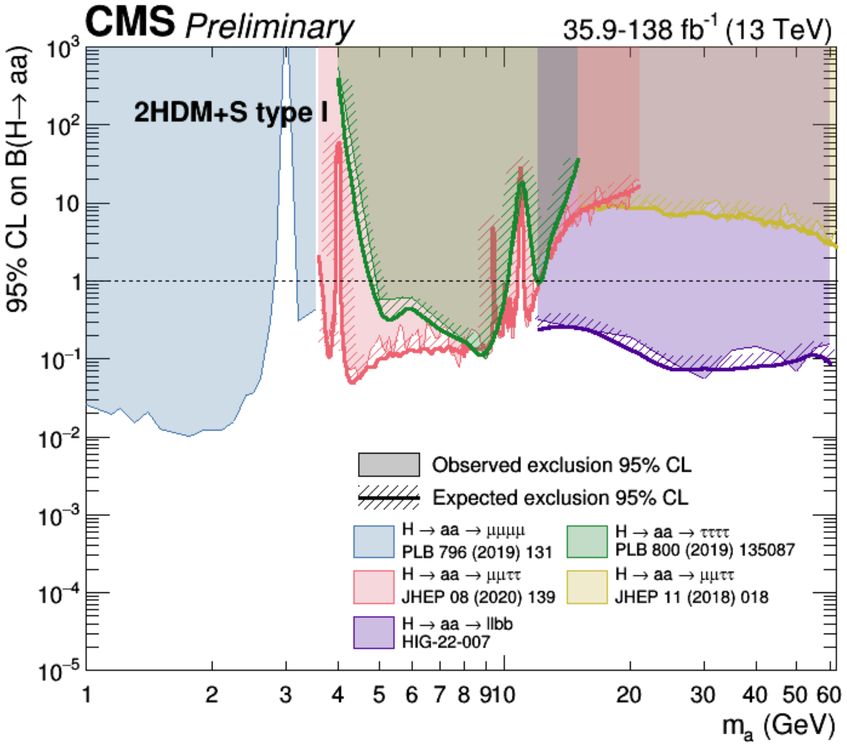
Full Run-2 results for $H \to aa \to 4\gamma$, $2\mu 2b$, and $2\tau 2b$ shown, with more to come

- Improved sensitivity from Run-1 with novel analysis techniques (ML, better modeling of signal/background, …)
- Combination of $bb\tau\tau$ and $bb\mu\mu$ yields stronger limits on BRs than the individual channels
- Direct searches benefit from increase in luminosity; exciting times ahead with ongoing Run-3

Despite no observations of significant excess over SM predictions for $H \to aa$ to date, many physics scenarios remain to be explored:

- Decays to pseudoscalars with different masses: $H \to a_1 a_2\ (m_{a_1} \neq m_{a_2})$
- Other boosted reconstructions for low pseudoscalar masses

2HDM+S Type I: Current summary plot



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Thank you for your time!