Searches for new physics in extended Higgs sectors in CMS

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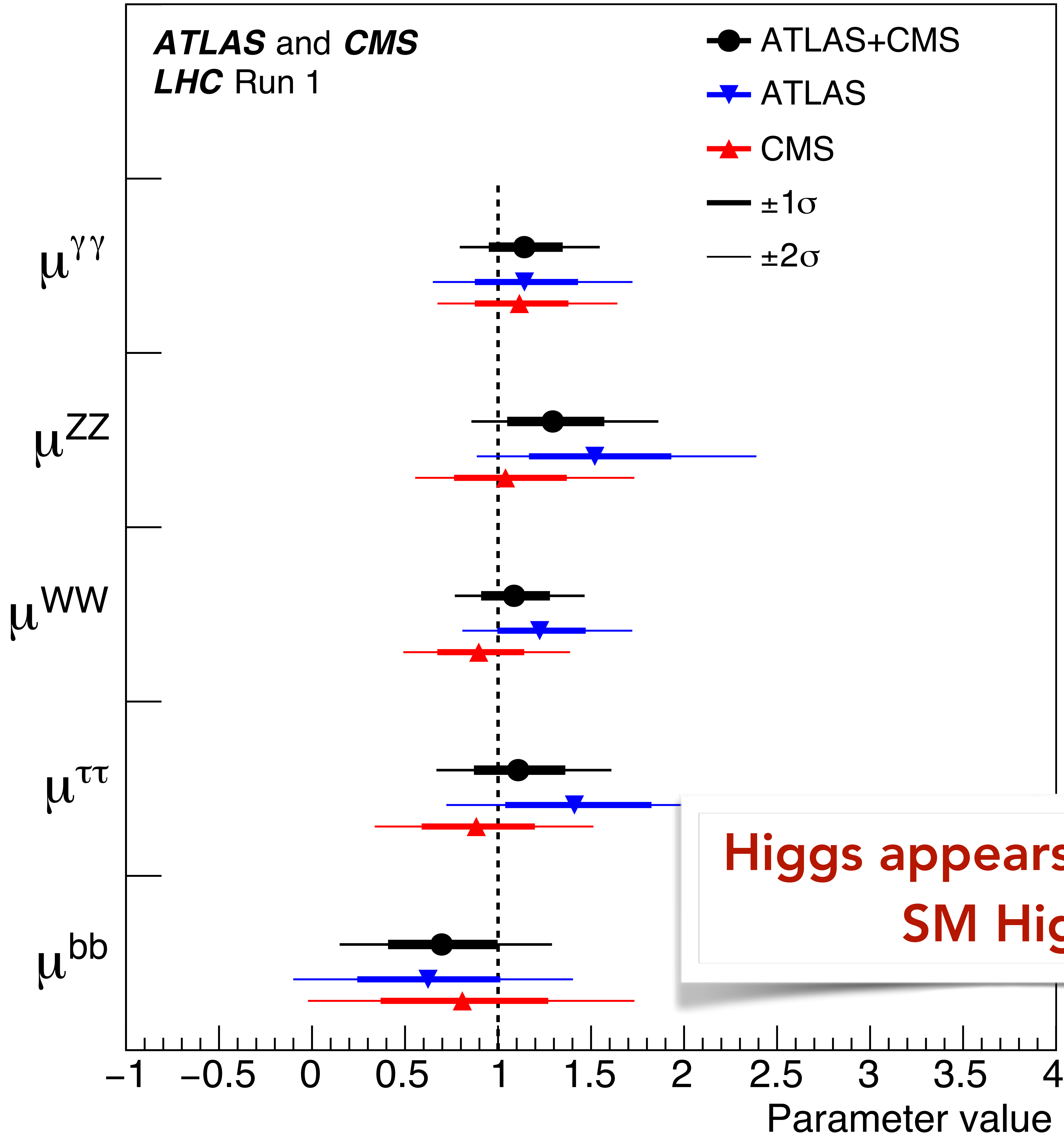
Introduction

- 125 GeV Higgs boson discovered by the CMS and ATLAS experiments in 2012
- Data collected during Run 1 and Run 2 of the LHC used for experimental measurements of the Higgs signal strength

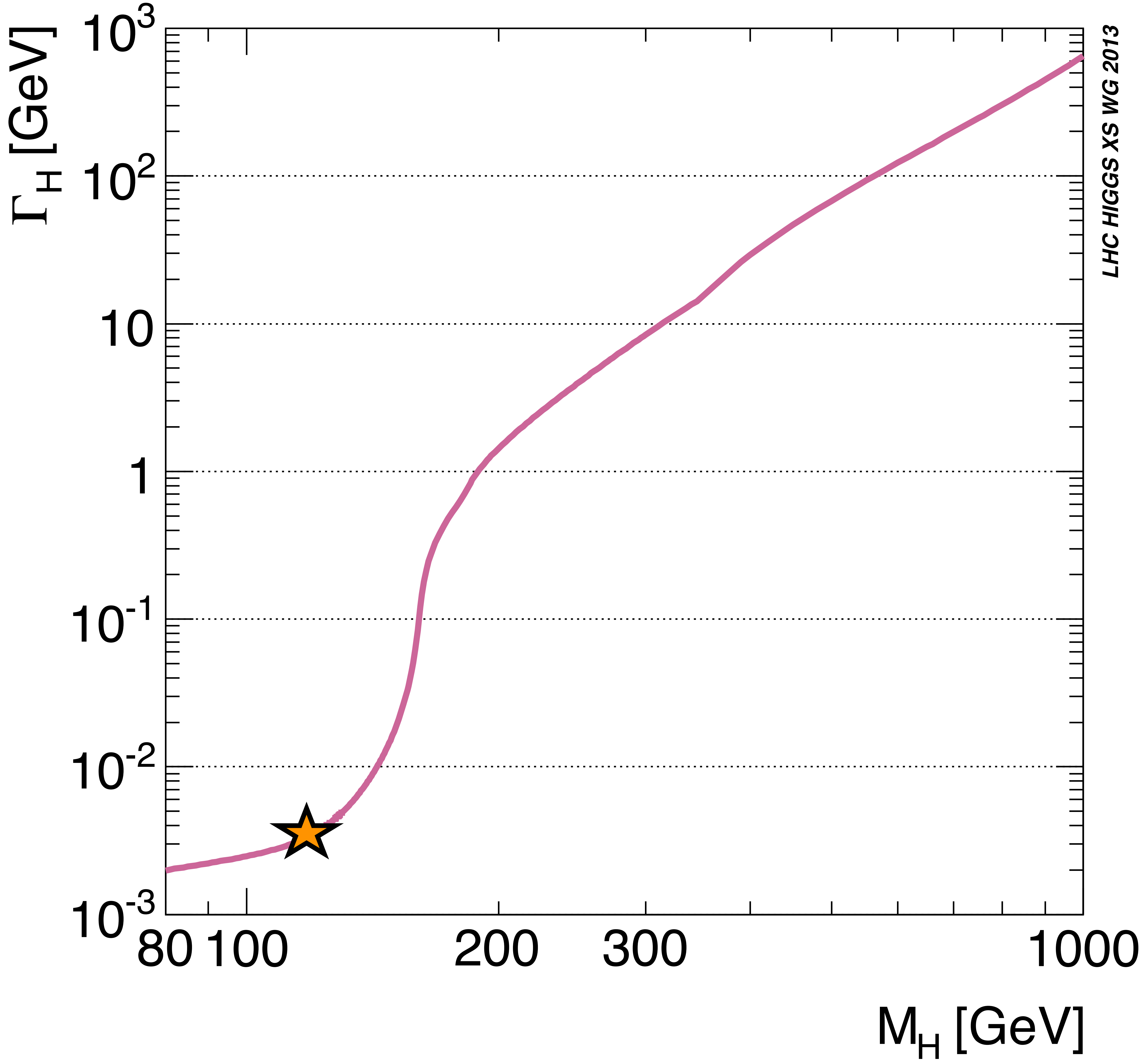


Higgs appears to be the SM Higgs

- SM is a highly successful theory, but it has several shortcomings
- Non-exhaustive list
  - Absence of gravity
  - Absence of explanation for Dark Matter
  - CP violation
  - The Hierarchy problem
  - ……..

What is special about the Higgs?

- How standard is the Higgs boson?
  - Extremely narrow width ★
    (Γ_h ~ 4.07 MeV ; Γ_h/m_h ~ 3.3 x10-5)
  - Experimentally, Γ_h constrained at GeV scale
  - Small coupling to another light state can open up additional sizable decay modes
  - Good reasons to suspect that **new physics couples preferentially to the Higgs boson**

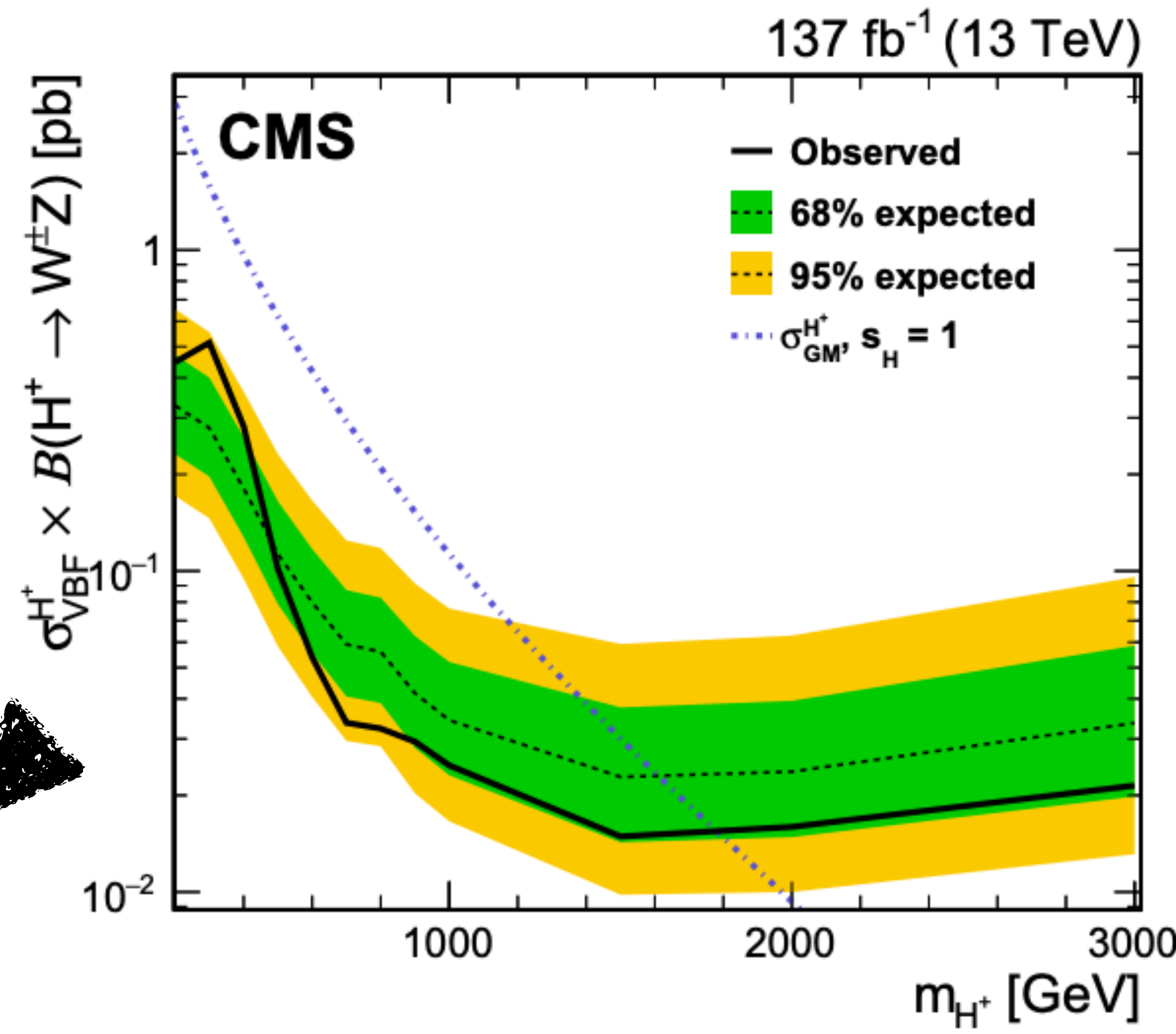


Higgs as a probe for BSM physics

Search for new BSM particles

- Neutral or charged exotic Higgs bosons

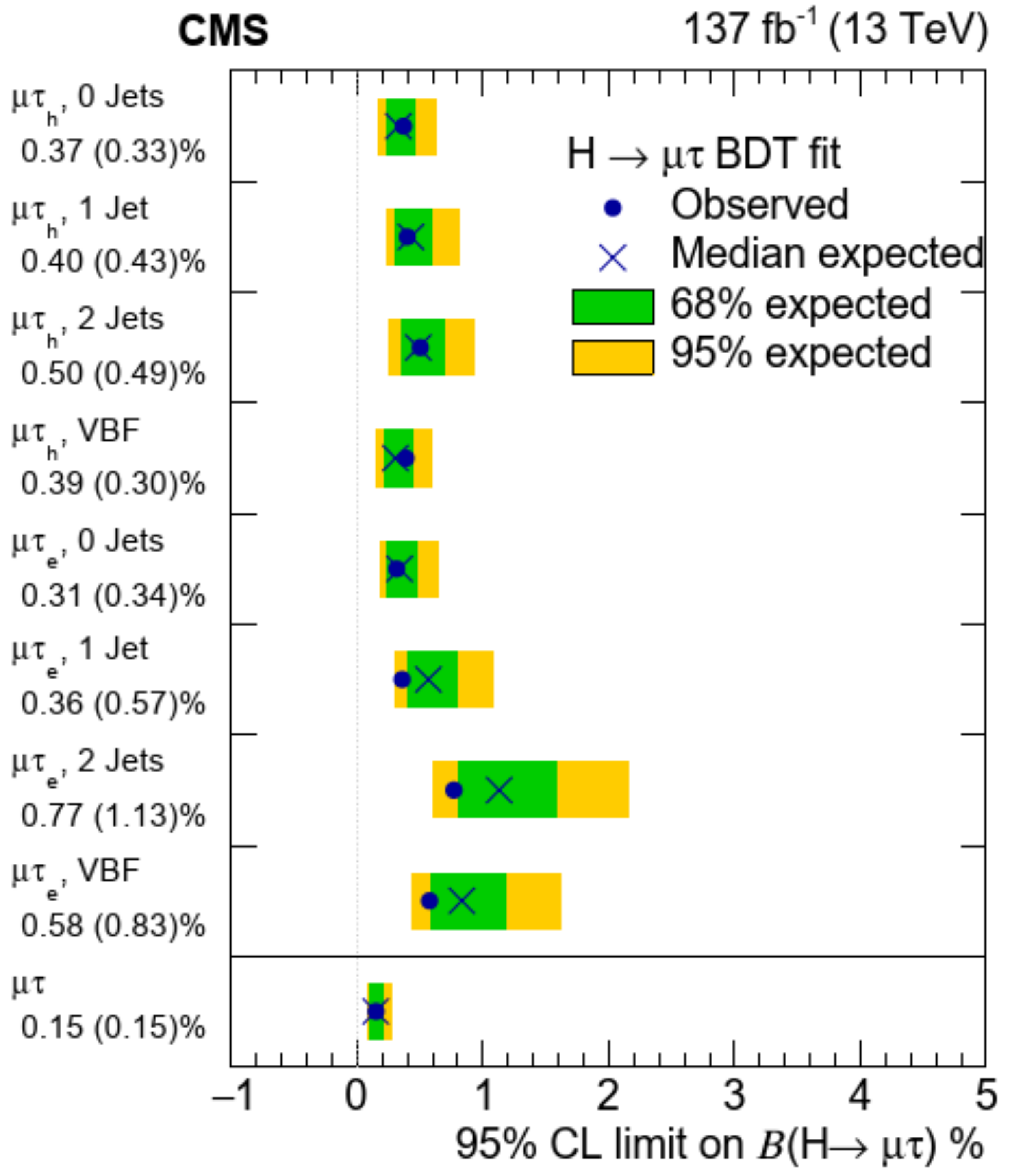
Search for VBF H± and H±±
arxiv:2104.04762
See Jie Xiao's talk



Decays of the Higgs to SM particles

- Rare decays predicted by the SM
  - Excess would indicate to BSM physics
- Decays forbidden in the SM
  - Lepton flavor violating decays of the Higgs

h→eτ/μτ
arxiv:2105.03007
See Jie Xiao's talk



Decays of Higgs to non-SM particles

- Invisible decays of the Higgs
- **Decays of the Higgs to light pseudoscalars, that decay to SM particles**

h→aa, a decaying to SM particles
Focus of this talk

h→aa final states

a→μμ

- Good mass resolution
- Easy to trigger on
- Easy identification, even with low p_T
- Low BR

a→bb

- Large BR
- Tough to trigger on
- Low identification efficiency
- Large jet backgrounds

a→ττ

- Large BR
- Trigger on leptonic decays of τ
- Low τ_h identification efficiency

h→aa→μμμμ

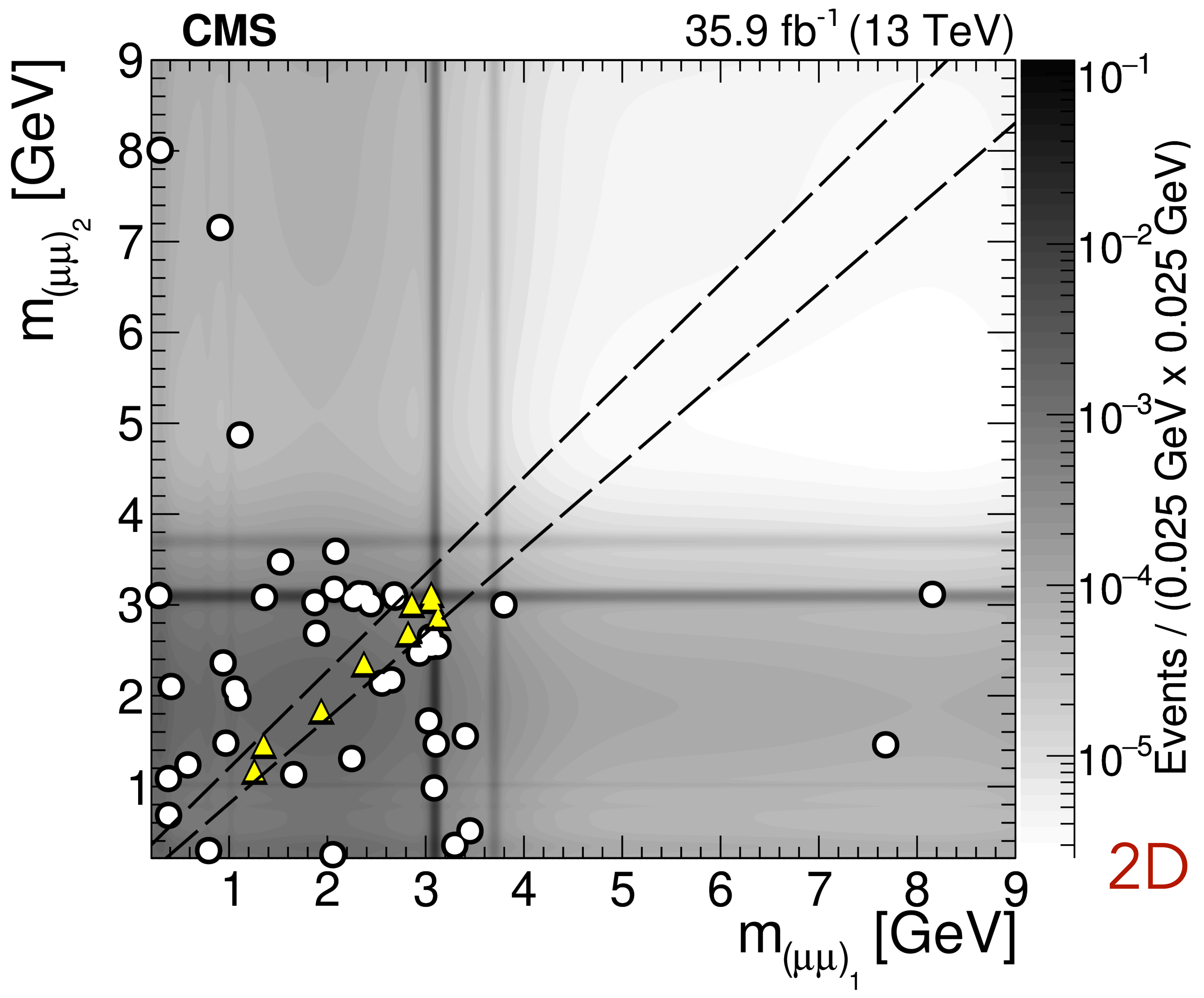
h→aa→μμbb

h→aa→μμττ

h→aa→bbττ

h→aa→4μ [(Phys. Lett. B 796 (2019) 131)](#) [35.9 fb^{-1} (13 TeV)]

- a is highly boosted and muons are less separated
- Model independent search
- Re-interpreted in context of
  - NMSSM (0.25 GeV < m(a) < 3.55 GeV)
  - Dark SUSY model (0.25 GeV < γ_d < 8.5 GeV; $c\tau\ \gamma_d$ up to100 mm)



2D di-muon mass template

Event selection

- Di-muons created from pairs of oppositely charged muons with $m_{\mu\mu}$ < 9 GeV
  - Ensures no contribution from Z boson decays or Υ meson system
- Exactly 2 dimuons in each event
  - Originate from same primary vertex $|z_{(\mu\mu)1} - z_{(\mu\mu)2}| < 0.1$ cm

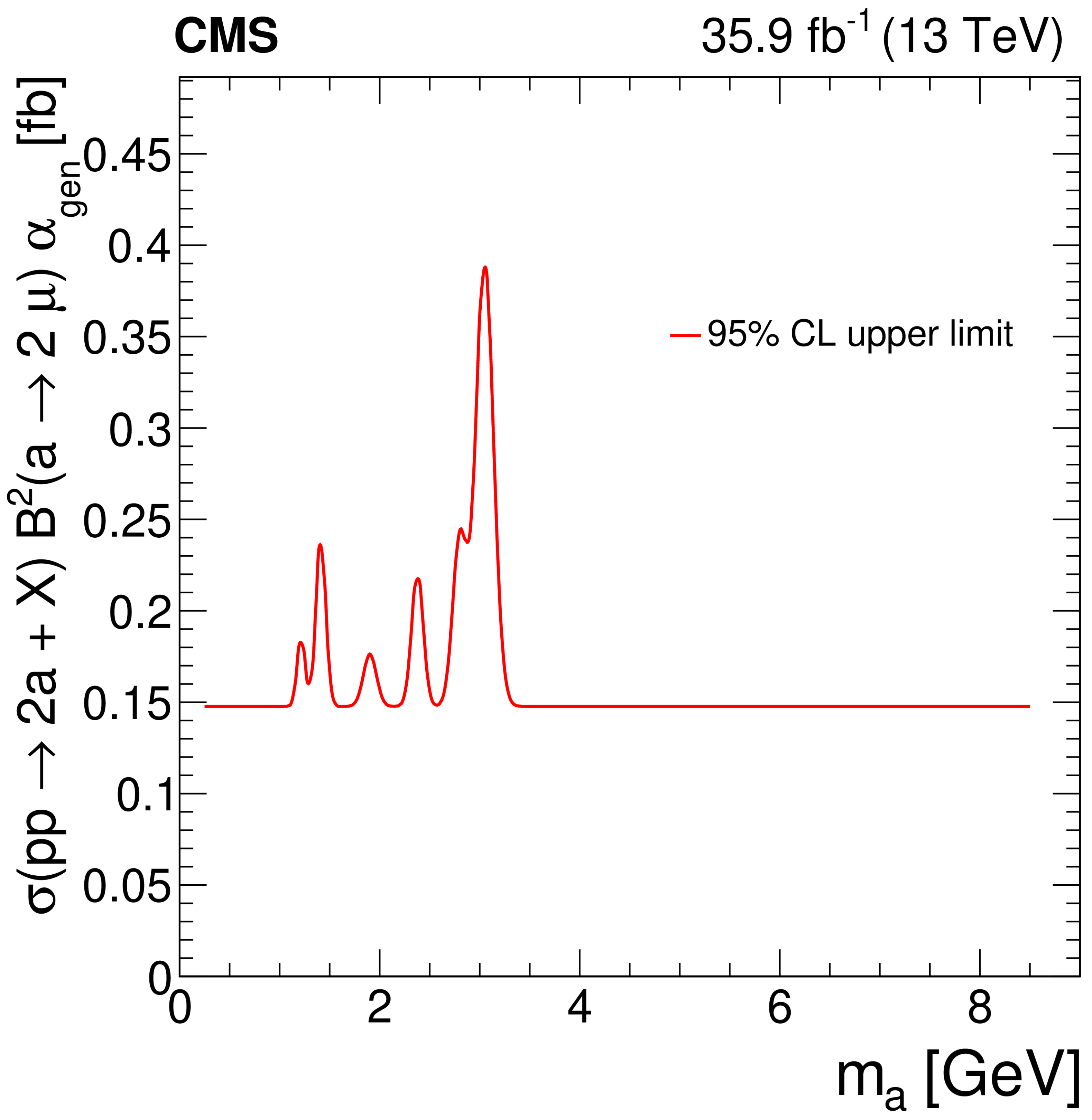
Backgrounds

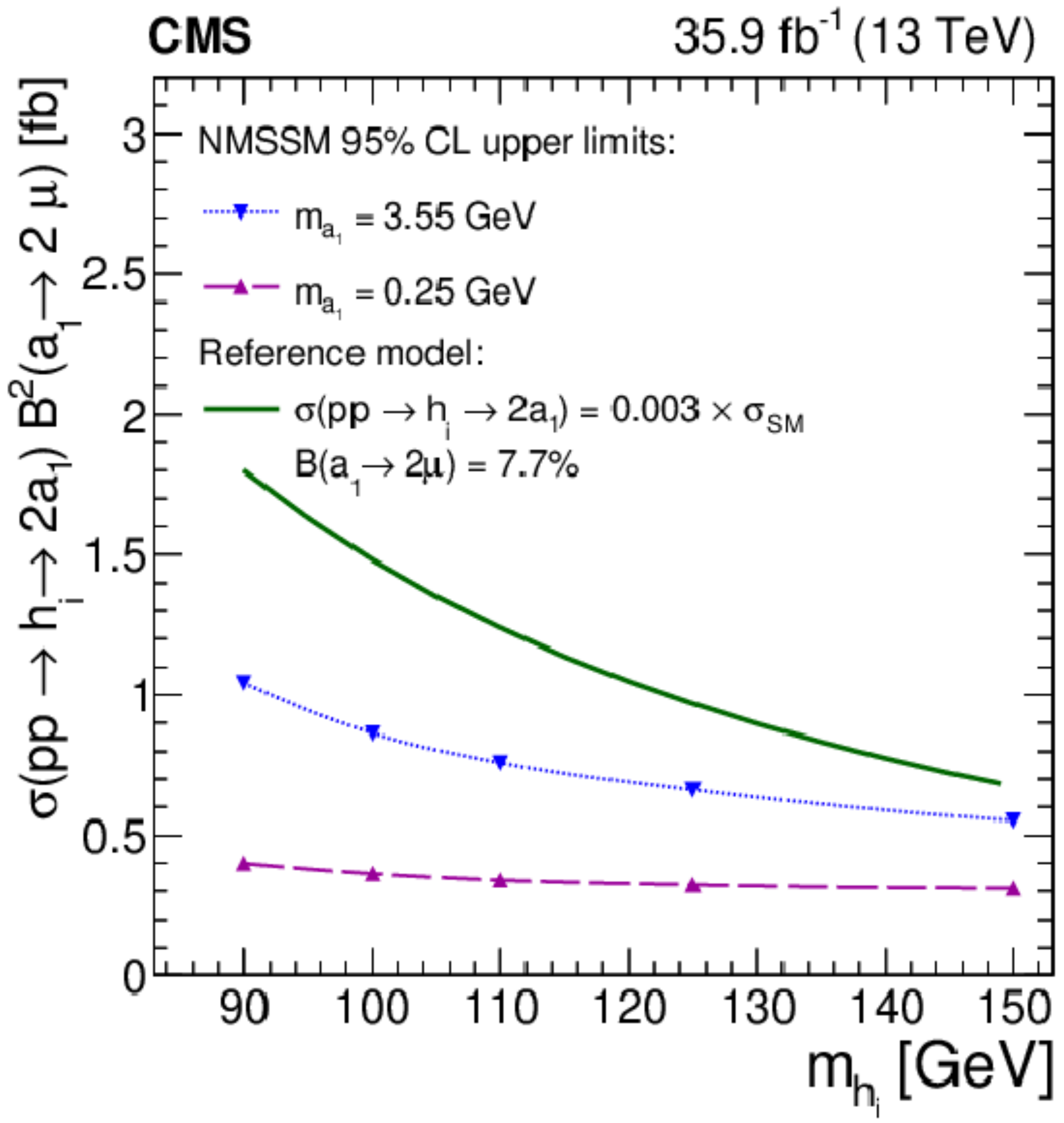
- $b\bar{b}$: largest background
- prompt double J/ψmeson decays
- Electroweak production of four muons

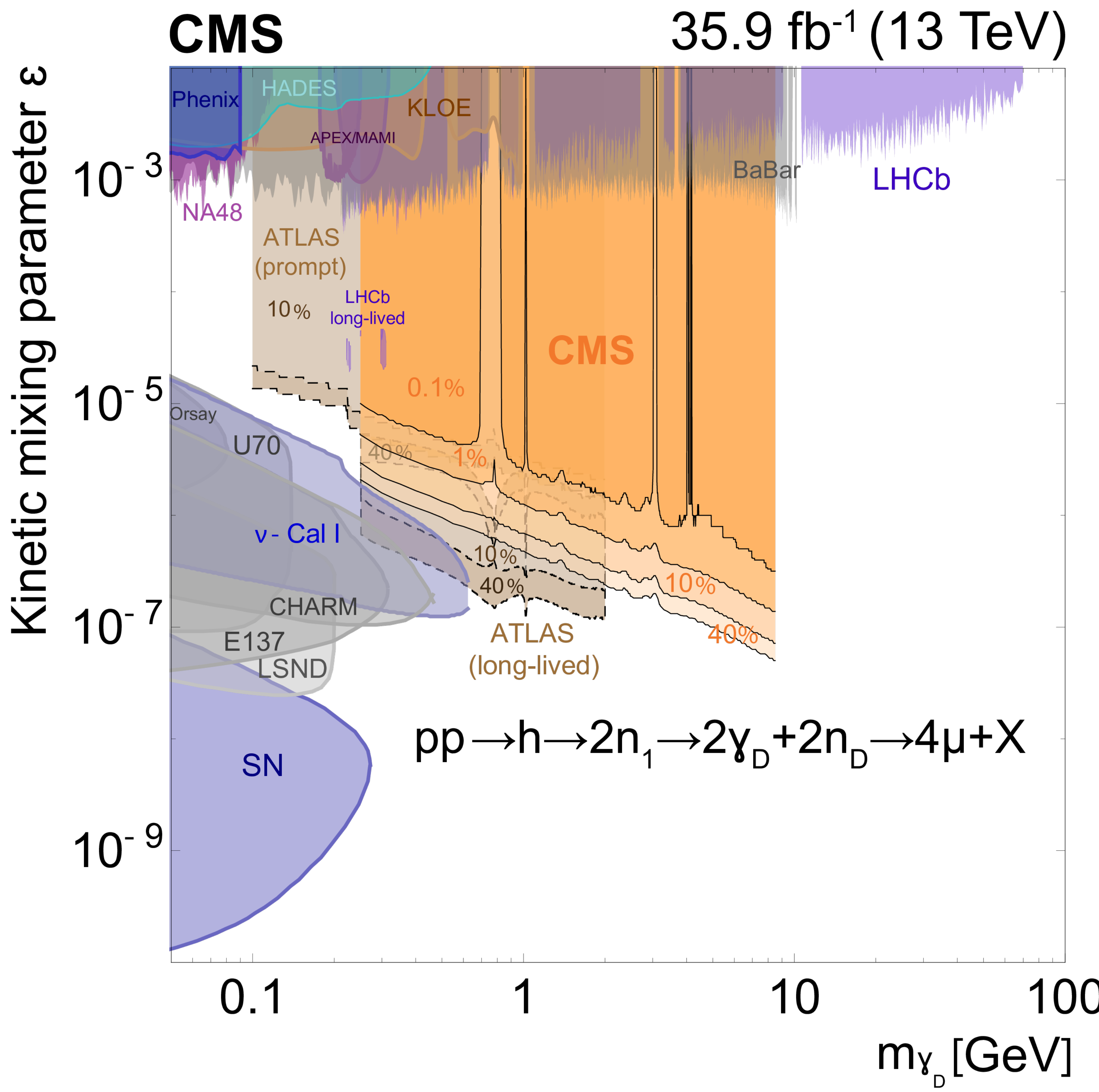
h→aa→4μ *(Phys. Lett. B 796 (2019) 131)* *[35.9 fb^{-1} (13 TeV)]*

- Model independent and model dependent results provided

- 95% CL upper limit set on σ(pp→2a+X)B²(a→2μ)αgen
- NMSSM results
- Dark SUSY (90% CL)







h→aa→μμbb *Phys. Lett. B 795 (2019) 398 [35.9 fb-1 (13 TeV)]*

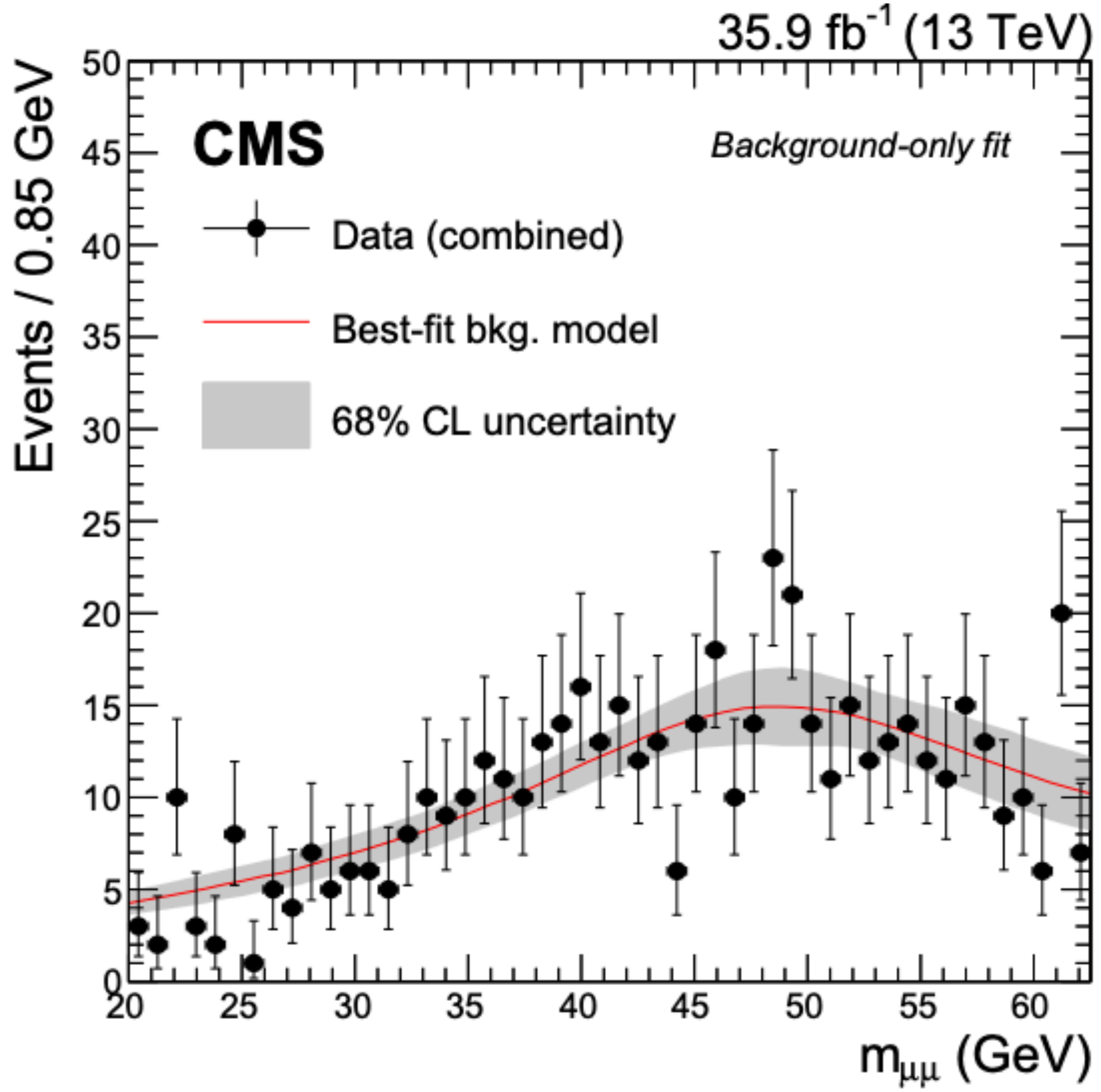
- 20 GeV < m(a) < 62.5 GeV
- ggF and VBF Higgs production mechanisms considered
- Analysis sensitivity decreases towards m(a) ~ 20 GeV
  - *a* becomes boosted and b jets start to merge

Event selection

- Two muons with opposite charge
  - p_T leading (sub-leading) muon > 20 (9) GeV
- Jets originating from b-quarks
  - Use track-based lifetime + secondary vertex information to identify
  - p_T leading (sub-leading) jet > 20 (15) GeV
- Both jets separated from muons ΔR > 0.5

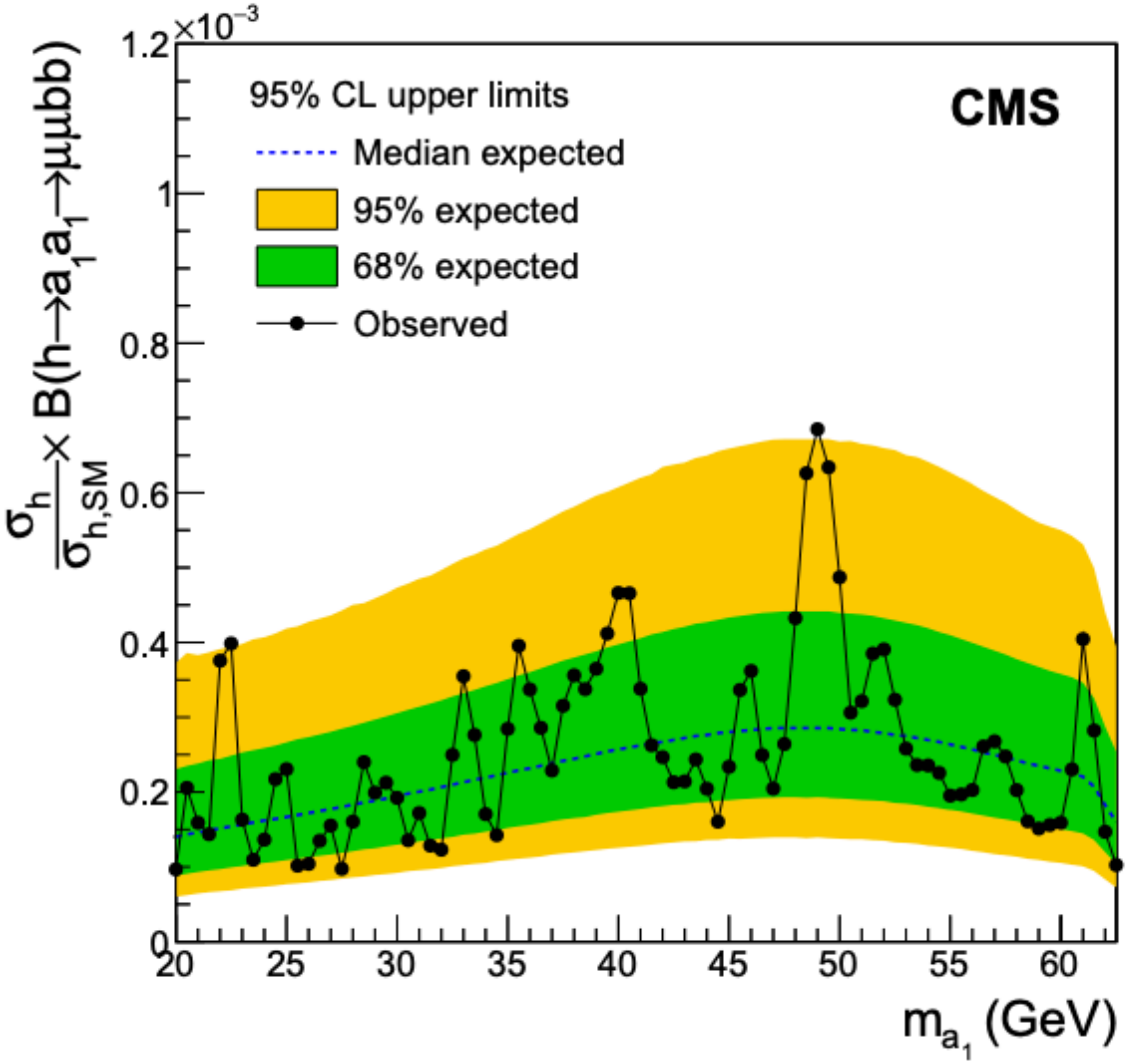
Signal and background modeling

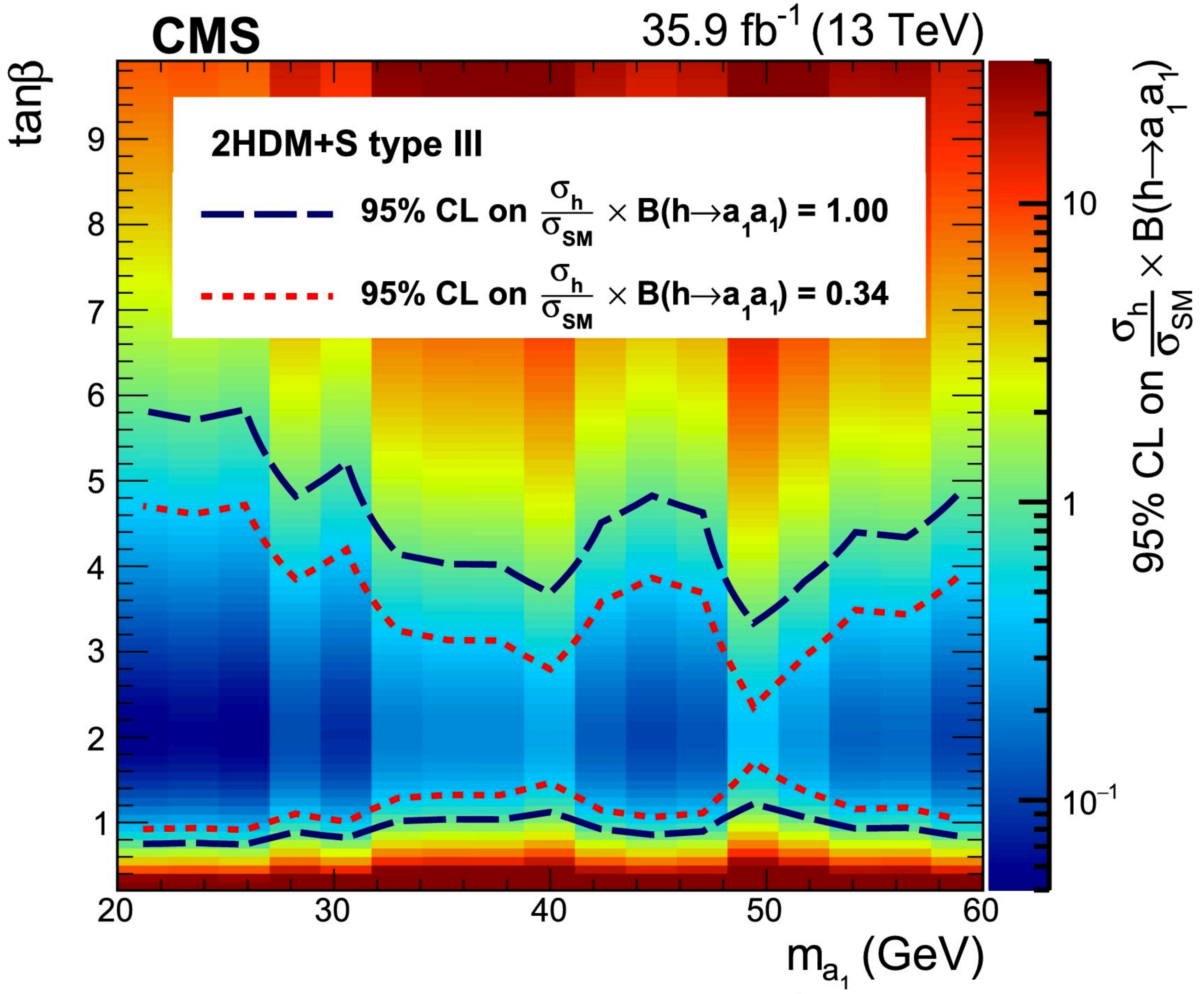
- Signal: weighted sum of Voigt +Crystal ball function
- Background: Data-driven using discrete profile method



h→aa→μμbb *Phys. Lett. B 795 (2019) 398 [35.9 fb⁻¹ (13 TeV)]*

- Unbinned fit to di-muon invariant mass distribution in data in each category
- 95% CL on BR (h→aa→μμbb) as a function of m(a)
- Translated into limits on BR (h→aa) in plane of (m(a), tanβ)

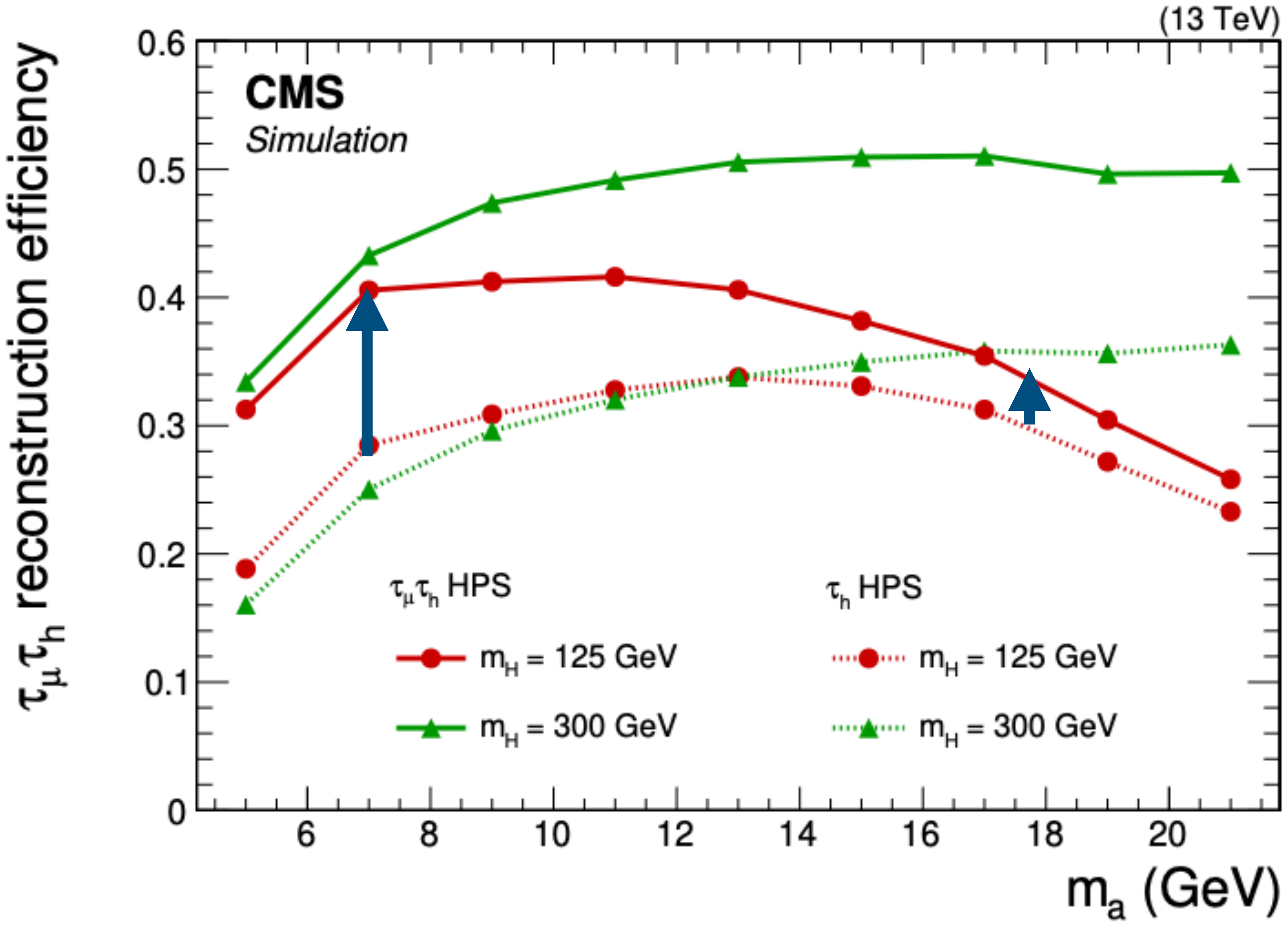




h→aa→μμττ *JHEP 08 (2020) 139 [35.9 fb-1 (13 TeV)]*

- 3.6 GeV < m(a) < 21 GeV
- ggF and VBF Higgs production mechanisms considered
- Large difference b.w m(h) and m(a)
  - μμ and ττ pairs have high Lorentz boost and are collimated
- Both, leptonic and hadronic τ decays considered
- Di-muons used to trigger

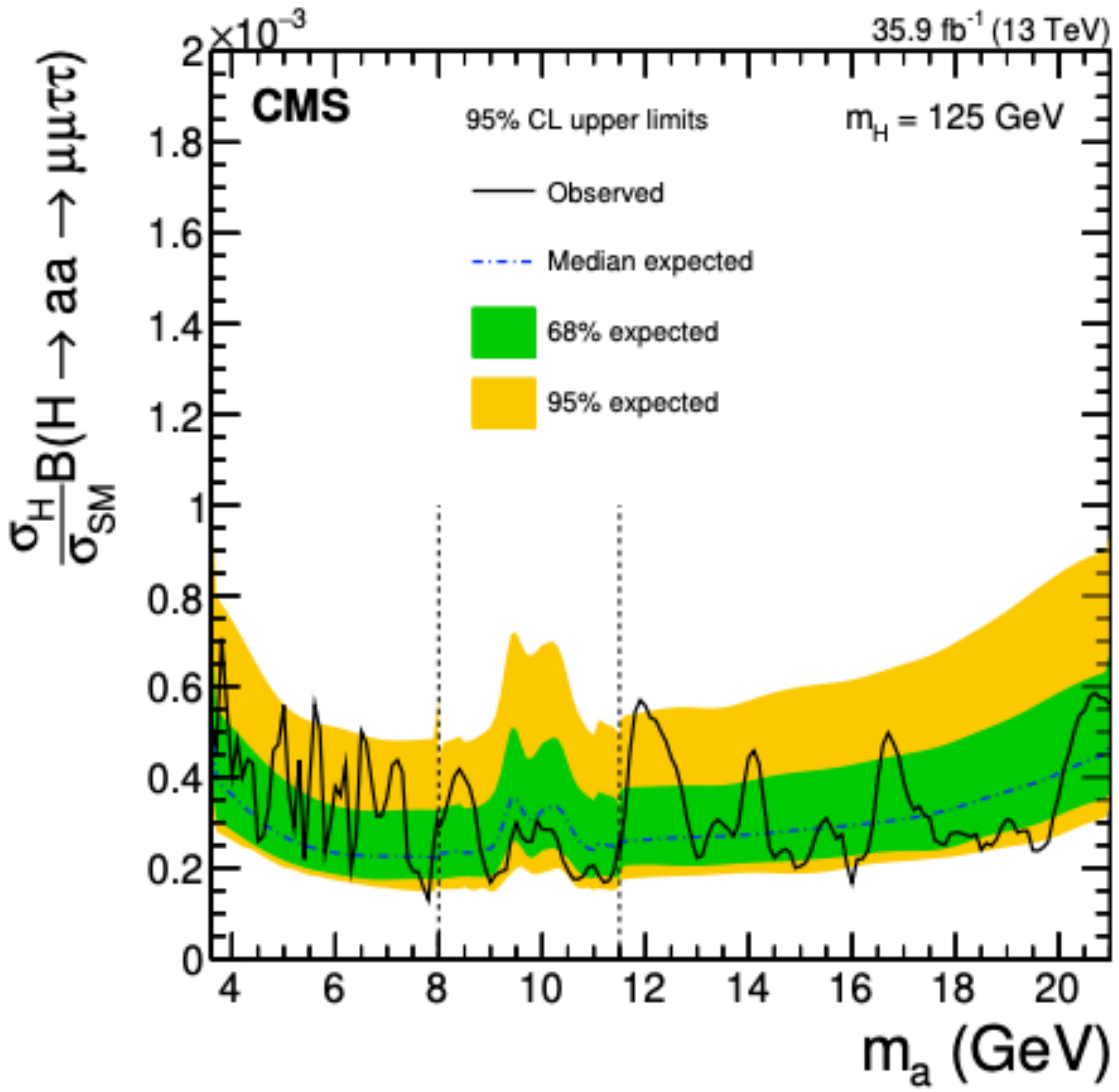
- Modified $\tau_\mu\tau_h$ reconstruction and identification
  - Hadron Plus Strips (HPS) algorithm: combine information from charged hadrons and π^0 (from ECAL)

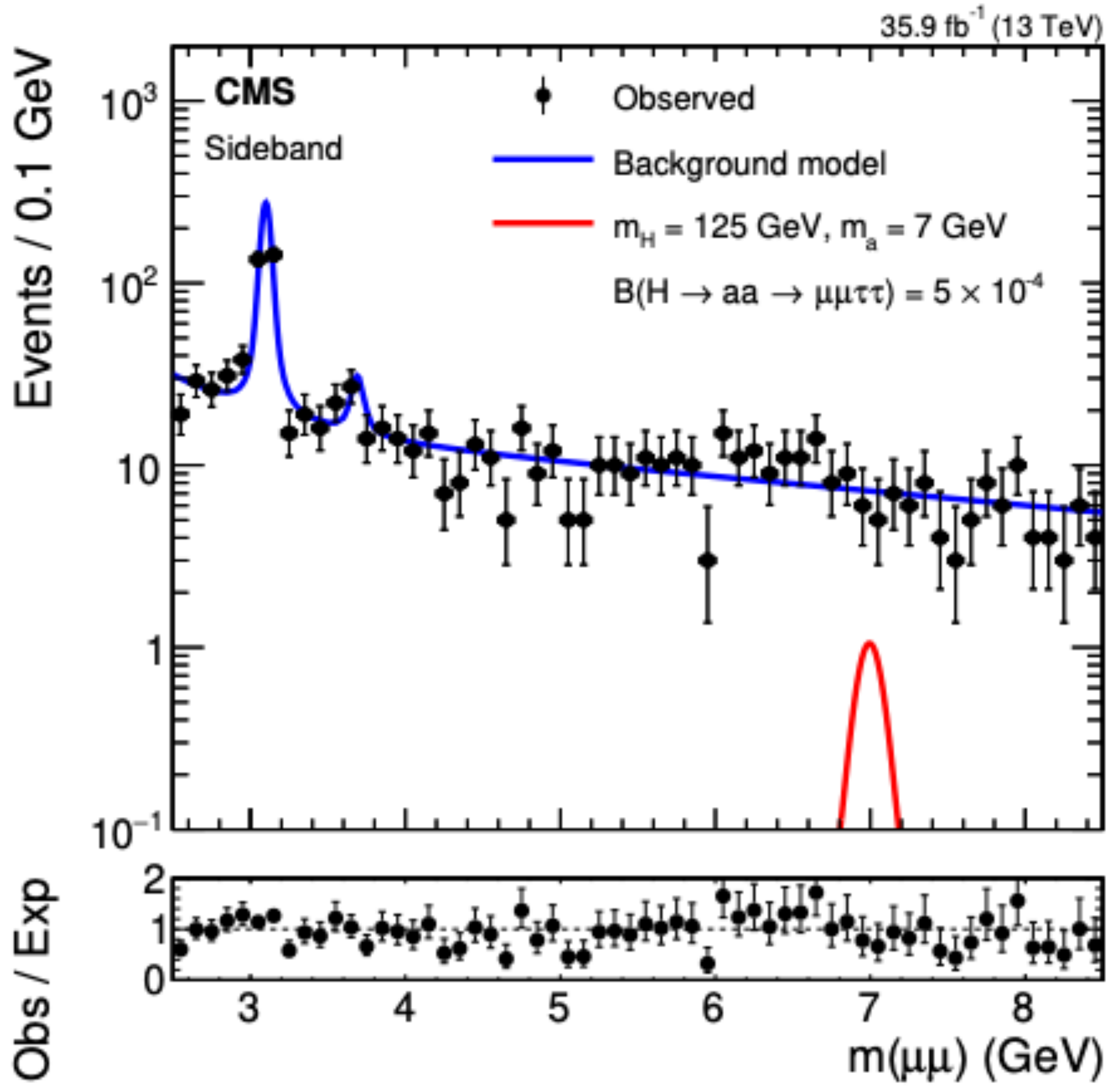


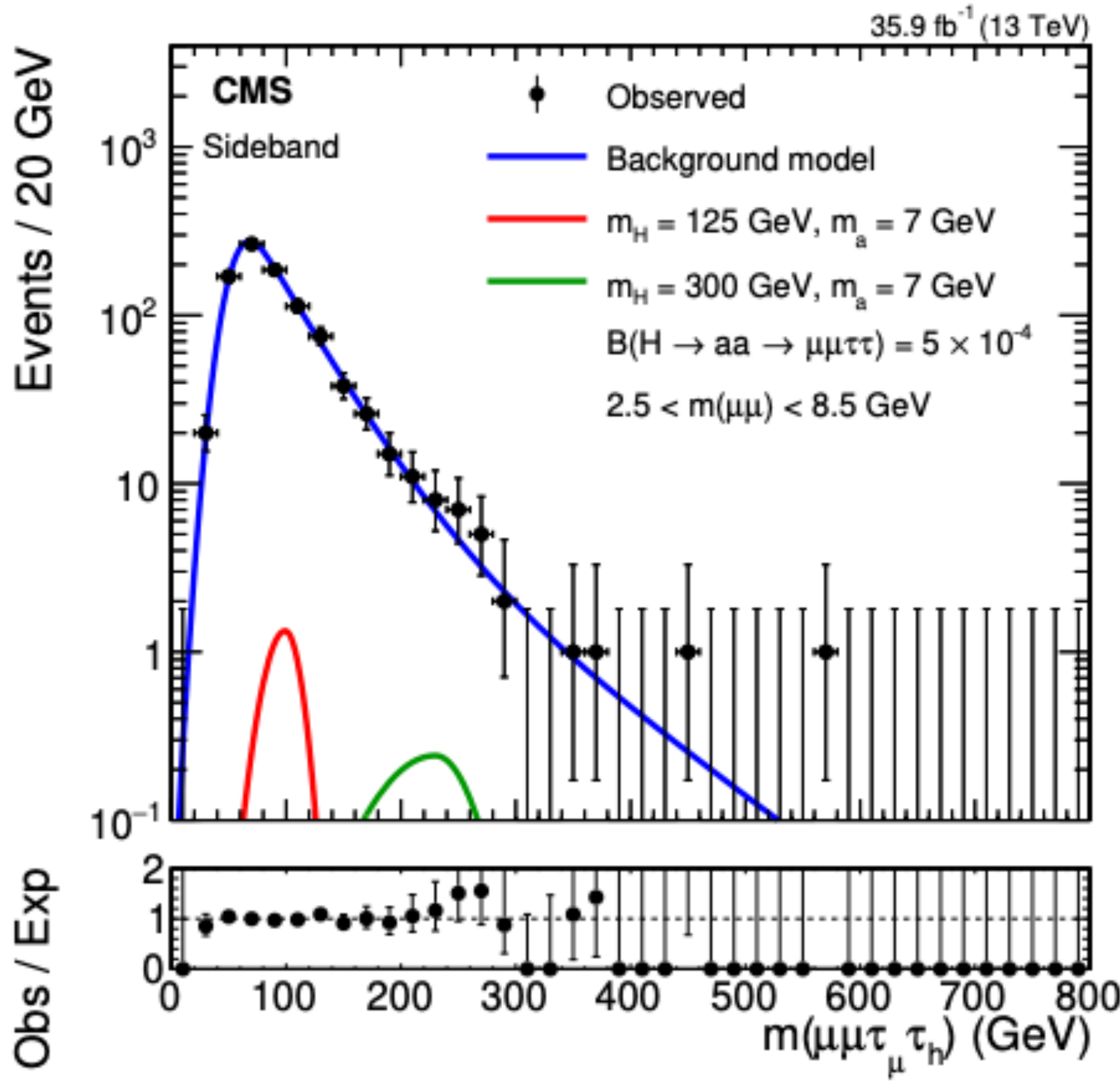
h→aa→μμττ *JHEP 08 (2020) 139 [35.9 fb-1 (13 TeV)]*

Background

- Main background: Drell-Yan in association with at least one jet misidentified as $\tau_\mu\tau_h$ candidate



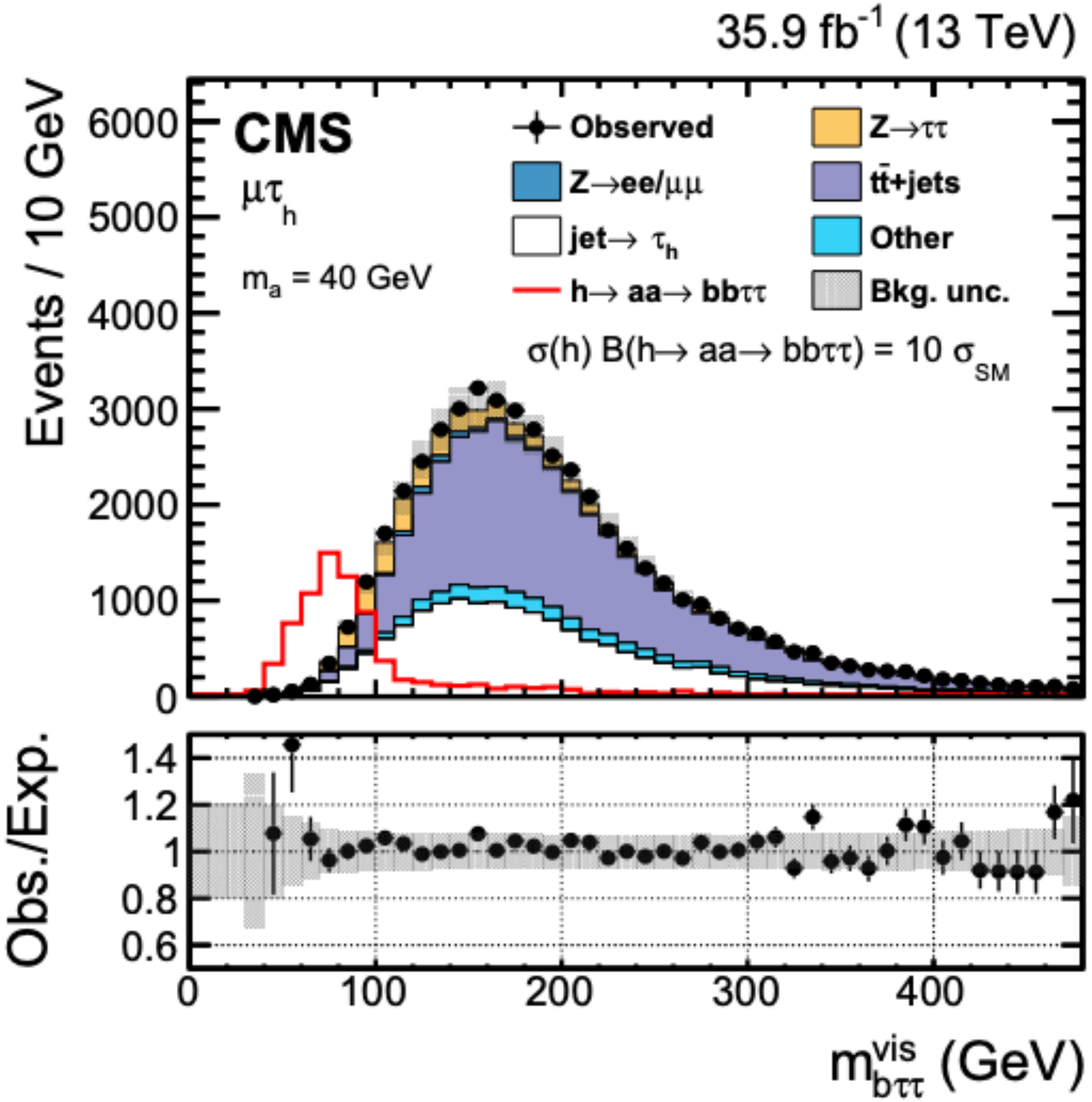




- 2D unbinned fit: $m_{\mu\mu}$ Vs $m_{\mu\mu\tau h\tau\mu}$ in 3 mμμ fit ranges
- Model-independent 95% CL upper limits on σ_H B(H → aa → μμττ)/σ_{SM}

h→aa→bbττ (Phys. Lett. B 785 (2018) 462) [35.9 fb^{-1} (13 TeV)]

- 15 GeV < m(a) < 60 GeV
- Final state objects are well separated
- Split into 3 ττ final states: eμ, $e\tau_h$, $\mu\tau_h$
- Events further separated into four categories based on signal to background ratio
  - Using invariant mass of visible τ decay products and b-tagged jet: $m^{vis}_{b\tau\tau}$

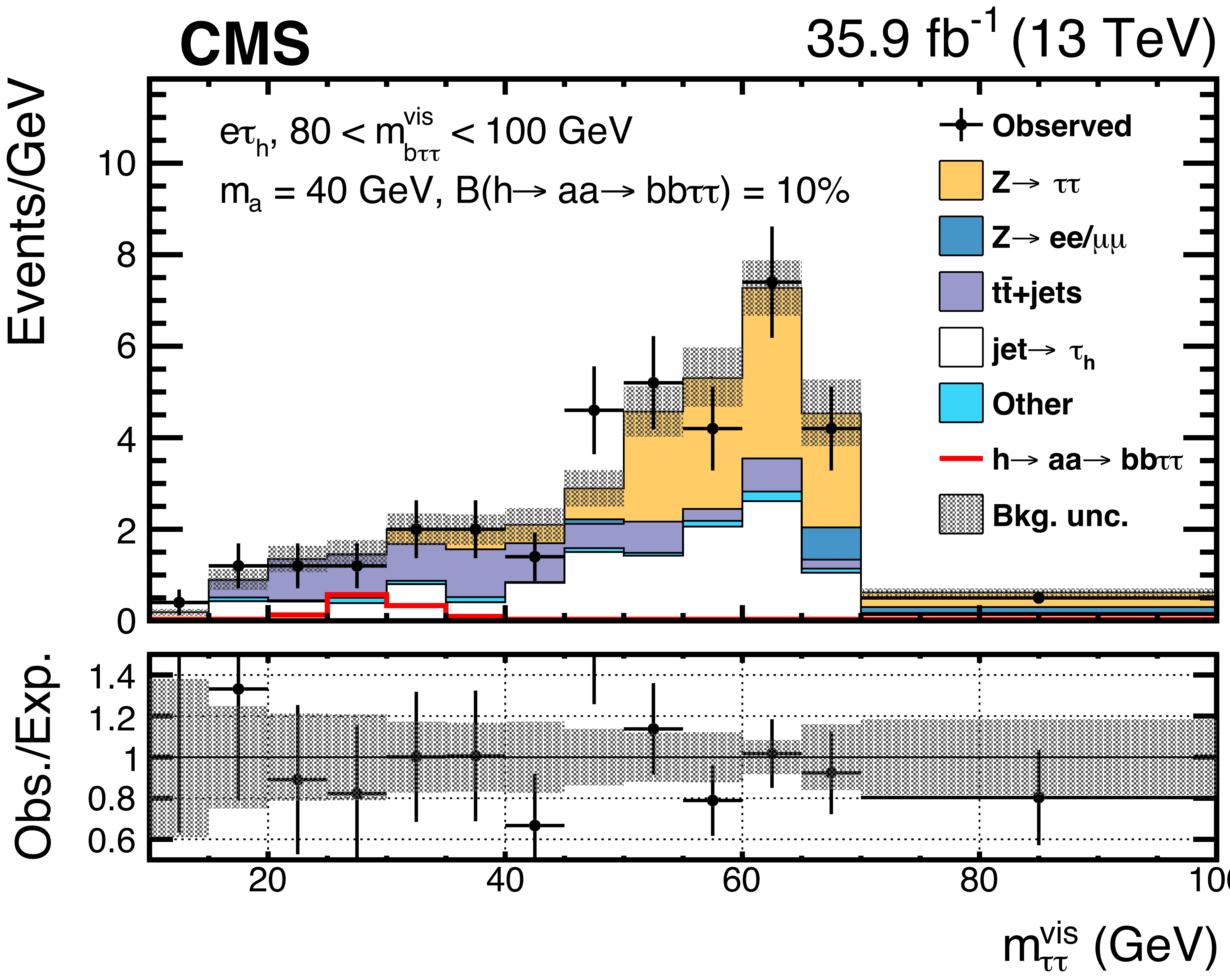


Background

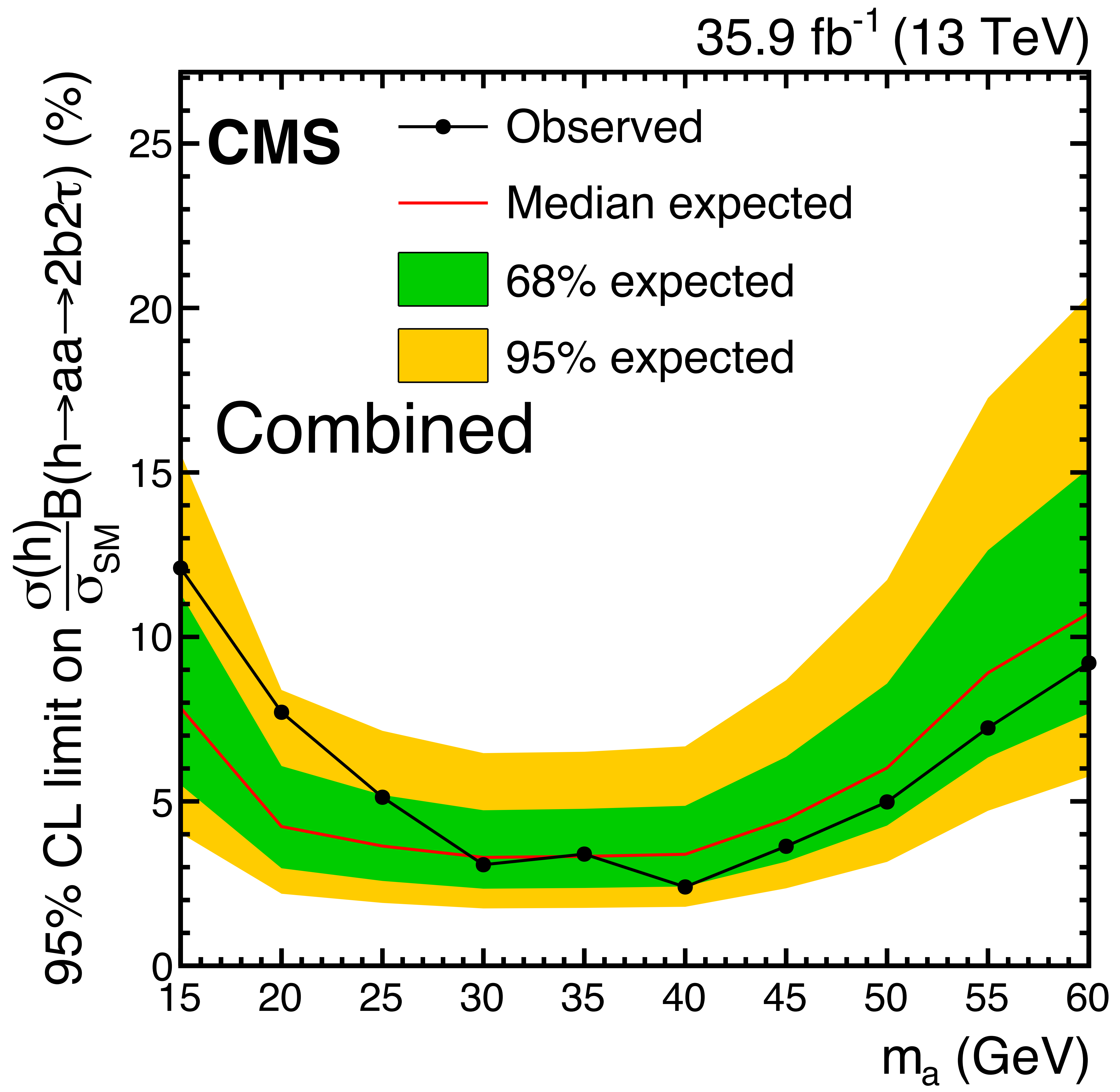
- Z → ll estimated from simulation
- Jet misidentified as τ_h candidate estimated from data
  - W+jets and QCD multijet events

h→aa→bbττ (Phys. Lett. B 785 (2018) 462) [35.9 fb^{-1} (13 TeV)]

- Fit to $m_{\tau\tau}$ distribution performed in each category and channel to obtain final results

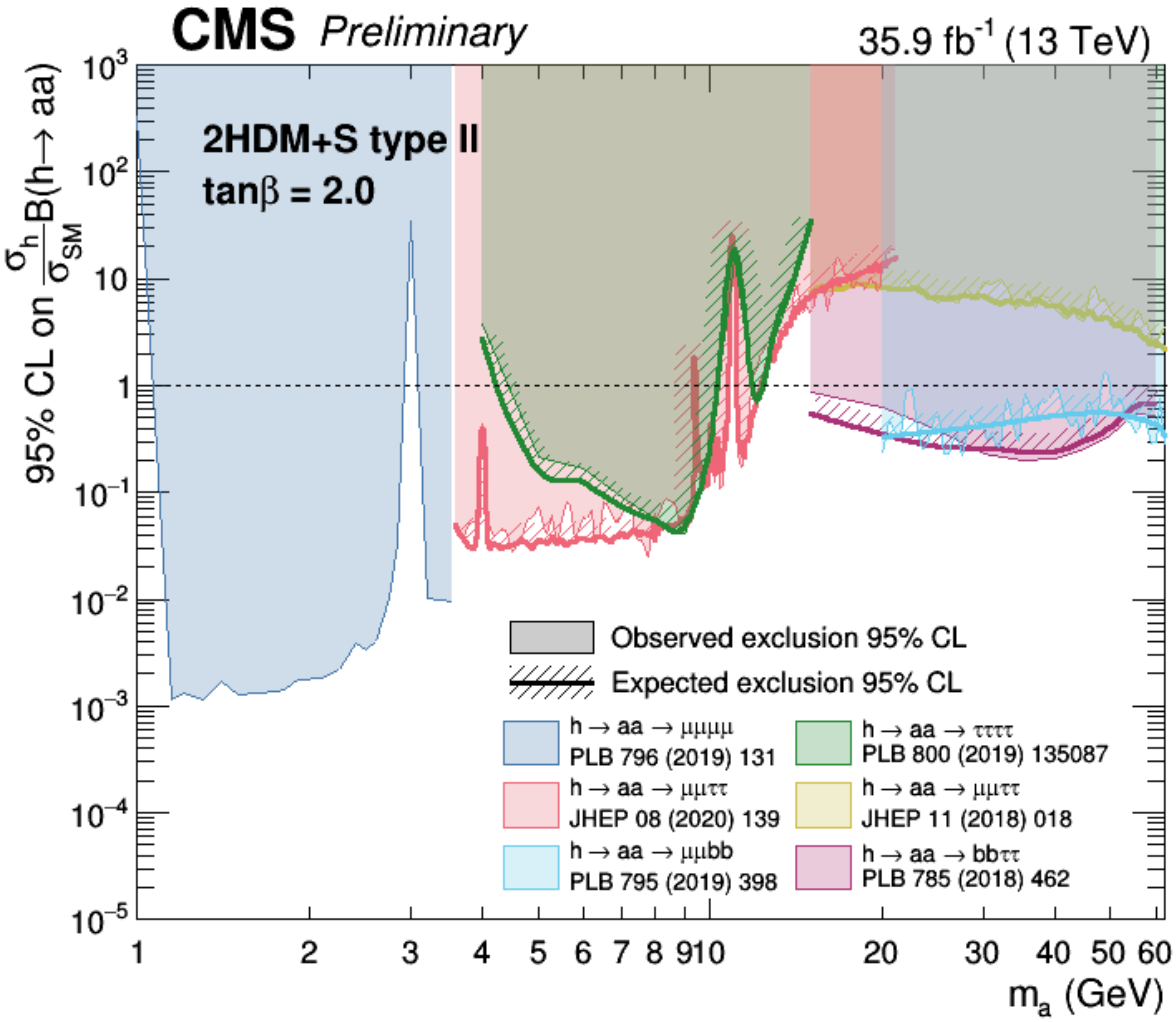


- 95% CL upper limits set on $\sigma(h)xB(h\rightarrow aa\rightarrow bb\tau\tau)/\sigma_{SM}$



Summary 2HDM+S results

- Several final states being investigated
- Boosted reconstruction techniques used
  - h→aa→μμμμ
  - h→aa→μμττ
- Well separated final state objects
  - h→aa→bbττ
- Current summary results from CMS here
- Analyses currently being performed with full Run 2 data



Conclusions

- So far, no deviations from SM

However,

- Higgs decays to pseudoscalars are a favorable place to search for signs of new physics
  - Rich set of $h \to aa$ searches being pursued by CMS
  - Many channels investigated in 2016
  - Results will be improved with the analysis of all data collected during Run 2 of the LHC
  - **Experiences from these analyses will help during Run 3 and beyond**

Backup

h→aa→4μ *(Phys. Lett. B 796 (2019) 131)* *[35.9 fb^{-1} (13 TeV)]*

- Each muon required to have pT > 8 GeV and |η| <2.4
- At least one muon must be high pT (|η| < 0.9 and pT > 17 GeV)

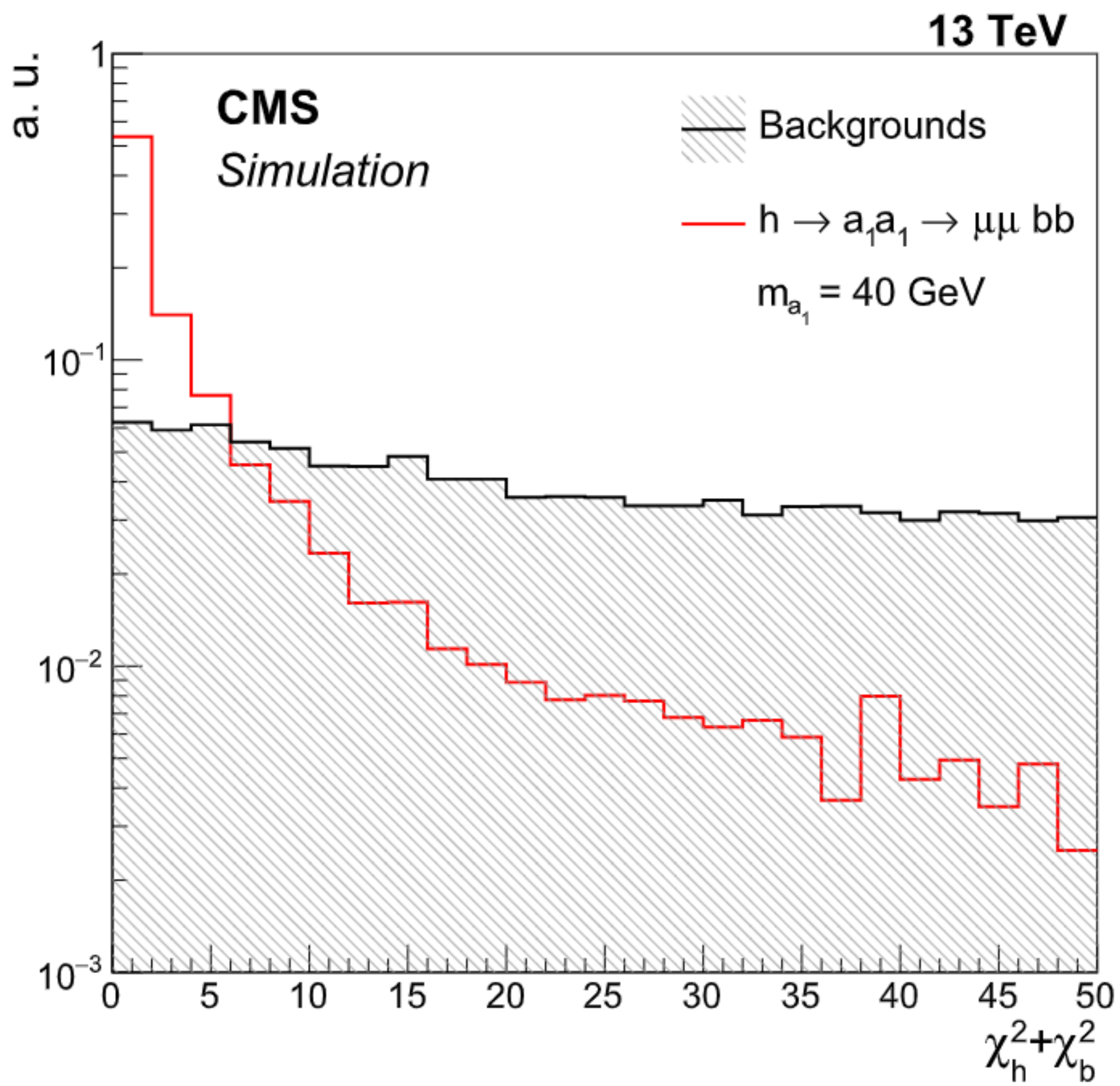
- NMSSM
  - m(h) ranges from 90 to 150 GeV
  - Motivated by constraints set by relic density measurements

- Dark SUSY
  - Higgs bosons decay to a pair of SUSY neutralinos h→2n1
  - Each SUSY neutralino in turn decays to a dark photon and a dark neu-tralino via n1→nD+γD
  - mnDis set to 1GeV; they are considered stable and thus escape detection.
  - Dark photons decay to a pair of muons 100% of the time
  - m(h) = 125 GeV and m(n1) = 10 GeV
- Model independence ensured by verifying that ratio of the full reconstruction efficiency fullover the generator lev acceptance αgenis independent of the signal model.

h→aa→μμbb *Phys. Lett. B 795 (2019) 398 [35.9 fb-1 (13 TeV)]*

- χ^2 constructed

$$\chi_{bb} = \frac{(m_{bb} - m_{\mu\mu})}{\sigma_{bb}} \quad \text{and} \quad \chi_h = \frac{(m_{\mu\mu bb} - m_h)}{\sigma_h}.$$



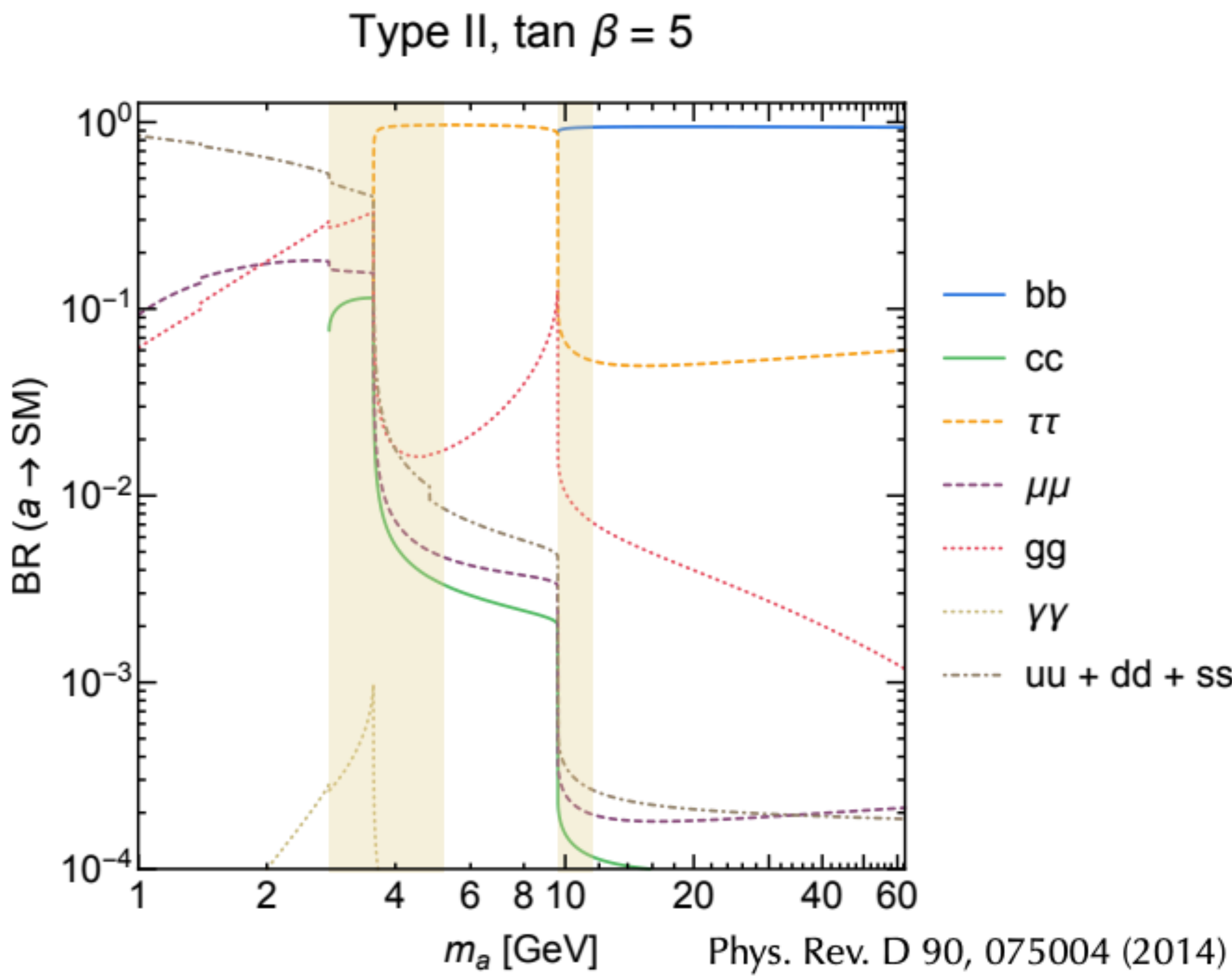
- Events selected with $\chi^2 < 5$
  - Signal efficiency of ~64% and background rejection of > 95%

h→aa→μμbb *Phys. Lett. B 795 (2019) 398 [35.9 fb^{-1} (13 TeV)]*

- Pt miss < 60 GeV
- Event categorization based on highest expected significance
  - Using b jet discriminator value

Two Higgs double + Scalar Singlet Model (2HDM+S)

- 2HDM one of the simplest extensions of SM
- After symmetry breaking, two Higgs doublets are created ϕ1, ϕ2
  - h, H: neutral Higgs bosons that are CP-even (scalar)
  - A: neutral Higgs Boson that is CP-odd (pseudoscalar)
  - H±: charged Higgs Boson
  - tanβ: ratio of VEV of the two Higgs doublets
  - α: the mixing angle between the CP-even Higgs bosons
- Different types based on type of interaction of the doubles with quarks and charged lepton
- Complex scalar singlet only couples to the Higgs complex fields
  - All couplings to SM fermions are through mixing of the scalar with the Higgs field
  - Small to preserve the SM nature of the Higgs sector



Phys. Rev. D 90, 075004 (2014)