Rare decays of the SM Higgs boson to light pseudoscalars in the CMS Experiment

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Exotic decays of SM Higgs boson to light scalars

Searches for $h \rightarrow aa$

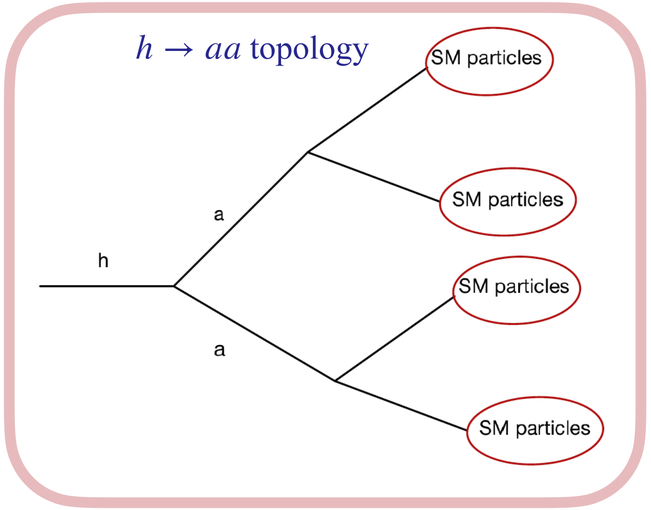
- CMS has put an upper limit of 16% on the B($h \rightarrow BSM$) at 95% CL → searches in exotic final states have potential for discovery

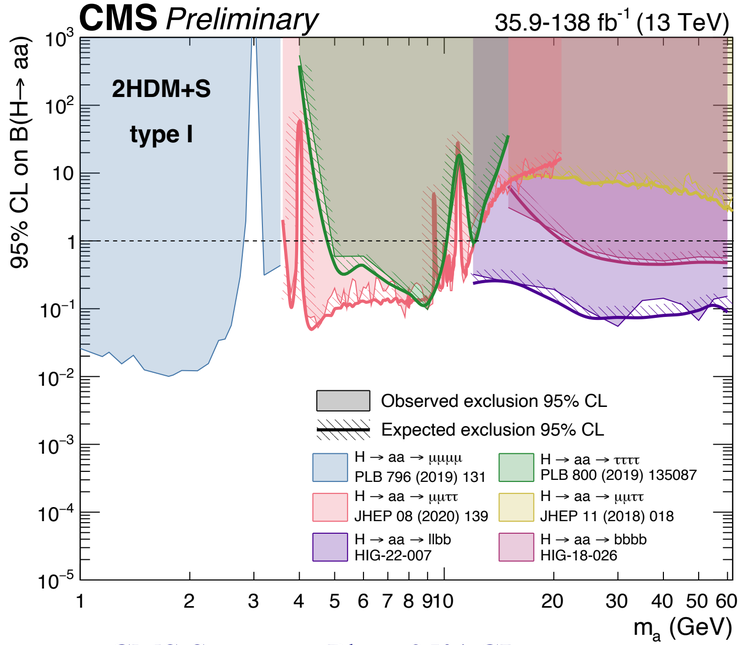
  $\Longrightarrow$Rare Higgs decays may provide window into BSM physics

- SM Higgs decay width is extremely narrow → even BSM particles with low couplings to SM Higgs can have reasonable branching fractions
  - Opportunity for rare Higgs decay searches!

Focus of talk: Searches for 125 GeV Higgs → 2 pseudoscalars (a bosons) → SM particles

- Popular interpretation in 2HDM+S Model: 2 Higgs Doublet+ Singlet extension of SM Higgs
  - Higgs doublets have vevs v_1, v_2, used to define $tan\beta \equiv \frac{v_1}{v_2}$
  - 4 types (Types I, II, III, IV) defined based on interactions with fermions
  - Model parameters set such that BR($a \rightarrow SM$) is close to BR($h \rightarrow SM$)
- Model independent searches explored in talk





CMS Summary Plot : 95% CL on B($h \rightarrow aa$ for 2HDM+S Type I)

Focus of talk: CMS $h \rightarrow aa$ searches

This talk will focus on recent CMS results analyzing Run-2 data:

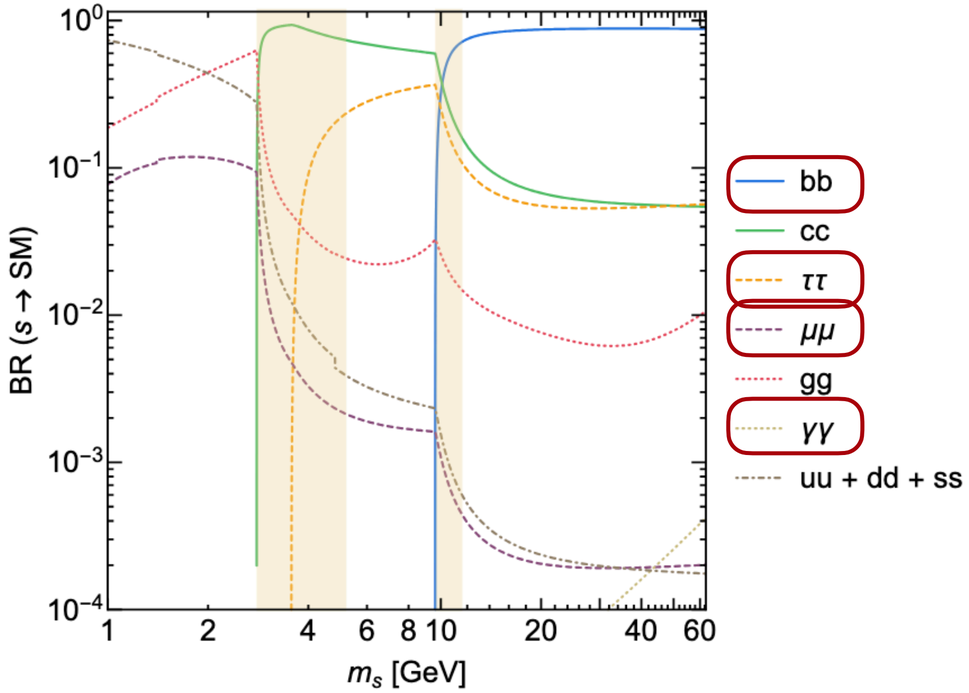
1. $H \rightarrow aa \rightarrow 4e$ (CMS-PAS-EXO-24-031)
   - Interpreted in ALP theories

   $10\ \text{MeV} \leq m_a \leq 100\ \text{MeV}$
2. $H \rightarrow aa \rightarrow 4\gamma$ (CMS-PAS-EXO-24-025)
   - Model independent search

   $1\ \text{GeV} \leq m_a \leq 15\ \text{GeV}$
3. $H \rightarrow aa \rightarrow 4\tau/2\tau 2\mu$ (CMS-PAS-SUS-24-002, arXiv:2508.06947)
   - Both model independent and 2HDM+S interpretations
4. $H \rightarrow aa \rightarrow 2b2\tau$ (CMS-PAG-HIG-22-007, EPJ C 84 (2024) 493)
   - 2HDM+S interpretation
   - Combination with $\mu\mu bb$ final state shown in paper

   $12\ \text{GeV} \leq m_a \leq 60\ \text{GeV}$

B($a \rightarrow SM$) for 2HDM+S Type I



arxiv:1312.4992

- Other recent searches not detailed in talk include $H \rightarrow aa \rightarrow \mu\mu hh$ (CMS-PAS-EXO-24-034) → See LLP talk by Jingyu Luo on 26th August

$H \rightarrow aa \rightarrow 4e$

Overview

- $10 < m_a < 100$ MeV
- Interpreted in axion-like particles theories $\Longrightarrow$ a is DM mediator
- Challenge: Highly collimated final state
- Final state: *eeee*
- Reconstruction of Merged e^-e^+ pairs (MEPs):
  - From GSF tracks in CMS silicon tracker
  - $\Delta R < 0.015$ between the tracks
  - BDT for identification of MEPs

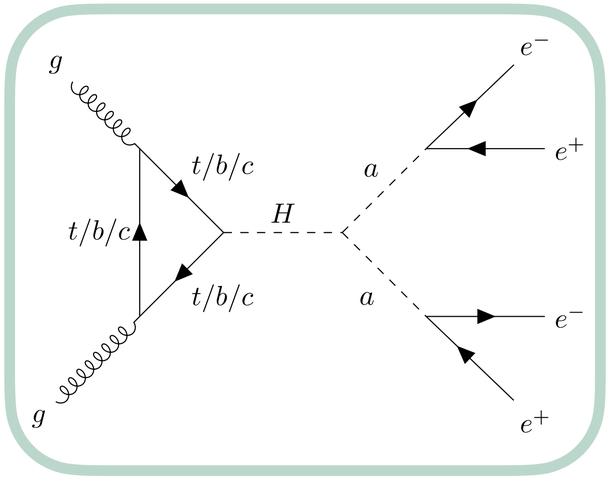
Analysis strategy: Require 2 MEPs

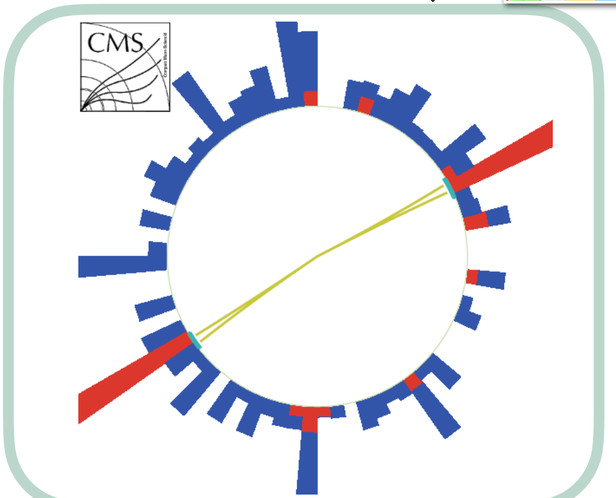
- Signal extraction from m_{4e}

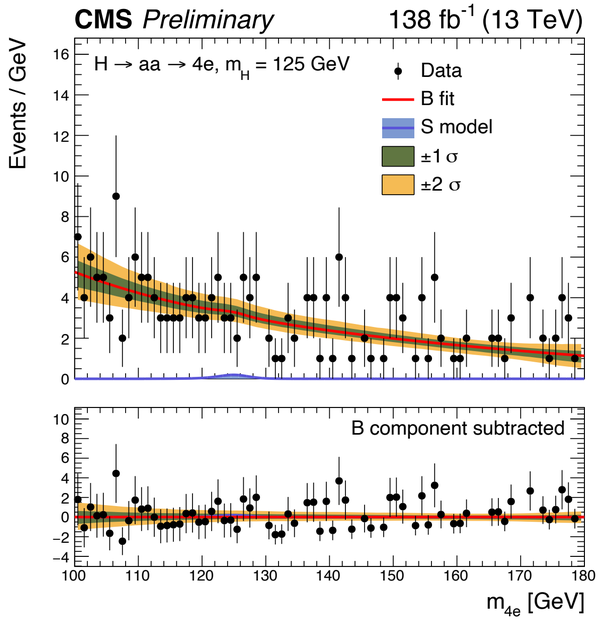
Backgrounds:

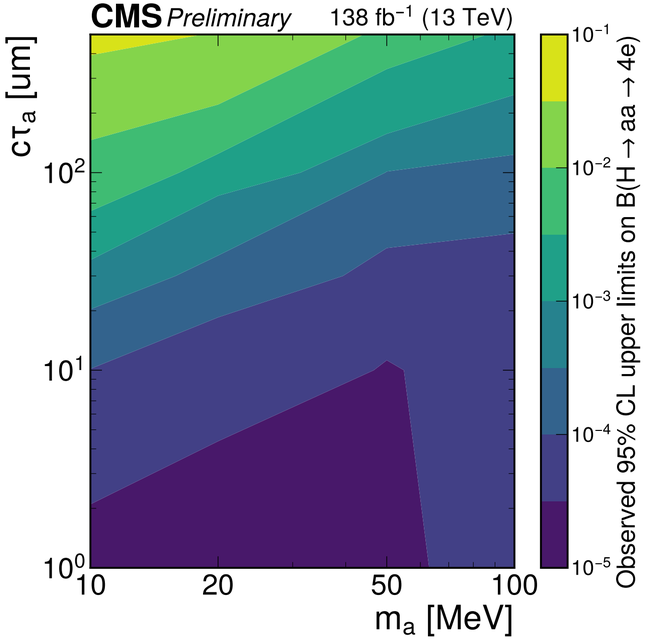
- Prompt and non-prompt photons- From Data in side-band regions
- Other processes- From MC

Results: First of its kind to set limits for $m_a < 100$ MeV







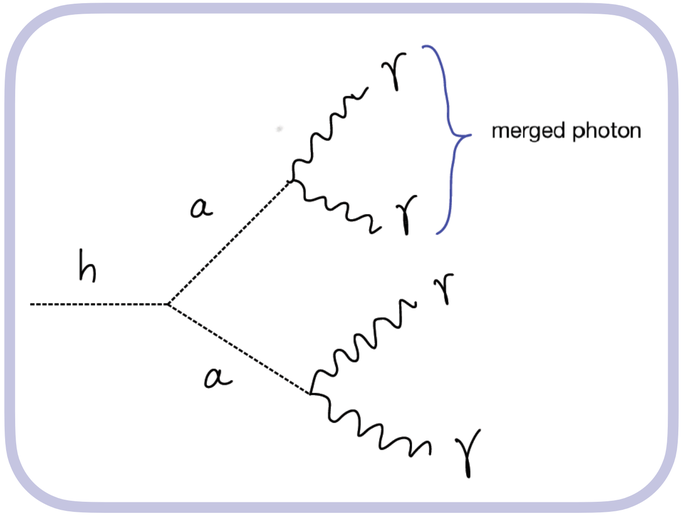


Observed and expected limits at 95% CL for different decay lengths of a

$H \rightarrow aa \rightarrow 4\gamma$

Motivation/Overview

- Model independent search: interpreted in NMSSM, ALP, 2HDM theories
- Final state: 1 merged pair of photons, 1 resolved photon
- Triggers used: diphoton triggers



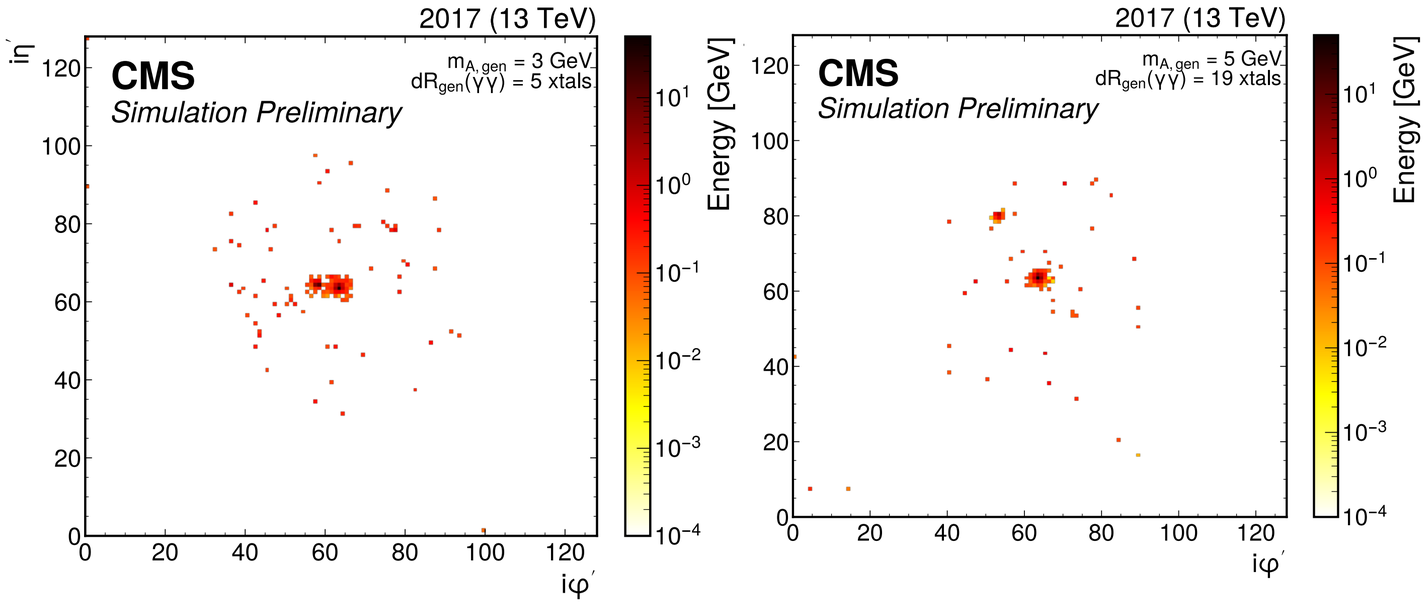
Event selections:

- Require exactly 3 reconstructed photons
- $m_{\gamma\gamma\gamma} > 90$ GeV
- $p_T(\gamma 1) > m_{\gamma\gamma\gamma}/3$ and $p_T(\gamma 2) > m_{\gamma\gamma\gamma}/4$

Background Estimation

1. QCD
2. photon+ jet:
3. Prompt di-photon

Backgrounds are estimated using data driven methods in Side-band region

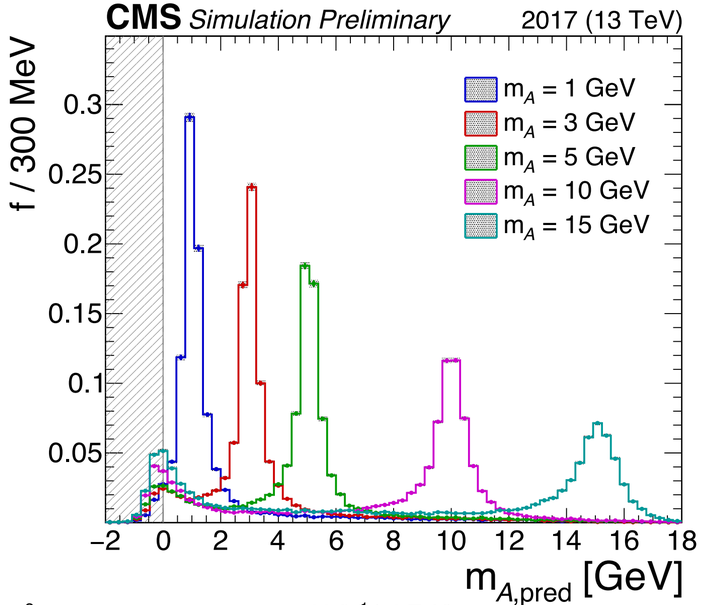


Energy deposit maps in CMS ECAL showing clusters reconstructed as photons

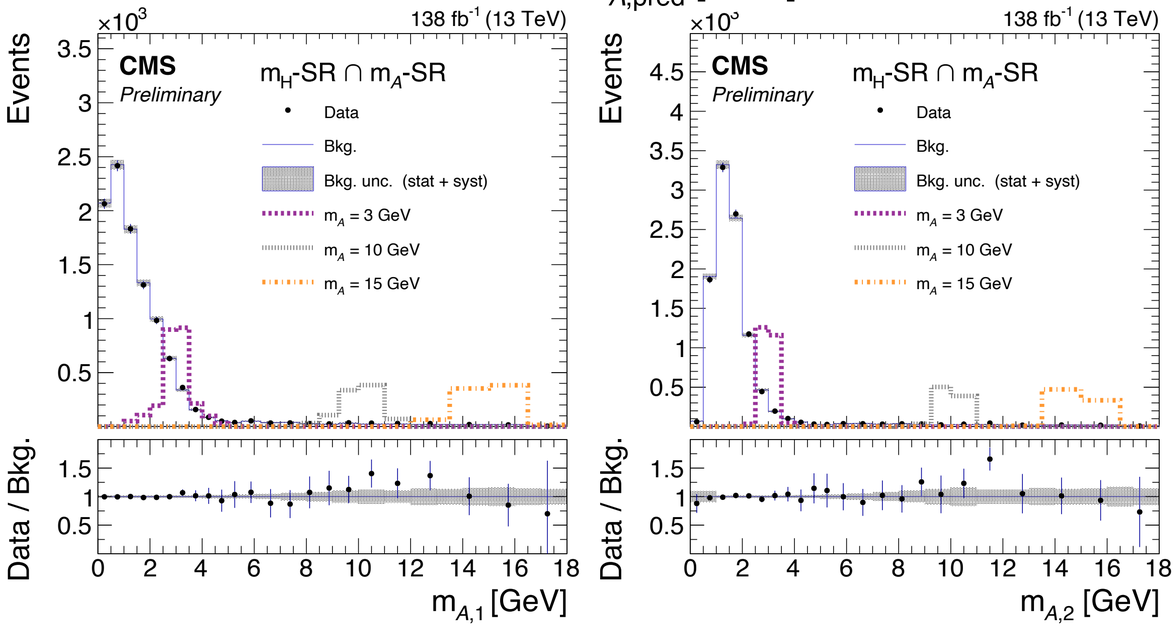
$H \to aa \to 4\gamma$

Analysis Strategy

- For a decaying to fully resolved $\gamma\gamma$: reconstruct p_4 sum of 2 of the closest γ
- For a decaying to merged $\gamma\gamma$: use ML techniques
  - ML regressor fed with ECAL rechit map images
  - GNN trained with privately produced particle guns
- Make 2D distribution of a masses
- Use $\Delta m_a = (m_a(\text{merged leg}) - m_a(\text{resolved leg}))$ and $m_{\gamma\gamma\gamma}$ to define:
  - Signal region (SR): $(\Delta m_a <= 2\text{GeV}) \cap (100 < m_{\gamma\gamma\gamma} < 140\ \text{GeV})$
  - Side band regions (SB): $\Delta m_a > 2\ \text{GeV}$
    - $m_{\gamma\gamma\gamma}$ outside SM Higgs mass window also used to define SBs
    - Used for background estimation



Predicted mass distributions from the ML regressor on the merged leg of $h \to aa \to 4\gamma$



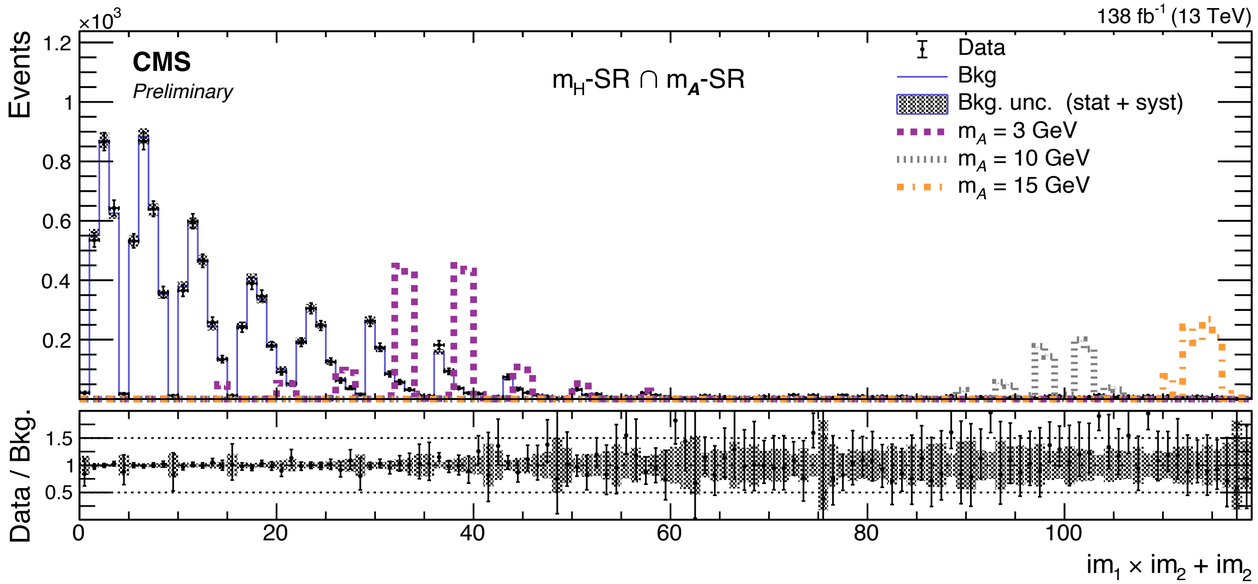
1D projections of the 2D m_a spectra in the SR

$H \rightarrow aa \rightarrow 4\gamma$

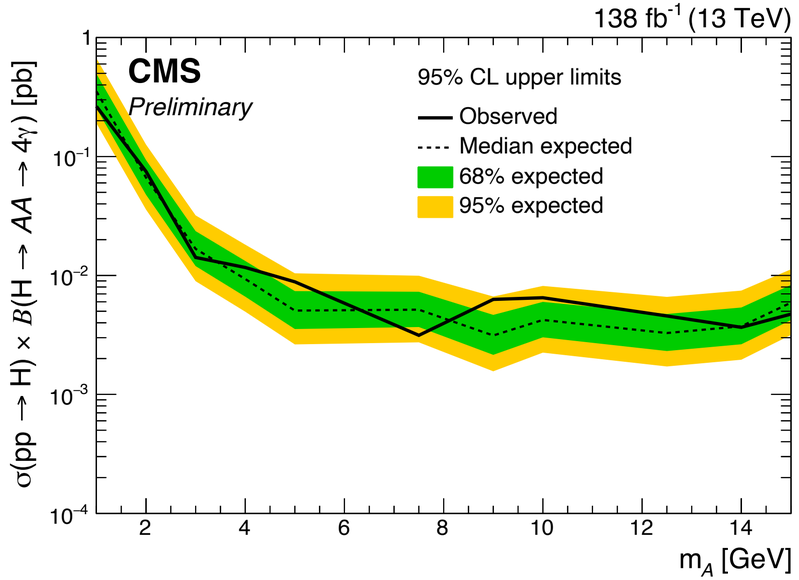
Results

- Signal extracted from simultaneous maximum likelihood fit in 2D m_a distribution

- Analysis sensitive in mass range between previous merged (arXiv:2209.06197) and resolved analyses (arXiv:2208.01469) in CMS



Unrolled distribution of the 2D m_a spectra in the SR

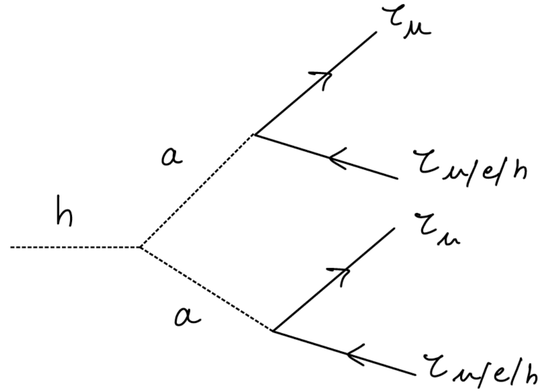


Observed Limits at 95% CL for the exclude signal strength of $h \rightarrow aa \rightarrow 4\gamma$

$H \rightarrow aa \rightarrow 4\tau/2\tau 2\mu$

Motivation/ Overview

- Interpreted in model independent as well as 2HDM+S theories
- Final state: $\tau_{\mu}$and $\tau_{1-prong}$
  - $a \rightarrow \mu\mu$ events also selected but analysis is not optimized for it

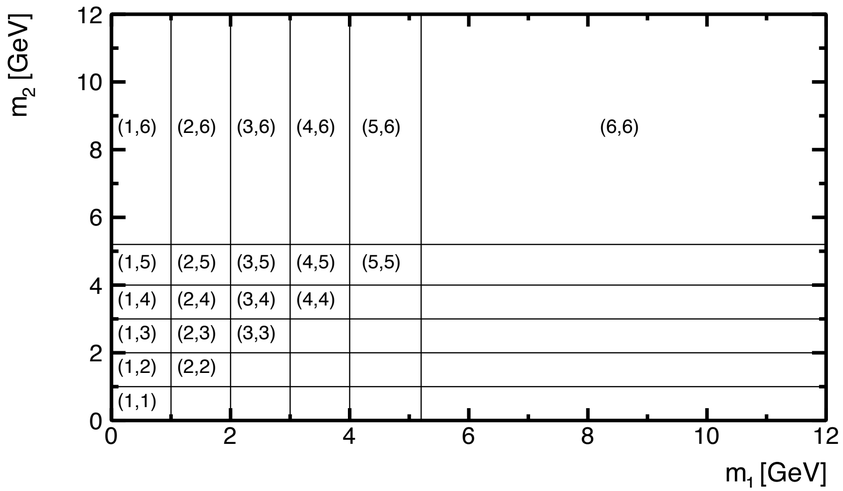


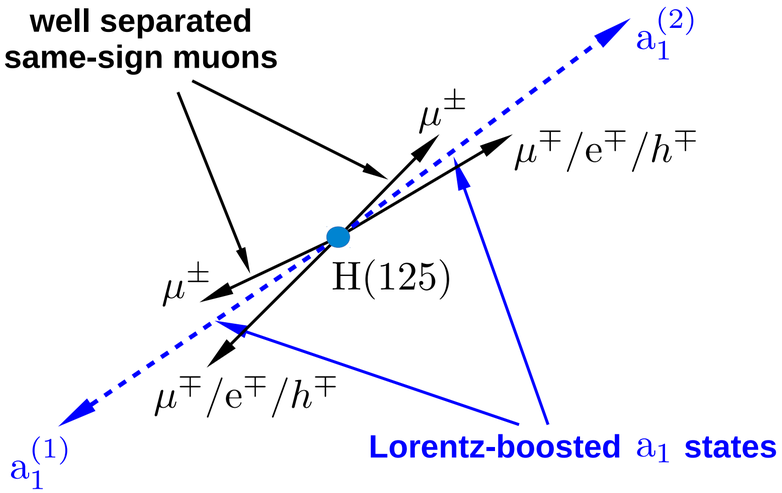
Event Selection:

- Same signed muons, well separated
- Opposite signed charged track nearby
- Triggers: Same signed dimuon triggers

Analysis strategy:

- Signal extraction from 2D map of $m_a(1)$, $m_a(2)$ distribution





Event selections

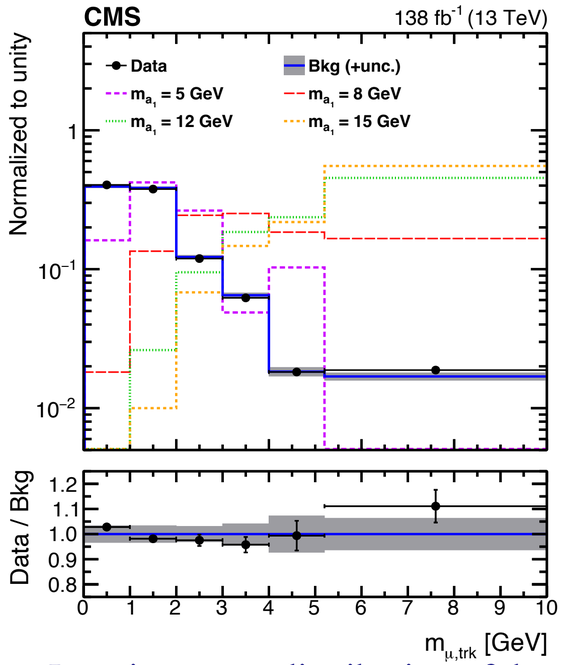
$H \rightarrow aa \rightarrow 4\tau/2\tau 2\mu$

Background estimation: Data driven methods used

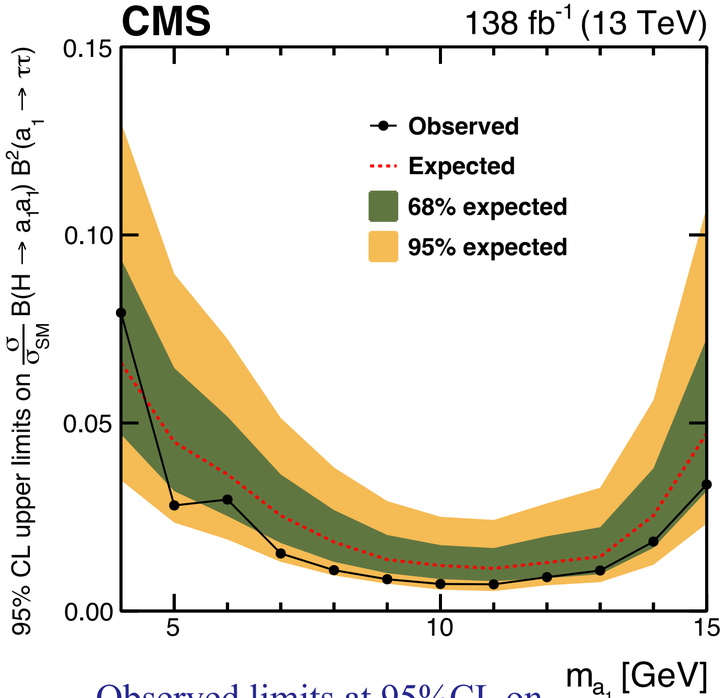
- Major background processes: QCD, Jets faking $\tau_{1-prong}$ (mostly W+jets), $Z \rightarrow \tau\tau$
- Background estimated in CR transferred to SR

Results: Both model independent and 2HDM+S interpretations

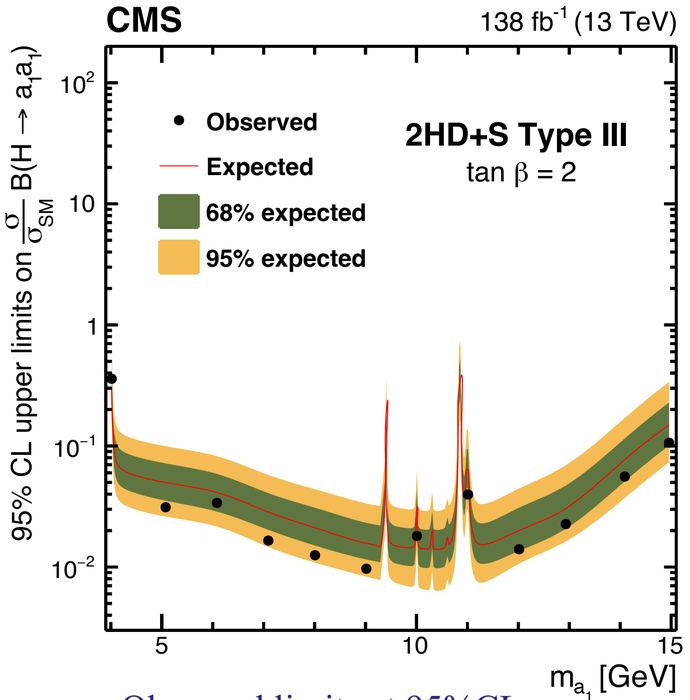
- Most sensitive limits set in 2HDM+S Type III



Invariant mass distribution of the the muon-track system for events passing signal selection



Observed limits at 95%CL on $\sigma(pp \rightarrow H + X)B(H \rightarrow a_1a_1)B^2(a_1 \rightarrow \tau\tau)$ relative to σ_{SM}

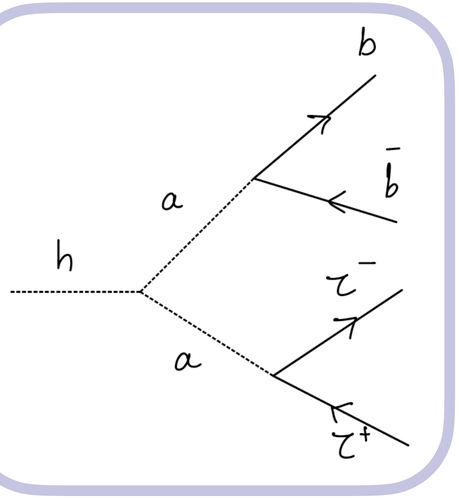


Observed limits at 95%CL on $\sigma(pp \rightarrow H + X)B(H \rightarrow a_1a_1)B^2(a_1 \rightarrow \tau\tau)$ relative to σ_{SM} for 2HDM+S Type III

$H \rightarrow aa \rightarrow 2b2\tau$

Motivation/ Overview

- Interpreted in 2HDM+S theory
- Final state: $bb\tau\tau$
  - favourable branching fractions for higher masses of a boson
- 3 channels: $e\tau_h, \mu\tau_h, e\mu$
- Triggers- single lepton and cross lepton triggers



Event Selection:

- Make $\tau\tau$ pairs: isolated and oppositely charged
- Events require at least one b-tagged jet
- Events categorized into: Exactly 1 b-jet, >1b-jet

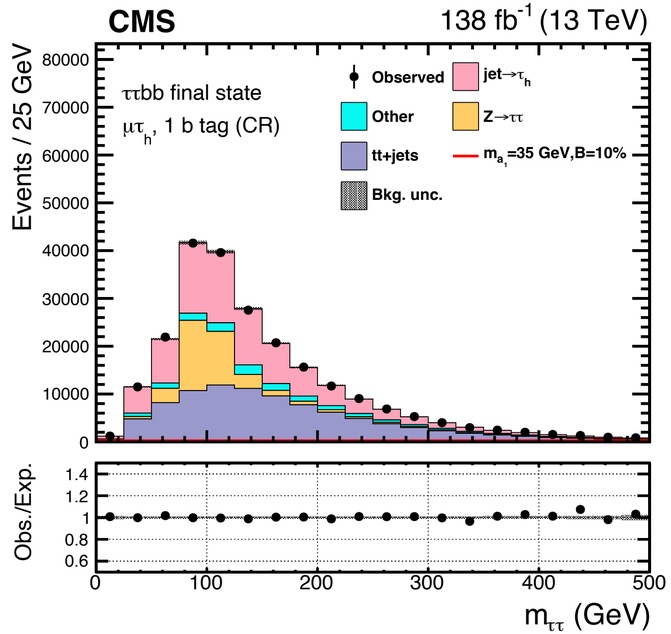
Background Estimation:

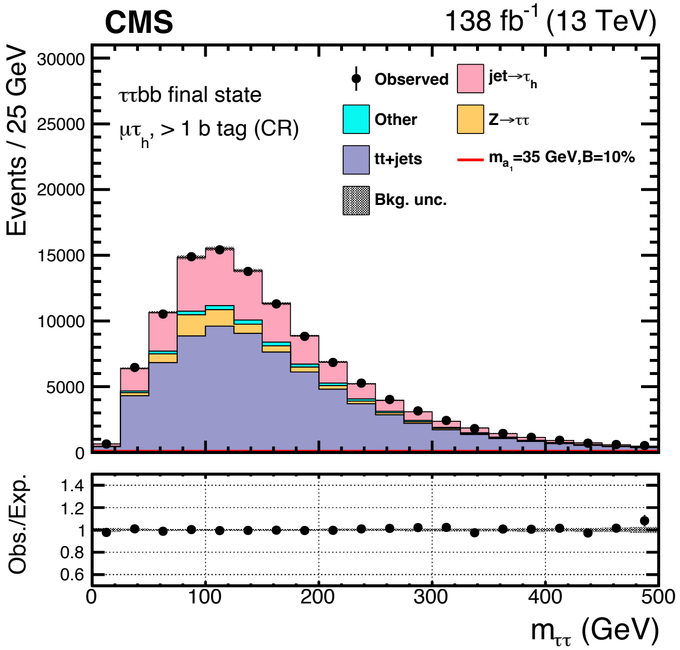
- QCD/ jets faking τ_h: from same signed/ anti iso region
- $Z \rightarrow \tau\tau$: Embedded samples used

From Data

- $t\bar{t}$
- Others: diboson, SM Higgs, single top, W+jets

From MC



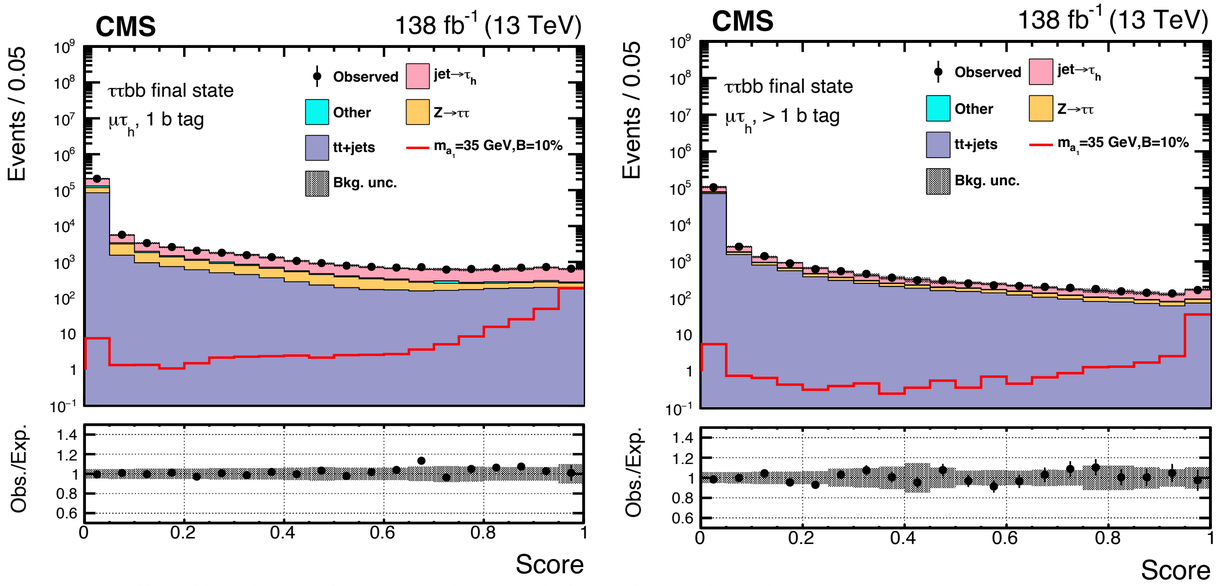


$H \rightarrow aa \rightarrow 2b2\tau$

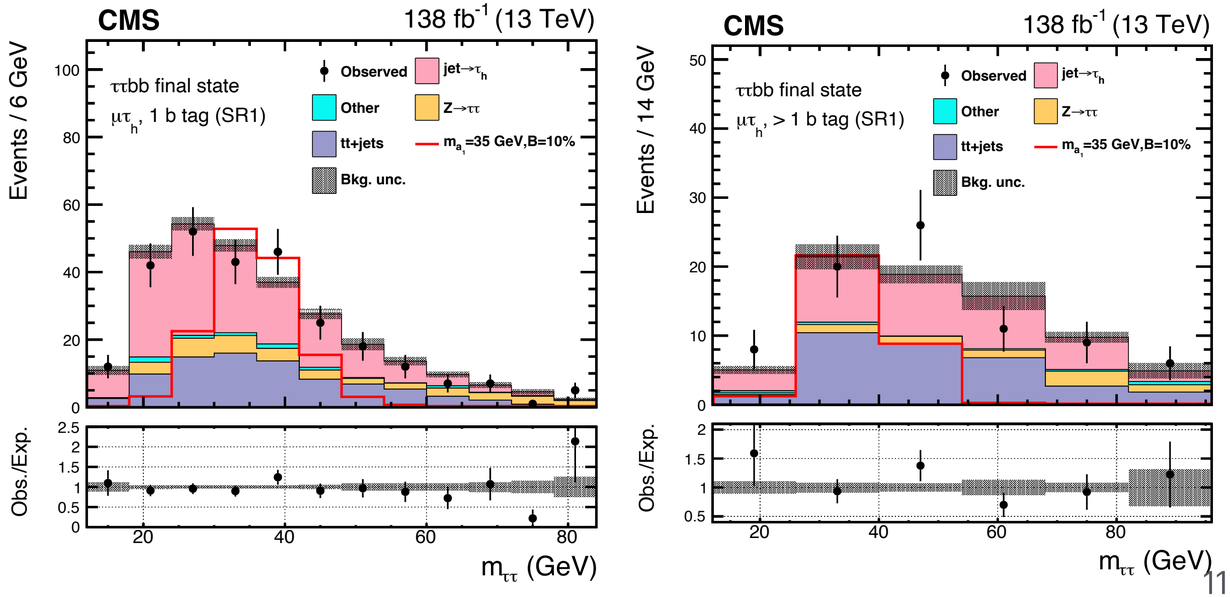
Analysis Strategy

- $m_{\tau\tau}$ reconstructed using SVFIT algorithm
- DNN used for binary event categorization into signal and background
  - DNN for each channel, each b jet category
  - Input features: kinematic variables such as pT, transverse mass of objects, angular separation between objects, Δm_a etc.
  - Cuts on DNN score to define SR
  - Low DNN score: CR
- Maximum likelihood fit on $m_{\tau\tau}$

DNN score distributions for $\mu\tau_h$ channel for 1b and >1b categories



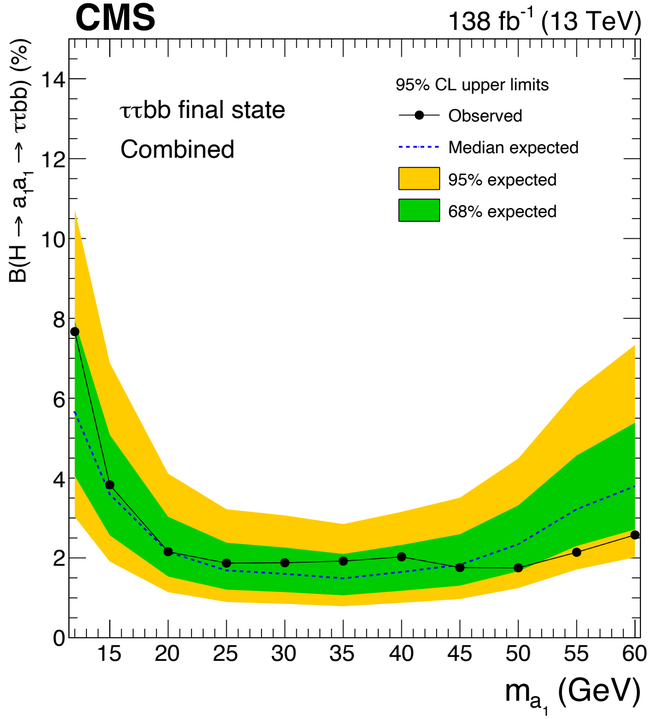
$m_{\tau\tau}$ distributions for $\mu\tau_h$ channel for 1b and >1b categories



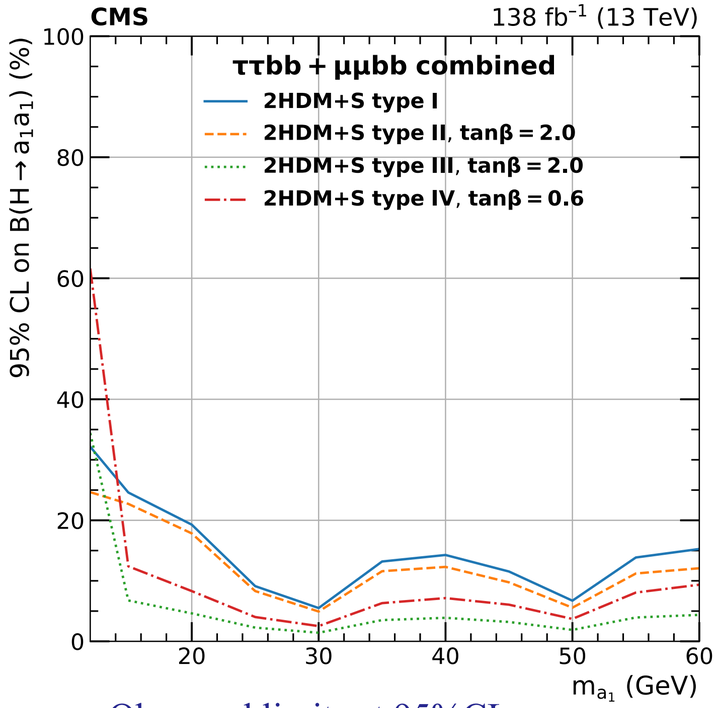
$H \rightarrow aa \rightarrow 2b2\tau$

Results

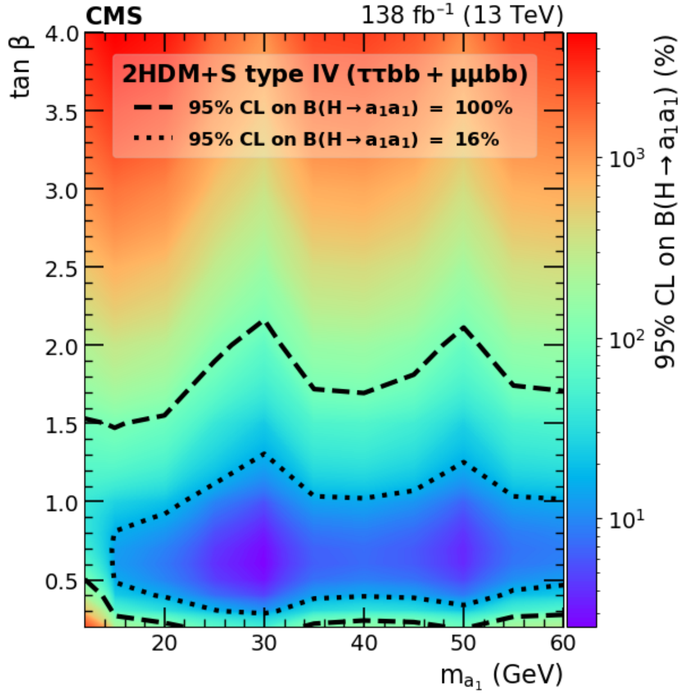
- Results presented for separately $bb\tau\tau$ search and also in combination with $h \rightarrow aa \rightarrow bb\mu\mu$
  - Analyses are mutually exclusive
- Most stringent limits are set in the type III interpretation of 2HDM+S



Observed limits at 95%CL on $B(H \rightarrow a_1 a_1 \rightarrow bb\tau\tau)$



Observed limits at 95%CL on $B(H \rightarrow a_1 a_1)$ obtained from combination of $bb\tau\tau$ and $bb\mu\mu$ final states



Observed limits at 95%CL on $B(H \rightarrow a_1 a_1)$ obtained from combination of $bb\tau\tau$ and $bb\mu\mu$ final states for 2HDM+S

Summary and Outlook

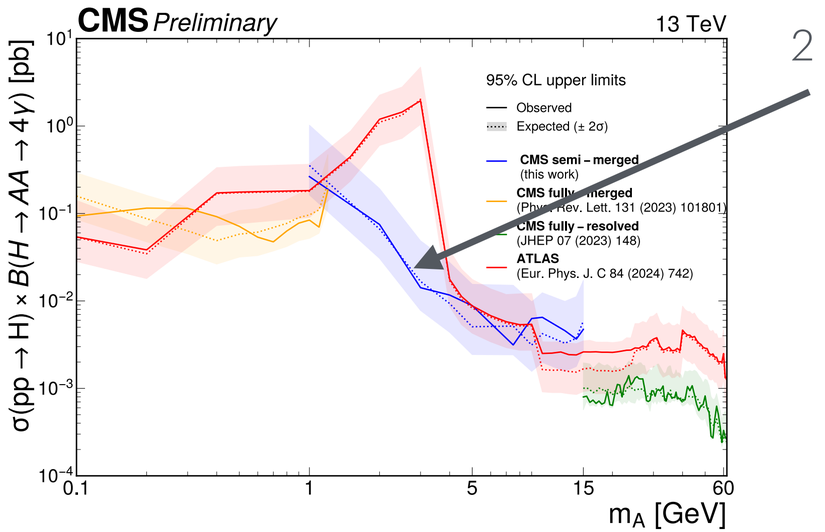
Highlights of selected CMS results:

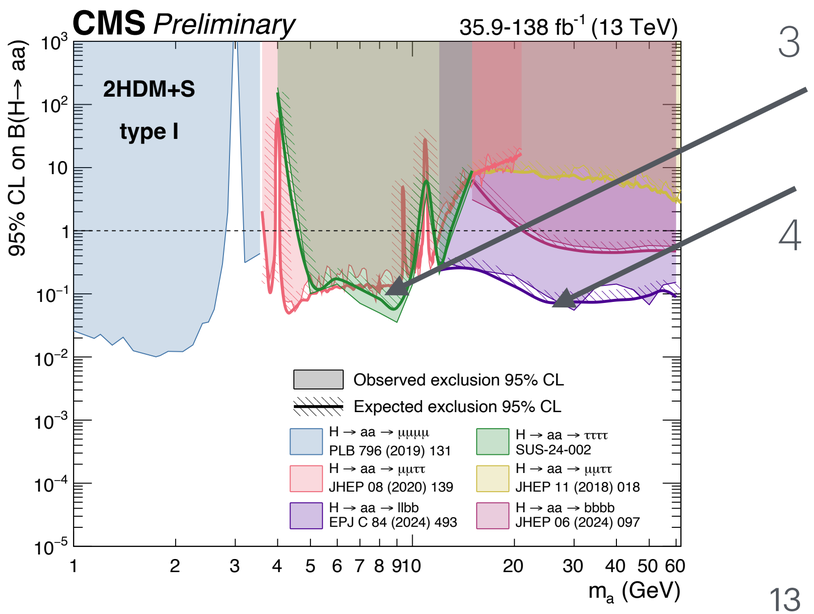
1. $h \to aa \to 4e$:
   - First of its find to set limits for $10 \leq m_a \leq 100$ MeV
2. $h \to aa \to 4\gamma$:
   - Bridges the gap between previous $h \to aa \to 4\gamma$ analysis in CMS
3. $h \to aa \to 2\mu 2\tau / 4\tau$:
   - Significant improvement over previous CMS result by factor of 2
4. $h \to aa \to bb\tau\tau + h \to aa \to bb\mu\mu$ combination:
   - Sets stringent limits for B($h \to aa$) interpretation in 2HDM+S model for $m_a \geq 15$ GeV

Future outlook:

- Potential for other final states to be explored in the future
- Also being probed at CMS: a bosons with different masses, i.e. $h \to a_1 a_2$ decays

Summary plot of observed limits at 95%CL on $\sigma(pp \to H + X)B(H \to a_1 a_1 \to 4\gamma)$
CMS-PAS-EXO-24-025





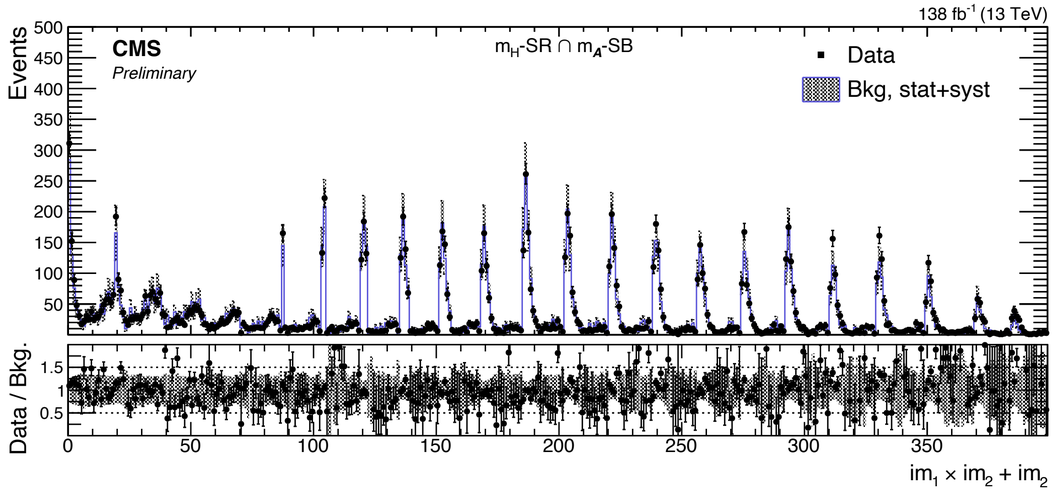
CMS Summary Plot : 95% CL on B($h \to aa$ for 2HDM+S Type I)

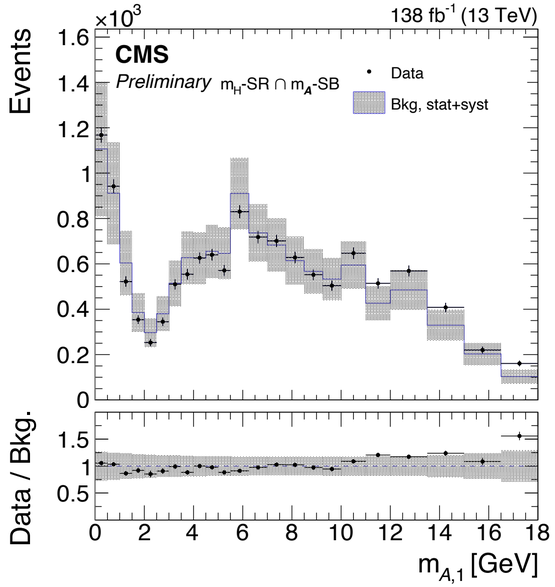
Thank you!

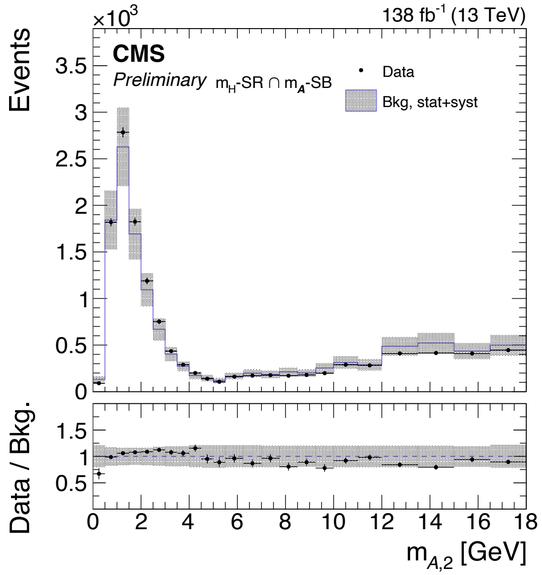
$H \rightarrow aa \rightarrow 4\gamma$

Background Estimation

- Derived from data from the 2D m_a shape template
- Assumptions:
  - shape of background template in SR = linear sum of background templates in SB regions
  - Ratio of events along 2D m_a diagonal derived from m_H SB = Ratio of events in the 2D m_a off diagonal region







$H \rightarrow aa \rightarrow 4\tau/2\tau2\mu$

Background Estimation

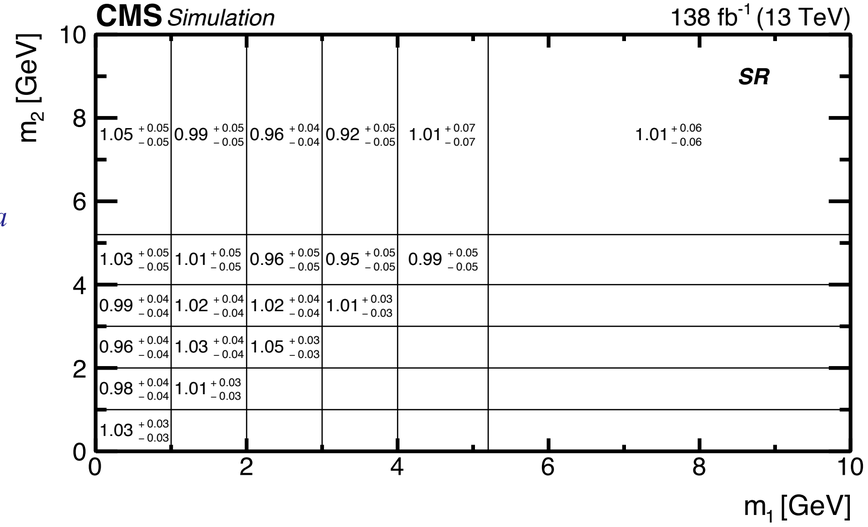
- QCD multijets are major source of background
- Background in SR, $f_{2D}(i,j) = C(i,j)\,(f_{1D}(i)\,f_{1D}(j))$

correlation matrix accounting for correlation of m1 and m2

content of bins in 1-D distributions of muon-track system invariant mass distribution

- $f_{1D}(i)$: Derived in CRs defined by inverting isolation for tracks
- $C(i,j)$: Derived in CR defined by requiring both isolated and non-isolated tracks close to muon

C(i j) in the 2D m_a template in SR



For $f_{1D}(i)$: inv. mass distribution for different isolation for tracks with highest p_T