Searches for exotic decays of the Higgs Boson to a pair of pseudoscalars at CMS

Lakshmi Priya Nair
DESY
On behalf of the CMS Collaboration

Rare Higgs decays to light pseudoscalars in BSM

- **Allowed branching ratio for exotic decays of the Higgs → O(10%)** (Nature 607 (2022) 60)

- **Several theoretical frameworks motivate H → aa decays**

  - **2HDM+S**

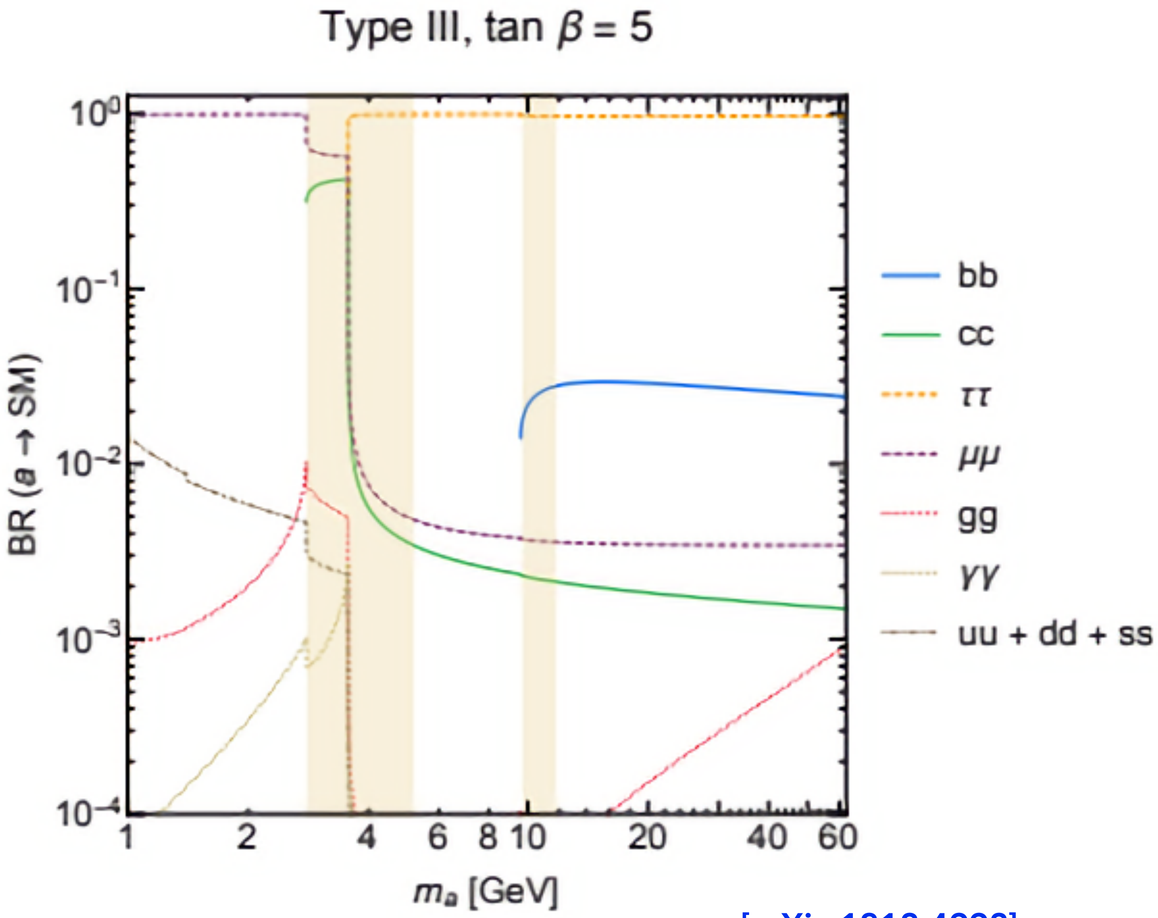
    - Extension of 2HDM by addition of a complex singlet

    - Higgs sector composed of 7 physical states:

      2 charged bosons ($H^{\pm}$), 3 scalars ($h_{1,2,3}$),
      2 pseudoscalars ($a_{1,2}$)

    - Four types of 2HDM+S (Type I, II, III, IV)

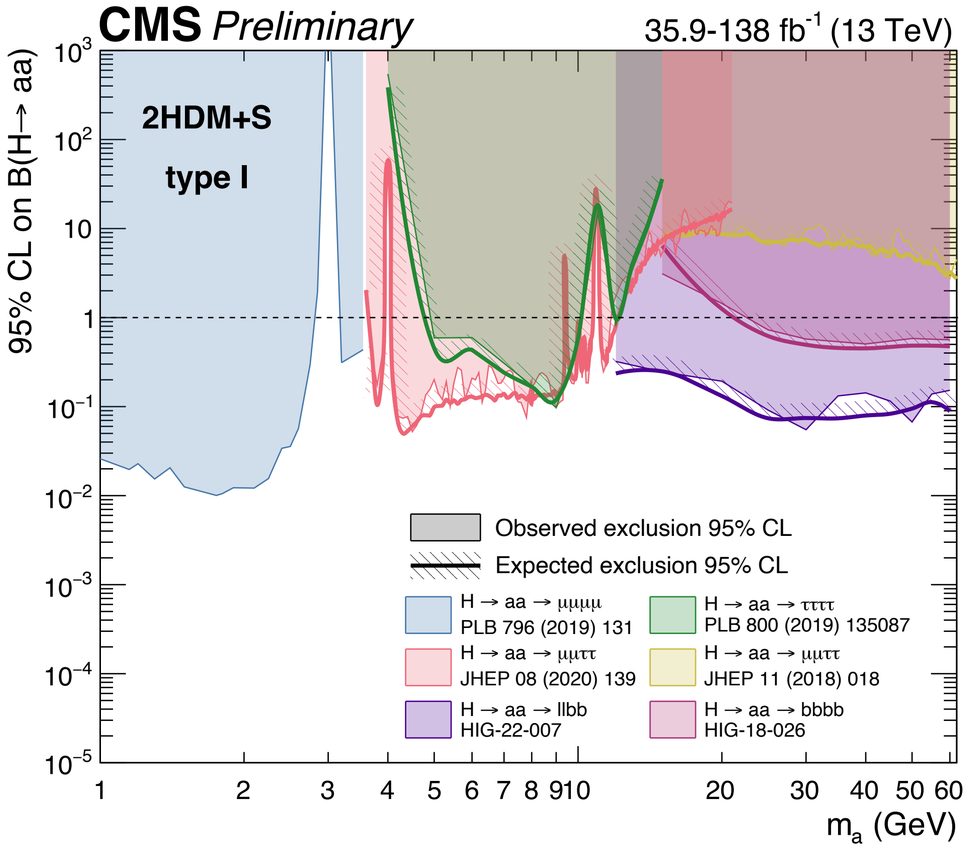
  - **Axion-like particles (ALPs), NMSSM, Portal Models**



[arXiv:1312.4992]

Searches for H → aa decays at CMS

- Several searches for the H → aa decays in both boosted and resolved topologies
  - H → aa → 4γ (boosted): Phys. Rev. Lett. 131 (2023) 101801
  - H → aa → 4γ (resolved): JHEP 07 (2023) 148
  - H → aa → μμ$\tau\tau$ (boosted): JHEP08(2020)139
  - H → aa → μμ$\tau\tau$ (resolved): JHEP11(2018)018
  - H → aa → μμbb/$\tau\tau$bb: Eur. Phys. J. C 84 (2024) 493
- **Scope of this talk: Latest public results since HH 2023**
  - H → aa → bbbb: JHEP06(2024)097
  - H → aa → μμμμ: arXiv:2407.20425
  - H → aa → $\tau\tau\tau\tau$: CMS-PAS-SUS-24-002 **NEW!**

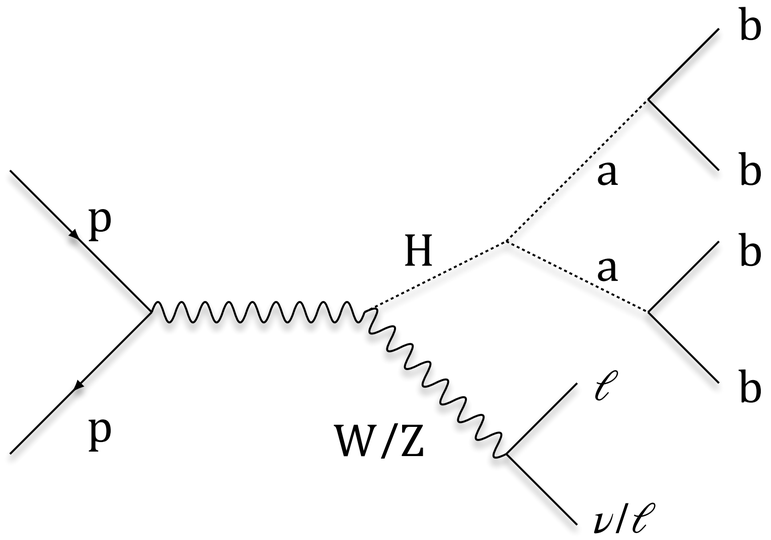


CMS summary plots: 2HDM+S searches at 13 TeV

$H \rightarrow aa \rightarrow 4b$

JHEP06(2024)097

- **Final state with 4b**
- **$a \rightarrow b\bar{b}$ dominant decay mode in most 2HDM+S scenarios**
- Analysis covers mass range **$15 < m_a < 60$ GeV**
- **Uses vector boson associated production of H (VH, V = W or Z)**
  - **Leptonic decay of the V boson**
    - QCD multijet background suppression
- **Main background sources**
  - $t\bar{t}$ + jets with at least one top quark decaying leptonically
  - V + $b\bar{b}$ production plus one or two mistagged jets



- Single lepton trigger for WH channel; dilepton for ZH
- WH channel → Exactly one e/μ
- ZH channel → Exactly one $e^+e^-/\mu^+\mu^-$ pair

$H \rightarrow aa \rightarrow 4b$

JHEP06(2024)097

- **Signal and control regions categorised in terms of n-btag and n-jets**
- **Signal region divided into 2 categories**
  - 3b → boosted
  - 4b → resolved
- **Control regions**
  - $t\bar{t}$+jets
    - Categorised based on flavour content of additional jets
    - Shape estimated from simulation
    - Normalisation determined from fit to data in CR
  - W+jets/Z+jets
    - Similar procedure as for tt+jets

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

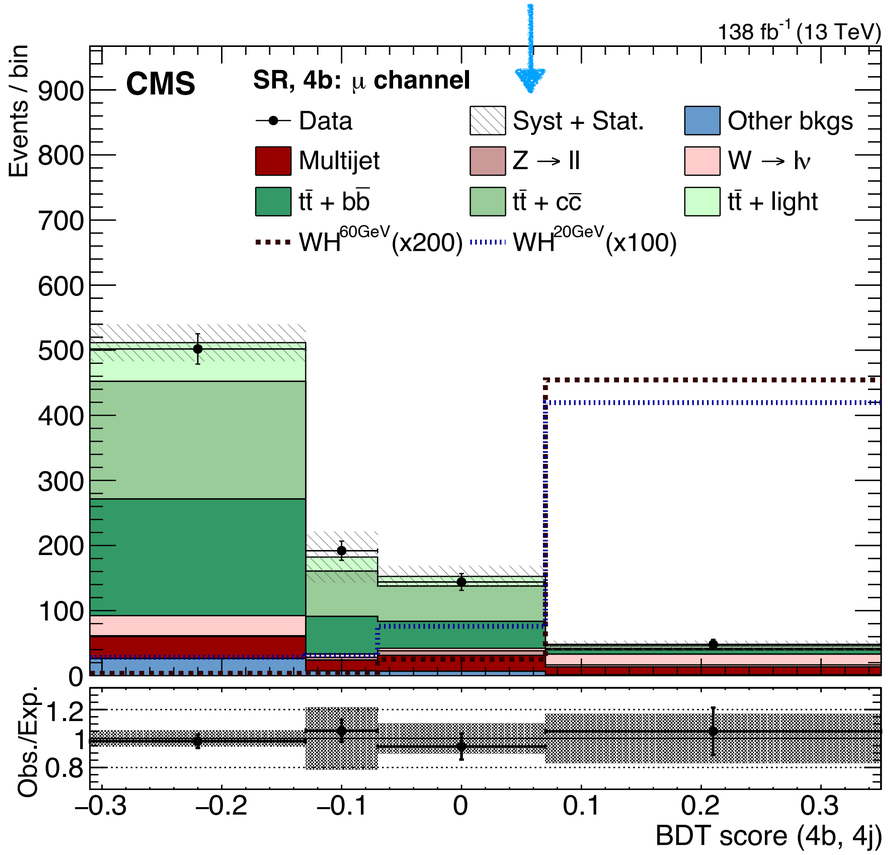
BDTs trained on signal and background events using kinematic variables

Different BDTs for WH and ZH channels and 3b, 4b categories

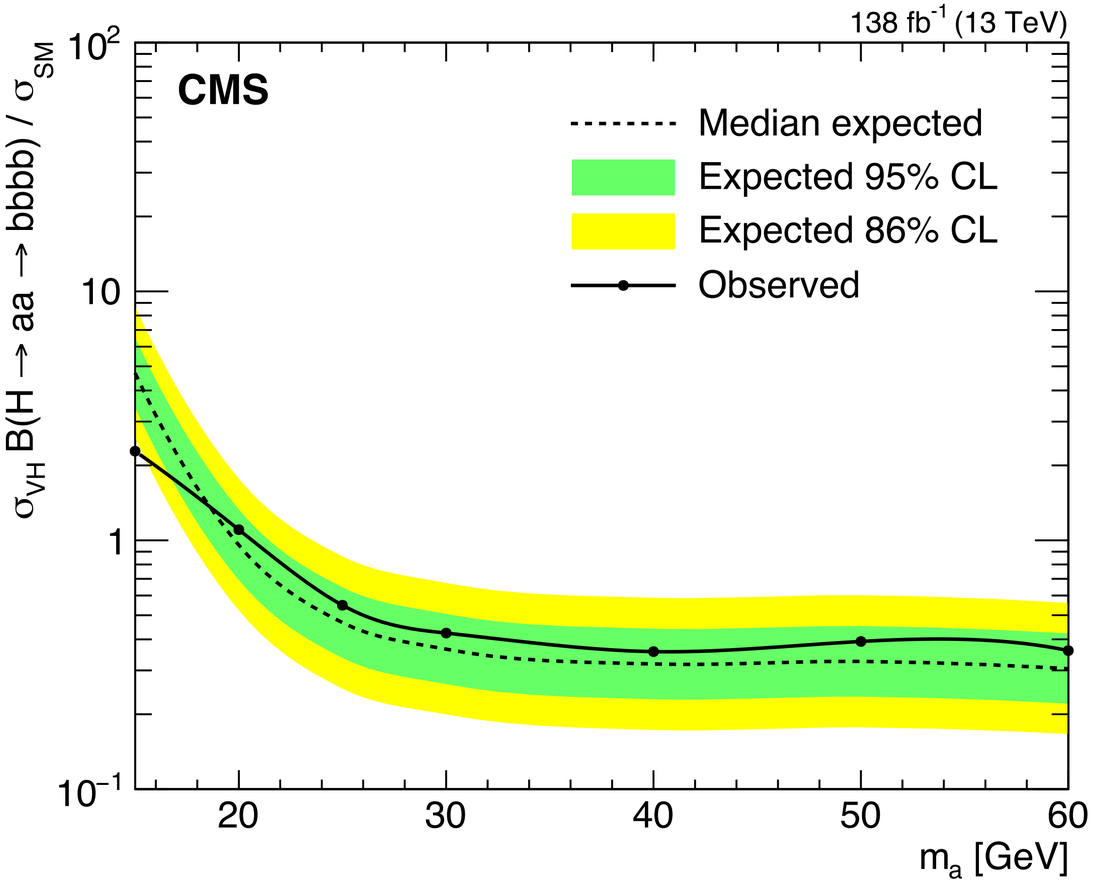
$H \rightarrow aa \rightarrow 4b$

JHEP06(2024)097

- **Signal extracted from fit to observed BDT score simultaneously across SR and CR**
- BDT score – Signal region with (4 b-jets & 4 jets) in the muon channel of WH



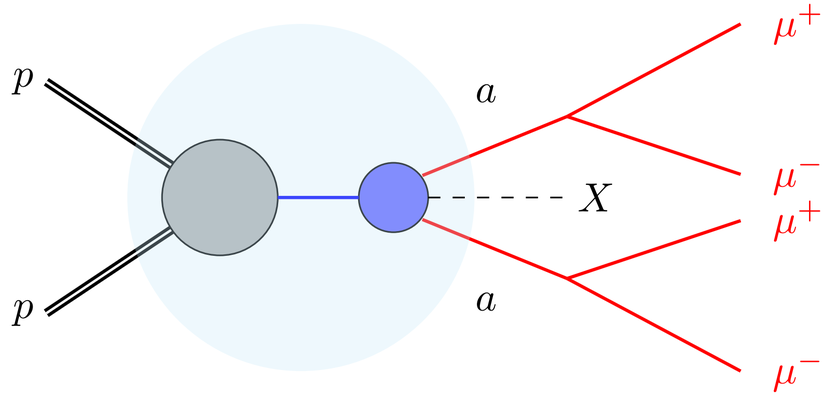
- No evidence for excess of events above SM background prediction
- **95% CL upper limits on** $\sigma_{VH}B(H \rightarrow aa \rightarrow 4b)/\sigma_{SM}$

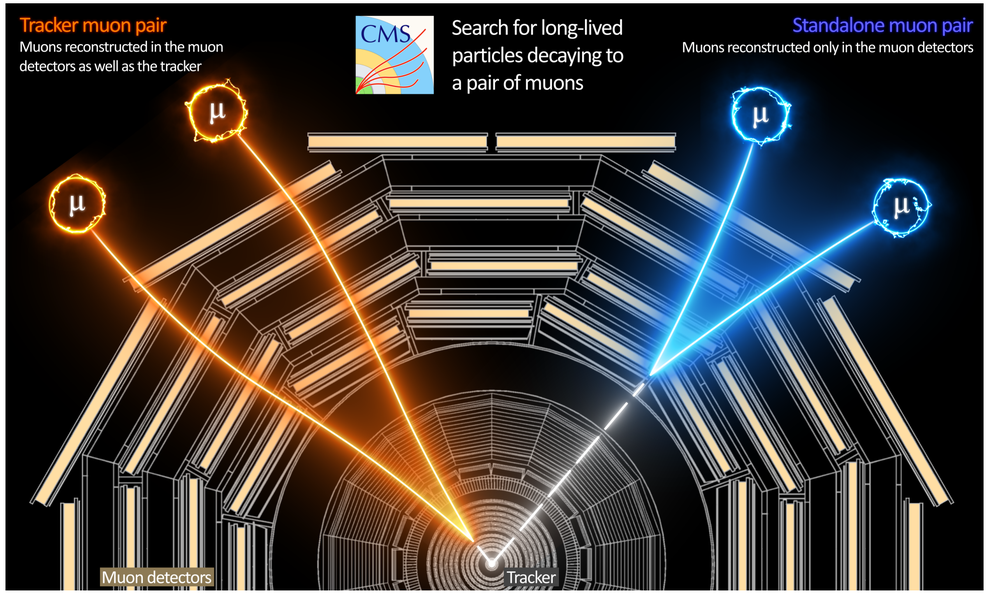


Diboson production in 4μ

arXiv:2407.20425

- **Model independent search in 4μ final state**
  - a → New neutral boson, produced from H, SM or non-SM portals
- Covers mass range **$0.21 < m_a < 60$ GeV**
- **Analysis performed with 2017 and 2018 data**
  - Combined with previously published 2016 results
- **Prompt and displaced-signatures considered**
  - Displaced → Only in 2018
  - New displaced muon trigger
    - Uses standalone (SA) muons
      - SA muons → Use only tracks in muon detector → Independent of PV



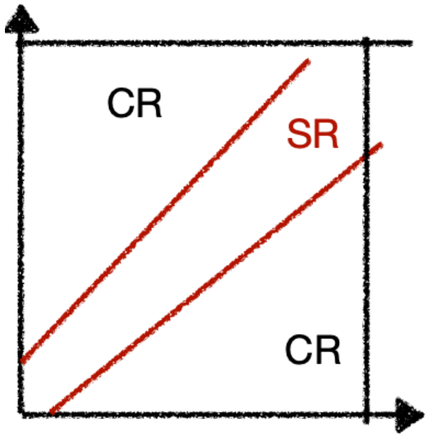


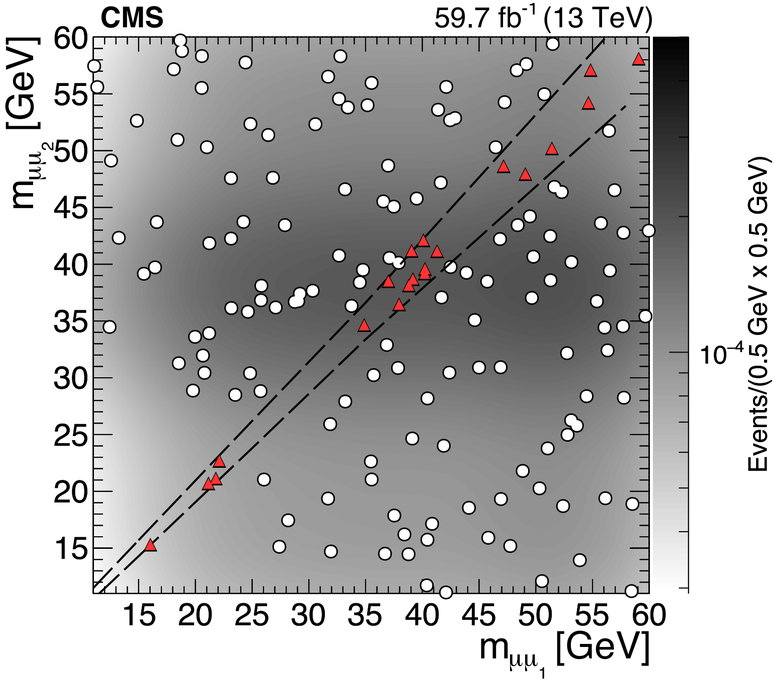
CMS Physics Briefing

Diboson production in 4μ

arXiv:2407.20425

- **Event selection**
  - 2017 → Select four muons from standard ParticleFlow reconstruction
  - 2018 → Allow one of the four muons to be an SA muon
  - **Two dimuon pairs with $m_{\mu\mu_{1,2}} < 60$ GeV**
- **Signal and control regions defined in a 2D plane of $m_{\mu\mu_1}$ and $m_{\mu\mu_2}$**
  - **SR → Signal mass window $|m_{\mu\mu_1} - m_{\mu\mu_2}| < W((m_{\mu\mu_1} + m_{\mu\mu_2})/2)$**
    - Window size optimised to contain 90% MC signal events
  - Background → Data driven
    - Divide mass range into regions below and above the Υ resonances



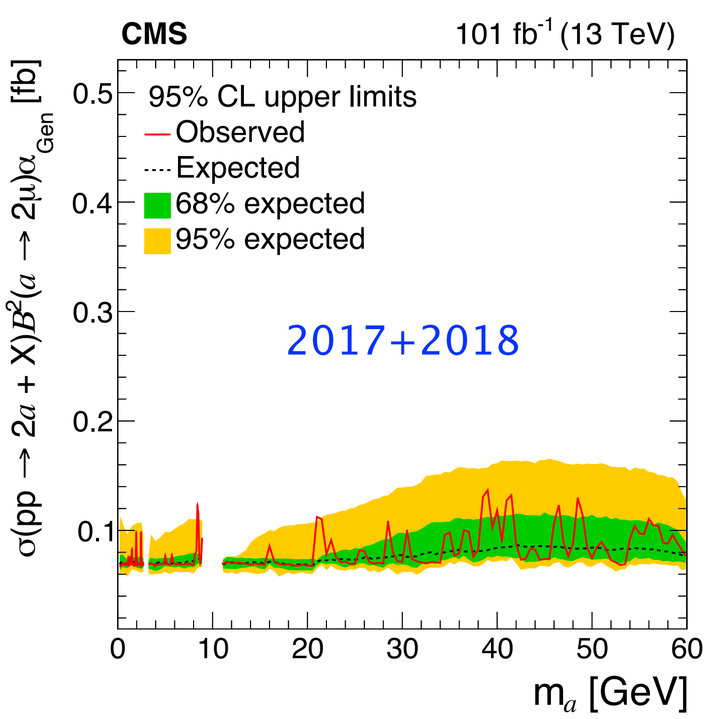


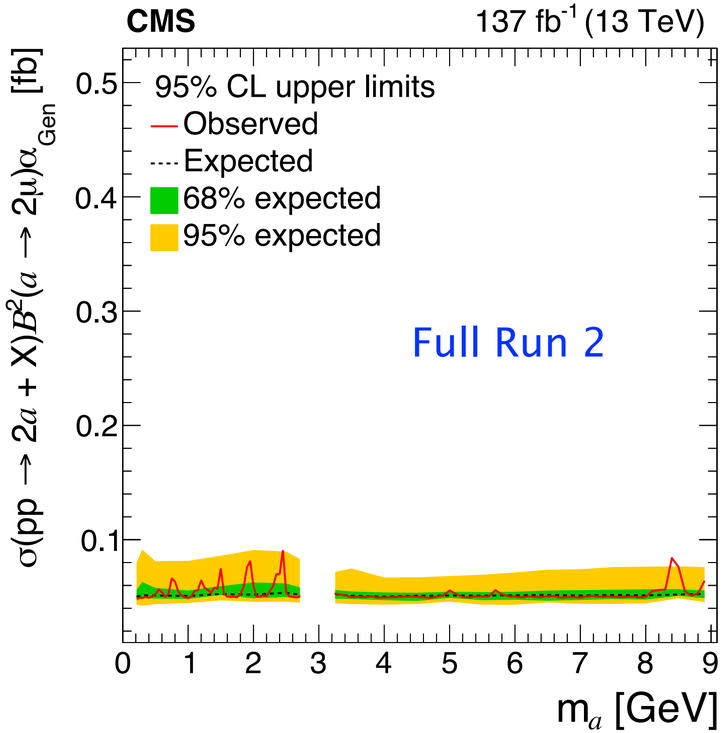
Diboson production in 4μ

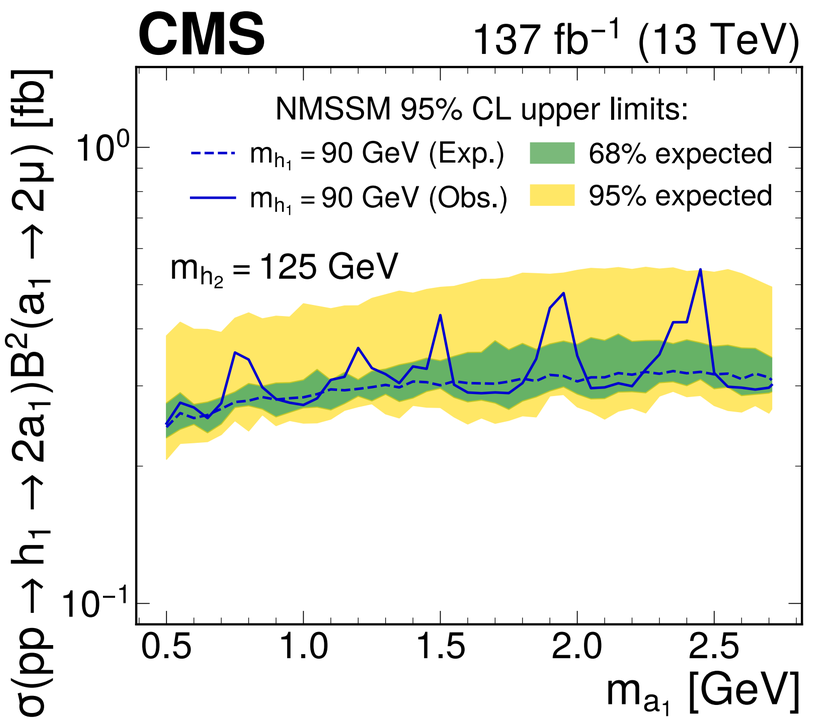
arXiv:2407.20425

- **Model-independent 95% CL upper limits on**
  $\sigma(\mathrm{pp} \to 2a + X)B^2(a \to 2\mu)\alpha_{gen}$
- α_{gen} → Fraction of events passing gen-level kinematic criteria

- NMSSM: a ≡ Pseudoscalar
- **95% CL upper limits set on**
  $\sigma(pp \to h_{1,2} \to 2a_1) \,.\, B^2(a_1 \to 2\mu)$





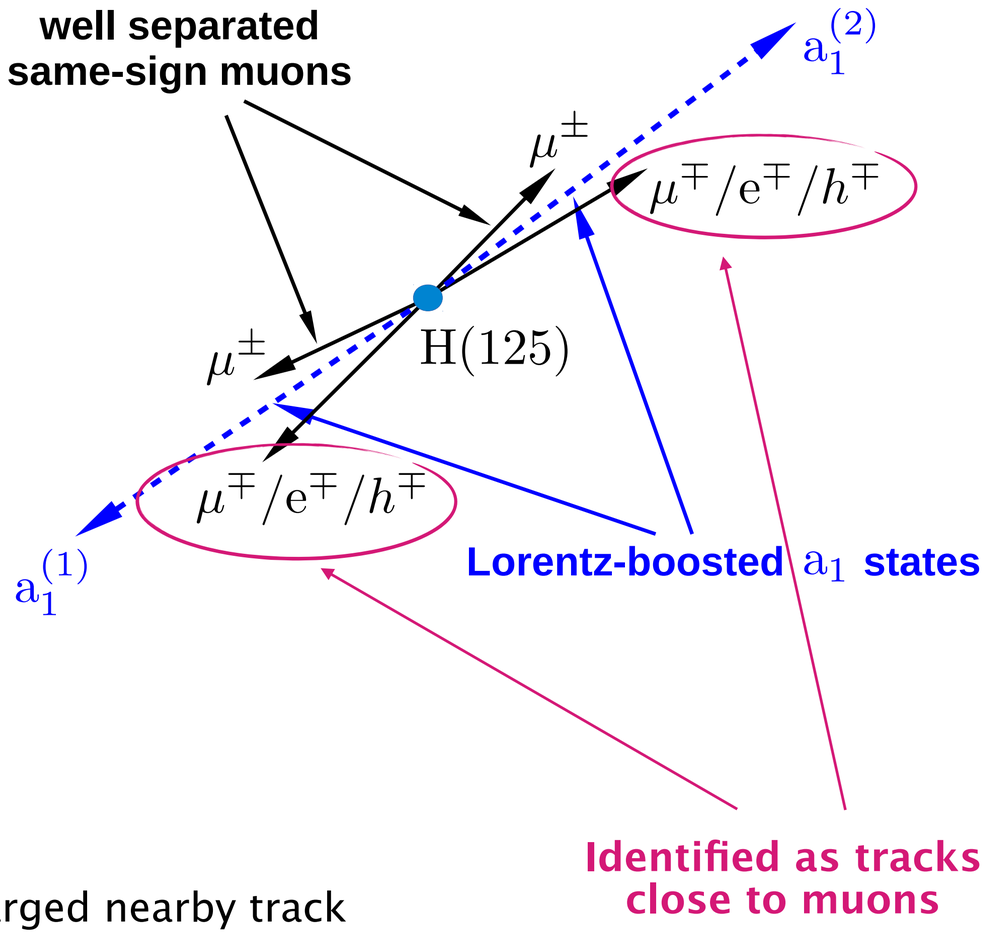


$H \rightarrow aa \rightarrow 4\tau$

NEW!

CMS-PAS-SUS-24-002

- Analysis targets $H(125) \rightarrow a_1 a_1$ decay, with $a_1 \rightarrow \tau_\mu \tau_{1\text{-prong}}$
- Probe low m_a regions: **$4 < m_a < 15$ GeV**
- **Highly boosted a bosons**
  - Decay products very collimated
  - Non-isolated leptons in final state
- **$H \rightarrow a_1 a_1 \rightarrow \mu\mu\tau_\mu\tau_{1\text{-prong}}$ also included** due to similar topology
- **Analysis strategy:**
  - Select same-sign muons with large angular separation
  - Require muons to be accompanied by only one oppositely charged nearby track
  - Reconstruct invariant mass of the two muon-track systems, m_1 and m_2

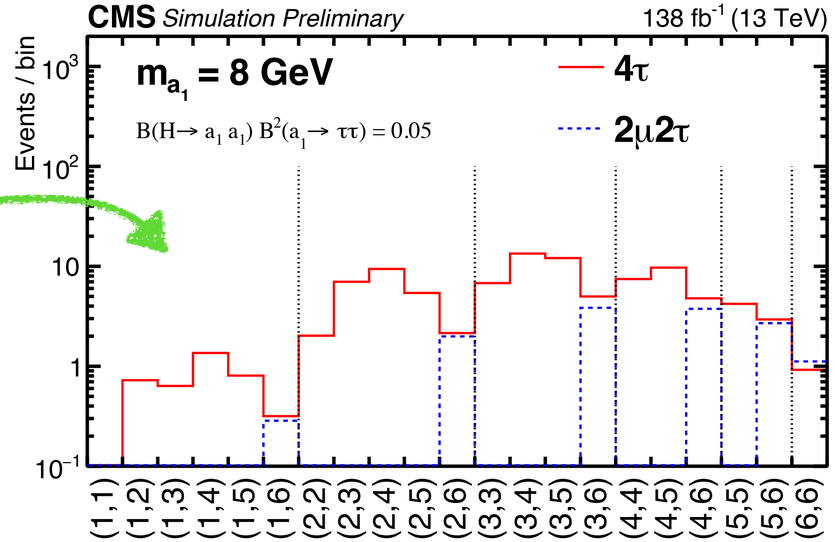


$H \rightarrow aa \rightarrow 4\tau$

NEW!

CMS-PAS-SUS-24-002

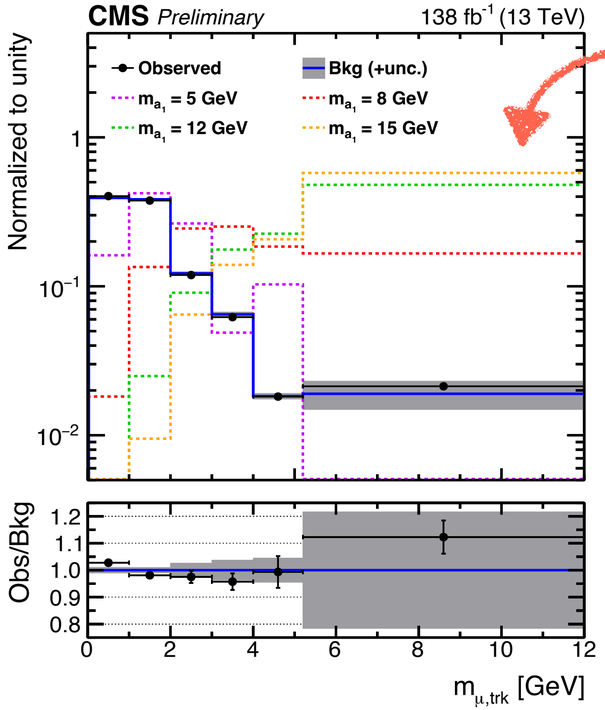
- **Signal modeling performed with simulated samples**



- **Background template constructed as:**

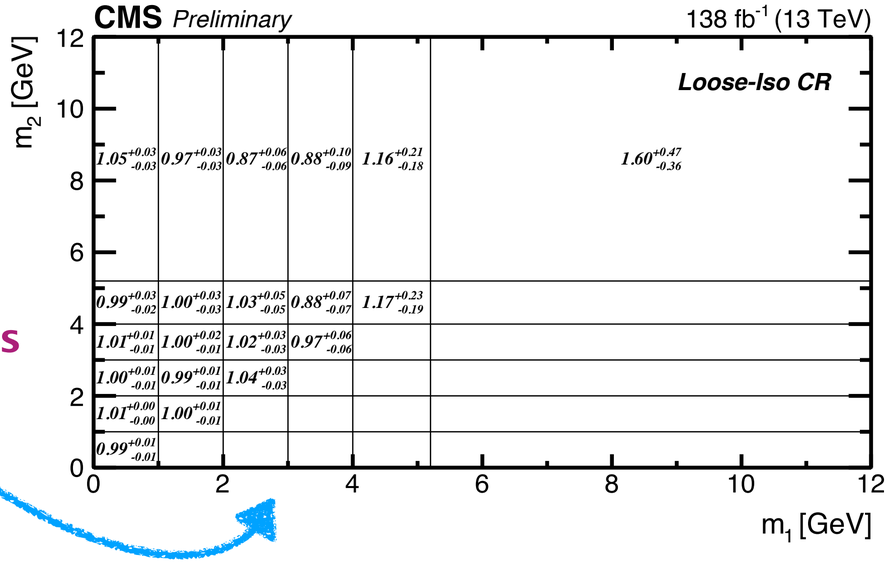
$$f_{2D}(i,j) = C(i,j)\ (f_{1D}(i)\, f_{1D}(j))^{sym}$$

- ✦ $f_{1D}(i)$ and $C(i,j)$ modelled using control regions in data



$f_{1D}(i)$: 1D muon–track inv mass distribution

$C(i,j)$: Correlation factors



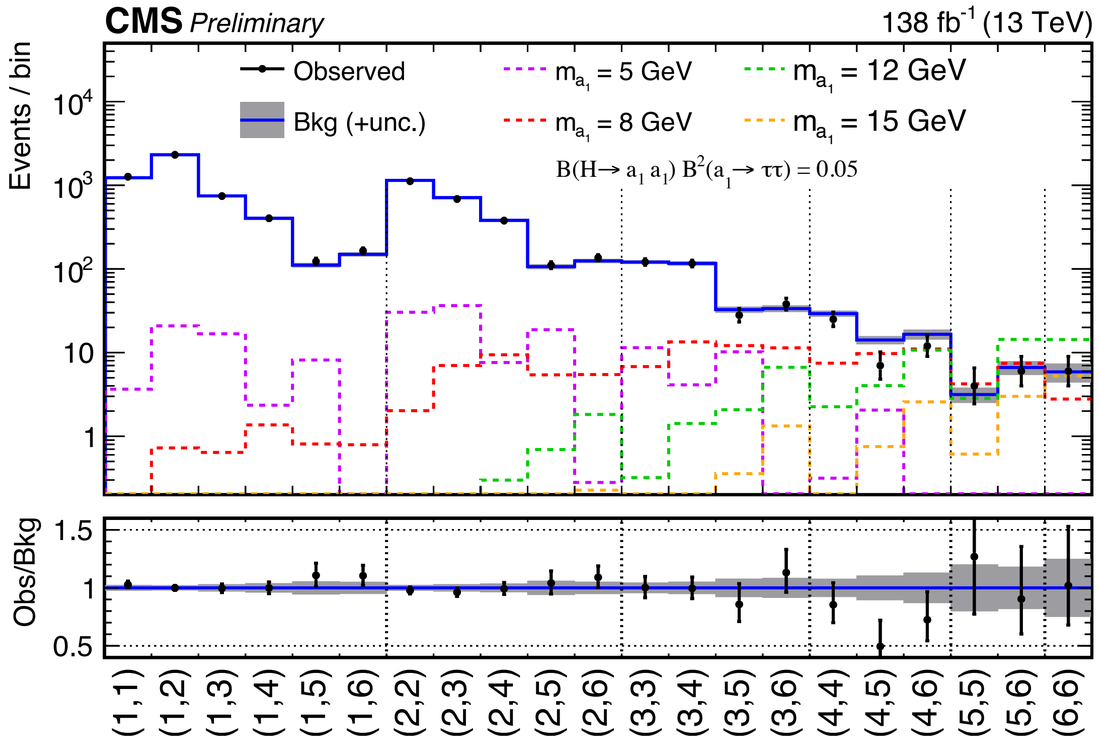
$H \rightarrow aa \rightarrow 4\tau$

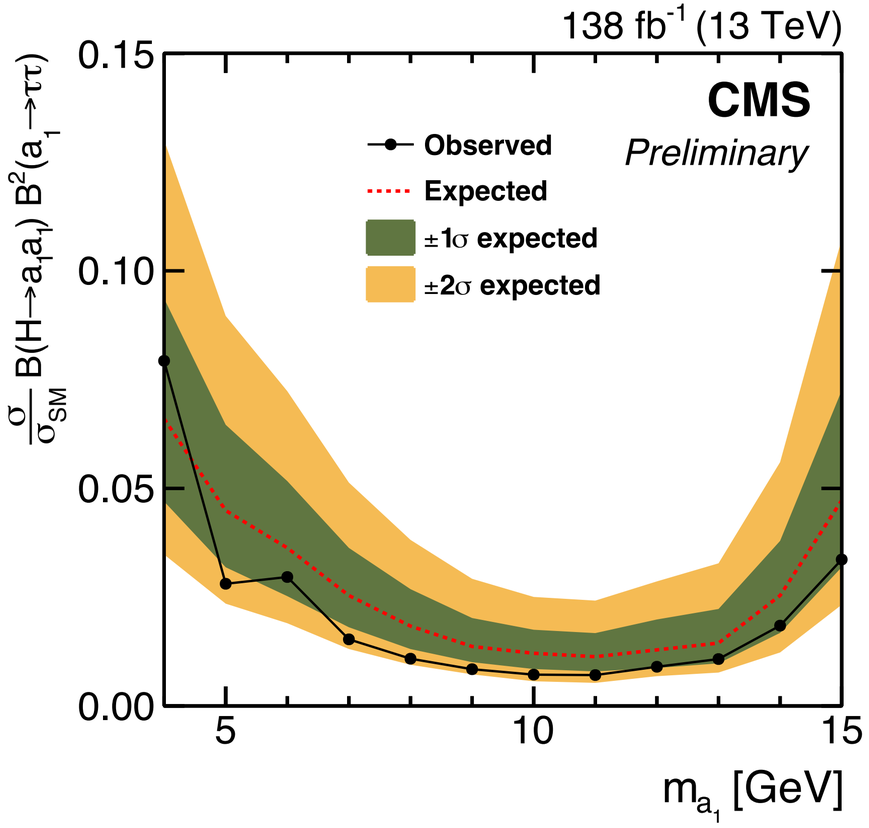
NEW!

CMS-PAS-SUS-24-002

- **2D distribution of invariant masses** of the muon-track systems used to discriminate between signal and background

- No significant deviation of observed events from SM background prediction
- **95% CL upper limits on** $\frac{\sigma}{\sigma_{SM}} . B(H(125) \rightarrow a_1 a_1) . B^2(a_1 \rightarrow \tau\tau)$



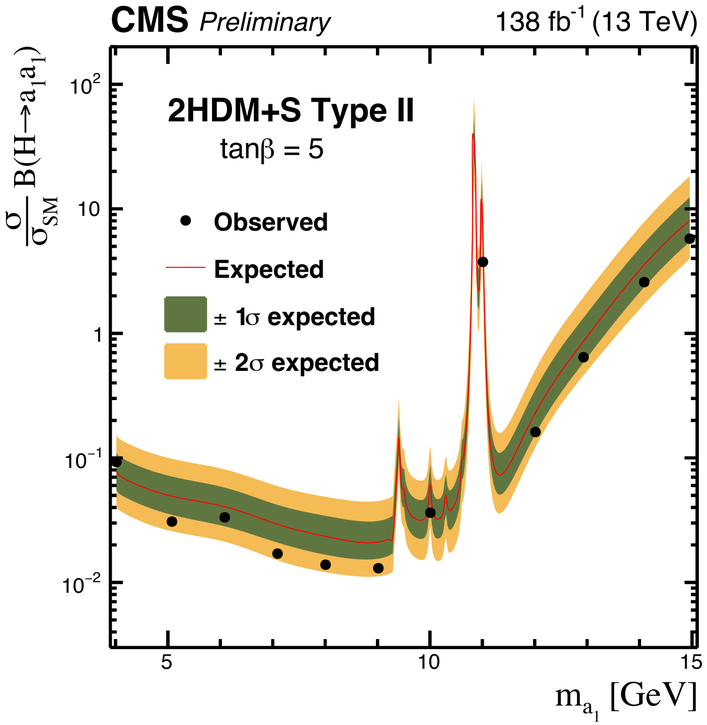


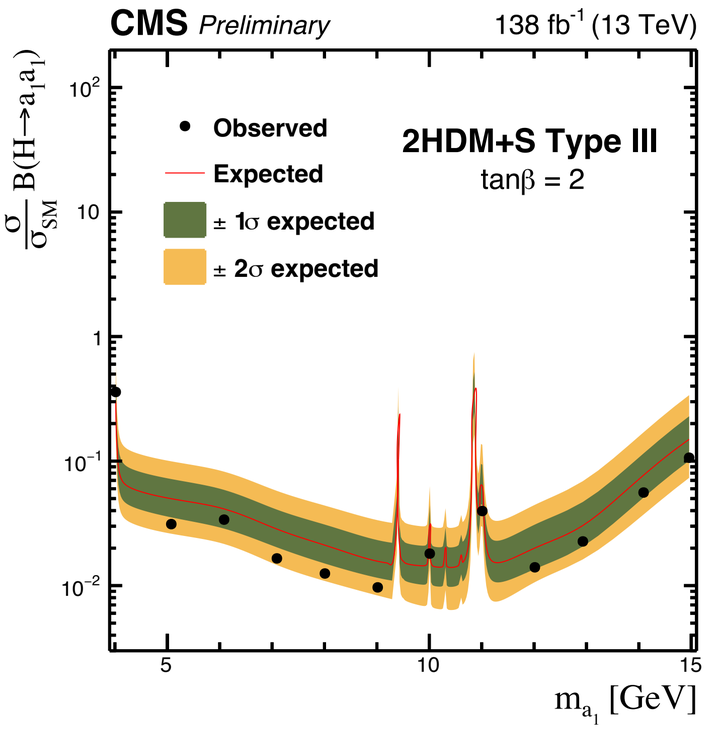
$H \rightarrow aa \rightarrow 4\tau$

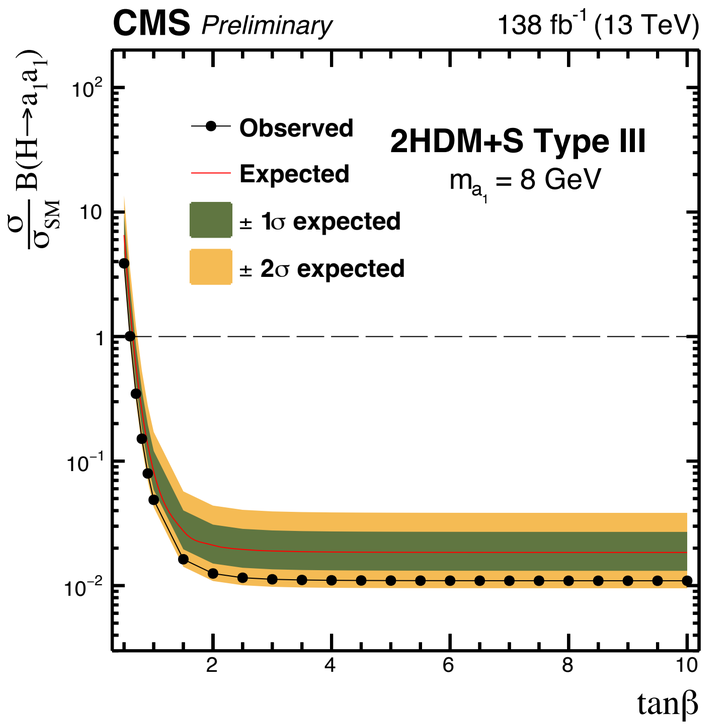
NEW!

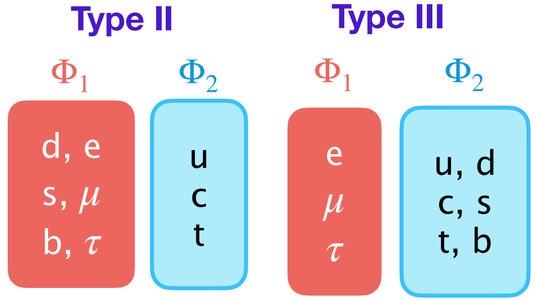
CMS-PAS-SUS-24-002

- **Model-dependent interpretations in the context of 2HDM+S as a function of m_{a_1} and tanβ**









- Most stringent limits for Type III for all mass points for tanβ > 2

Summary

- Rich set of H → aa searches performed in CMS targeting multiple final states
  - Extensive range of masses of the pseudoscalar boson covered, from very boosted to non-boosted topologies
- Presented the latest searches for exotic Higgs decays
  - H → aa → 4b: First search in this channel by CMS!
  - H → aa → 4μ: Explores new parameter phase space!
  - H → aa → 4τ: Improved sensitivities achieved!
- Focus on model-dependent interpretations
- No significant excess or deviation yet → Vast parameter phase-space still to be probed!

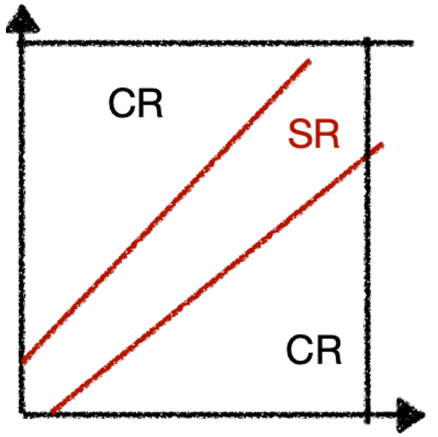
Stay tuned for several more interesting results!

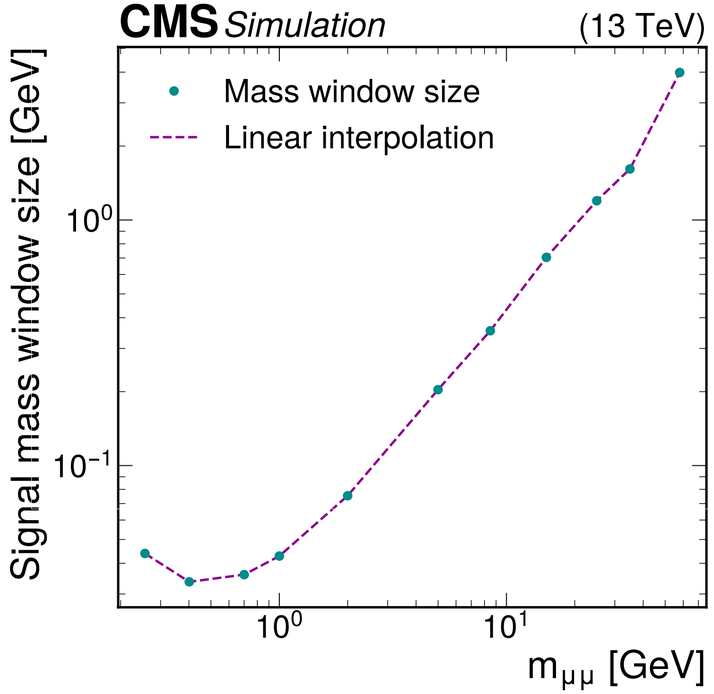
Backup

Diboson production in 4μ

arXiv:2407.20425

- **Signal Mass Window**
  - Determined by fitting MC signal shape with a double-sided Crystal Ball function to contain 90% events
  - Extract sigma parameter (signal resolution) for each simulated point
  - Plot as a function of the invariant dimuon mass
  - Interpolate the data points to create continuous mass window
  - Wider mass window size at masses below 0.4 GeV due to deteriorating mass resolution for the near-collinear dimuon system in decays of low-mass bosons

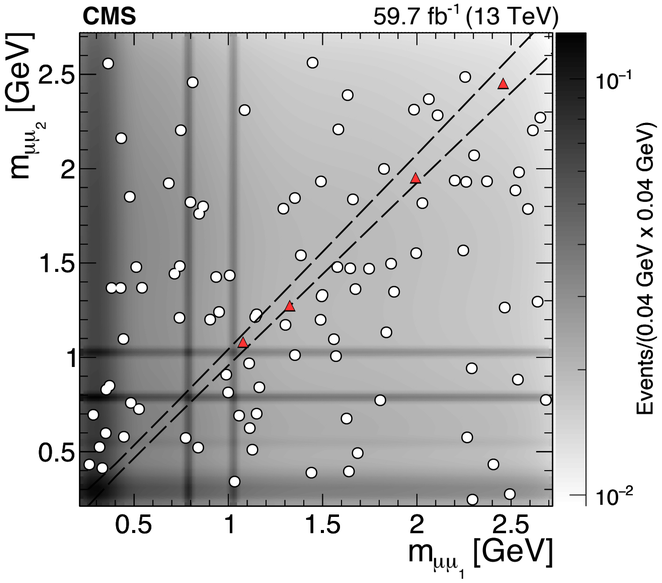


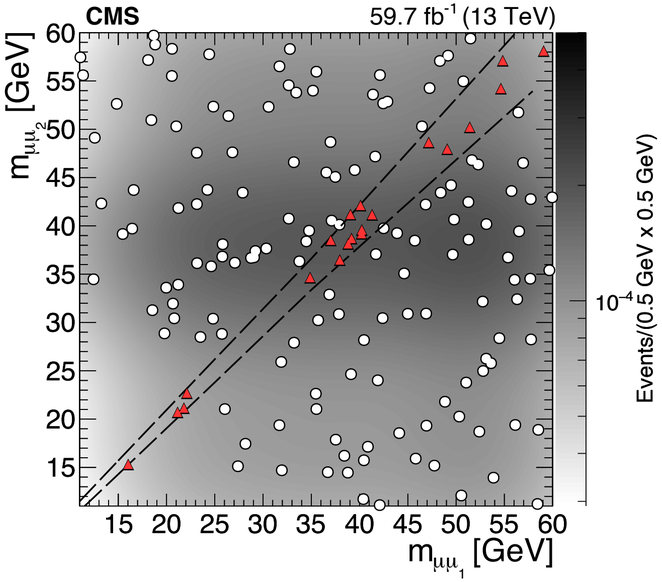


Diboson production in 4μ

arXiv:2407.20425

- **Background Modeling**
  - Below the Upsilon resonance (0.25 – 9 GeV):
    - Dominated by QCD multijet processes (e.g. Two b quarks decay to 2μ + X) or low mass resonances $\omega, \rho, \phi, \Psi(2S)$
    - Used a data-driven two-dimensional template
  - Above the resonance (11–60 GeV):
    - Electroweak processes with two Z bosons, top pair, and Drell-Yan (DY)
    - Used a kernel density estimate (KDE) method with normalization derived from data
  - Calculate PDF density of signal region and control region
    - Number of events in the signal region: $N_{B_{SR}} = \frac{I_{SR}}{I_{CR}} N_{CR}$

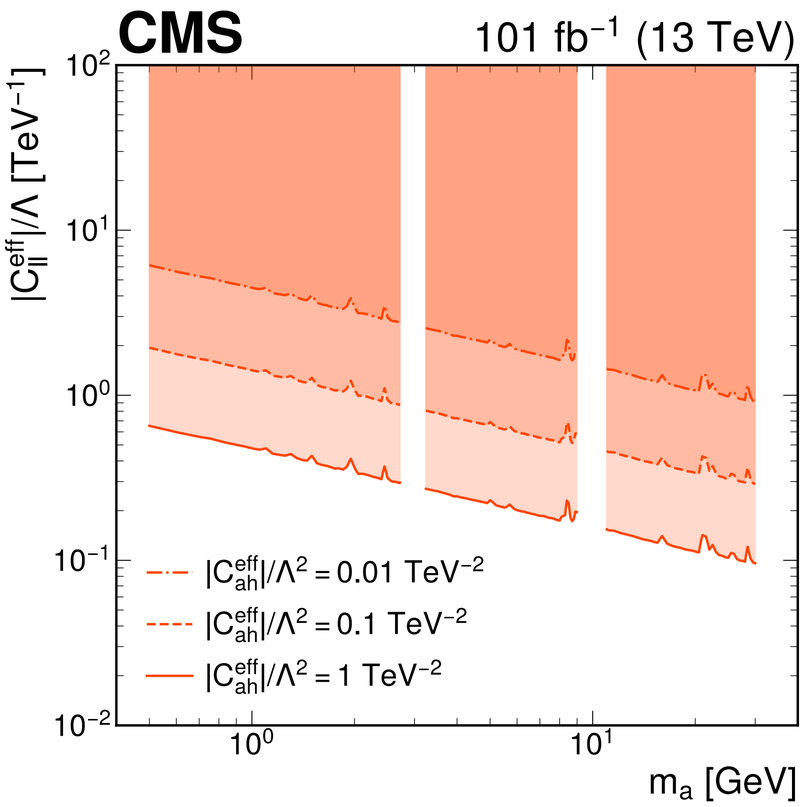




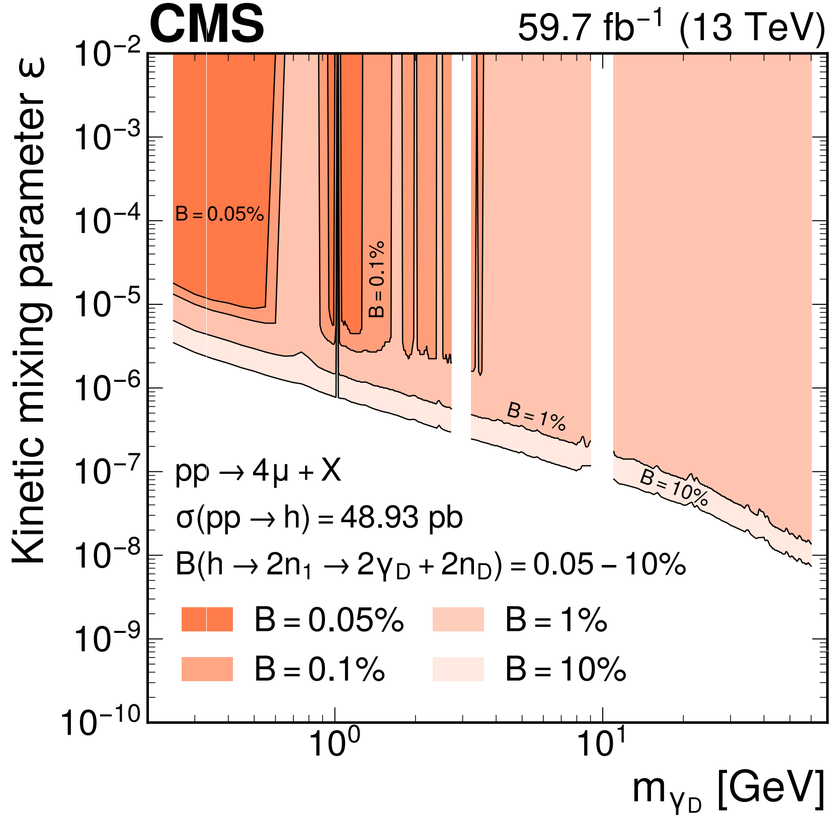
Diboson production in 4μ

arXiv:2407.20425

- ALP models: a ≡ ALP
- **Limits on the effective coupling of the ALP to the SM leptons,** for different choices of the ALP to the SM Higgs



- Dark SUSY scenario:
  $pp \rightarrow h \rightarrow 2n_1 \rightarrow 2\gamma_D + 2n_D \rightarrow 4\mu + X$
- **Limits set on product of H production cross section and BR oh Higgs decay to a dark photon pair**



$H \rightarrow aa \rightarrow 4\tau$

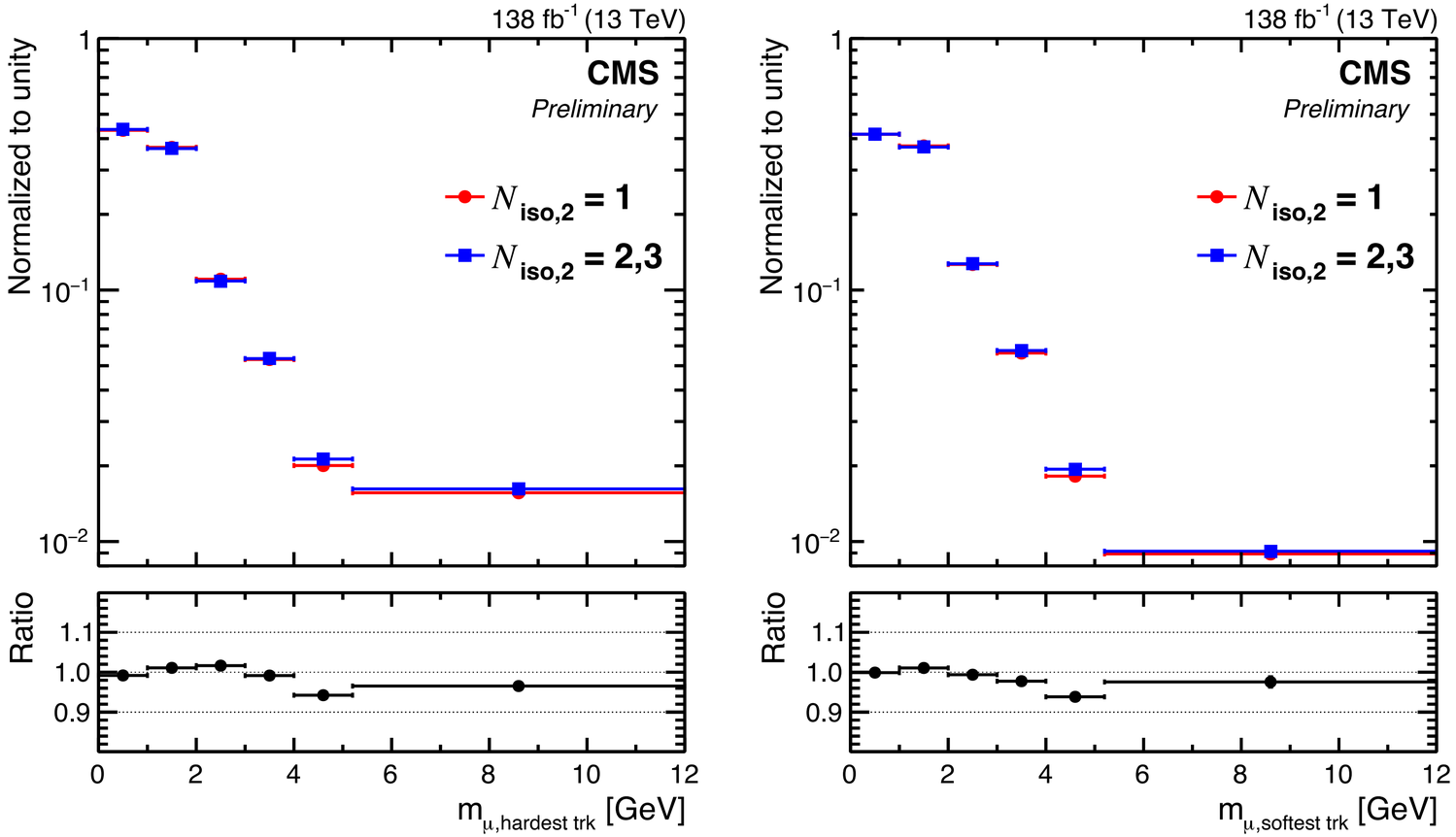
CMS-PAS-SUS-24-002

- Performed from specific **QCD-enriched** control region in data called N_{23} :
  - First muon with one associated signal track
  - Second muon **non-isolated**, i.e with two or three close-by isolation tracks
- **Invariant mass of first muon and associated track used to construct** $f_{1D}(i)$
- Modelling based on the **assumption** that **kinematic distributions for first muon-track system not affected by isolation requirement of second system**
- **Hypothesis verified using additional control regions:**
  - $N_{iso,2\,=\,1}$ → second muon has only one "signal" track **(just like the SR)**
  - $N_{iso,2\,=\,2,\,3}$→ second muon has two or three "isolation" tracks **(as in N_{23} region)**
  - In both cases, first muon has $N_{iso} > 1$, $N_{sig} \geq 1$

$H \rightarrow aa \rightarrow 4\tau$

CMS-PAS-SUS-24-002

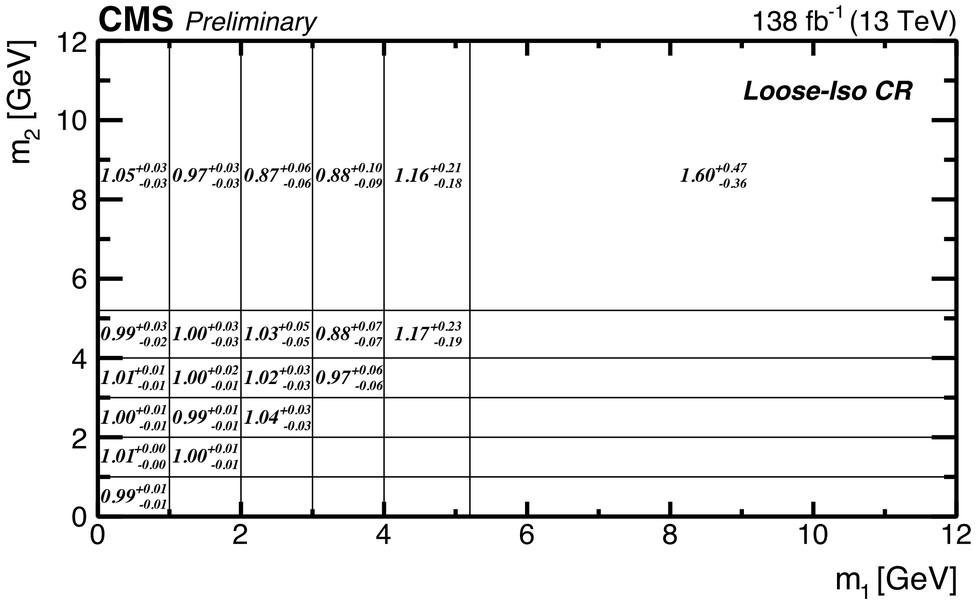
- **Invariant mass distributions of the first muon and its softest or hardest accompanying track** between the two different isolation scenarios of the second muon

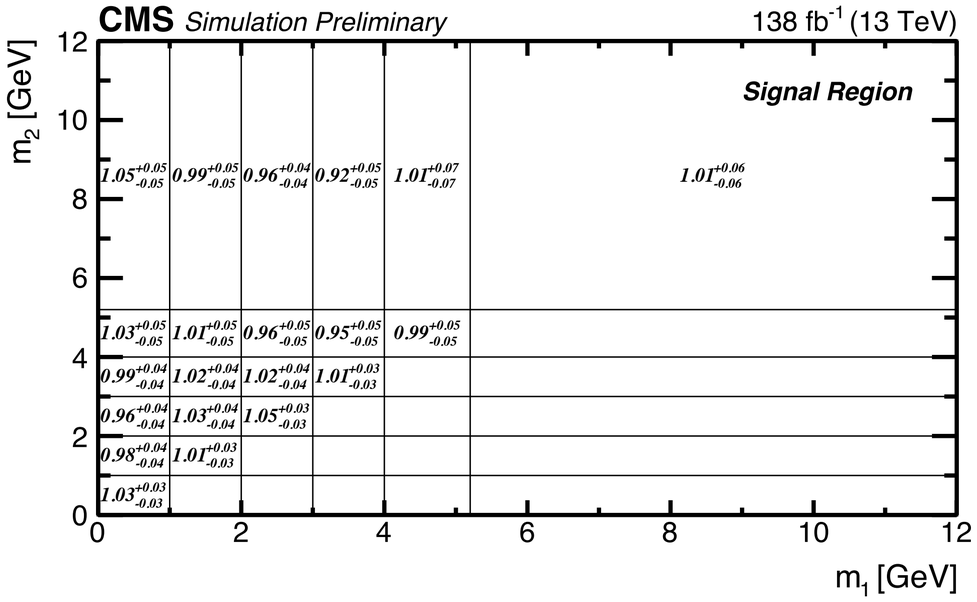


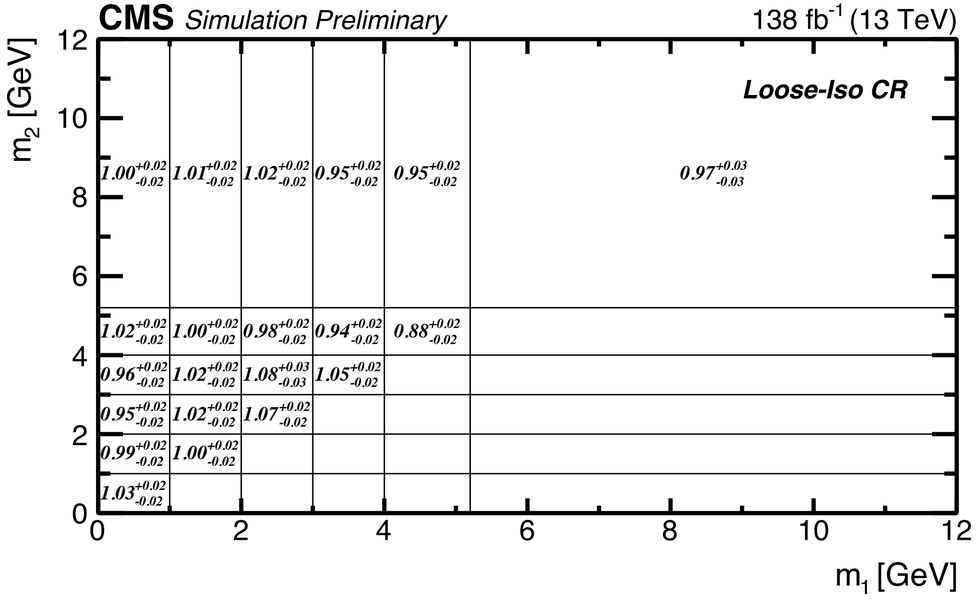
- **Distributions differ in each bin by less than 7%**
  - Inv. mass of the muon-track system forming an a_1 candidate **not highly sensitive** to the isolation req. on the second muon
- **Observed differences treated as shape uncertainty** in the normalized $f_{1D}(i)$ template

$H \rightarrow aa \rightarrow 4\tau$

CMS-PAS-SUS-24-002







- To obtain estimates of $C(i,j)$ in the signal region:

$$C(i,j)^{SR}_{data} = C(i,j)^{CR}_{data} \times \frac{C(i,j)^{SR}_{MC}}{C(i,j)^{CR}_{MC}}$$

Coefficients in data in SR

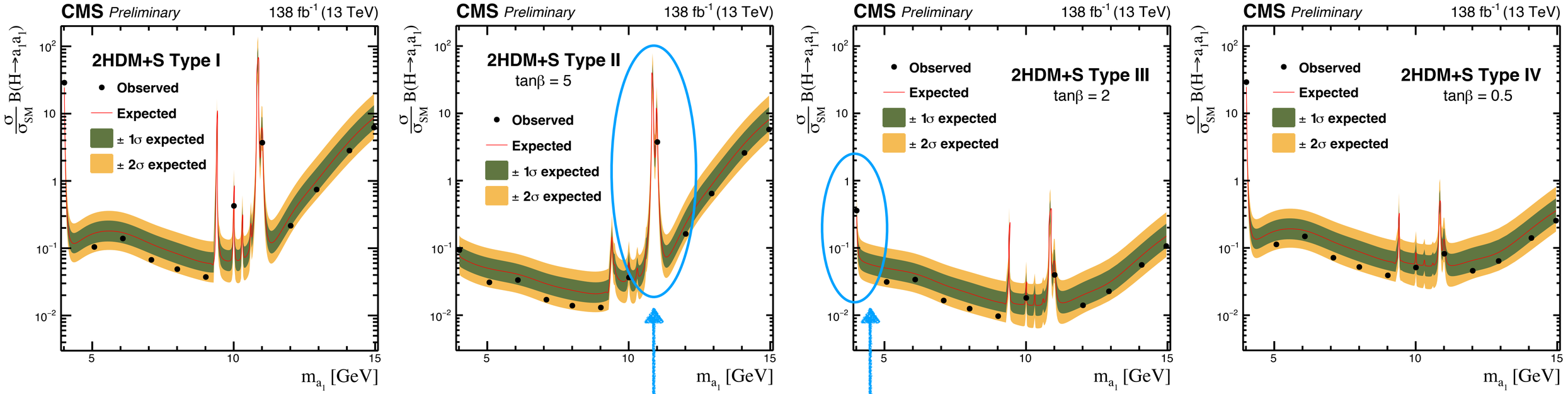
Coefficients in data in CR

Extrapolation factor

$H \rightarrow aa \rightarrow 4\tau$

CMS-PAS-SUS-24-002

- **95% CL upper limits on $\frac{\sigma}{\sigma_{SM}} . B(H(125) \rightarrow a_1 a_1)$ vs m_{a_1} for benchmark tanβ for 2HDM+S Type I, II, III, IV**



- **Peak like structures in mass regions where quarkonium states like η_c and η_b present**
- Mixing of a_1-quarkonium states → Sudden increase in the hadronic decay width due to non-perturbative QCD

	$m_{\eta_b(n)}$	$\lvert R_{\eta_b(n)}(0)\rvert$	$m_{\eta_c(n)}$	$\lvert R_{\eta_c(n)}(0)\rvert$
$n = 1$	9.4	2.71	2.98	0.90
$n = 2$	10.0	1.92	3.64	0.73
$n = 3$	10.3	1.66	3.99	0.67
$n = 4$	10.6	1.43	—	—
$n = 5$	10.85	1.41	—	—
$n = 6$	11.0	0.91	—	—

JHEP03(2018)178