# Exotic Higgs decays at CMS

## Higgs 2021

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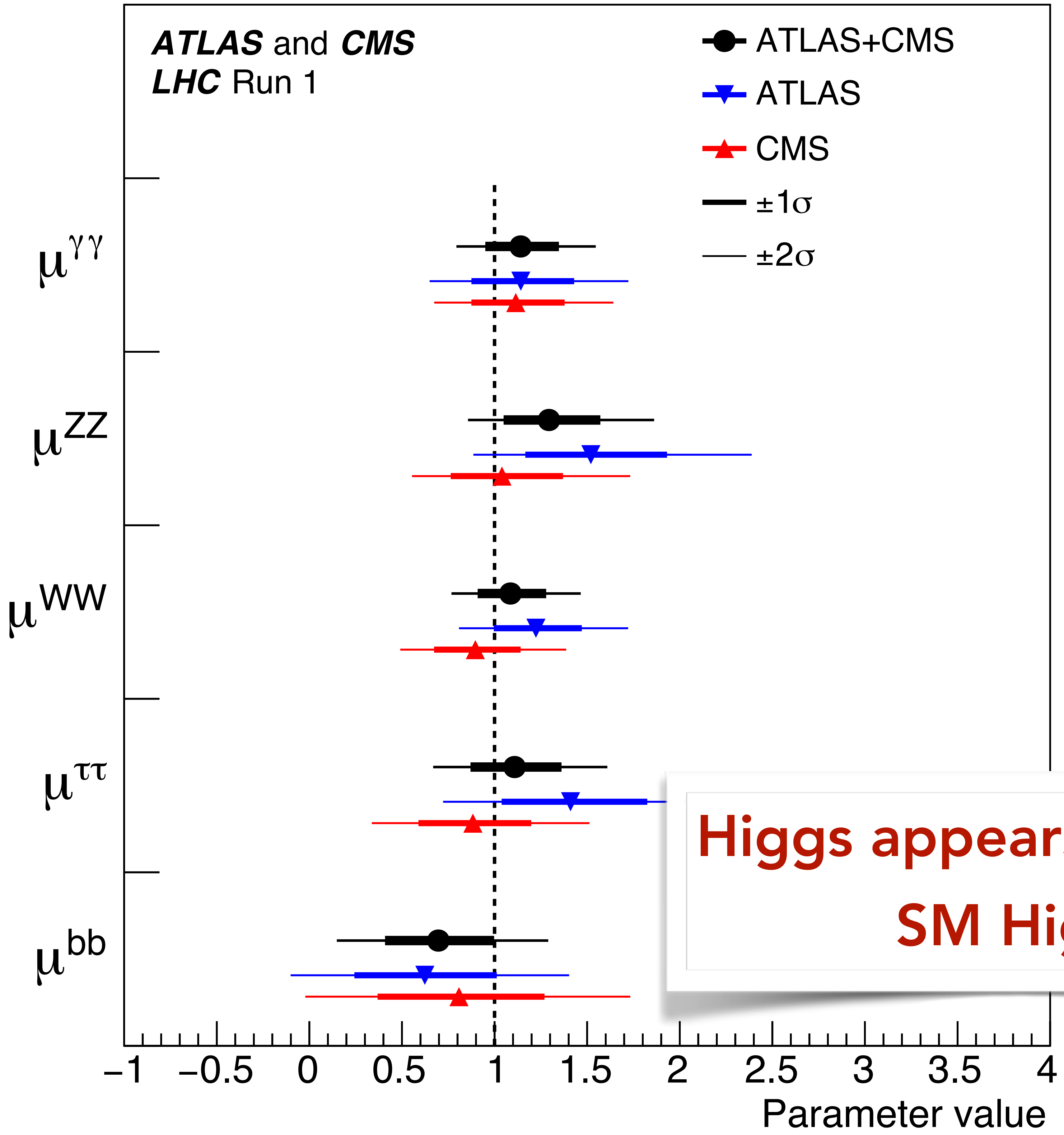
# Introduction

- 125 GeV Higgs boson discovered by 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
  - ……..

# Higgs as a probe for BSM physics

**Search for new BSM particles**

- Neutral or charged exotic Higgs bosons

**Decays of Higgs to SM particles**

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

**Decays of Higgs to non-SM particles**

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

Search for H± and H±±

See Fabio's talk

$H \to Z\gamma$, $H \to \mu^+\mu^-$, and more!

See James's talk

LFV decays

$H \to e\tau/\mu\tau$

Invisible Higgs decays in VBF

See Nicholas's talk

**Focus of this talk!**

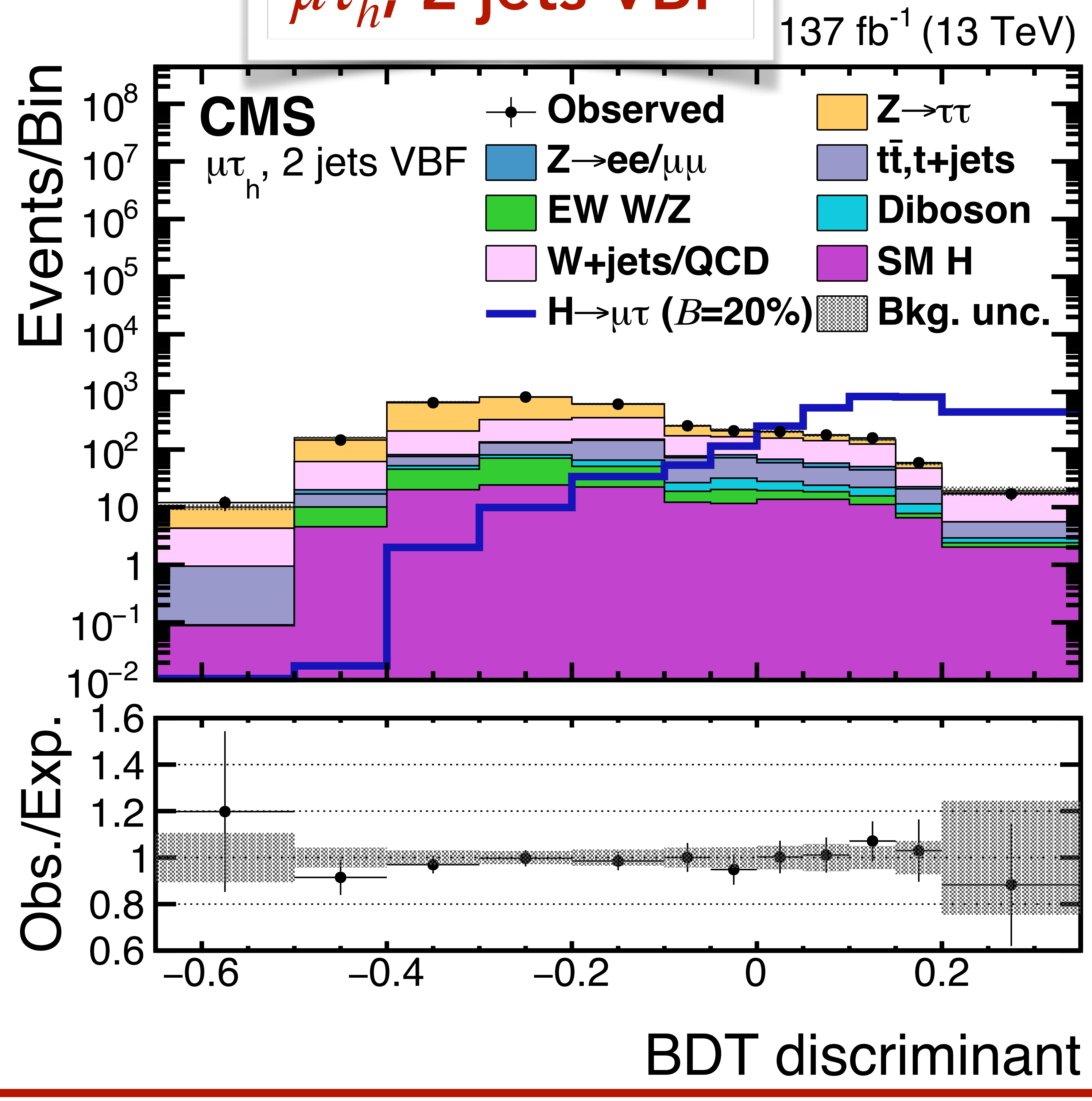
$H \to aa$, **a decaying to SM**

$H \to aa \to \gamma\gamma\gamma\gamma$

# LFV decays: $H \to e\tau/\mu\tau$ arxiv:2105.03007

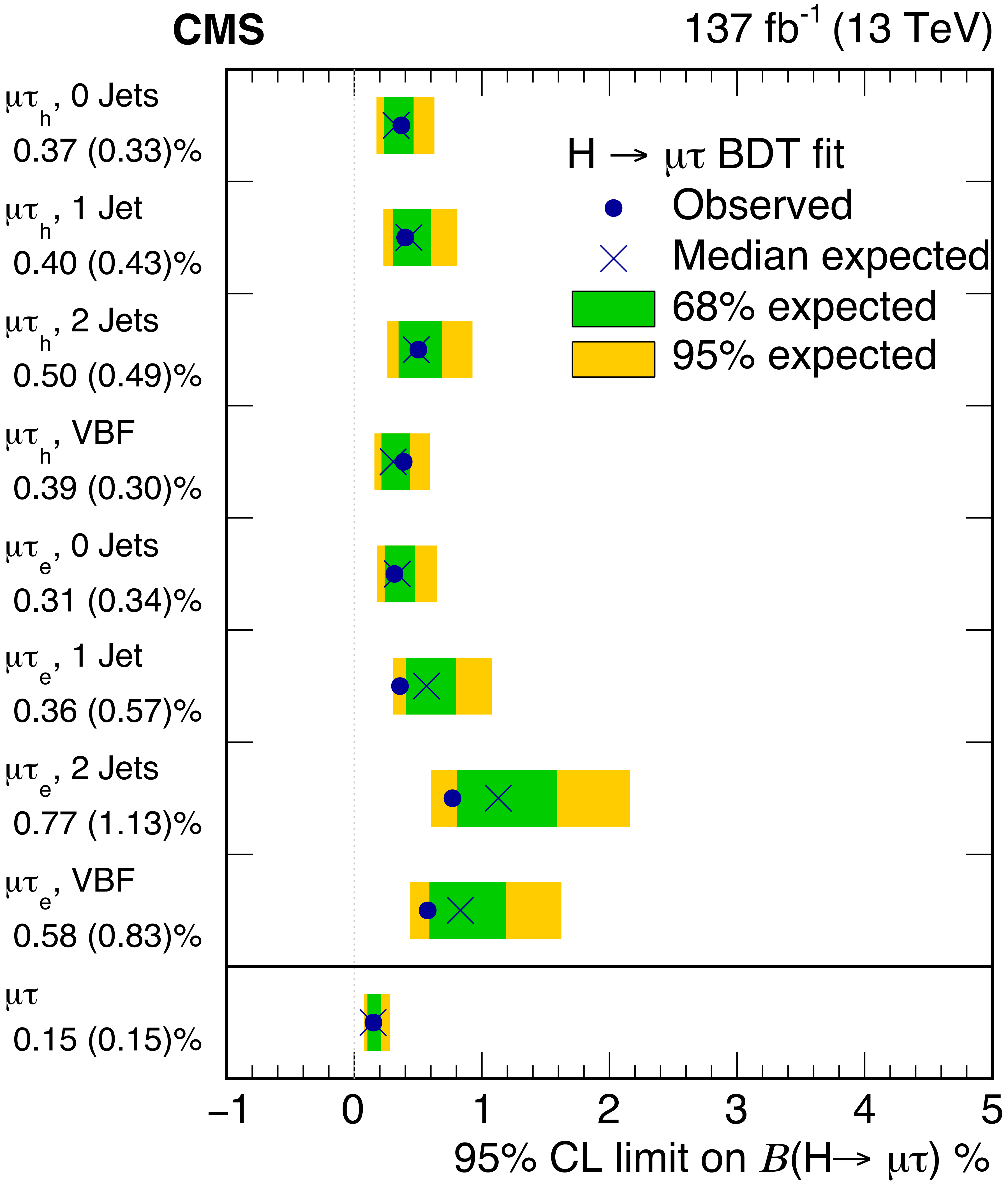
- LFV decays forbidden in the SM
  - SUSY and some composite Higgs model allow LFV Yukawa couplings $Y_{e\mu}, Y_{e\tau}, Y_{\mu\tau}$
- Channels and final states: $H \to \mu\tau_h, H \to \mu\tau_e, H \to e\tau_h, H \to e\tau_\mu$
- Categories:
  - $gg \to H$: 0 jet, 1 jet, 2 jets
  - $qq \to H$: 2 jets
- $Z \to \tau\tau$, top quark processes, mis-identified objects are the major backgrounds
  - Background estimation using data driven techniques + simulation
- BDT's trained in each channel separately
  - Maximum likelihood fit to BDT output discriminators
  - Simultaneously over all channels and categories

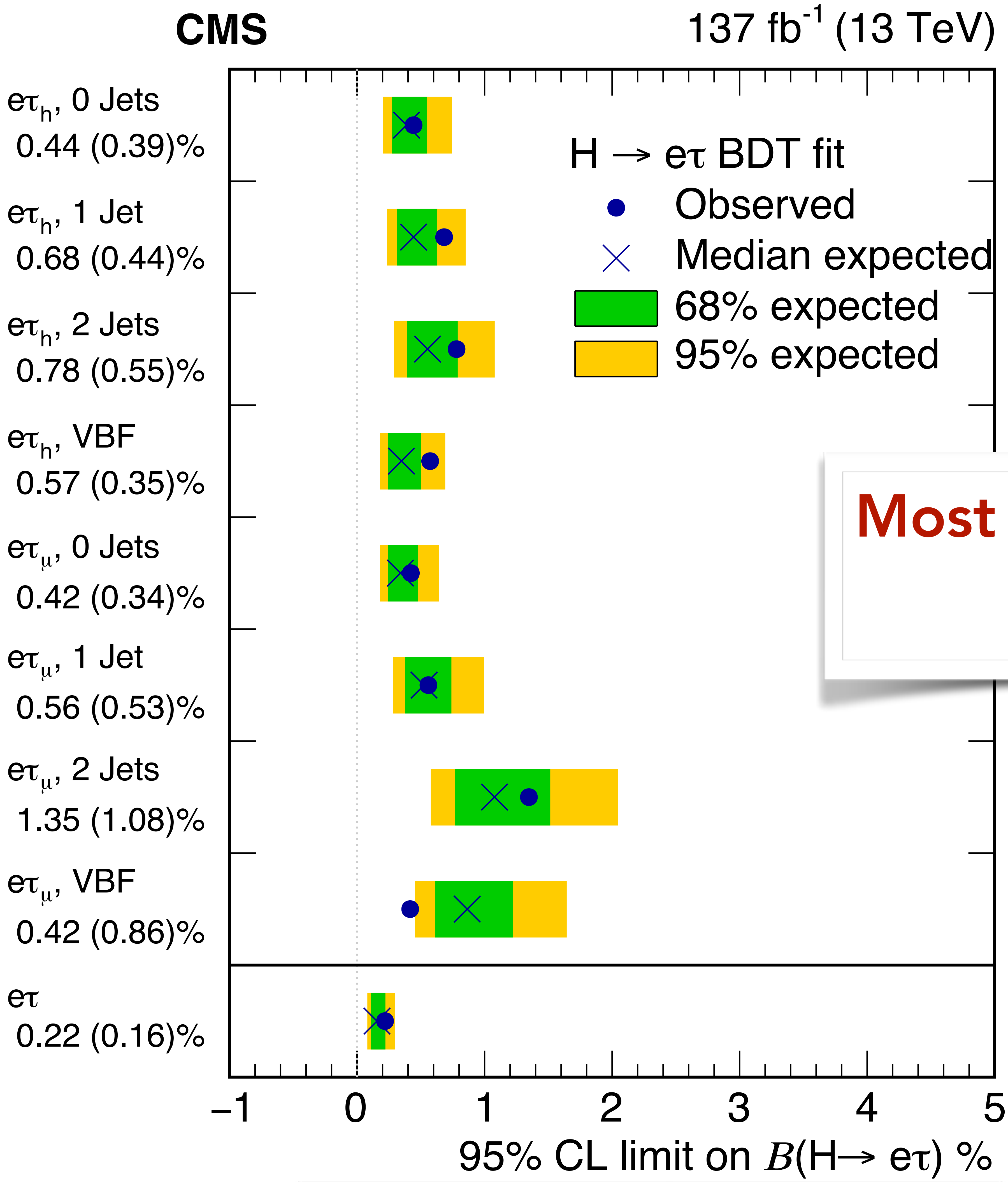
$\mu\tau_h$, 2 jets VBF



# LFV decays: $H \to e\tau/\mu\tau$ arxiv:2105.03007

- Results using full run 2 data




**Most stringent limits to date!**

**BR($H \to \mu\tau$) < 0.15%**

**BR($H \to e\tau$) < 0.22%**

# LFV decays: $H \rightarrow e\tau/\mu\tau$

arxiv:2105.03007

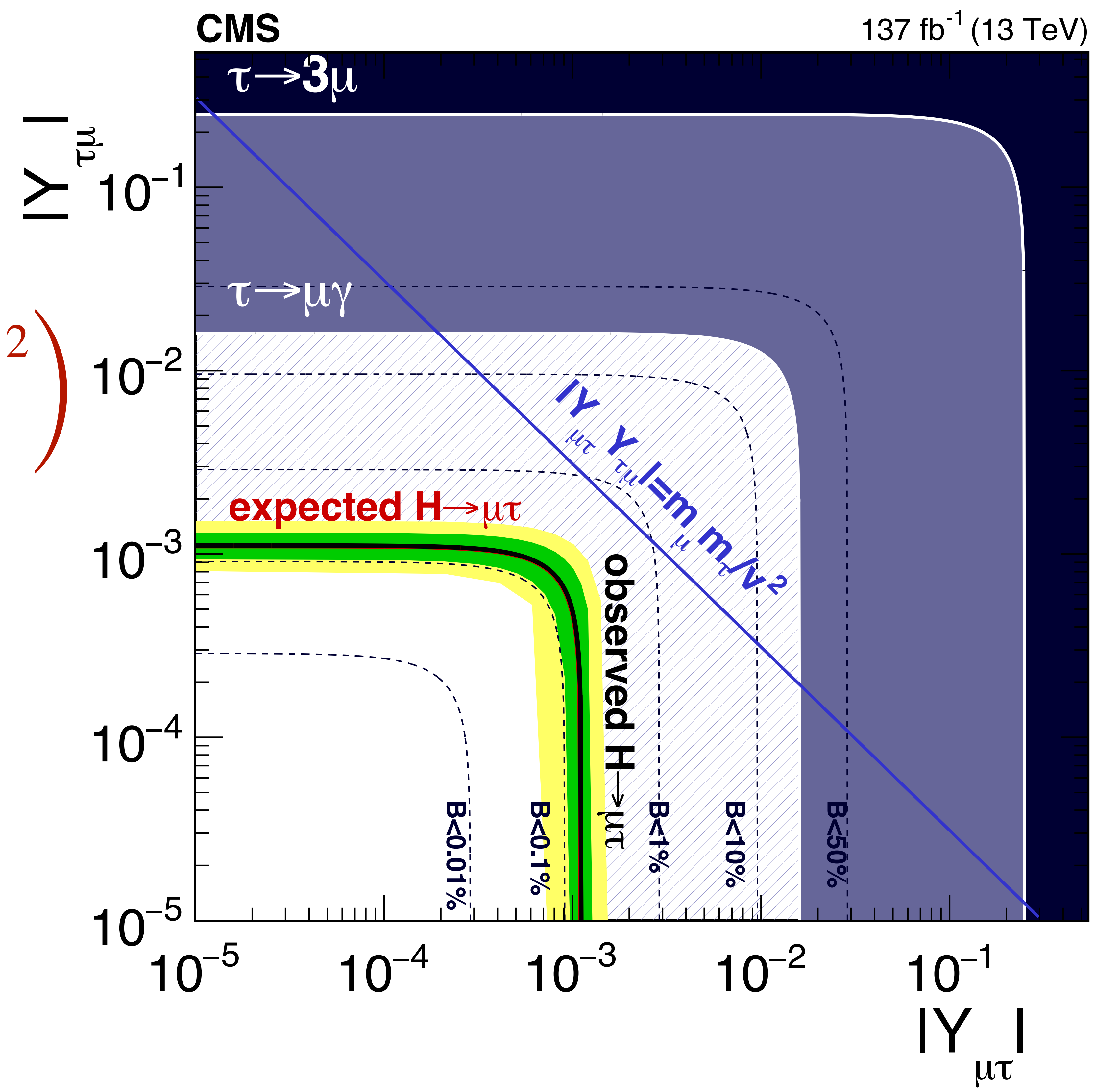
**Most stringent limits to date!**

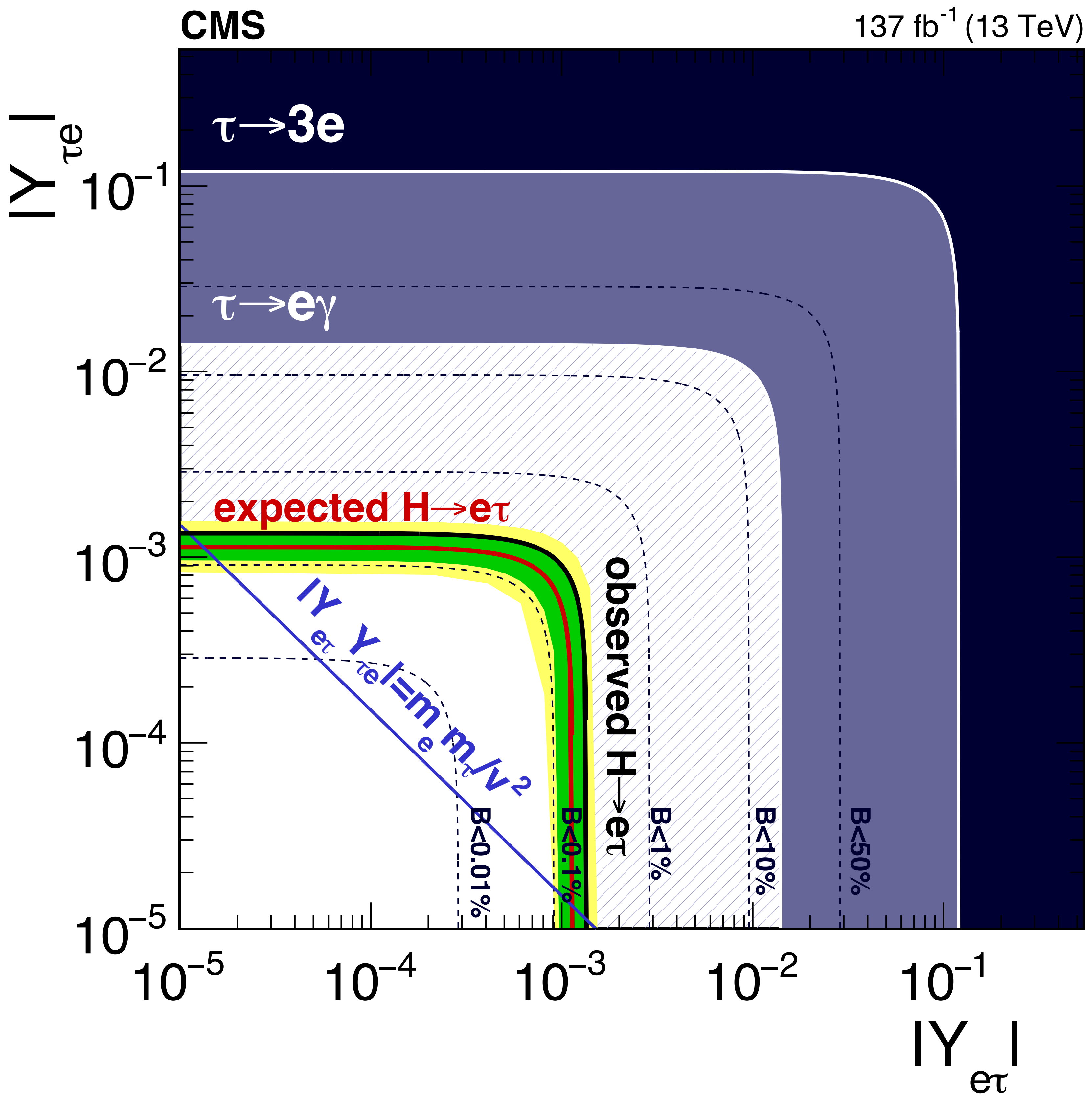
- Also put constraints on Yukawa couplings

$$\Gamma\left(\mathrm{H} \rightarrow \ell^{\alpha}\ell^{\beta}\right) = \frac{m_{\mathrm{H}}}{8\pi}\left(\left|Y_{\ell^{\alpha}\ell^{\beta}}\right|^2 + \left|Y_{\ell^{\beta}\ell^{\alpha}}\right|^2\right)$$

$$\mathscr{B}\left(\mathrm{H} \rightarrow \ell^{\alpha}\ell^{\beta}\right) = \frac{\Gamma\left(\mathrm{H} \rightarrow \ell^{\alpha}\ell^{\beta}\right)}{\Gamma\left(\mathrm{H} \rightarrow \ell^{\alpha}\ell^{\beta}\right) + \Gamma_{\mathrm{SM}}}$$

here, $\ell^{\alpha}, \ell^{\beta}$ are different flavored leptons



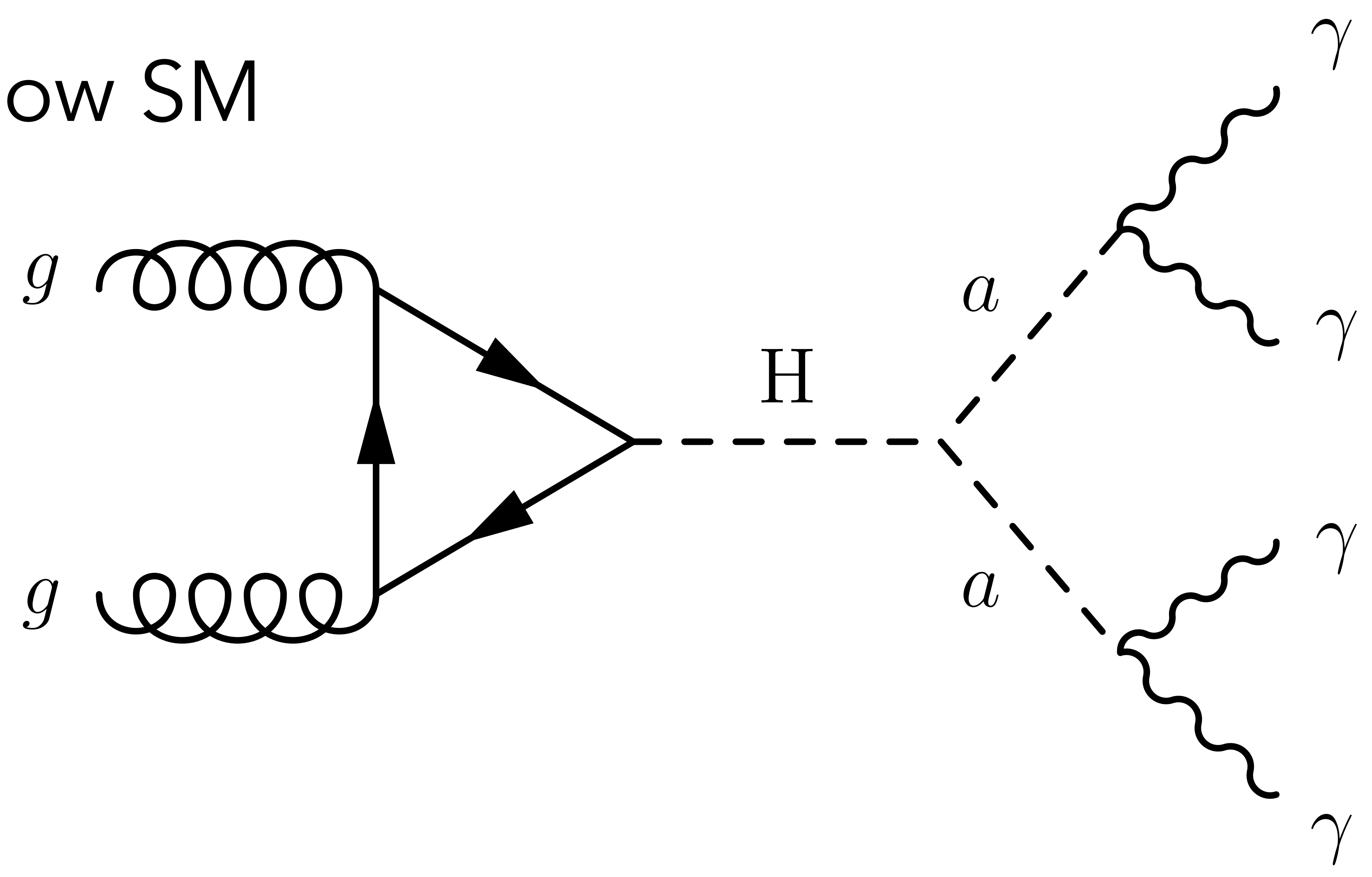




$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.1 \times 10^{-3}$$

$$\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 1.35 \times 10^{-3}$$

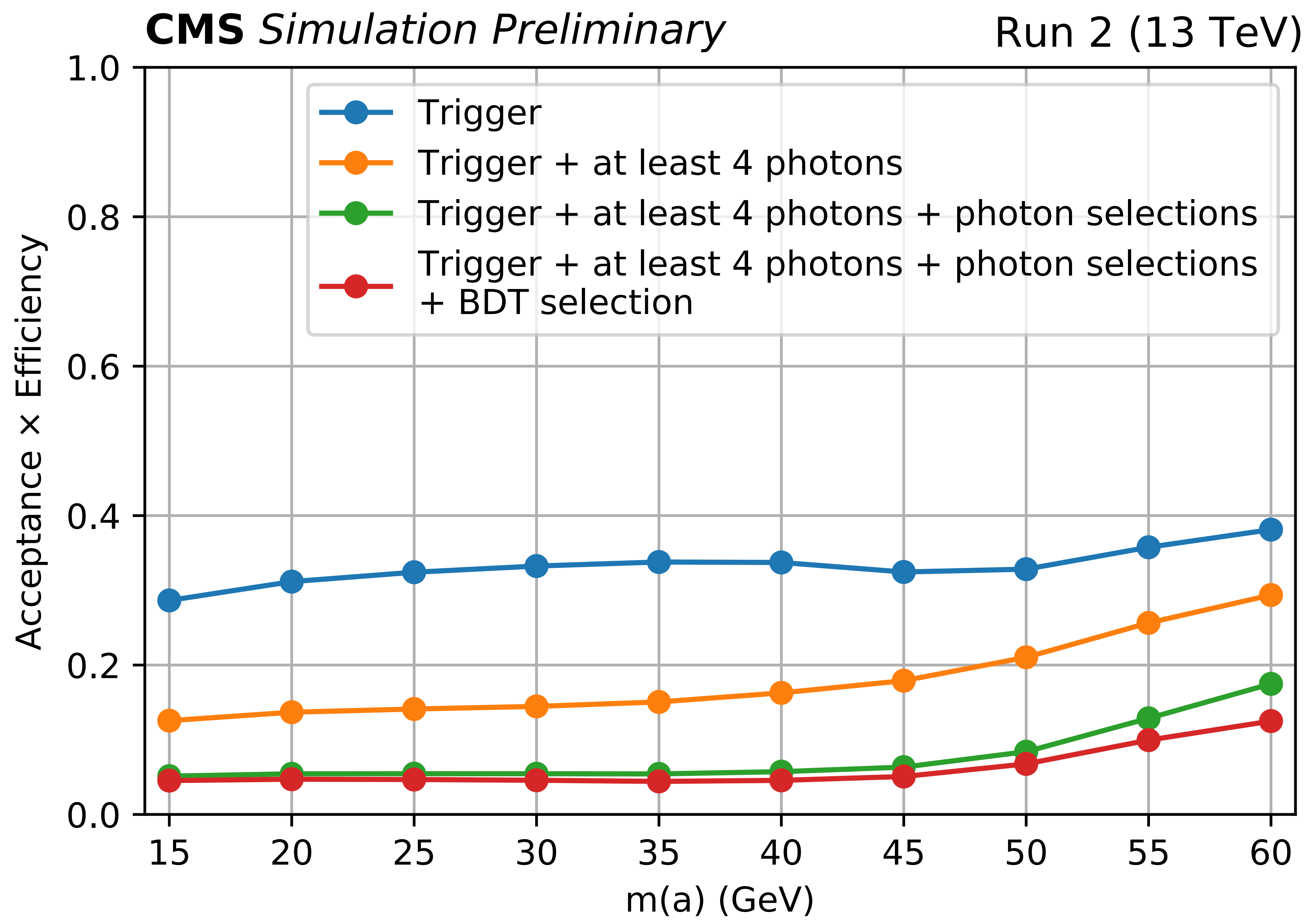
# $H \to aa \to \gamma\gamma\gamma\gamma$ CMS-HIG-21-003

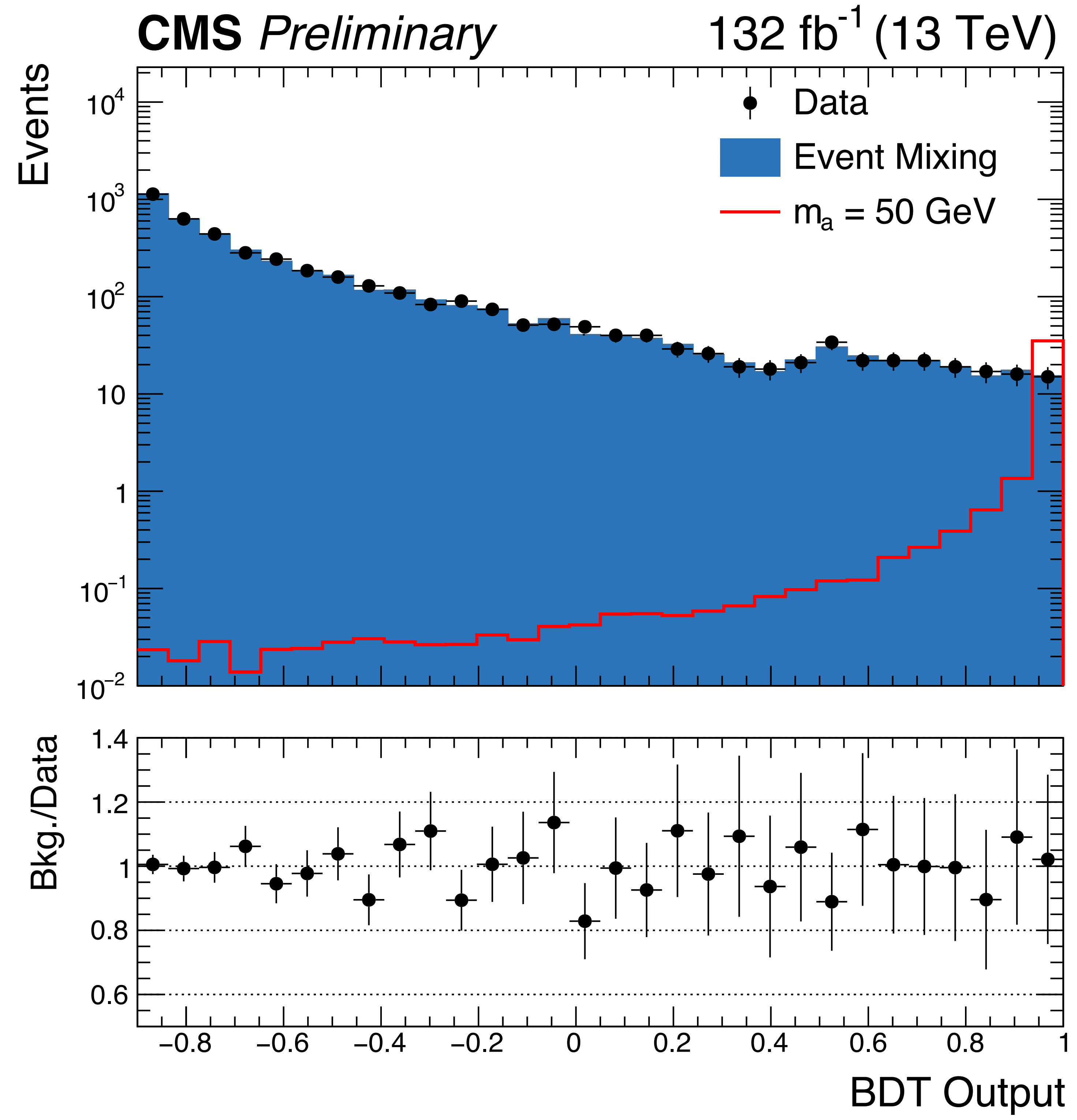
- Light pseudoscalars are a possibility in various BSM scenarios
- In various BSM scenarios, coupling of *a* to fermions can lower BR($a \to \gamma\gamma$). But
  - Four photon final state provides a clean signature: low SM background
  - In some models, *a* may only decay into photons
- Analysis considers 4 fully resolved photons
  - $m_a$ ranges from 15 to 60 GeV
  - Wide opening angle b.w photon pairs
- First CMS search in this final state
  - Previous result from ATLAS: EPJC 76 (2016) 210



# $H \to aa \to \gamma\gamma\gamma\gamma$ CMS-HIG-21-003

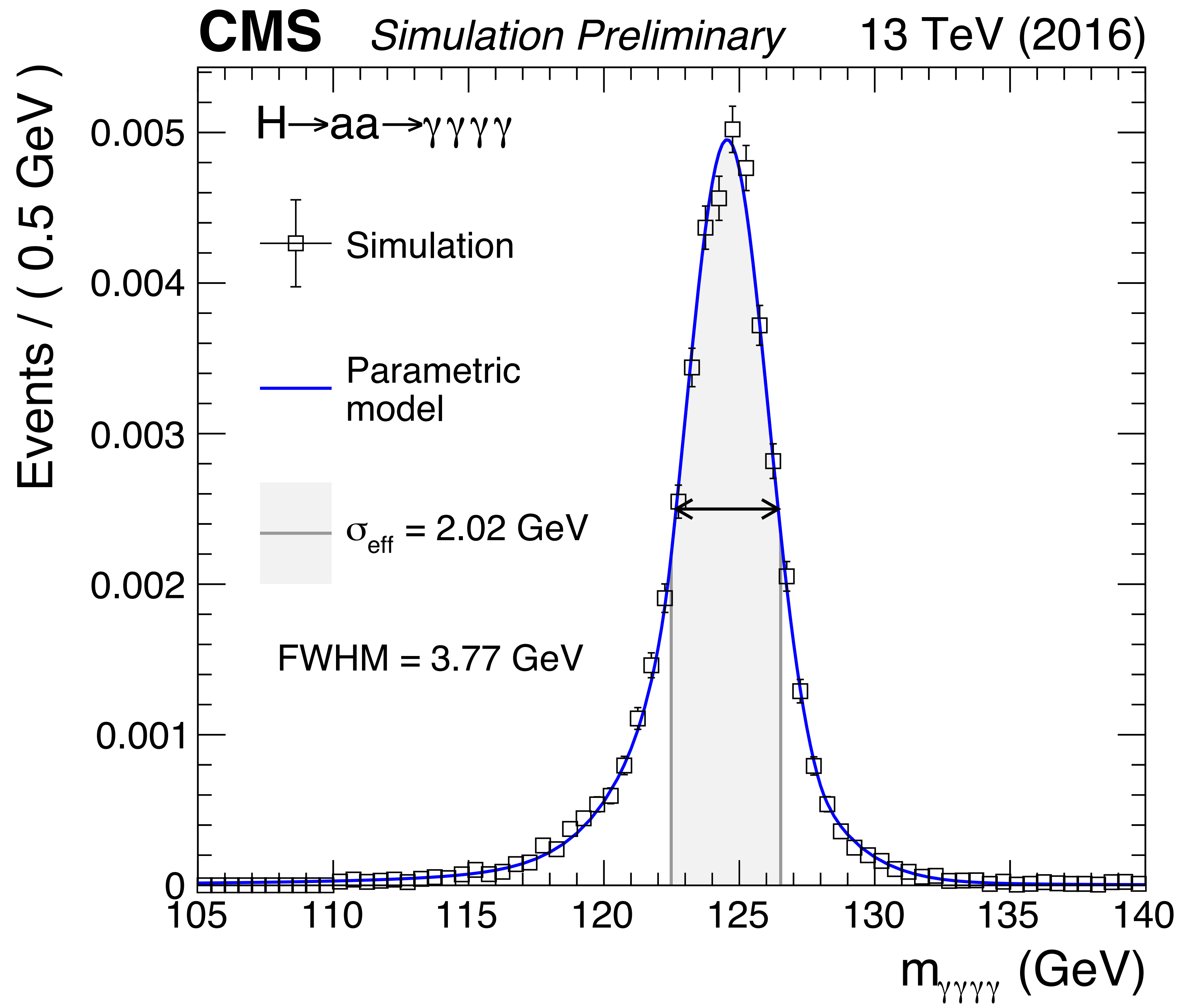
- Strategy in a nutshell
  - Select events with 4 well isolated photons using a di-photon trigger
  - Construct Higgs candidate using the photons
  - $m_{\gamma\gamma\gamma\gamma}$ peaks around 125 GeV for signal
  - Signal extracted by fit to $m_{\gamma\gamma\gamma\gamma}$ distribution in data
- MVA based categorization
  - Utilize ID and kinematic information of the 4 photons
  - Background estimation using data-driven technique (only used for training)
  - Parametrized training
    - Output is uniform and sensitive to the complete $m_a$ range



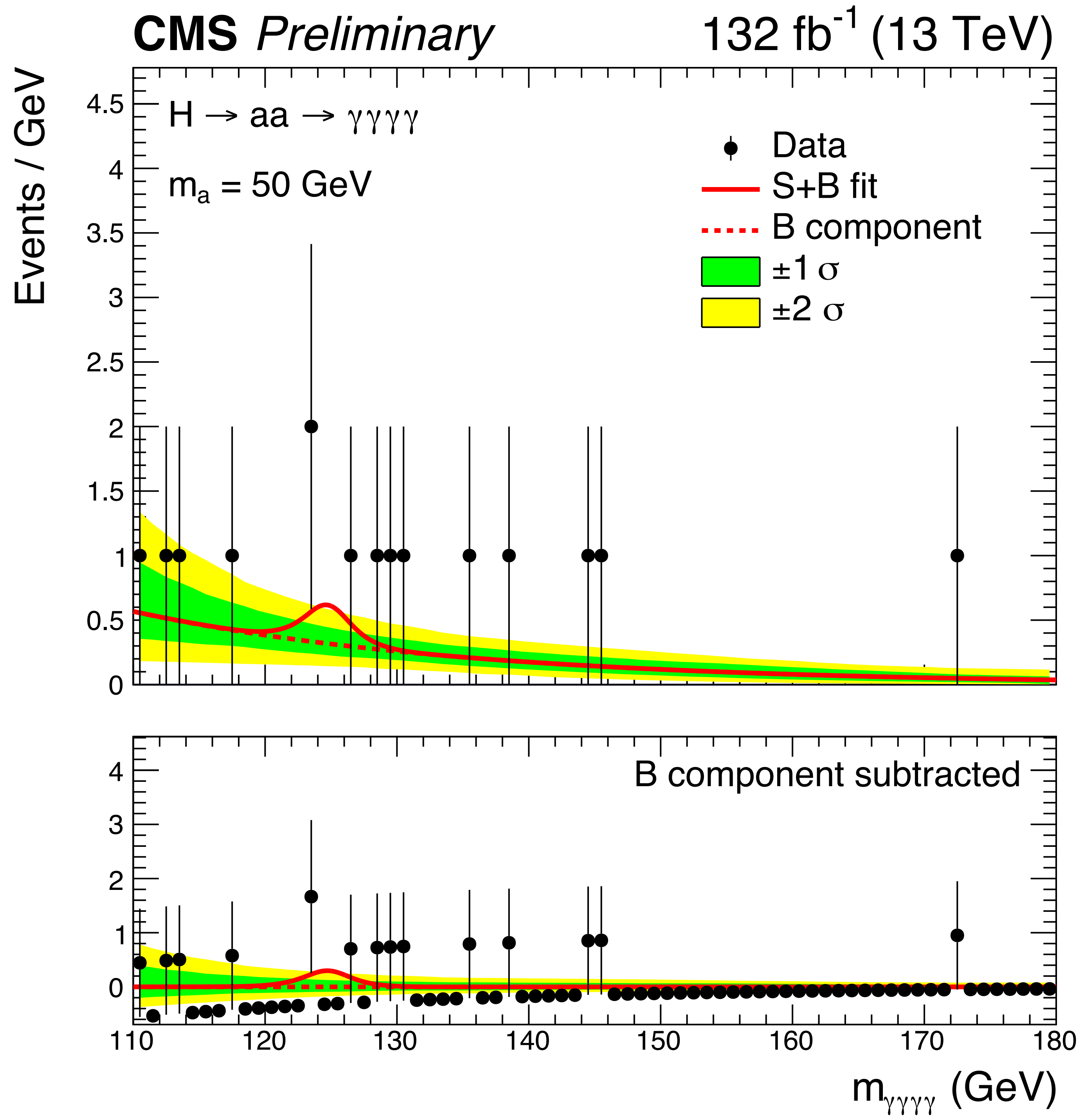



# $H \to aa \to \gamma\gamma\gamma\gamma$ CMS-HIG-21-003

- Signal model
  - Signal shape for $m_{\gamma\gamma\gamma\gamma}$ constructed from simulation
  - Modeled using Double-sided crystal ball function

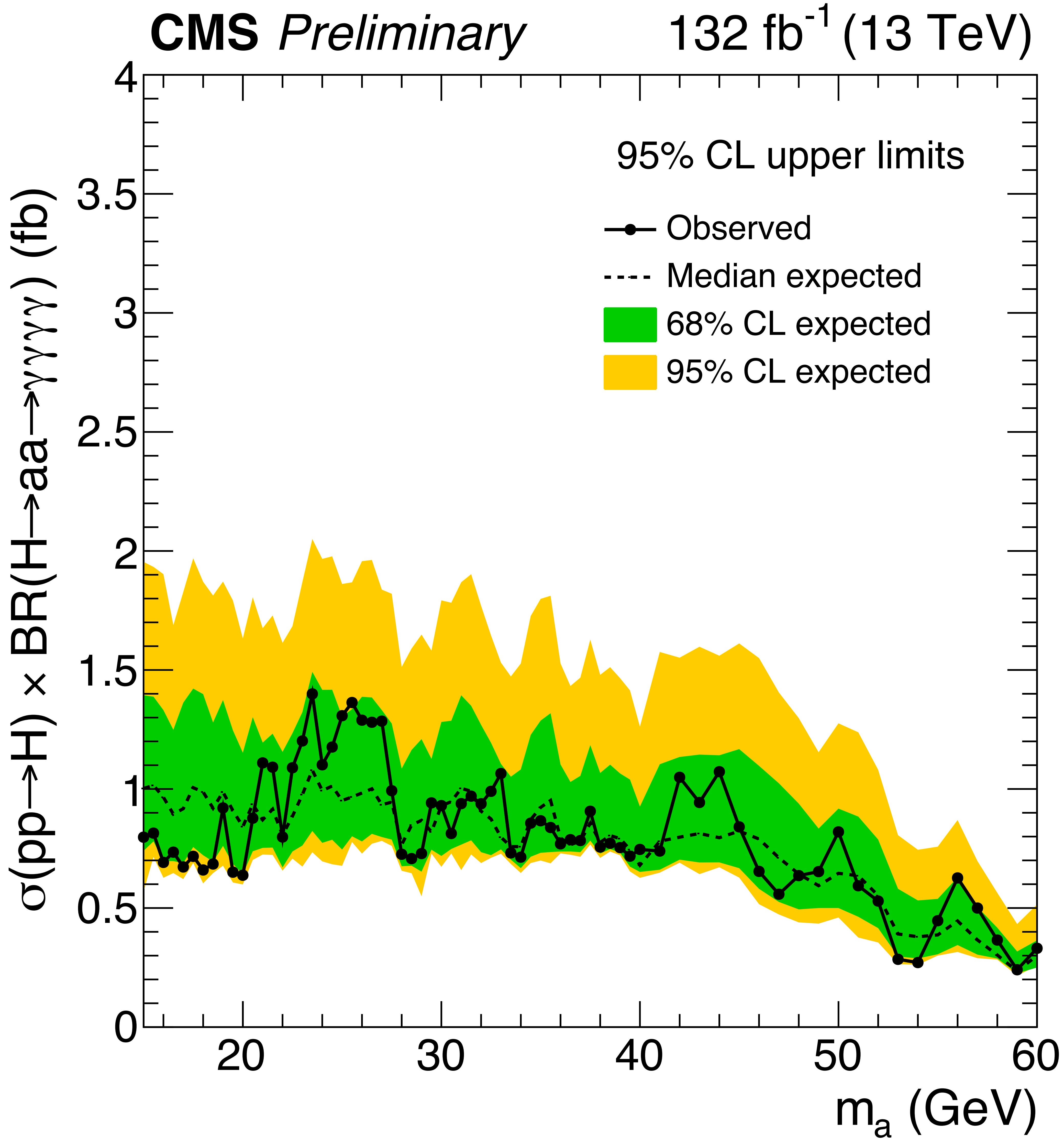



- Background model
  - Built directly using data (full run 2)
  - Using discrete profiling method
    - Choice of background pdf treated as discrete nuisance parameter
  - Unique background model constructed for each mass hypothesis



# $H \to aa \to \gamma\gamma\gamma\gamma$ CMS-HIG-21-003

- Results
  - Set limits (95% CL) on $\sigma(pp \to H) \times BR(H \to aa) \times BR(a \to \gamma\gamma)^2$
  - $m_a$ granularity of 0.5 GeV up to $m_a$ = 40 GeV and 1 GeV for $m_a$ > 40 GeV
  - No significant deviation from background-only hypothesis
  - Observed limits in agreement with expected limits within two standard deviations
- **First result from CMS in this final state**



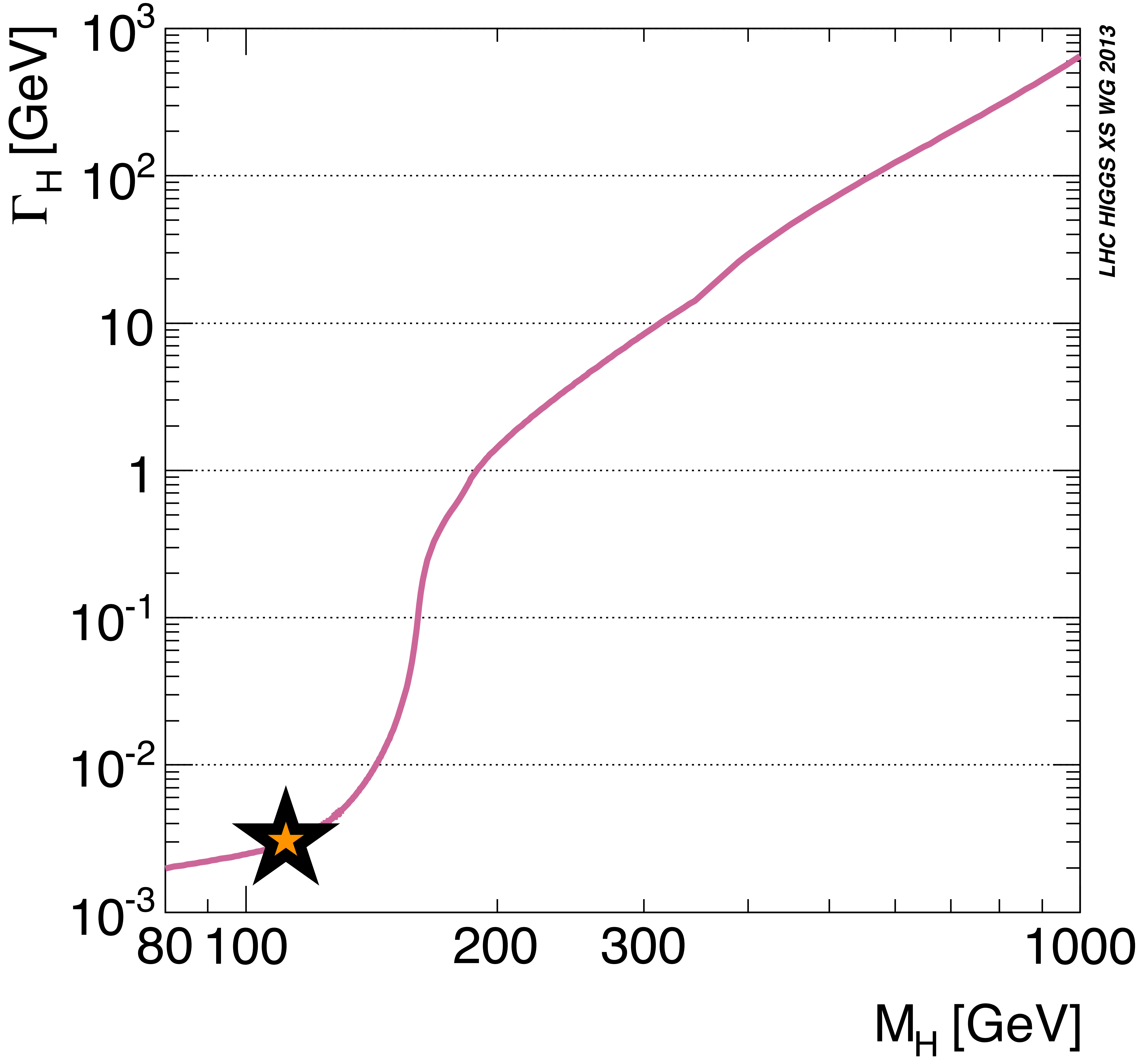
# Conclusions

- So far, no deviations from SM
- However,
  - Searches involving the Higgs boson are a favorable place to search for signs of new physics
  - Rich set of $H \rightarrow aa$ searches being pursued by CMS
    - Many channels investigated using 2016 data and a few full run 2 results have been completed: *See summary of results* ***here***
  - SUSY and composite Higgs being probed by LFV decays of the Higgs
- No significant excess or deviation
  - Exclude many scenarios, but some phase spaces are still uncovered
- Experience and techniques gained from these analyses will help during Run 3 (which is just around the corner!) and beyond

# Backup

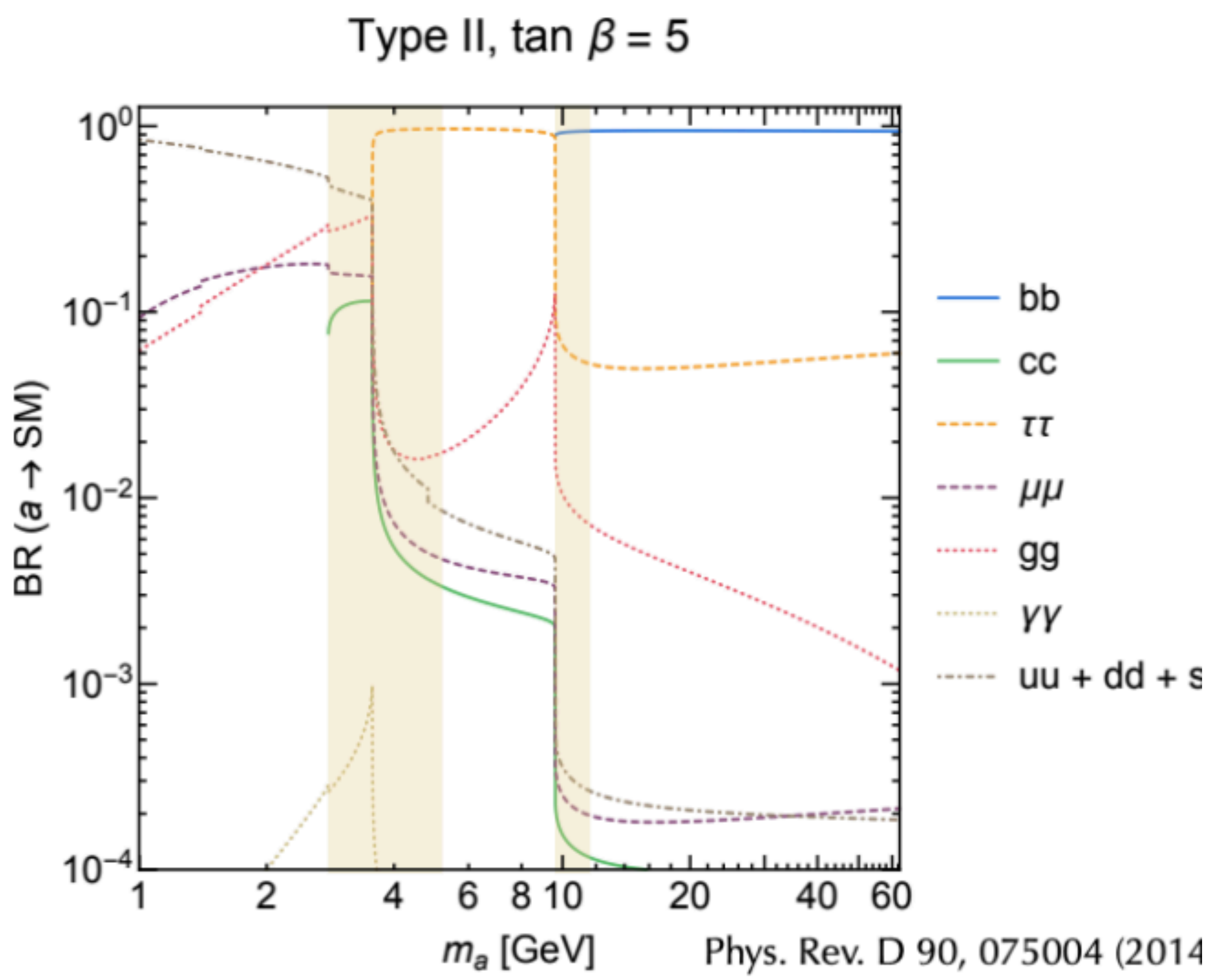
# What is special about the Higgs?

- How standard is the Higgs boson?
  - Extremely narrow width ★ ($\Gamma_h$ ~ 4.07 MeV ; $\Gamma_h/m_h$ ~ 3.3 x10$^{-5}$)
  - Experimentally, $\Gamma_h$ 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



# 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

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