Search for exotic Higgs decays to light neutral scalars $H \to aa \to 2b2\mu/2b2\tau$ at CMS
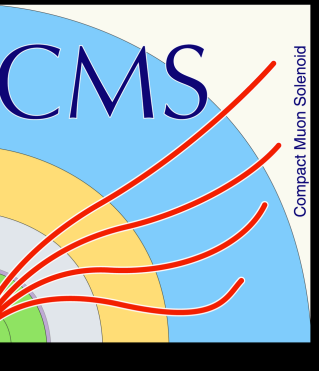
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Abstract: Properties of an extended Higgs sector remain loosely constrained by current measurements, making direct searches for exotic Higgs decays a powerful probe of new physics. We present a recent search at CMS for exotic decays of the 125 GeV Higgs boson into two light neutral scalars to final states with bottom quarks and tau leptons or muons, $h \to aa \to 2b2\tau/2b2\mu$ (HIG-22-007, EPJ C 84, 493 (2024)). This search sets some of the most stringent limits to date in several scenarios of Two Higgs Doublet Models extended with a singlet scalar (2HDM+S), for scalar masses ranging from 12 GeV to 60 GeV.

$h \to aa$ in 2HDM+S

Theories with supersymmetry (SUSY), such as Two Higgs Doublet Models (2HDM), may provide a compelling solution to the hierarchy problem:

- Four types of 2HDM extended with a singlet scalar (2HDM+S) prevent flavour-changing neutral currents at tree-level, and predict seven Higgs particles
- 2HDM+S are parametrized with $\tan\beta$, the ratio of vacuum expectation values of the two doublets ϕ_1, ϕ_2

	Type I	Type II	Type III (lepton-specific)	Type IV (flipped)
right-handed leptons	ϕ_1	ϕ_2	ϕ_2	ϕ_1
up-type quarks	ϕ_1	ϕ_1	ϕ_1	ϕ_1
down-type quarks	ϕ_1	ϕ_2	ϕ_1	ϕ_2
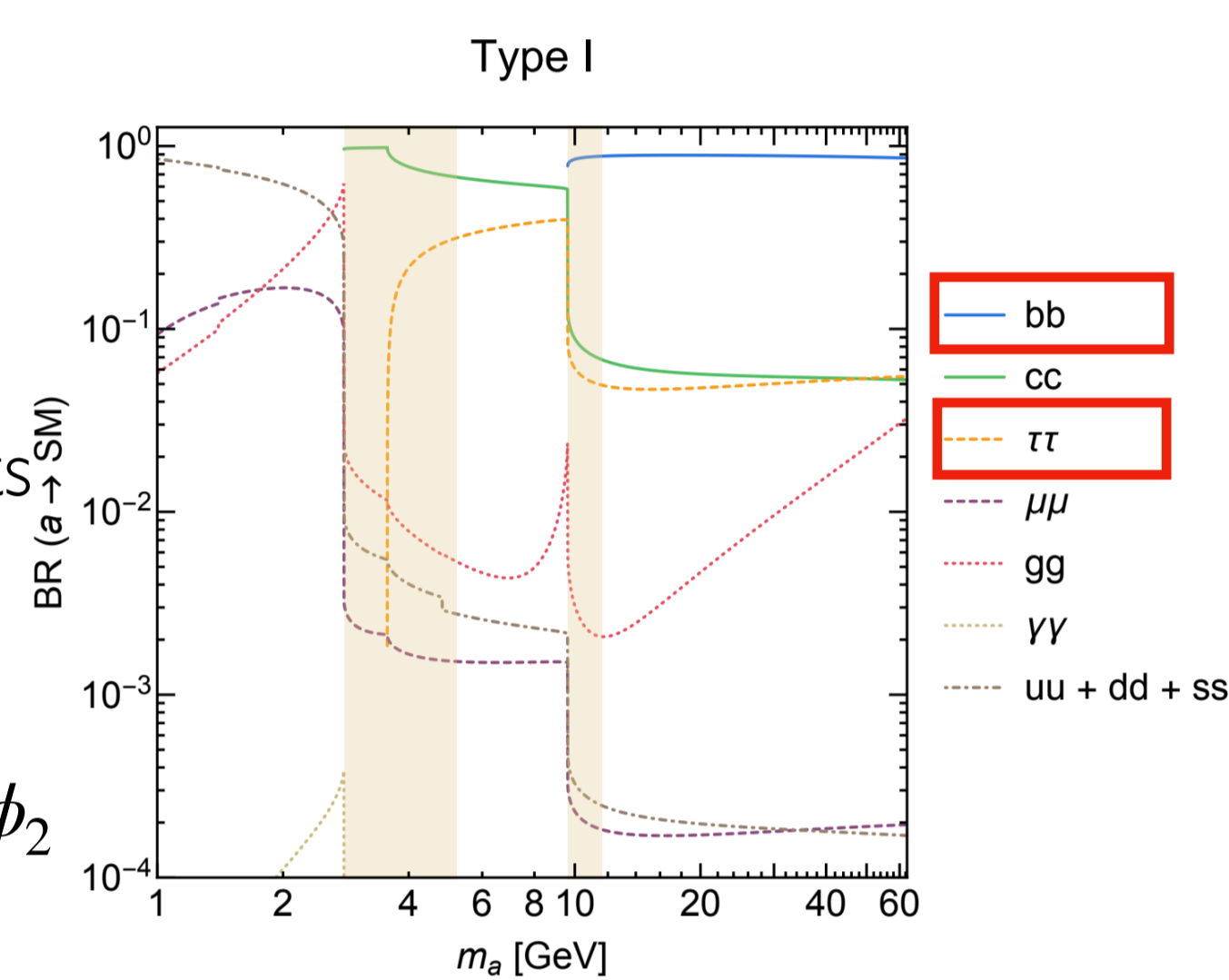
Predicted branching fraction of exotic decays of the 125 GeV Higgs boson $B(h \to aa)$ in 2HDM+S Type I (arXiv:1312.499). Emphasis on bb and $\tau\tau$ own.

Main improvements for full Run-2 analysis

Main improvements with respect to the 2016-only search:

- Reconstruction of full di-tau mass $m_{\tau\tau}$ (instead of visible-only components)
- More sophisticated event categorization with 1 and 2 b-tag jet categories and DNN-based categorization, instead of cut-based
- Combination with full Run-2 $2b2\mu$ results (HIG-21-021)

$2b2\mu$ search strategy: exploit clean di-muon mass resolution, with $m_{\mu\mu} = m_{bb}$ and $m_{2\mu2b} = 125$ GeV

Limits on $B(H \to aa \to 2b2\mu)$ for m_a (15, 60) GeV
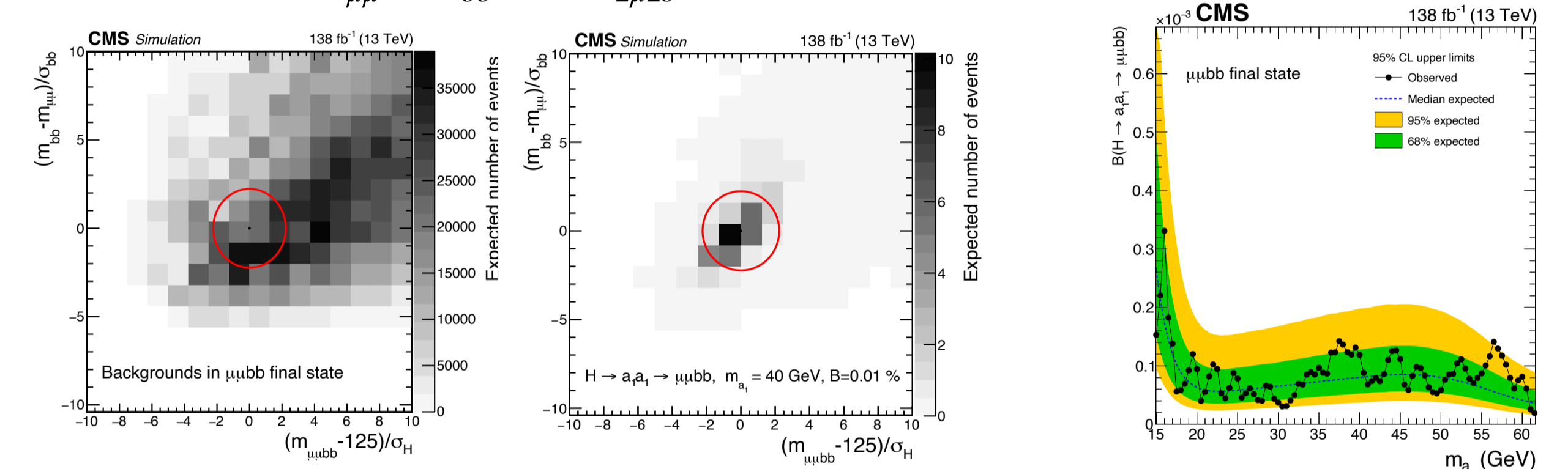
Analysis strategy: $h \to aa \to 2b2\tau$

Three $\tau\tau$ channels ($\mu\tau_h$, $e\tau_h$, $e\mu$) were targeted, with events also required to have at least 1 b-tag jet:

Backgrounds: Data-driven methods used for jet faking τ_h ($\mu\tau_h$, $e\tau_h$), and QCD background ($e\mu$), and Embedded samples for $Z \to \tau\tau$ (all channels)

| Object selection: All years			
	$e\mu$	$e\tau_h$	$\mu\tau_h$
pT(b)	>20 GeV	>20 GeV	>20 GeV
$|\eta(e)|$	<2.4	<2.1	-
$|\eta(\mu)|$	<2.4	-	<2.1
$|\eta(\tau(h))|$	-	<2.3/2.1	<2.3/2.1
$|\eta(b)|$	<2.4	<2.4	<2.4
iso(e)	<0.10	<0.15	-
iso(μ)	<0.15	-	<0.15
ΔR	>0.3	>0.4	>0.4
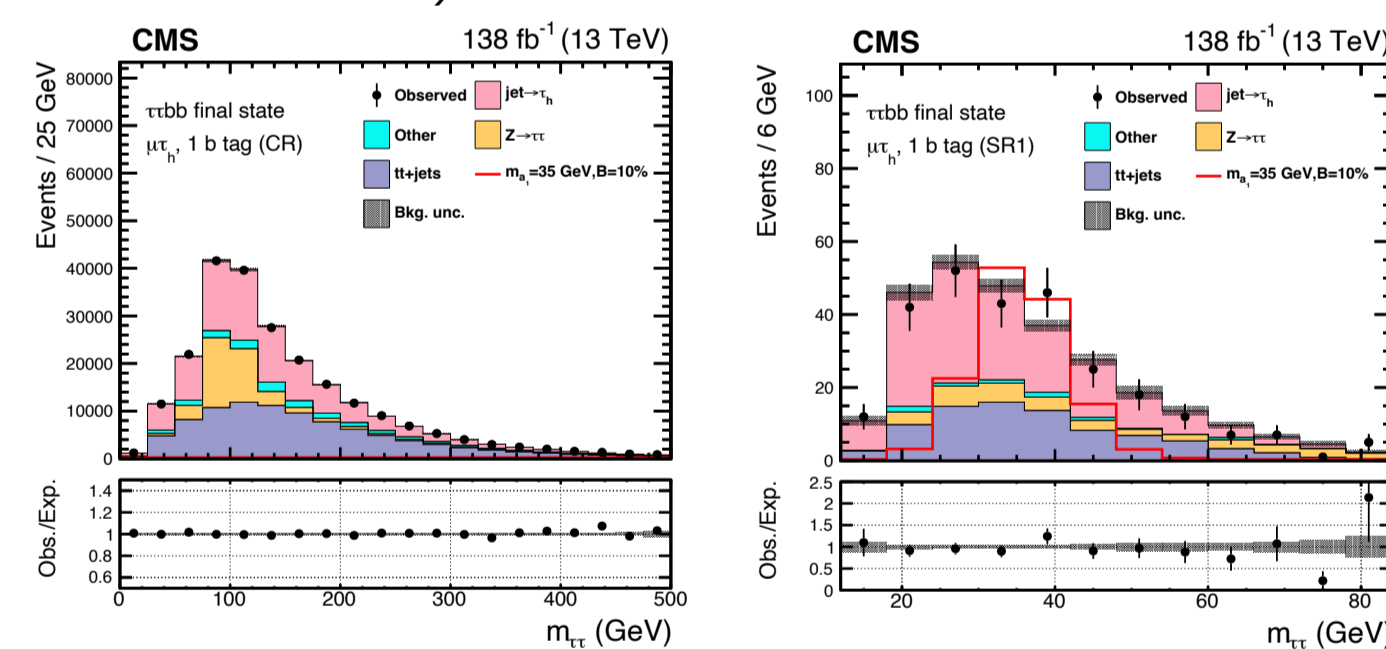
Post-fit $m_{\tau\tau}$ in $\mu\tau_h$ channel, 1 b-tag jet, control region (left) and signal region (right)

Events with 1 and 2 b-tag jets are separated, and a deep neural network was used to further categorize events. The final fit was performed to the full $m_{\tau\tau}$ (reconstructed from visible components)

Full Run-2 Results: $h \to aa \to 2b2\tau$

Observed limits of 2-6% on $B(h \to aa \to 2b2\tau)$, compared to 3.5-11% from 2016-only analysis

$\mu\tau_h$ channel

$e\tau_h$ channel

$e\mu$ channel

all channels

Combined results with the $2b2\mu$ final state give some of the most stringent limits on $B(h \to aa)$ in the mass range m_a 12 to 60 GeV at CMS
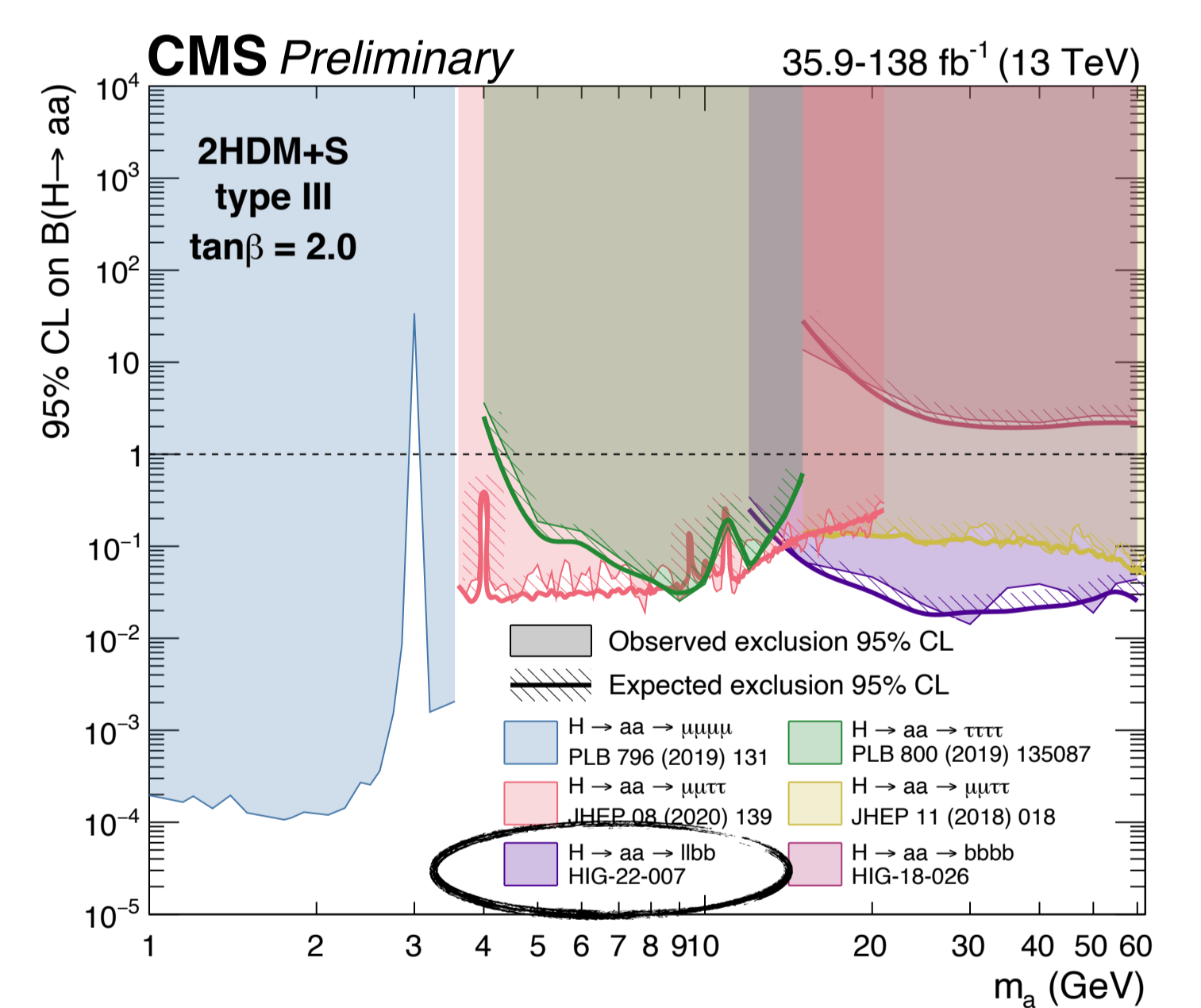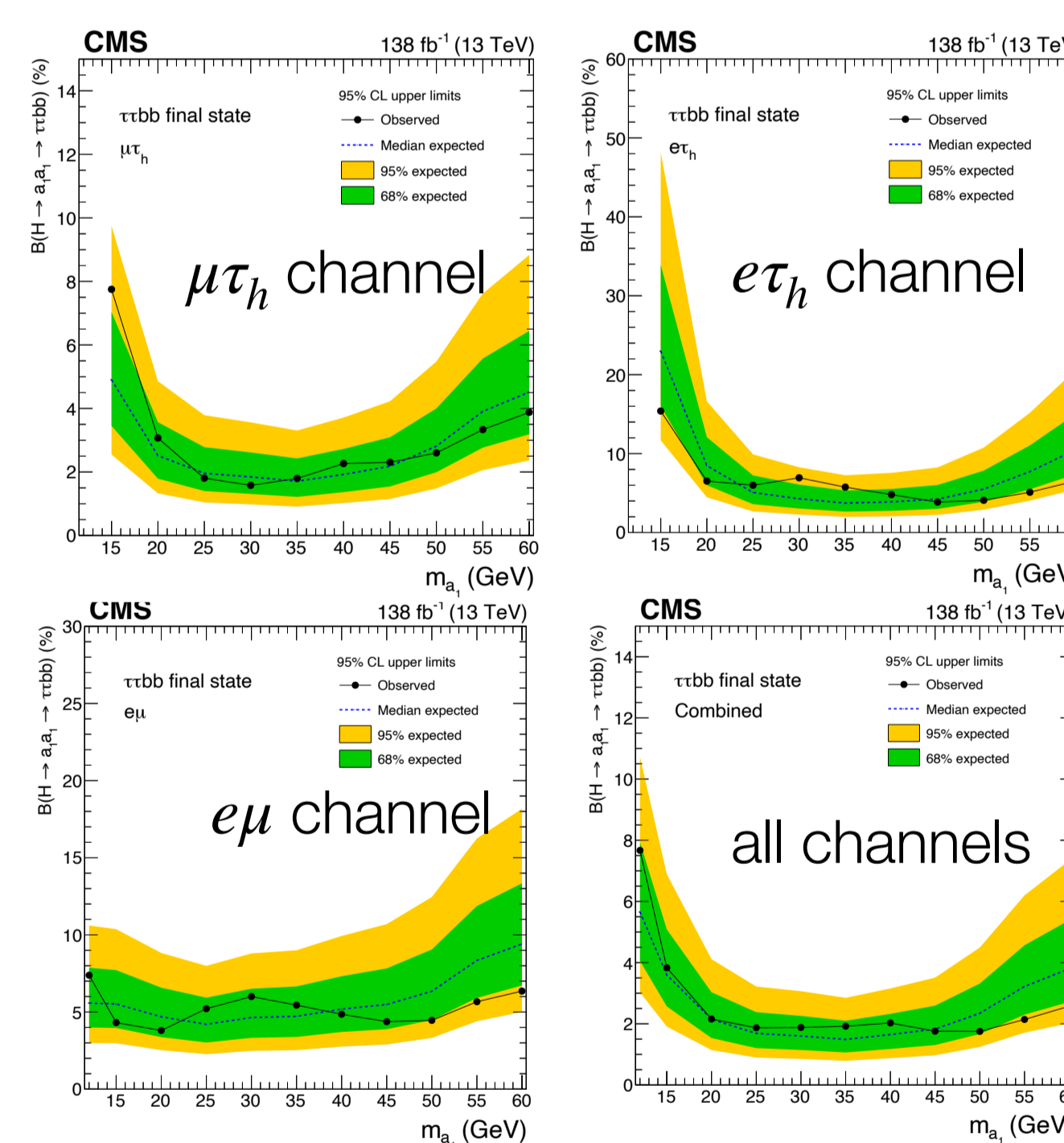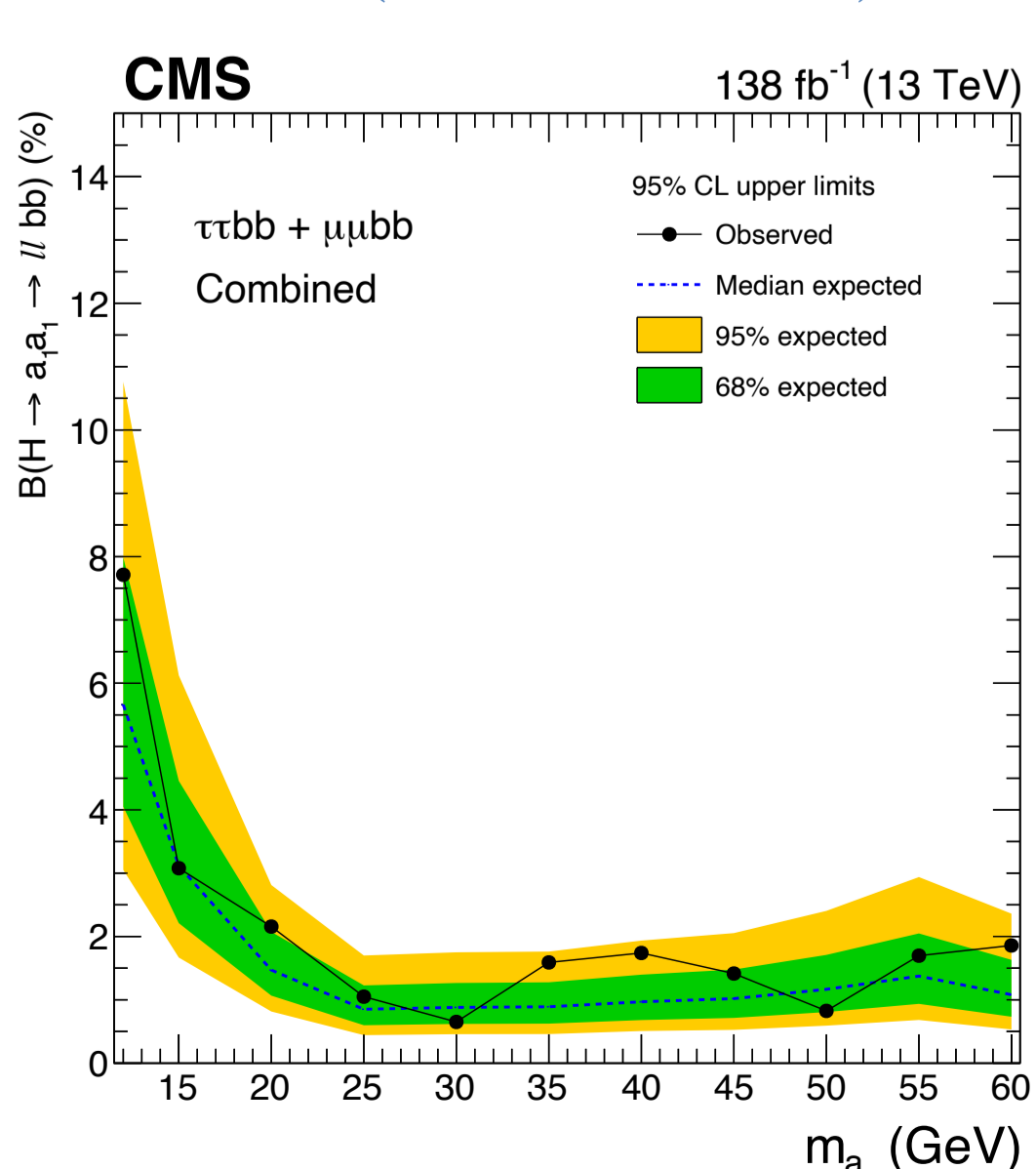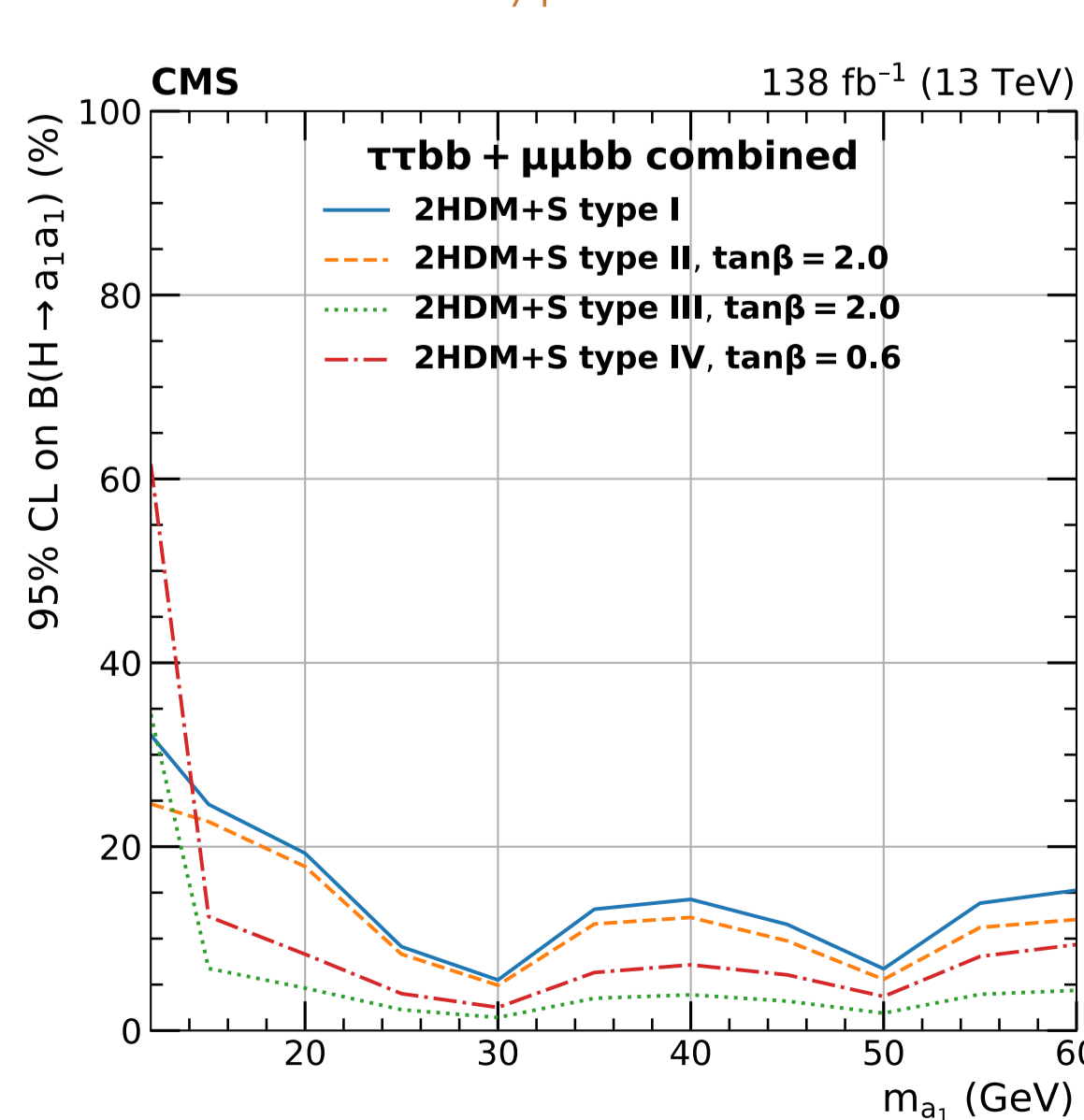
CMS 2HDM+S Run 2 summary plot

Combined Run-2 results: $h \to aa \to 2b2\tau/2b2\mu$

Results from $h \to aa \to 2b2\tau$ and $h \to aa \to 2b2\mu$ (HIG-21-021) are combined to obtain stronger limits than the individual analyses:
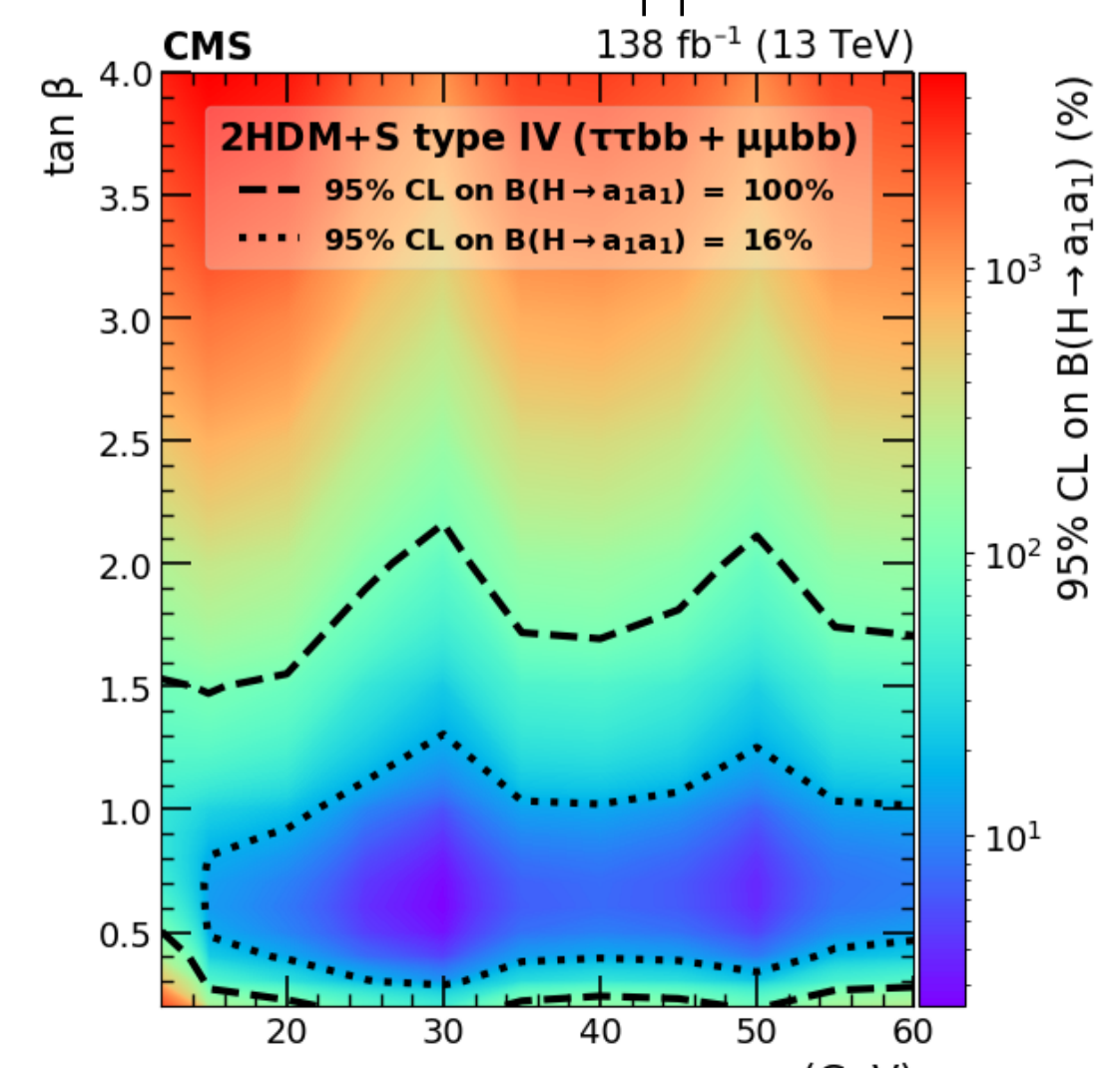
Combined model-independent limits on $B(H \to aa \to 2\ell2b)$

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

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

Conclusions and future work

- The Higgs is a one-of-a-kind way to test theories such as Two Higgs Doublet Models extended with a singlet scalar (2HDM+S) which may provide a natural solution to the hierarchy problem
- The full Run-2 search for $h \to aa \to 2b2\tau$, combined with the $2b2\mu$ final state, gives the some of the most stringent limits on $B(h \to aa)$ for m_a from 12 to 60 GeV
- Analysis is statistics-limited: future work will explore new phase spaces

References
1. $h \to aa \to 2b2\tau/2b2\mu$: HIG-22-007 (arXiv:2402.13358). Eur. Phys. J. C 84, 493 (2024).
2. $h \to aa \to 2b2\mu$: CMS-PAS-HIG-21-021.
3. Curtin et al. 2017 (arXiv:1312.4992v6).
4. Summary of 2HDM+S searches at 13 TeV (Run 2), HIG public results (https://twiki.cern.ch/twiki/bin/view/CMSPublic/Summary2HDMSRun2).
5. Poster template originally by Nikki Marinsek.

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