Searches for rare decays of the Higgs boson into light pseudoscalars at CMS

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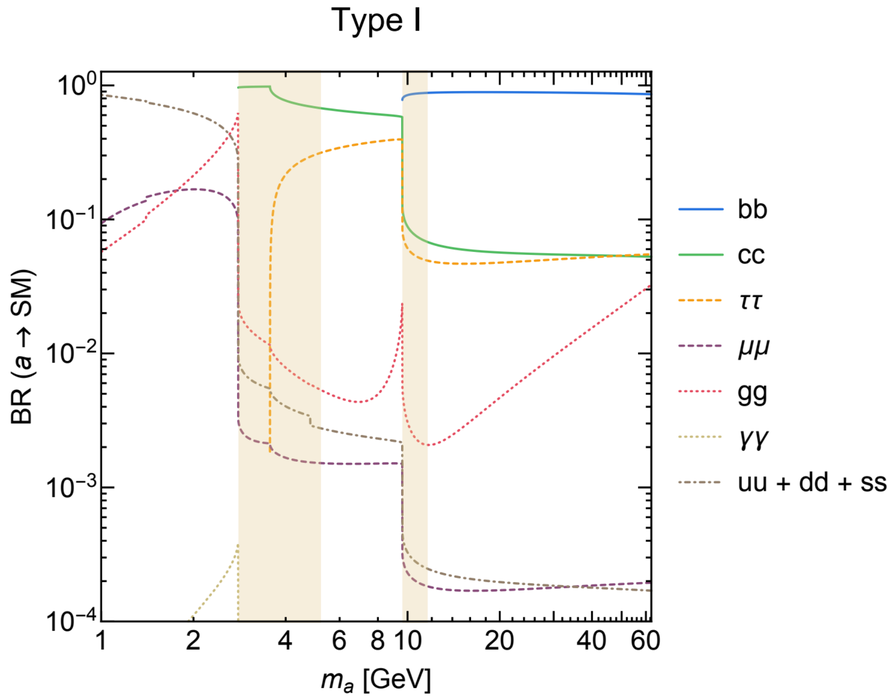
Rare Higgs decays to light pseudoscalars in beyond-SM theories

Beyond-SM theories with extended Higgs sectors may provide natural solutions to the hierarchy problem and particle candidates for dark matter: perform **direct searches for rare/exotic Higgs decays**

In 2HDM+S (2 Higgs Doublet Models extended with one scalar):

- The two Higgs doublets have vacuum expectation values (VEVs) v_1, v_2, define $\tan\beta \equiv \frac{v_2}{v_1}$
- Seven scalar and pseudoscalar particles in the Higgs sector, one of which can be identified as the 125 GeV Higgs
- Four types of 2HDM+S (Types I, II, III, and IV) forbid flavour-changing neutral currents (FCNC) at leading order

This talk: latest searches for Higgs decays to light pseudoscalars at CMS, with interpretations in 2HDM+S and other models



Predicted branching ratios of exotic decays of the pseudoscalar $B(a \to X\bar{X})$ in 2HDM+S Type I (arxiv:1312.4992)

Scope of this talk: CMS $H \to aa$ results

This talk highlights three CMS Run-2 results made public in 2024:

$H \to aa \to 4\mu$ (CMS-PAS-HIG-21-004)

- Interpretations in four benchmark models, not only 2HDM+S
- Explores new parameter space

$H \to aa \to 4b$ (HIG-18-026, JHEP 06, 097 (2024))

- Sets most stringent limits in several 2HDM+S scenarios for m_a (12, 60) GeV

$H \to aa \to 2b2\mu/2b2\tau$ (HIG-22-007, EPJ C 84, 493 (2024))

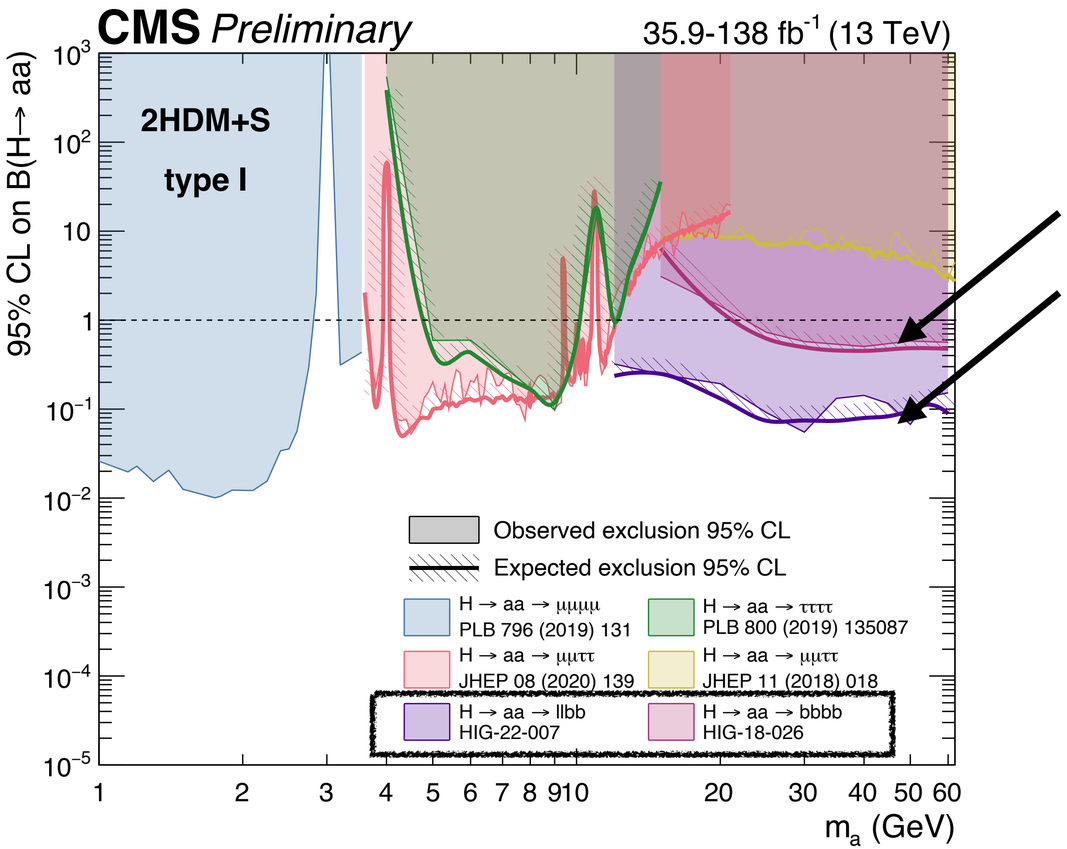
- Sets most stringent limits in several 2HDM+S scenarios for m_a (12, 60) GeV

Not discussed today, but stay tuned:

$H \to aa \to 4\tau$ (Run 1: HIG-14-019, JHEP 01, 079 (2016))

$H \to aa \to 2\mu2\tau$ boosted (2016-only: HIG-18-024, JHEP 08, 139 (2020))

$H \to aa \to 2\mu2\tau$ resolved (2016-only: HIG-17-029, JHEP 11, 018 (2018))



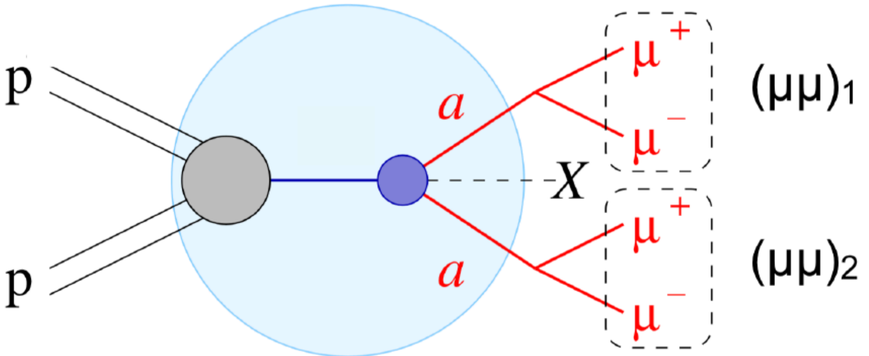
CMS summary plot: exclusion limits at 95% CL on $B(H \to aa)$ in 2HDM+S Type I

$H \to aa \to 4\mu / X \to 4\mu$: overview (CMS-PAS-HIG-21-004)

Model-independent search for new bosons decaying to four muons with full Run-2

Improvements with respect to 2016-only search:

- Increased dataset: 60-137 fb^{-1}, up from 36 fb^{-1}
- New parameter space: dimuon mass from $0.21 < m < 60$ GeV (was $0.25 < m < 8.5$ GeV), and with muon lifetimes $0 < c\tau < 100$ mm
  - Enabled by a new standalone (SA) displaced muon trigger deployed in 2018
  - SA only requires tracks in the muon system
- Two new model interpretations: axion-like particle (ALP) models and vector portal models
- Improved limits in combined 2017 and 2018 results with 2016: for MSSM + Dark sector ("MSSMD" or "Dark SUSY") and NMSSM



CMS-PAS-HIG-21-004

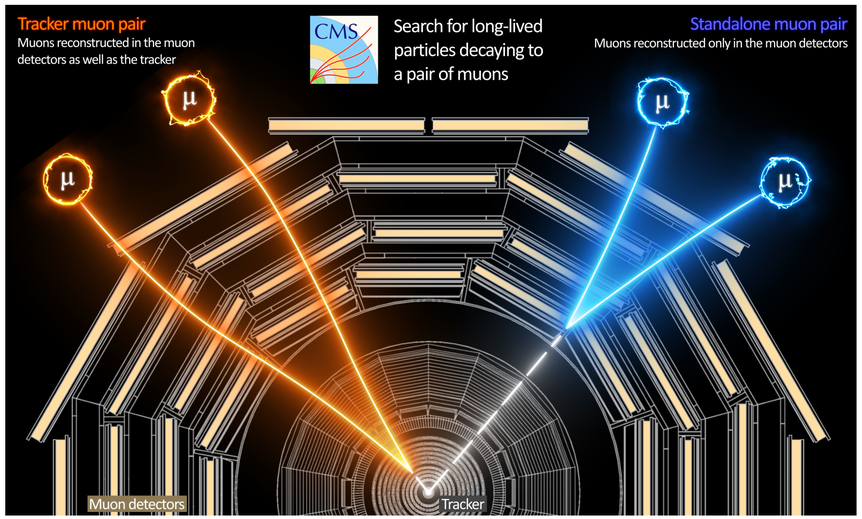


Image from CMS physics briefing

$H \to aa \to 4\mu / X \to 4\mu$ analysis strategy (CMS-PAS-HIG-21-004)

Prompt or long-lived particles decay into two dimuon pairs, each with an identical invariant mass

- Prior to 2018, select four muons from standard ParticleFlow reconstruction
- In 2018, allow up to one of the four muons to be a standalone (SA) muon selected by the displaced double muon trigger

Define signal region (SR) and control regions (CRs) in a two-dimensional plane of the two dimuon masses, m_1 and m_2

- Signal region: $|m_1 - m_2| < f\left(\frac{m_1 + m_2}{2}\right)$
- Window size $f\left(\frac{m_1 + m_2}{2}\right)$ is derived to contain 90% of signal events at each mass point

Background estimation: data-driven, divided as above or below Υ resonance

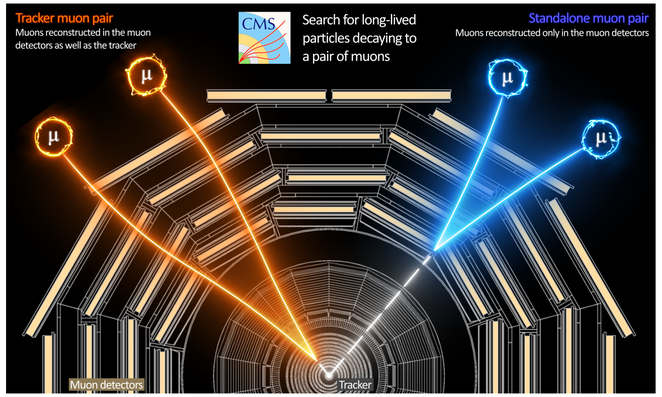
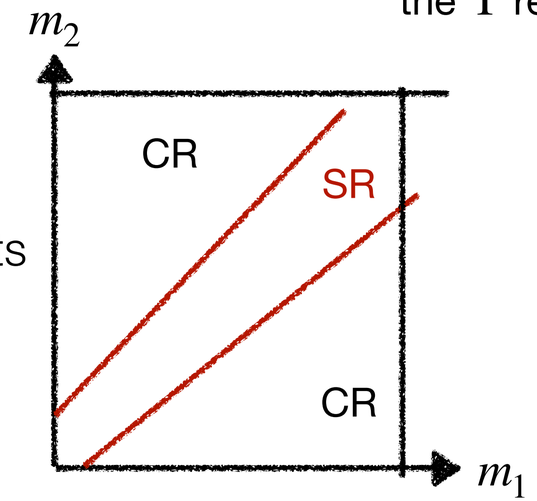
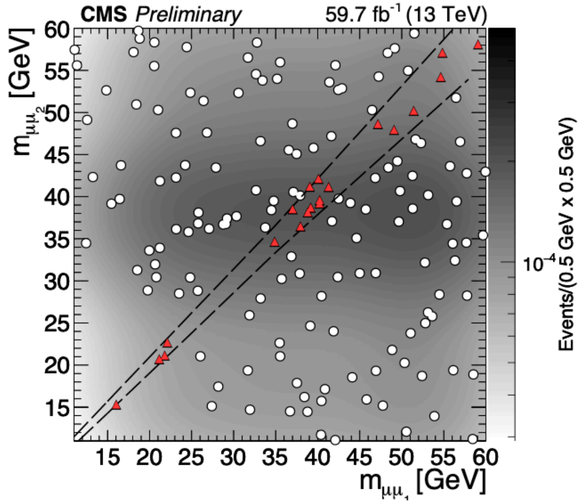


Image from CMS physics briefing

Data events in the SR and CR regions, above the Υ resonance (above 11 GeV)

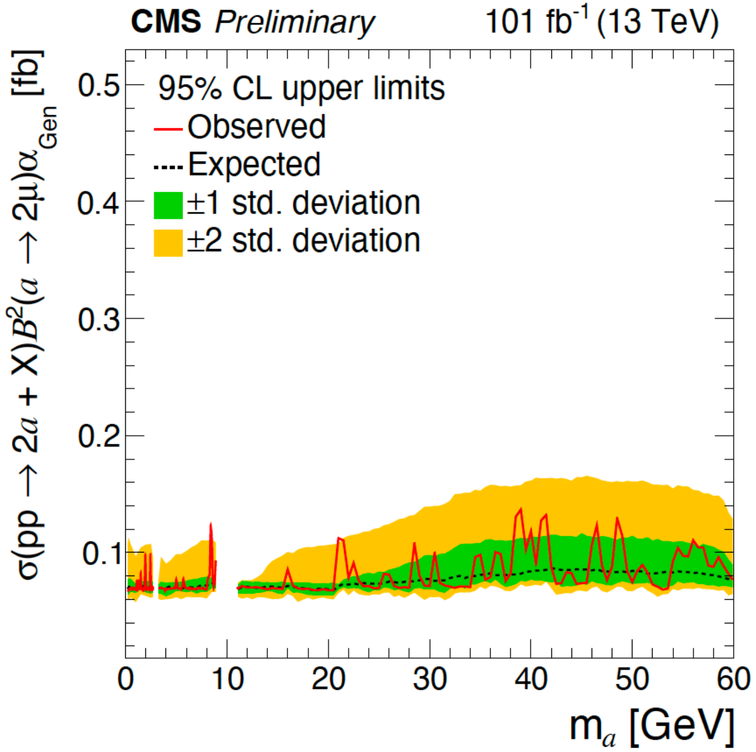


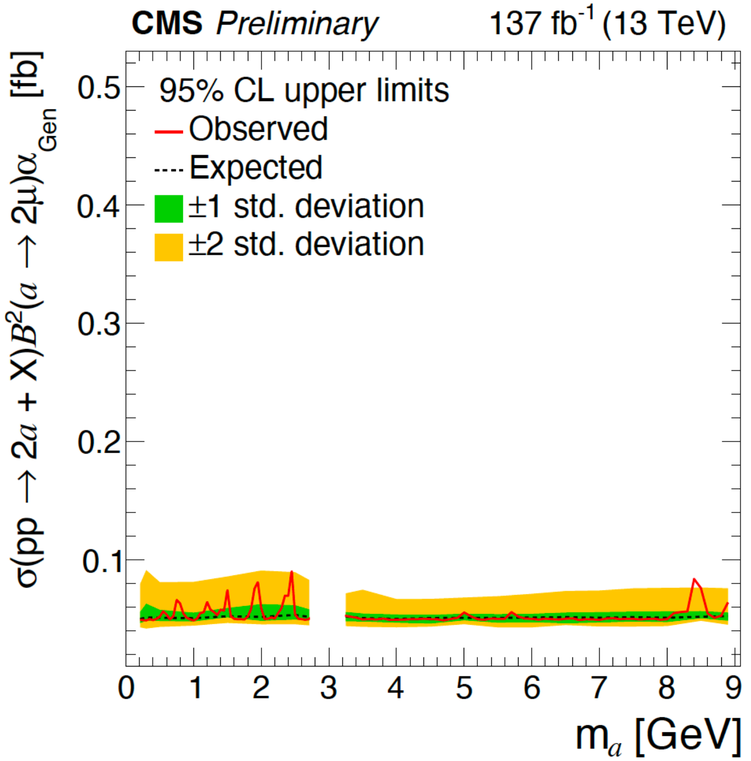


$H \to aa \to 4\mu / X \to 4\mu$ results (CMS-PAS-HIG-21-004)

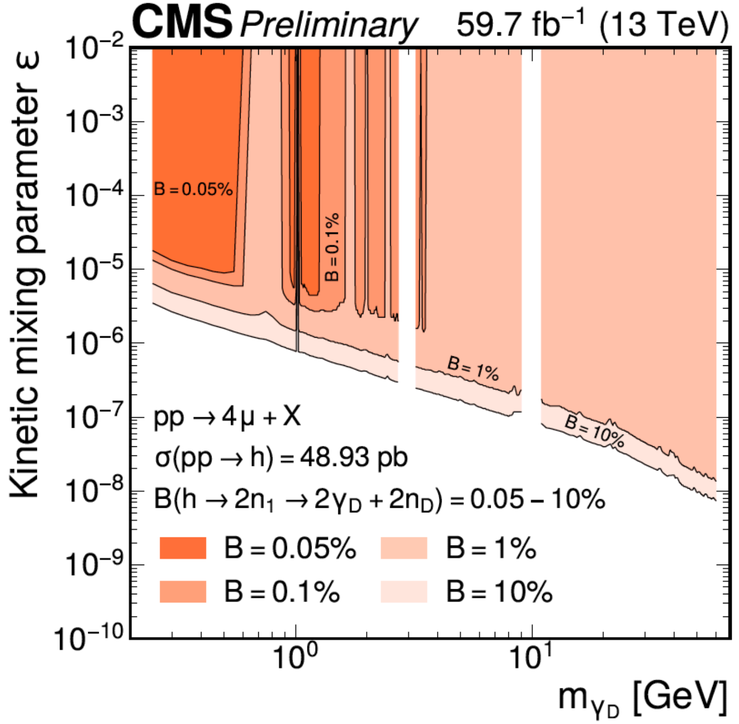
Model-independent 95% CL limits on

$\sigma(pp \to 2a + X)B^2(a \to 2\mu)\alpha_{gen}$ for combined 2017 and 2018 analyses (left) and with full Run-2 (right):





Dark SUSY scenario: for various BRs for the h to two dark photons γ_D, exclude regions of the kinetic mixing parameter vs. dark photon mass: $pp \to h \to 2n_1 \to 2\gamma_D + 2n_D \to 4\mu + X$



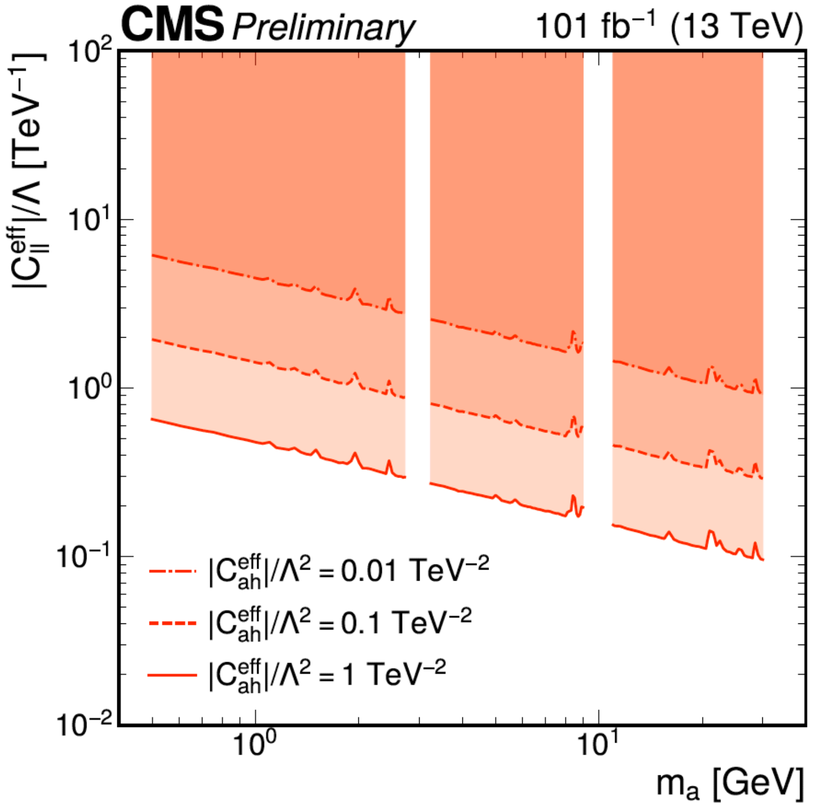
Expanded mass point range compared to previous analysis. Mass ranges that overlap with J/Ψ and Υ resonances are excluded from the search.

$H \to aa \to 4\mu / X \to 4\mu$ results continued (CMS-PAS-HIG-21-004)

Axion-like particles (ALP) models: for ALP a, $h \to 2a$,

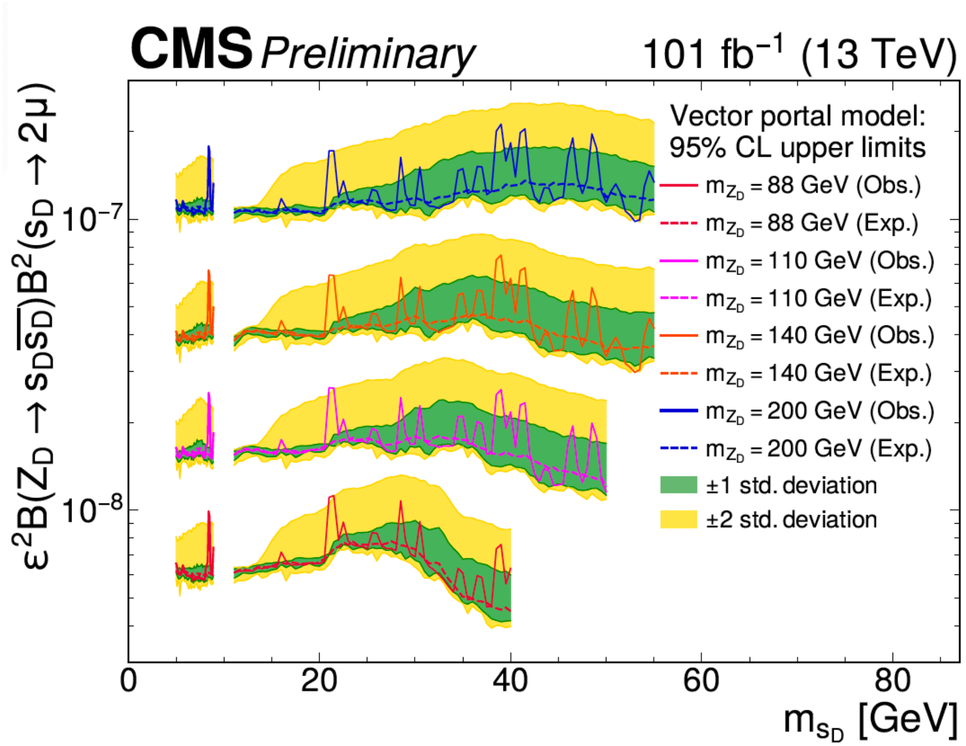
ALP decays promptly to dimuon

Below: 95% CL observed upper limits on the effective coupling of the ALP to the SM leptons, for different choices of the ALP to the SM Higgs



Vector portal model with a dark scalar boson s_D:

A massive dark vector boson Z_D decays to two new scalar boson ($Z_D \to s_D \bar{s}_D$). s_D decays promptly to dimuon. *Below:* Upper limits on branching fraction for different Z_D masses as a function of s_D mass



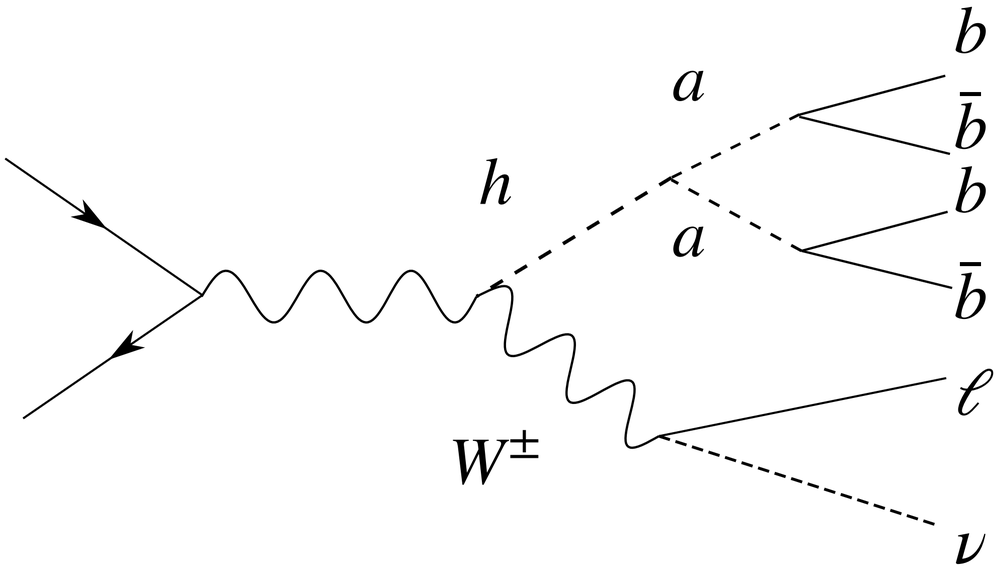
CMS-PAS-HIG-21-004

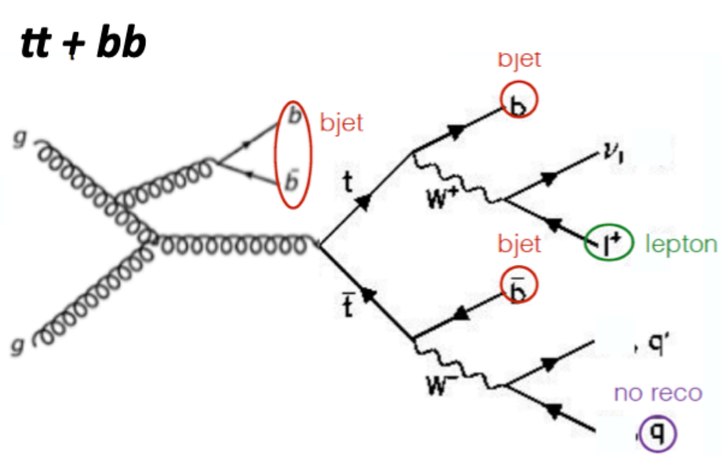
$H \to aa \to 4b$ in VH: overview (HIG-18-026)

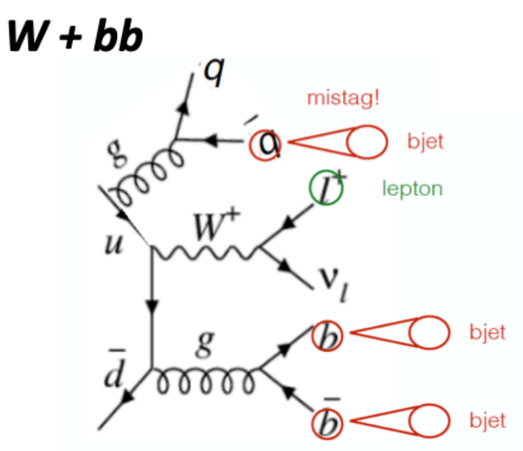
Search for in $H \to aa \to 4b$ with VH production with V (i.e. W or Z) decaying leptonically

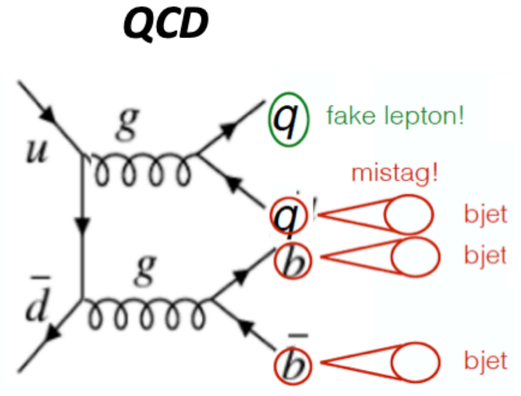
- Masses m_a (12, 60) GeV
- ggH and VBF are difficult to trigger on in this fully hadronic final state
- As m_a increases, the b quarks tend to be collimated

Backgrounds (ttbar, W/DY+Jets) estimated from MC, QCD estimated from data-driven method







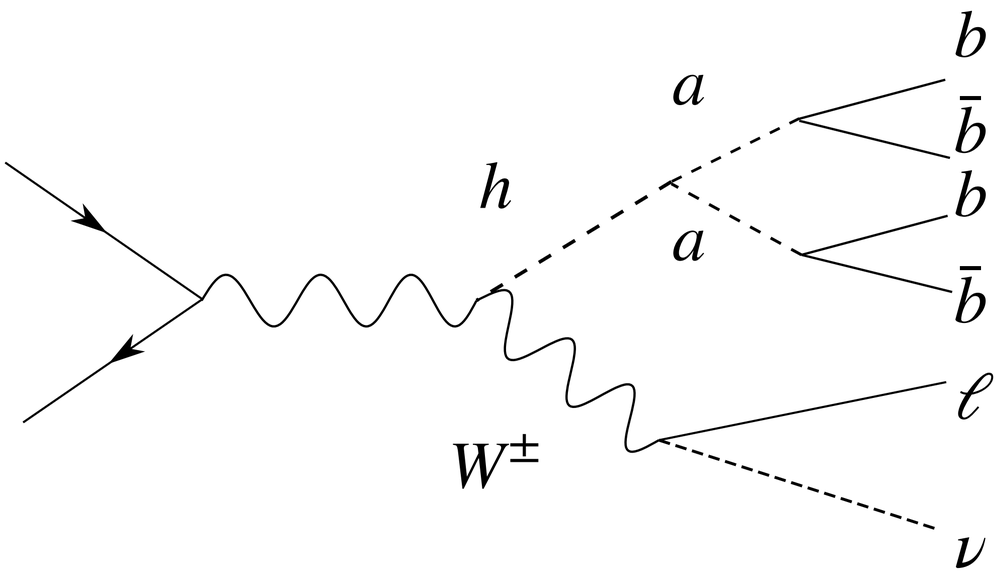


JHEP 06, 097 (2024)

$H \to aa \to 4b$ in VH: event categories (HIG-18-026)

Control regions (CRs) and signal regions (SRs) based on event categorization in (n-btag, n-jet) bins

- **WH channel:** use single-lepton triggers: at least one electron or muon
- **ZH channel:** use di-lepton triggers, require exactly one e^+e^- or $\mu^+\mu^-$ pair



Label	(N_b, N_j)	Description
	WH channel	
SR (3b)	(3b, 3–4j)	3b signal region
SR (4b)	(4b, 4j)	4b signal region
CR (3b)	(2b, 3j)	W/$t\bar{t}$+jets control region
CR (4b)	(2b, 4j)	$t\bar{t}$+jets control region
	ZH channel	
SR (3b)	(3b, ≥3j)	3b signal region
SR (4b)	(4b, ≥4j)	4b signal region
CR (3b)	(2b, 3j)	DY control region
CR (4b)	(2b, 4j)	DY control region

BDTs are trained on signal events using kinematic variables, for WH and ZH and in the 3b and 4b event categories, and applied to data to obtain an observed BDT distribution

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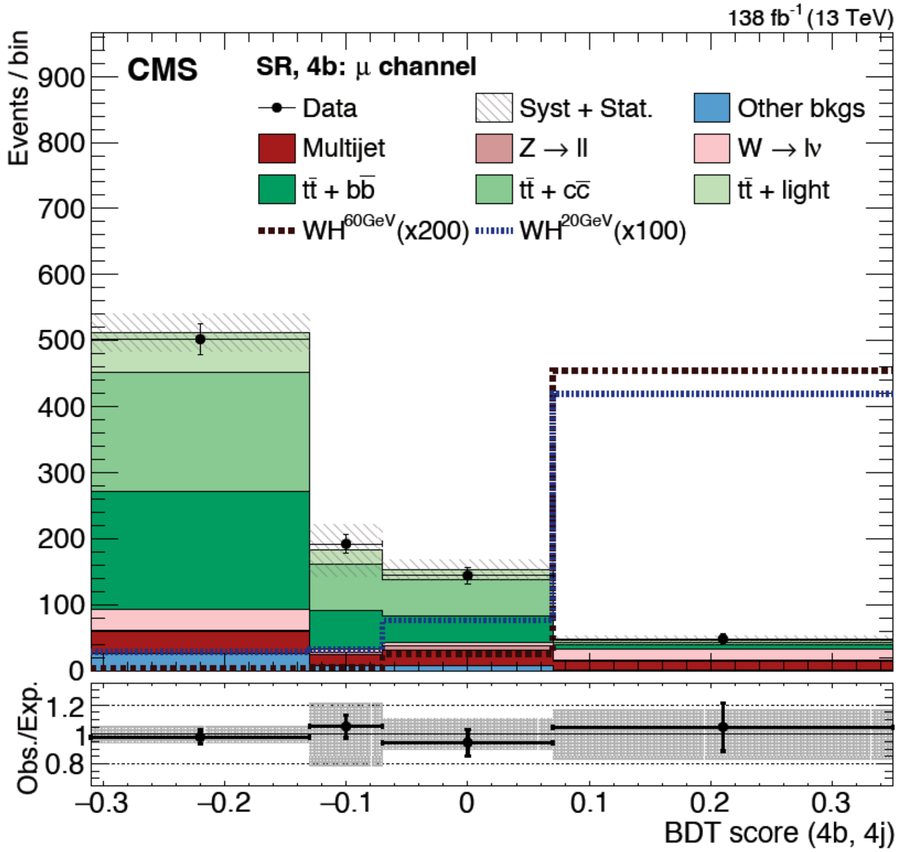
$H \to aa \to 4b$ in VH: results (HIG-18-026)

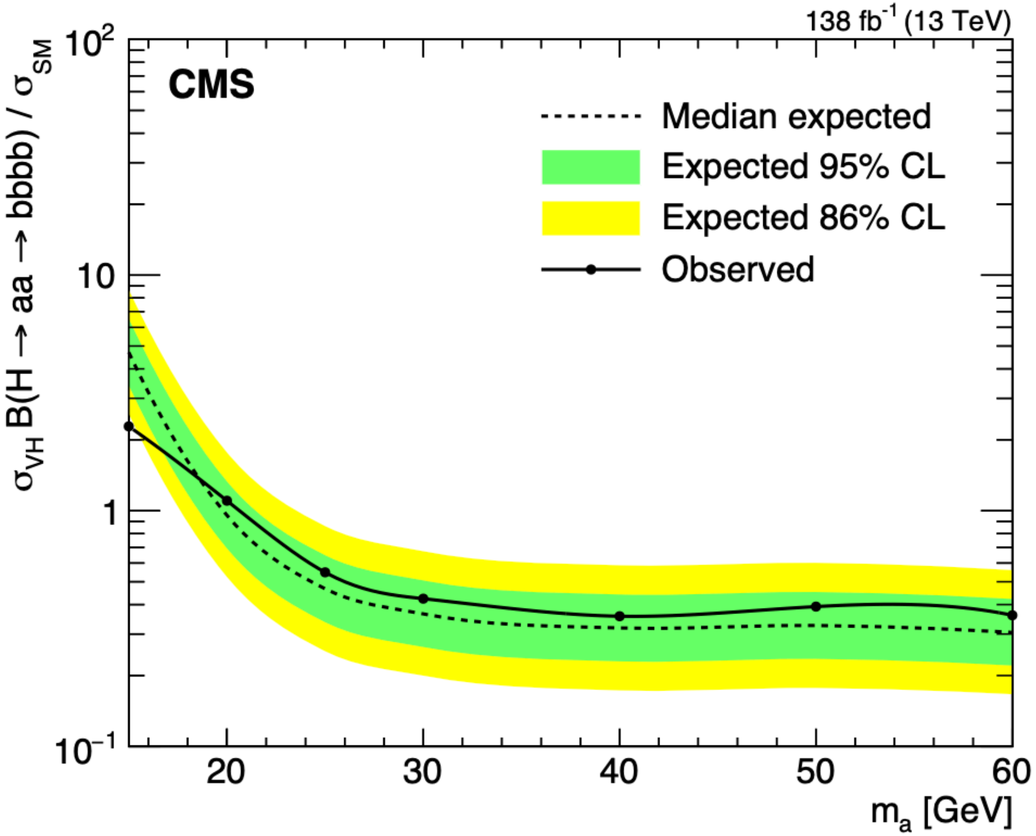
Signal extracted from fit to observed BDT score

Below: signal region with (4 b-tag jets, 4 jets) in the muon channel of WH



95% CL upper limits on

$\sigma_{VH}B(H \to aa \to b\bar{b}b\bar{b})/\sigma_{SM}$ are set on the WH and ZH channels: combined results



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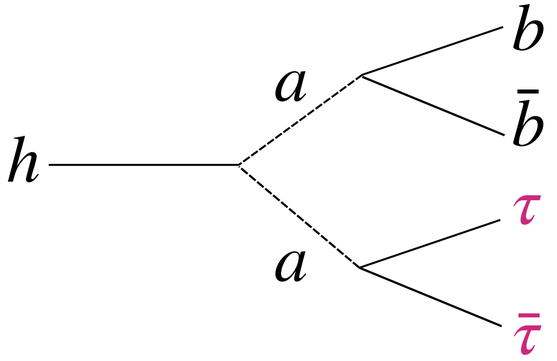
$H \to aa \to 2\tau 2b$: brief overview (HIG-22-007)

Search for m_a in (12, 60) GeV, three $\tau\tau$ final states considered: $e\mu$, $\mu\tau_h$, $e\tau_h$

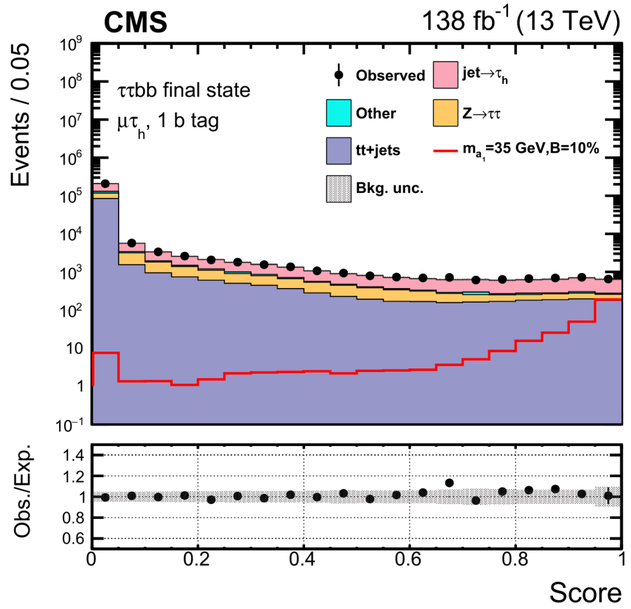
Compared to 2016-only search:

- Improved object selection: DeepTau ID, DeepJet b-tagging
- Full $m_{\tau\tau}$ is reconstructed and used for the final fit, instead of the visible-only components
- DNN-based categorization instead of cut-based

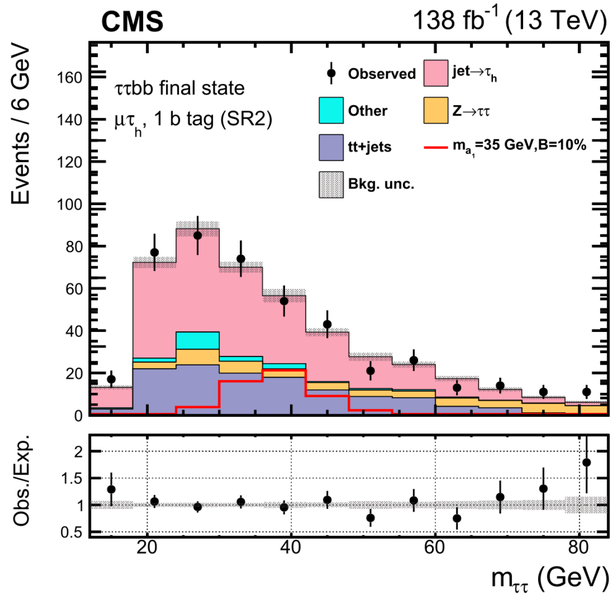


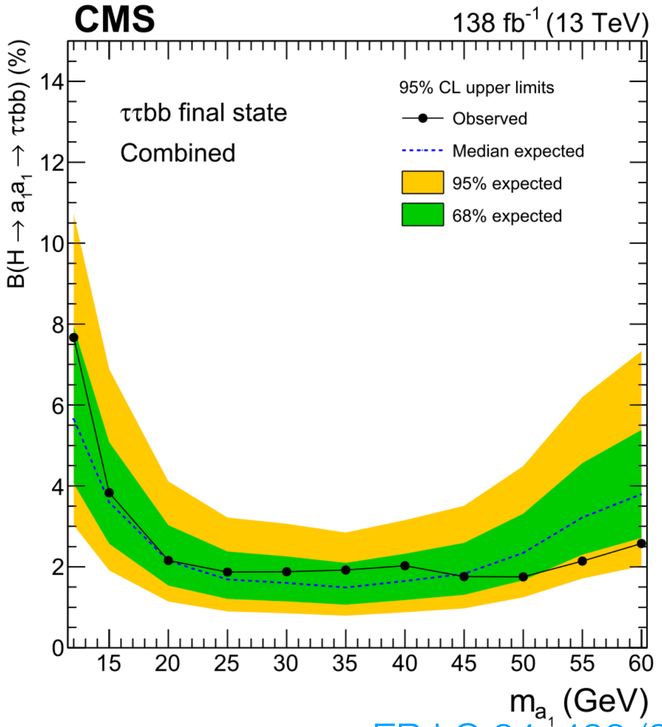
Results extracted from maximum likelihood fit to $m_{\tau\tau}$

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)



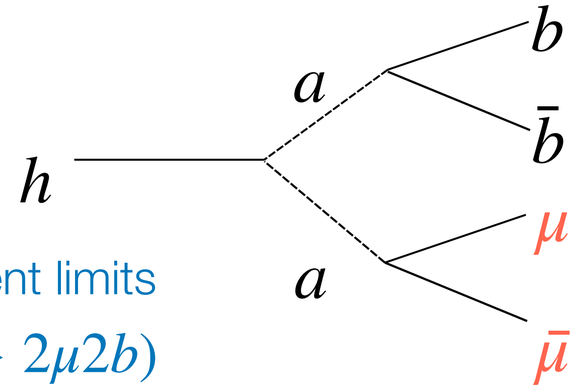


EPJ C 84, 493 (2024)

$H \to aa \to 2\mu 2b$: brief overview (HIG-22-007)

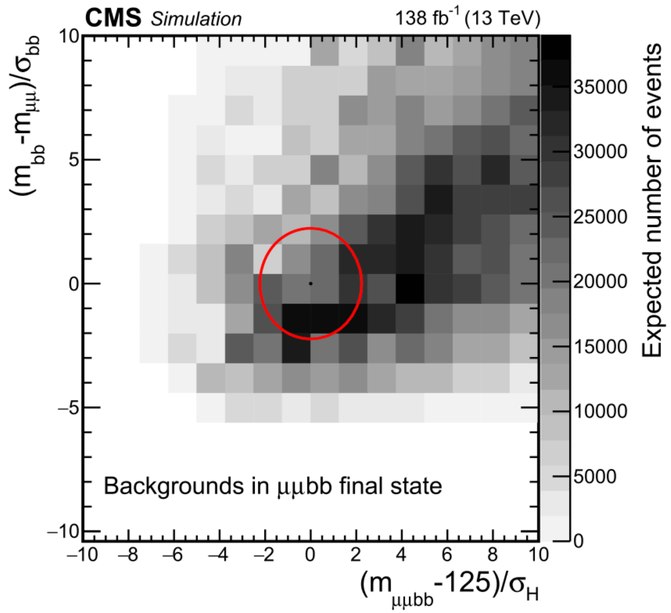
Search for m_a (12, 60) GeV: precise di-muon mass resolution and large BR to bb

- Define two variables 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 further categorize events based on jet properties
- Unbinned maximum likelihood fit to $m_{\mu\mu}$, using parametric signal and background models

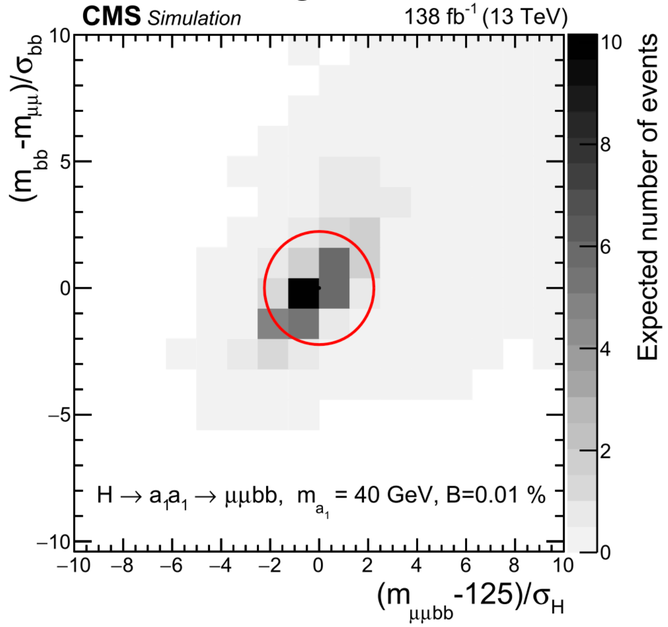


Distribution of χ_d components before de-correlation

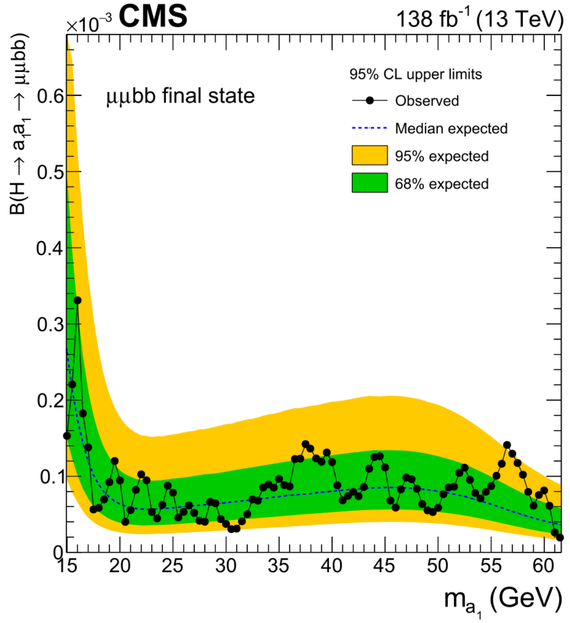
Background



Signal



Model-independent limits on $B(h \to aa \to 2\mu 2b)$



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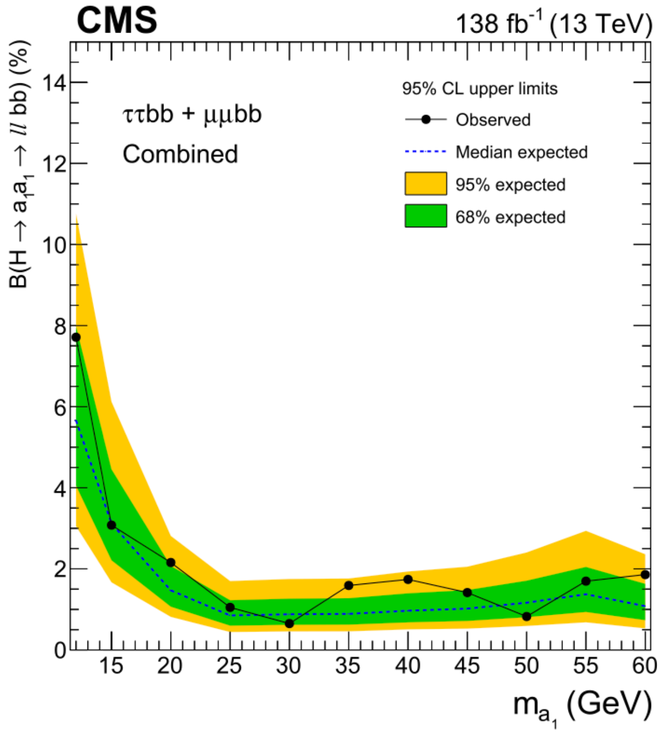
Combination: $H \to aa \to 2b2\tau/2b2\mu$ (HIG-22-007)

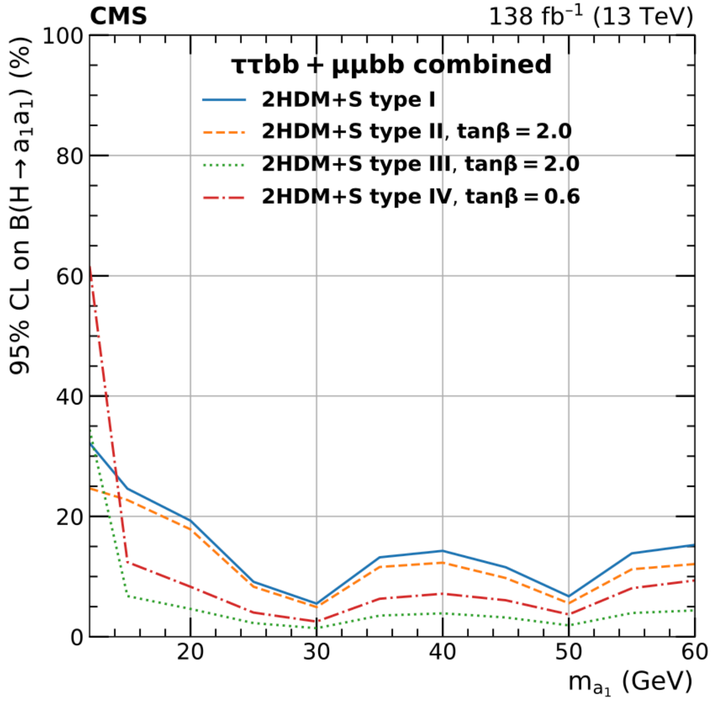
Combination yields more stringent limits on $B(H \to aa)$ and $B(H \to aa \to 2\ell 2b)$ than the individual analyses

- Combination possible since event selection is mutually exclusive

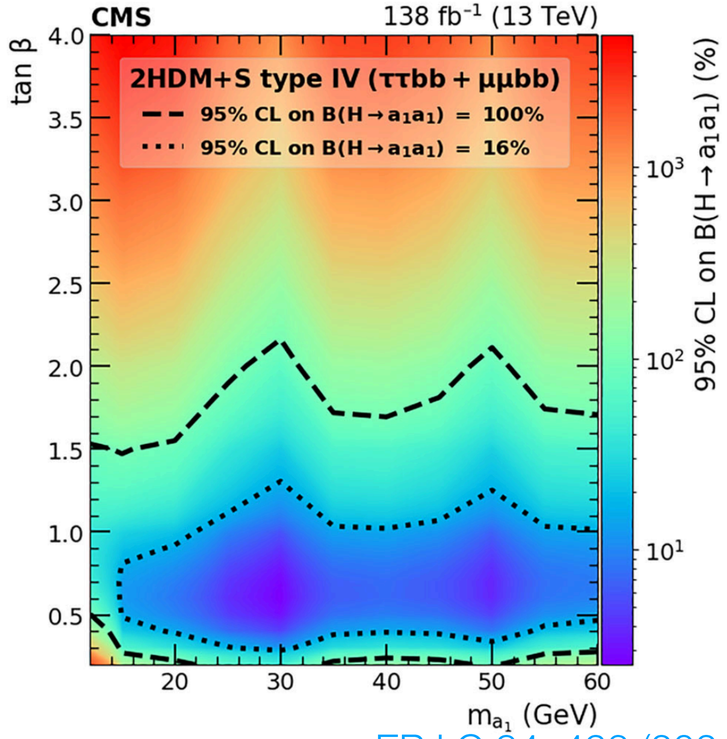
Observed combined model-independent limits on $B(H \to aa \to 2\ell 2b)$



Observed combined limits on $B(H \to aa)$ for 2HDM+S Types I, II, III, and IV



Observed upper limits on $B(H \to aa)$ in % for Type IV 2HDM+S. Values of $\tan\beta$ vs. m_a inside the contours are allowed within that upper limit



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Outlook and summary

CMS full Run-2 results published this year:

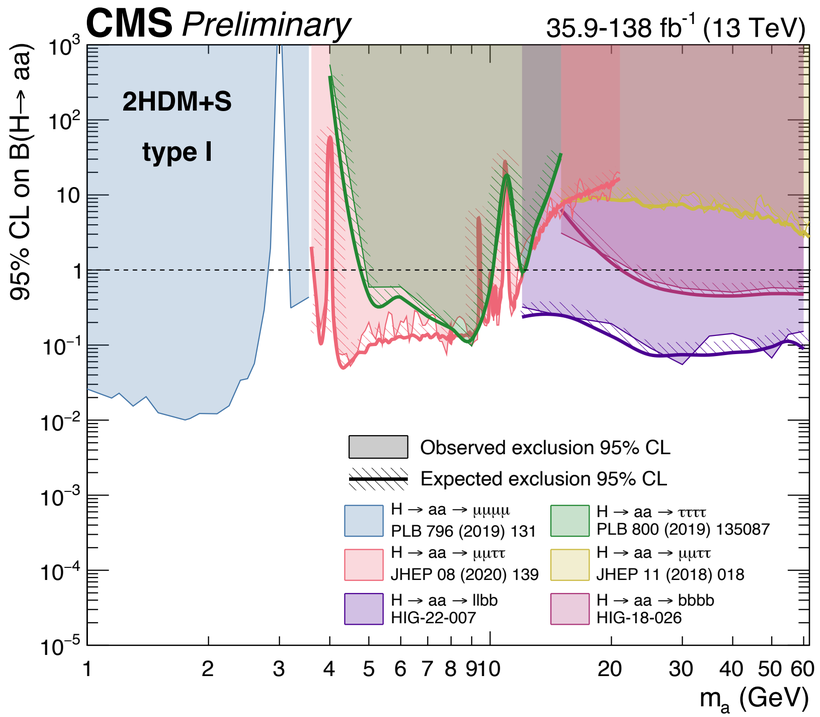
$H \to aa \to 4\mu / X \to 4\mu$ (CMS-PAS-HIG-21-004)

- 2018 displaced muon trigger, interpretations in four different models
- $0.21 < m < 60$ GeV, lifetimes $0 < c\tau < 100$ mm

$H \to aa \to 4b$ (HIG-18-026)

$H \to aa \to 2b2\tau/2b2\mu$ (HIG-22-007)

- Interpretations in 2HDM+S scenarios give the most stringent limits to date for $B(H \to aa)$ for m_a in (12, 60) GeV



Limits on $B(H \to aa)$ in 2HDM+S Type I (CMS summary plot)

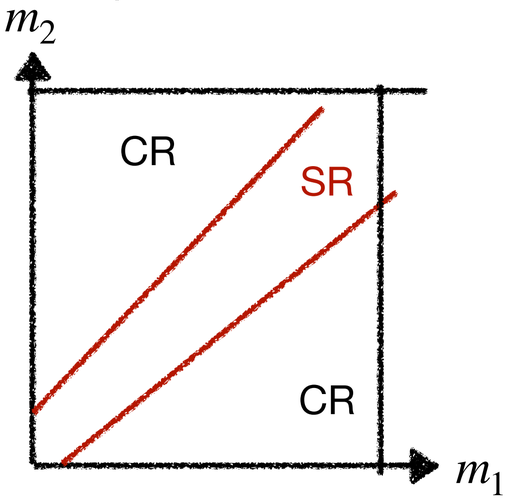
Despite no observations of significant excess over SM predictions for $H \to aa$ to date, **many physics scenarios remain to be explored:**

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

Thank you for your time!

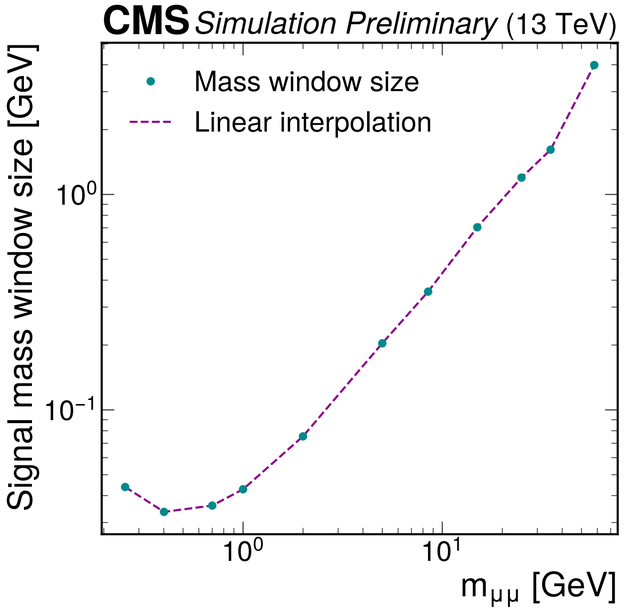
Backup

$H \to aa \to 4\mu / X \to 4\mu$ mass window (CMS-PAS-HIG-21-004)



The mass window size is a function of the invariant dimuon mass

- Derived from a Crystal Ball function fitted to MC signal events to contain 90% of events
- Wider mass window size at m below 0.4 GeV is due to deteriorating mass resolution for the near-collinear dimuon system in decays of low-mass bosons



$H \to aa \to 4\mu / X \to 4\mu$ background estimation (CMS-PAS-HIG-21-004)

All backgrounds are modeled with data-driven methods

Below the Upsilon Υ resonance (0.25 - 9 GeV):

- Dominated by QCD multijet processes
  - E.g. Two b quarks decay to $2\mu + X$ (X spectator particle) or low-mass meson resonances ω, ρ, ϕ, and $\psi(2S)$
- Used a data-driven two-dimensional template $T(m_{\mu\mu_1}, m_{\mu\mu_2})$

Above the Υ resonance (11-60 GeV):

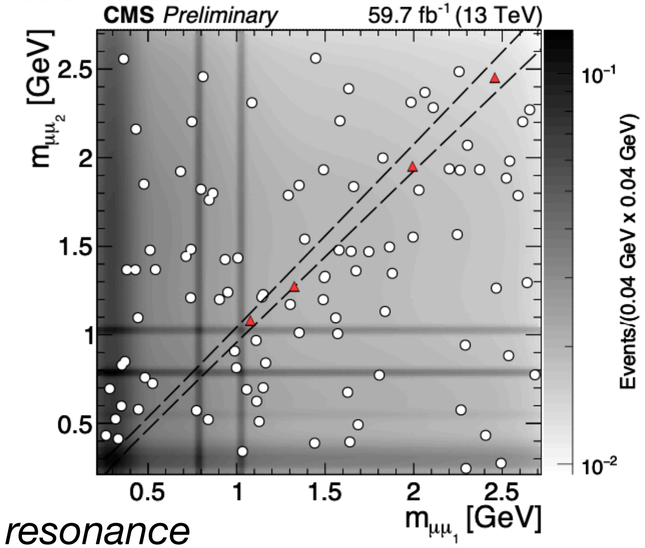
- Electroweak processes with two Z bosons, $t\bar{t}$, and Drell-Yan (DY)
  - Also considered: radiated photon in the DY process that converts into a dimuon
- Used a kernel density estimate (KDE) method with normalization derived from data

Calculate PDF density of signal region I_{SR} and control region I_{CR}

- Number of events in the signal region: $N_{B_{SR}} = \frac{I_{SR}}{I_{CR}} N_{CR}$

Data events passing all selections are shown in red:

Below Υ resonance



Above Υ resonance