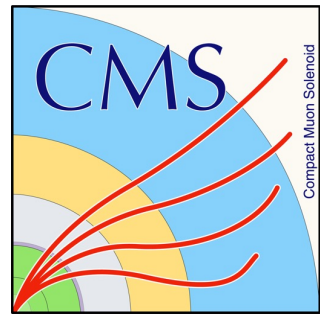
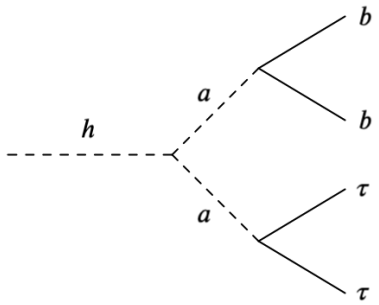




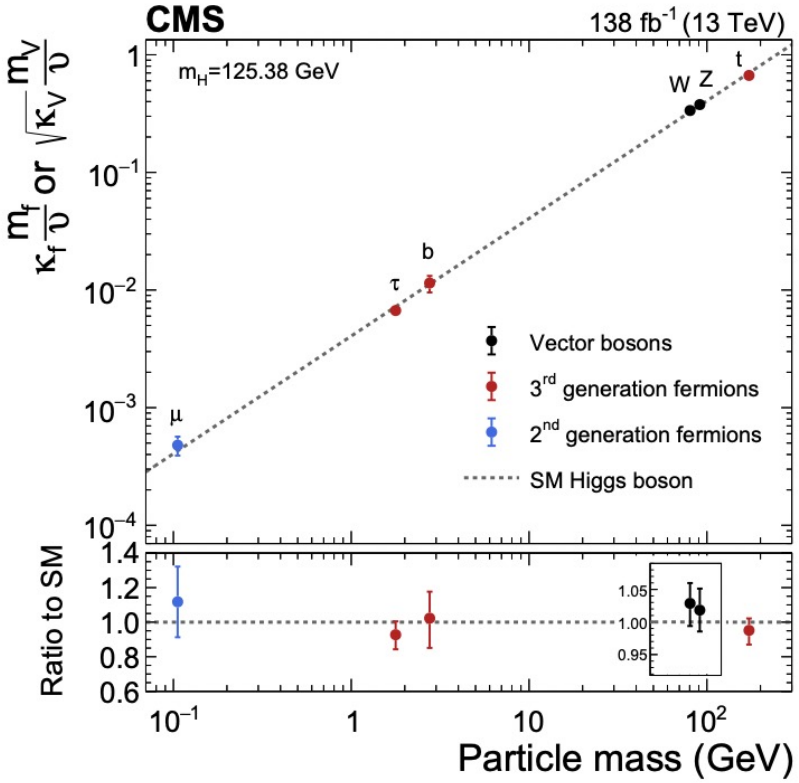
Searches for exotic Higgs boson decays with the CMS experiment

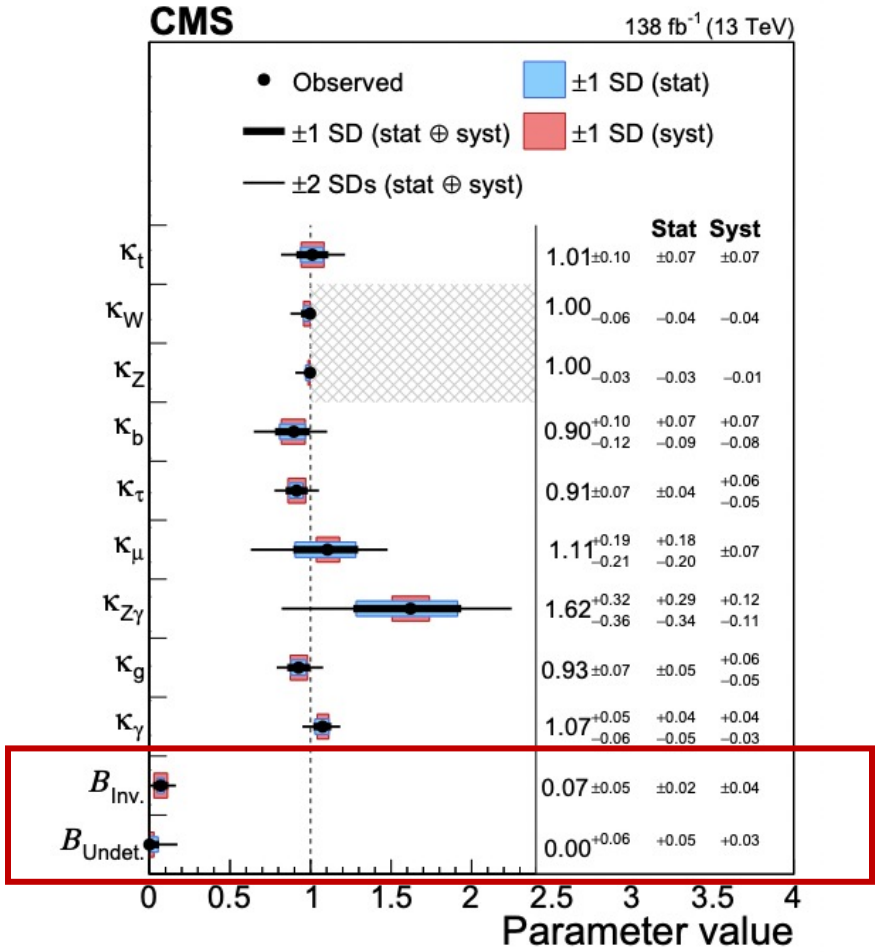
Ho Fung Tsoi (University of Wisconsin-Madison, USA)
on behalf of the CMS Collaboration

European Physical Society Conference on High Energy Physics (EPS-HEP2023)
Hamburg, Germany
Aug 21-25, 2023

Introduction

- A SM-like Higgs boson at a mass of ~125 GeV observed in 2012
- 10 years since then, collected data corresponding to 30x more Higgs production allowed more precise measurements of the particle
- Despite good compatibility with the SM prediction so far, there is still room for exotic Higgs decays to new particles beyond the SM





Nature 607, 60-68 (2022)

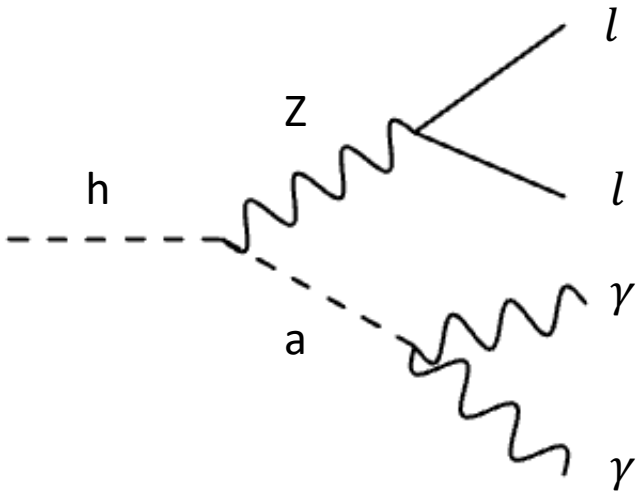
Outline

Run-2 CMS searches covered in this talk:

- $H_{125} \rightarrow Za \rightarrow ll\gamma\gamma$ CMS-PAS-HIG-22-003 *(2023 result)*
- $H_{125} \rightarrow aa$
  - bb$\mu\mu$/bb$\tau\tau$ + combination CMS-PAS-HIG-22-007 *(2023 result)*
  - 4γ resolved JHEP 07 (2023) 148 *(2022 result)*
  - 4γ merged 2209.06197 (accepted to PRL) *(2022 result)*
- $H_{125} \rightarrow$ Invisible
  - ttH/VH + full combination 2303.01214 (submitted to EPJC) *(2023 result)*
- $H_{125} \rightarrow$ LFV final states
  - eμ 2305.18106 (submitted to Phys. Rev. D) *(2023 result)*
  - eτ/$\mu\tau$ Phys. Rev. D 104, 032013 *(2021 result) (backup)*

Search for Higgs decays to Z boson + light pseudoscalar

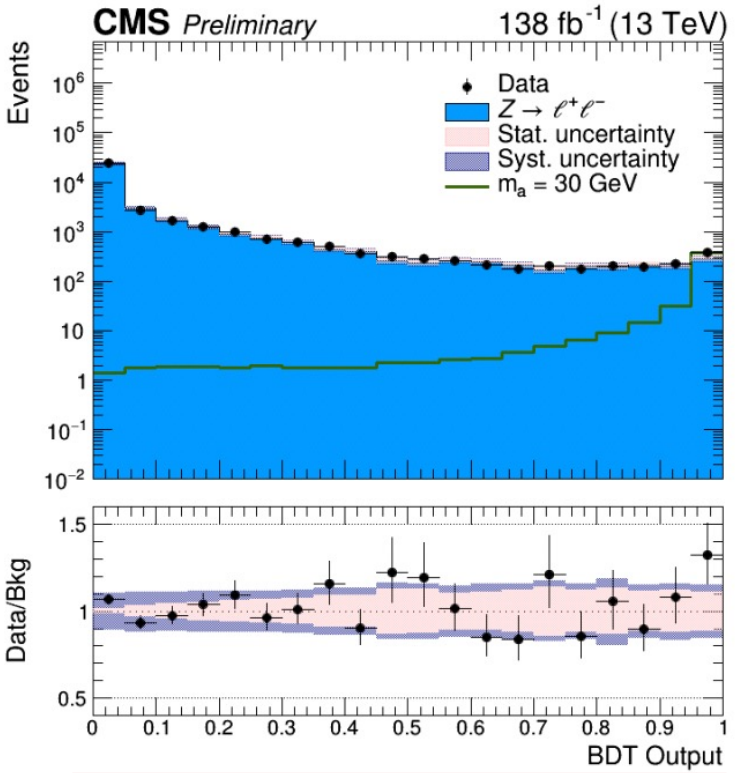
$$H_{125} \rightarrow Za \rightarrow ll\gamma\gamma$$



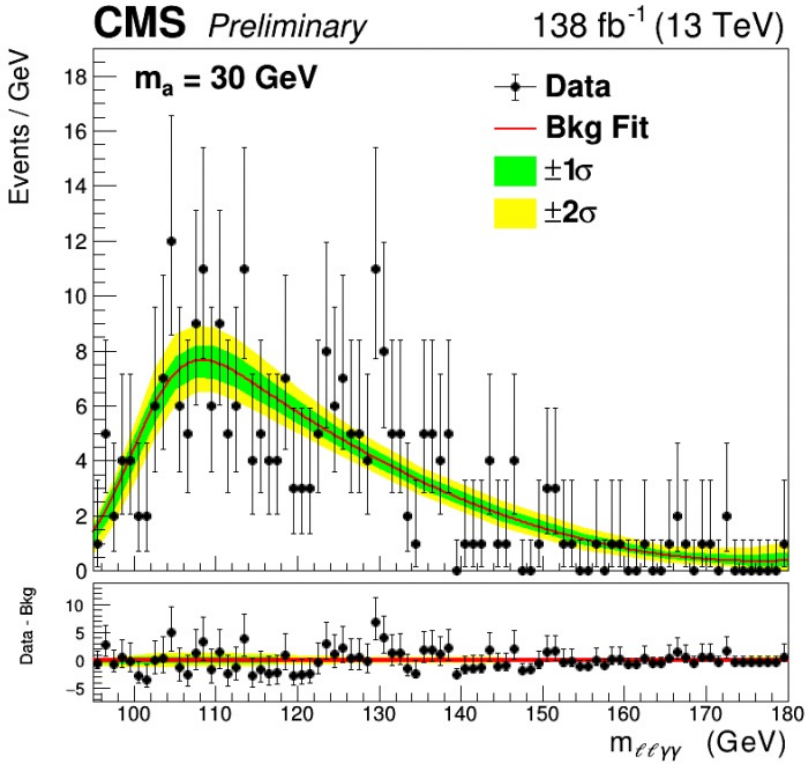
$H_{125} \rightarrow Za \rightarrow llγγ$ CMS-PAS-HIG-22-003 *(2023 result)*

First search in LHC looking for the signature $Za \rightarrow llγγ$

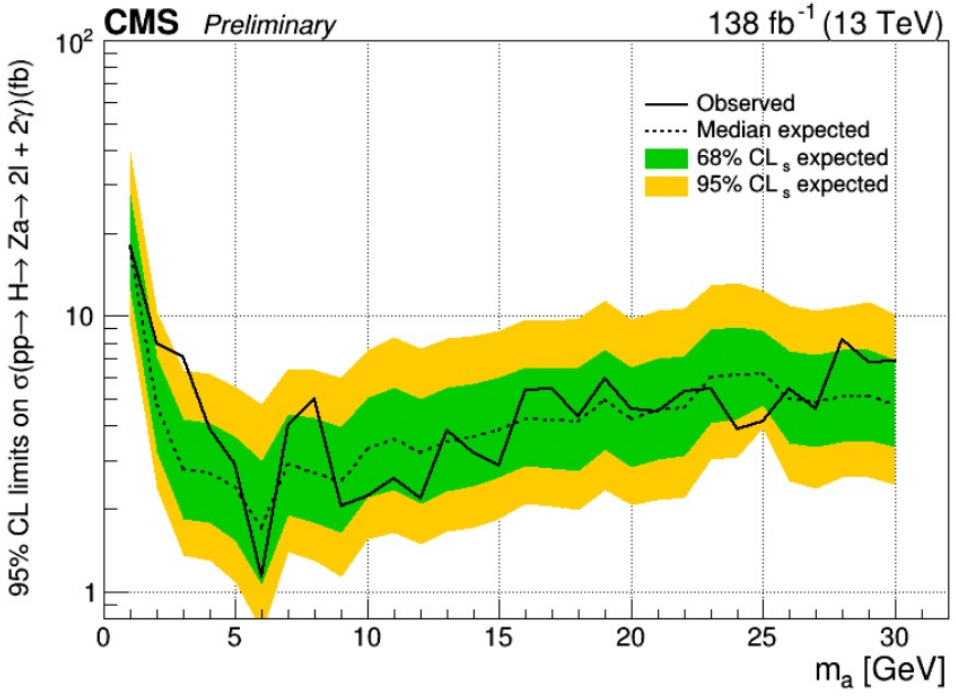
- Consider 1 < m(a) < 30 GeV, below which the two photons are fully merged
- Major BGs: Z(ll) with jet→ γ fakes, estimated by data-driven method
- Train a BDT classifier parameterized in m(a) for event categorization
- Limits set on σ(H)×B(H → Za → $llγγ$) and ALP models



BDT score for m(a) = 30 GeV



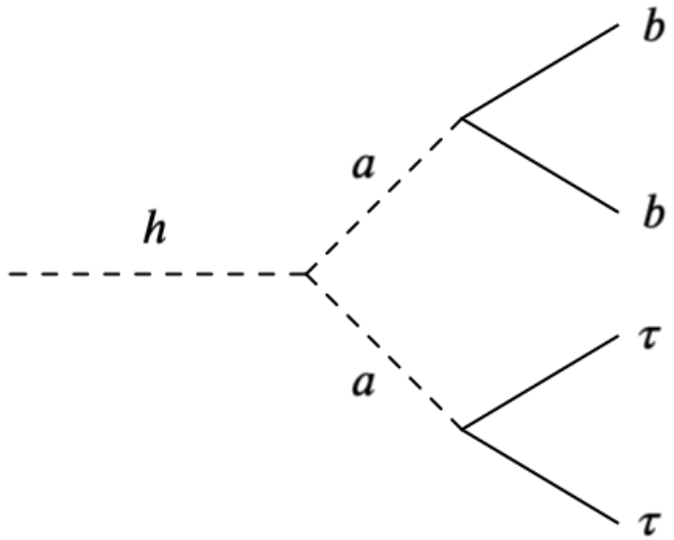
$m_{llγγ}$ signal region for m(a) = 30 GeV



Limits on σ(H)×B(H → Za → $llγγ$)

Searches for Higgs decays to light pseudoscalars

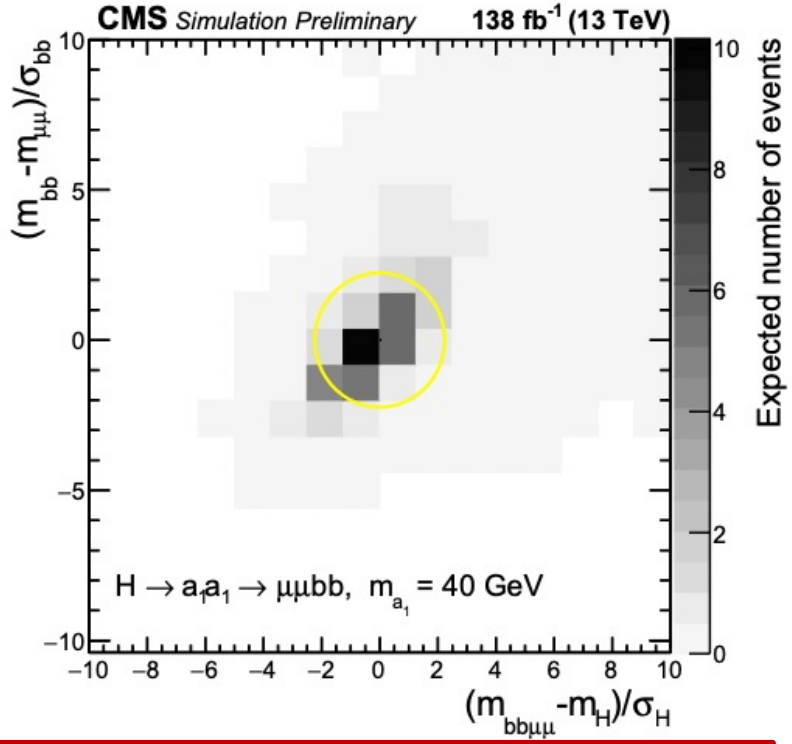
$H_{125} \rightarrow aa$



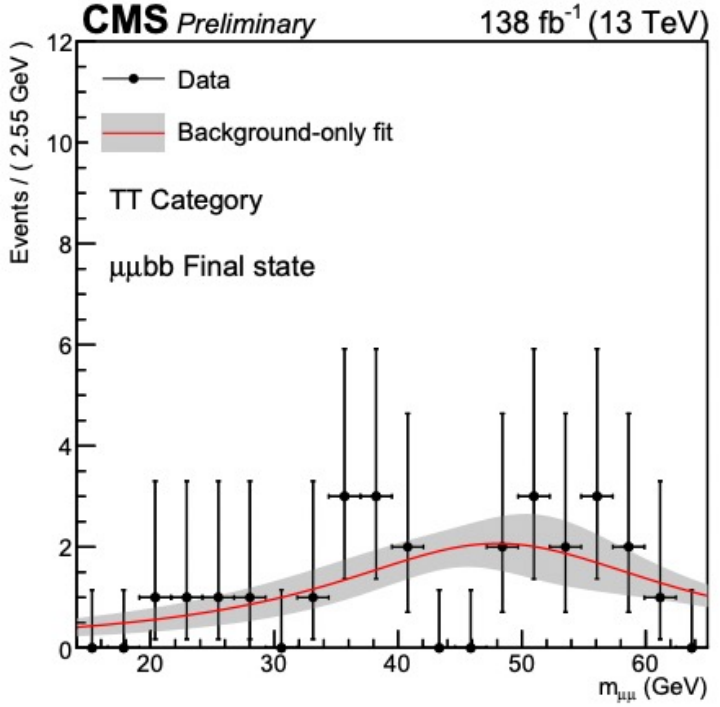
$H_{125} \rightarrow aa \rightarrow \mu\mu bb$ / $\tau\tau bb$ CMS-PAS-HIG-22-007 *(2023 result)*

$\mu\mu bb$ final state

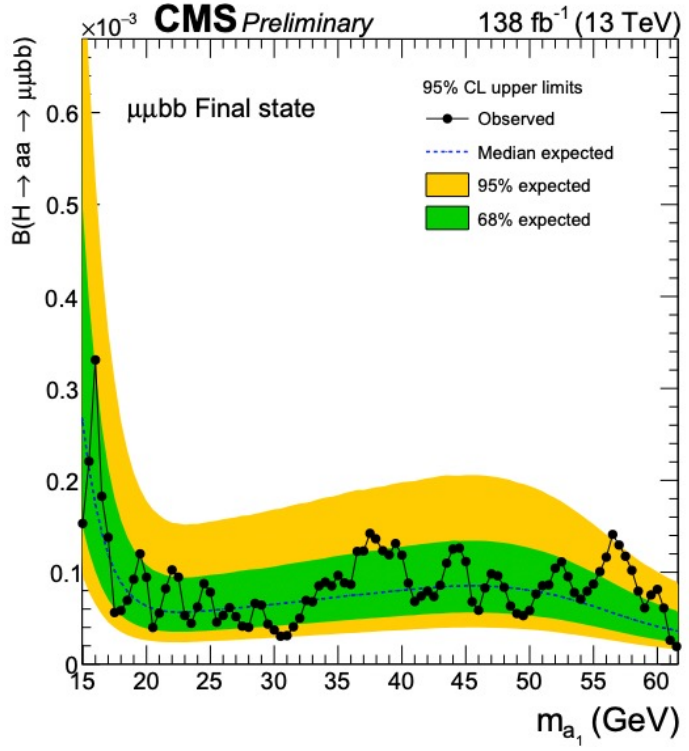
- Excellent resolution in m($\mu\mu$), and large branching ratio B(a → bb)
- Major BGs: top-pair and Z+jets, estimated by data-driven method
- Cut-based categorization using jet variables and object compatibility with signal
- Limits set on B(H → aa → $\mu\mu bb$), interpretation in 2HDM+S combining with $\tau\tau bb$ channel



Optimization variables measuring compatibility with signal



m($\mu\mu$) in tight b-tag signal region

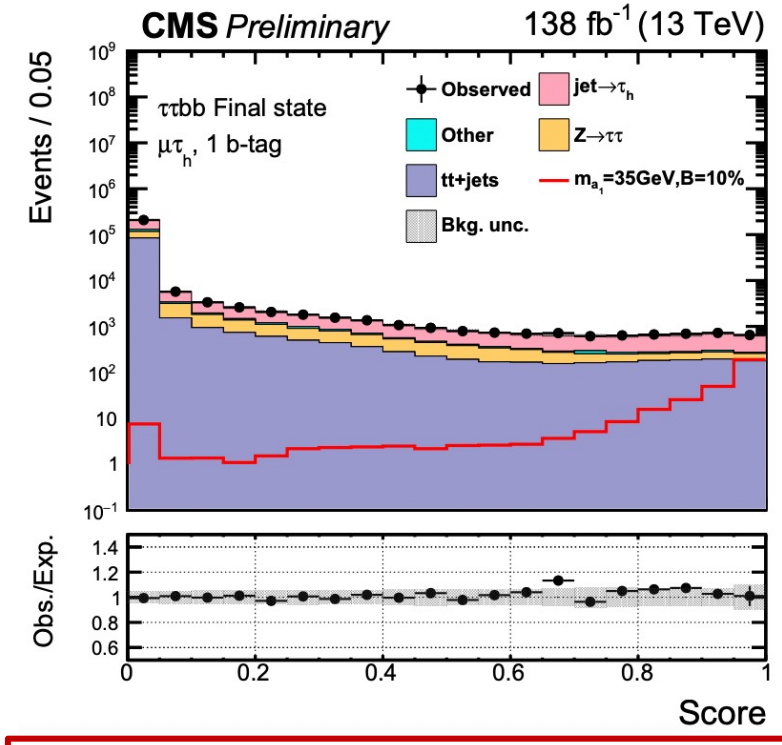


Limits on B(H → aa → $\mu\mu bb$)

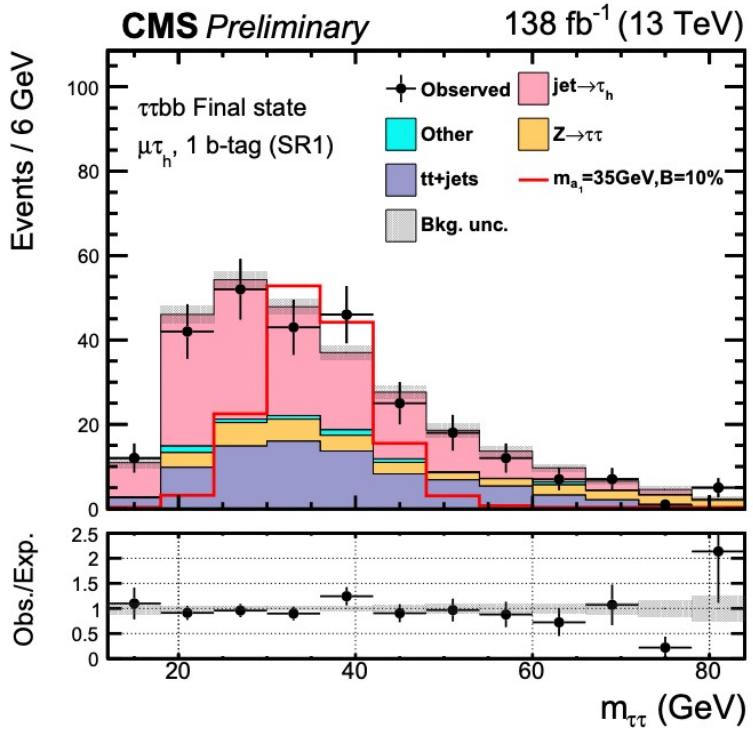
$H_{125} \rightarrow aa \rightarrow \mu\mu bb$ / $\tau\tau bb$ CMS-PAS-HIG-22-007 *(2023 result)*

$\tau\tau bb$ final state

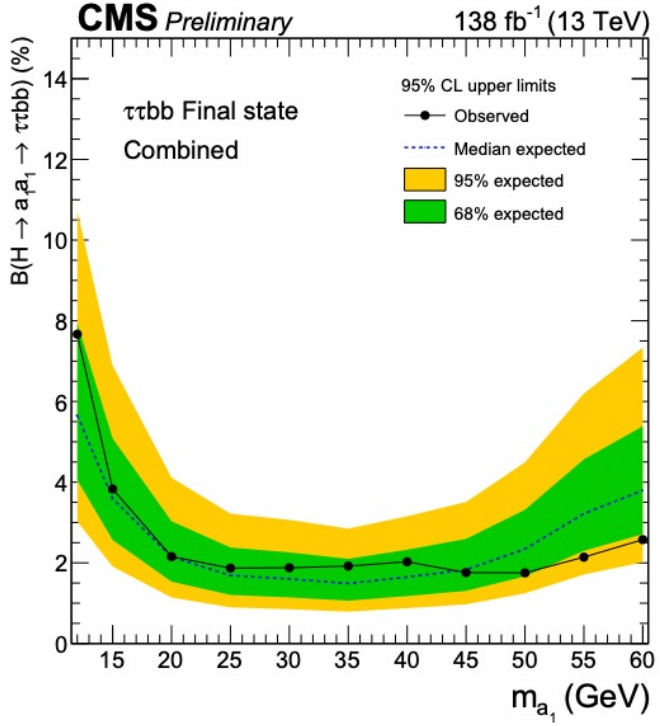
- Large branching ratios B(a → bb/$\tau\tau$) and most sensitive channel in 12 < m(a) < 60 GeV
- Three $\tau\tau$ decay channels: $\mu\tau_h$ (most sensitive) / eτ_h / eμ
- Major BGs: top-pair, Z+jets and jet→ τ_h fakes
- Categorization based on number of b-tag jets (1 or > 1) and DNN classifier
- Limits set on B(H → aa → $\tau\tau$bb), interpretation in 2HDM+S combining with $\mu\mu$bb channel



DNN score for 1 b-tag $\mu\tau_h$ category



m($\tau\tau$) in 1 b-tag $\mu\tau_h$ signal region

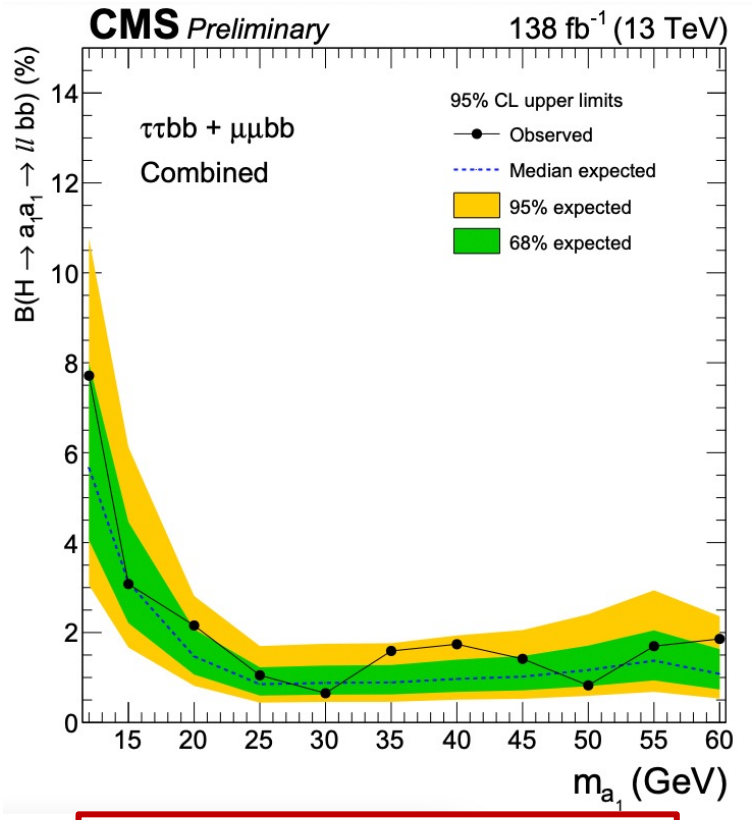


Limits on B(H → aa → $\tau\tau$bb)

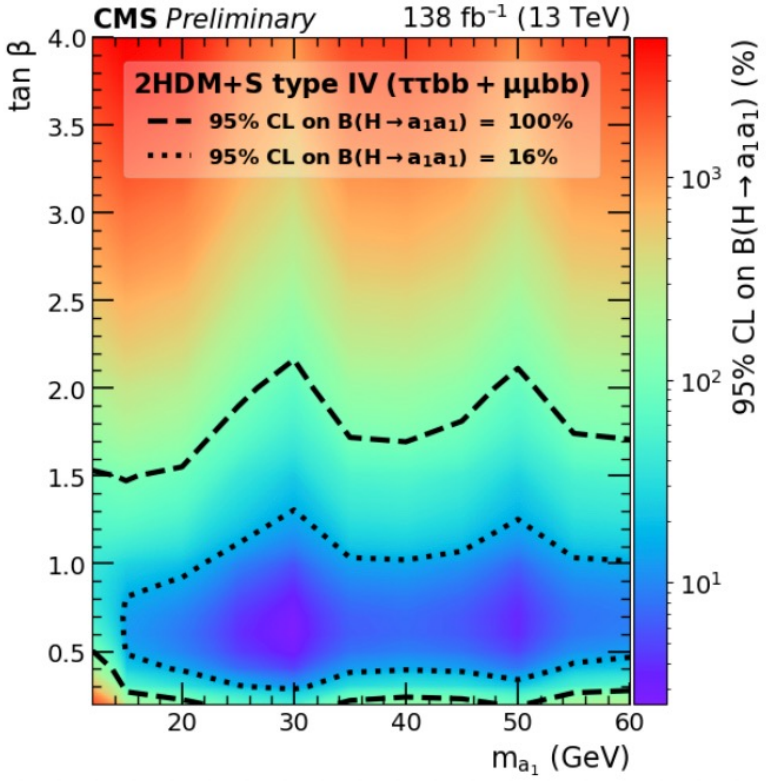
$H_{125} \rightarrow aa \rightarrow \mu\mu bb / \tau\tau bb$ CMS-PAS-HIG-22-007 *(2023 result)*

Combination of $\mu\mu bb$ and $\tau\tau bb$

- Interpretation in 2HDM+S (four coupling types can avoid FCNC at LO)
- Most stringent limits in 12 < m(a) < 60 GeV

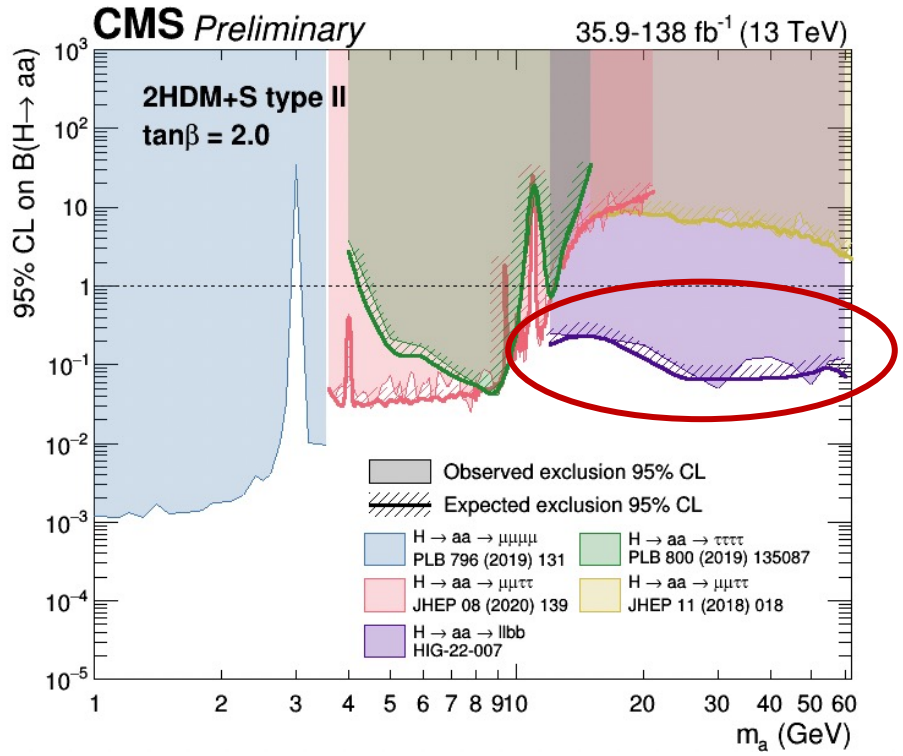


2HDM+S type-independent limits on B(H→aa→ llbb)



Limits on B(H→aa) for type IV of 2HDM+S

Summary of 2HDM+S searches at 13 TeV (Run 2)

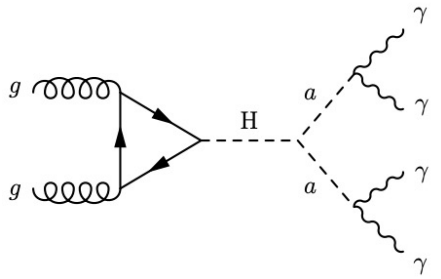


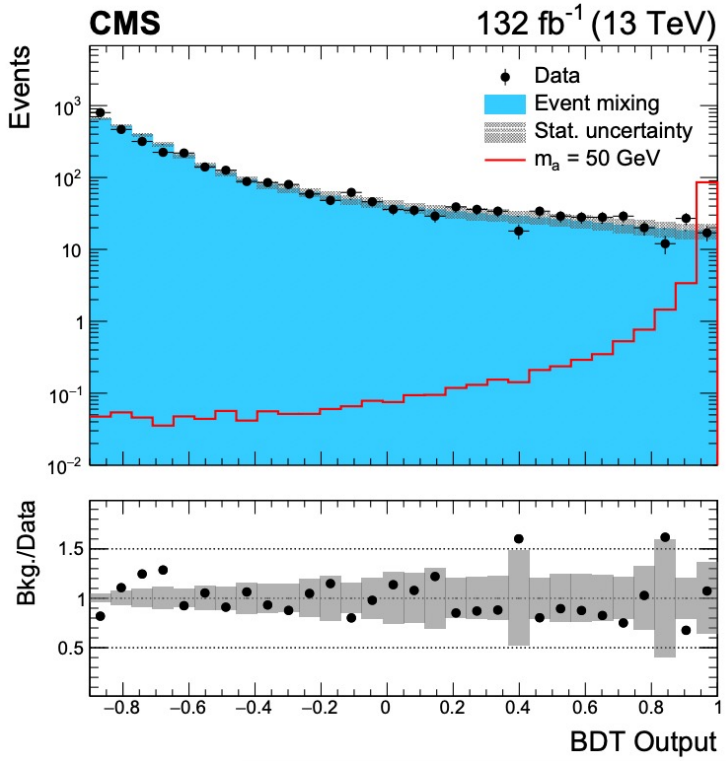
Limits on B(h→aa) for type II (tanβ = 2) of 2HDM+S

$H_{125} \rightarrow aa \rightarrow 4\gamma$ (resolved) JHEP 07 (2023) 148 *(2022 result)*

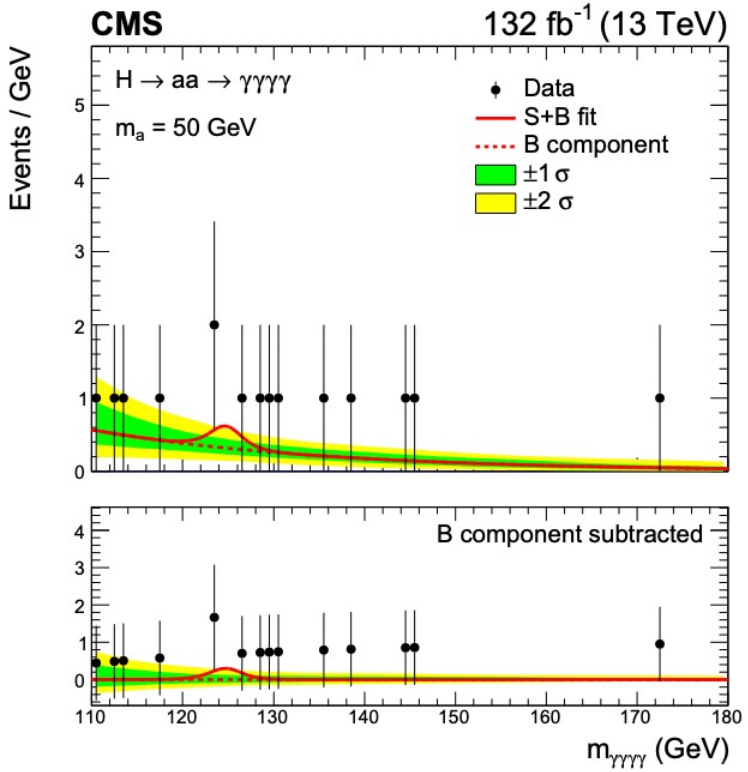
Consider 15 < m(a) < 62 GeV → well isolated and fully reconstructed photons

- Clean signature
- Major BGs: photons+jets processes, estimated by data-driven method
- Train a BDT parameterized in m(a) for event categorization
- Limits set on σ(H)×B(H → aa → 4γ)

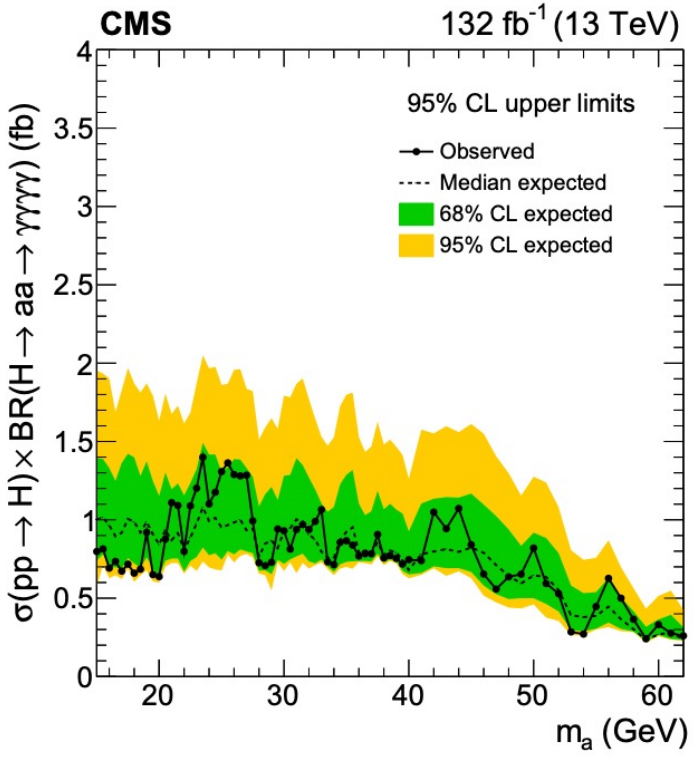




BDT score for m(a) = 50 GeV



$m_{\gamma\gamma\gamma\gamma}$ signal region for m(a) = 50 GeV



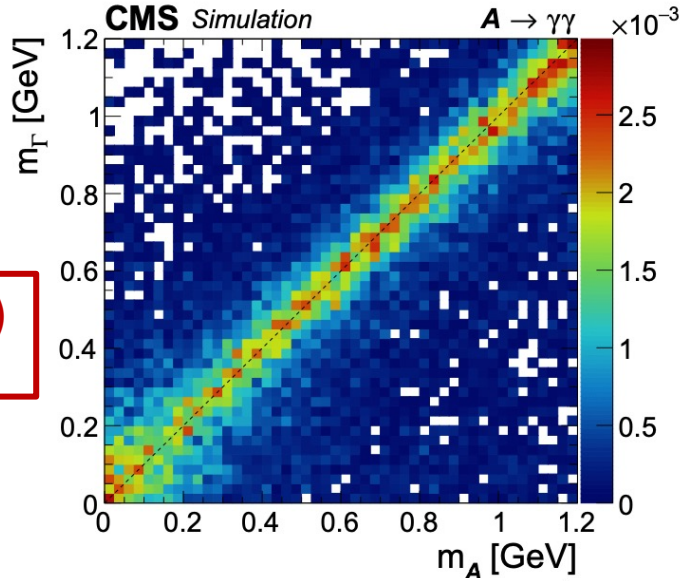
Limits on σ(H)×B(H → aa → $\gamma\gamma\gamma\gamma$)

$H_{125} \rightarrow aa \rightarrow 4\gamma$ (merged) 2209.06197 (accepted to PRL) *(2022 result)*

Consider 0.1 < m(a) < 1.2 GeV → merged $\gamma\gamma$ reconstructed as a single photon-like object Γ

- Major BGs: $H \rightarrow \gamma\gamma$ and multijet processes
- Train a regressor to predict m(Γ) based on low-level detector information
- Limits set on $B(H \rightarrow aa \rightarrow 4\gamma)$

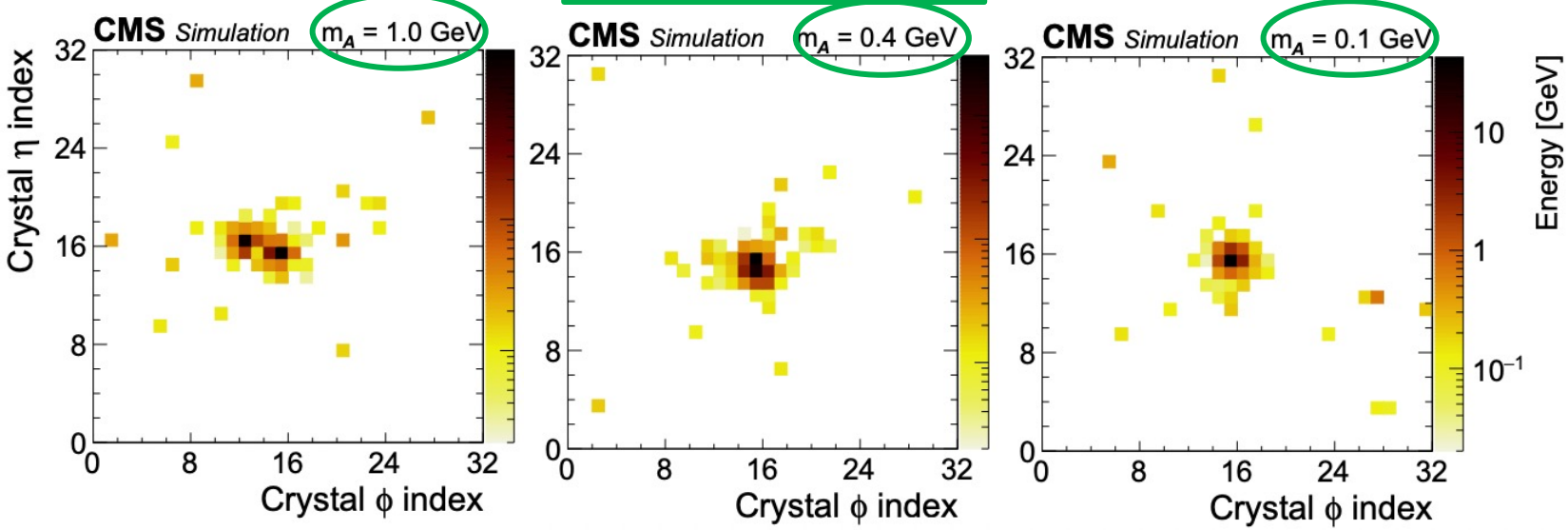
Predicted m(Γ) vs generated m(a)
2204.12313 (accepted to Phys. Rev. D)

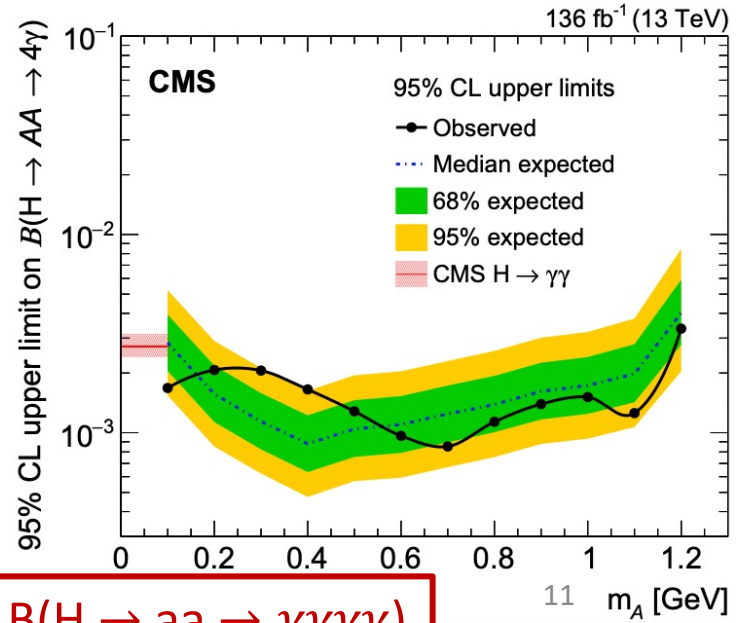


Barely resolved

Shower merging but distinct maxima

Instrumental merging

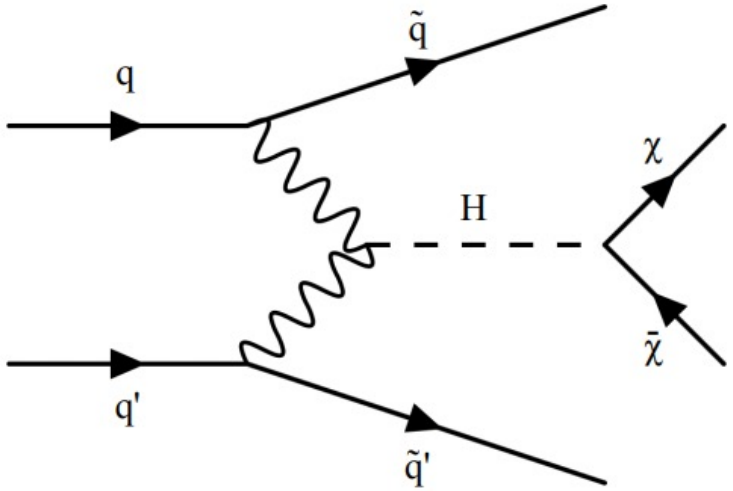




Limits on $B(H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma)$

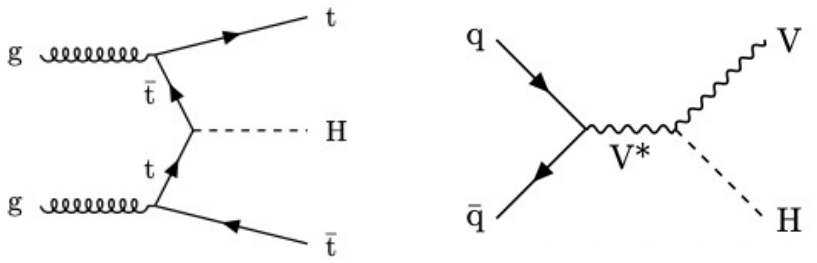
Searches for invisible Higgs decays

$H_{125} \rightarrow$ invisible



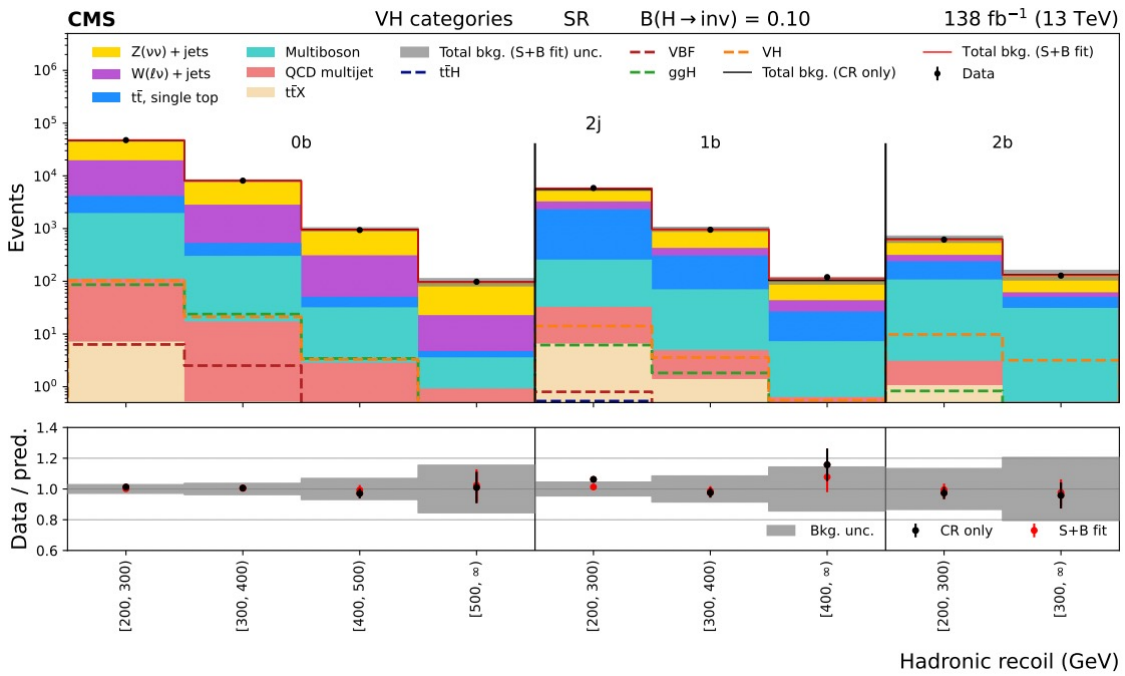
$(tt/V)H_{125} \rightarrow$ invisible 2303.01214 (submitted to EPJC) *(2023 result)*

- SM: $B(H_{125} \rightarrow inv) \sim 0.1\%$, via $H_{125} \rightarrow ZZ^* \rightarrow 4\nu$
- This rate can be enhanced in BSM, e.g. Higgs portal models where the Higgs boson can decay to a pair of DM particles of mass $m(\text{DM}) < m(\text{H})/2$

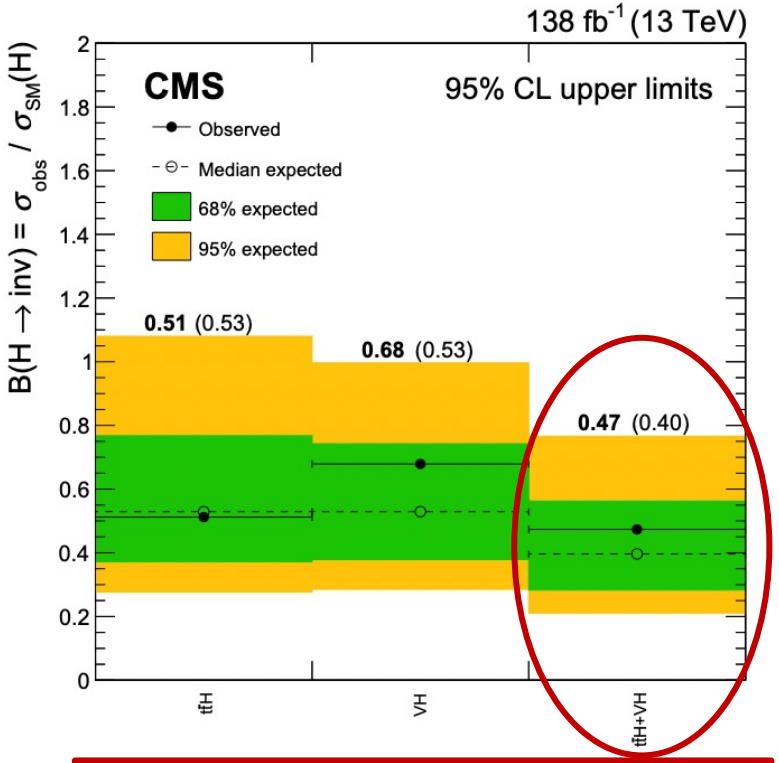


Recent CMS search looks at fully hadronic ttH/VH channels

- Major BGs: $Z(\nu\nu)$ and tt/W+jets with lost leptons
- Use missing p_T as discriminating variable
- Signal extracted from hadronic recoil distribution



Hadronic recoil signal region in VH categories



Limits on B(H→inv) from ttH+VH

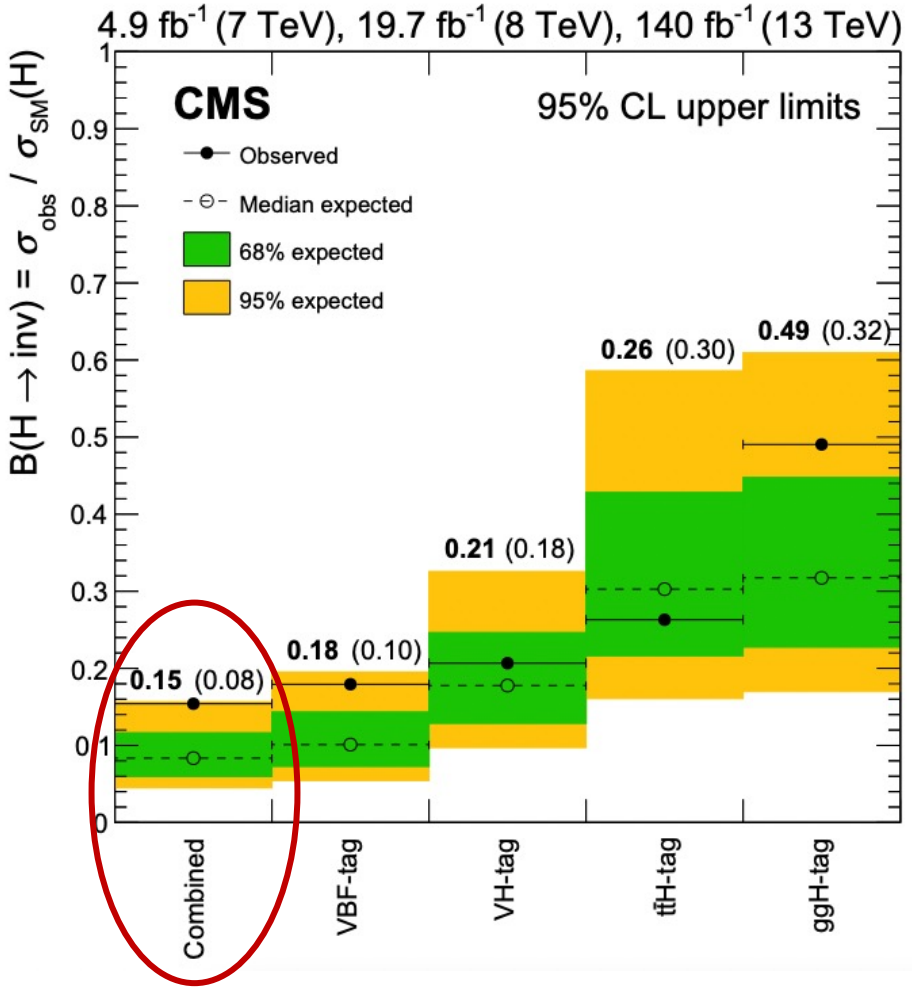
Combined $H_{125} \rightarrow$ invisible 2303.01214 (submitted to EPJC) *(2023 result)*

Combination of Run 1 + Run 2

- First combination of all production channels
  - VBF + MET
  - Z(ll) + MET
  - V(qq) + MET
  - Jet + MET
  - tt(semi-lep/lep/had) + MET

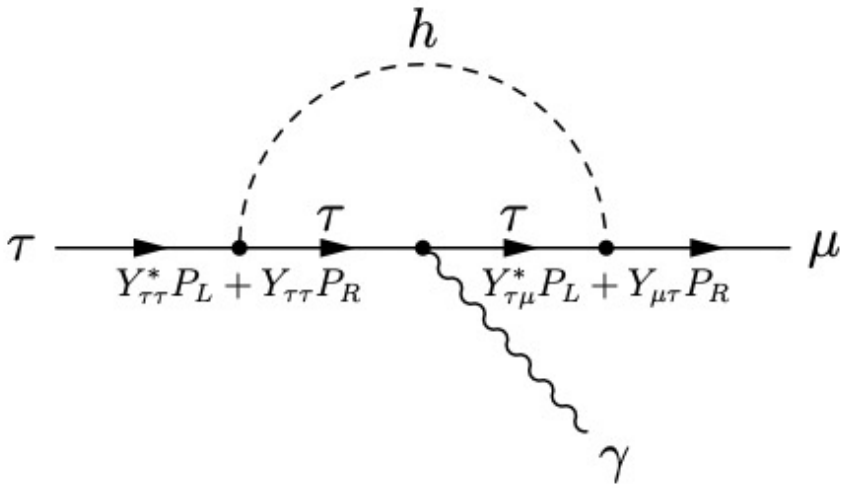
- Sensitivity driven by the VBF channel Phys. Rev. D 105, 092007 (2022)
- Combined limit B($H_{125} \rightarrow$ inv) < 15% (8% expected)
  - First result below 10% @ 95% CL

- Competitive with ATLAS results: B($H_{125} \rightarrow$ inv) < 11% (8% expected) Phys. Lett. B 842, 137963 (2023)



Limit on B(H→inv), with sensitivity breakdown

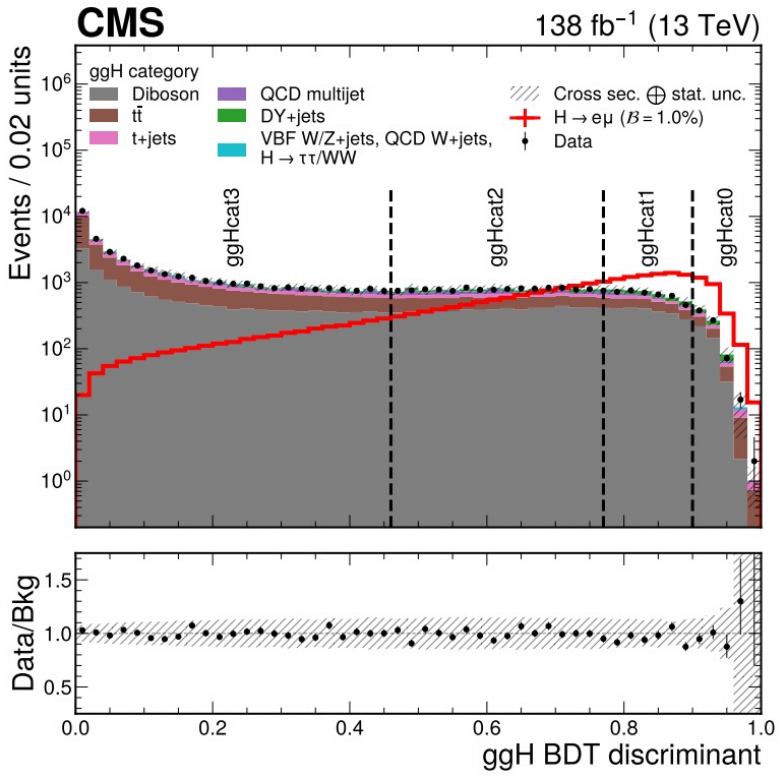
Searches for lepton-flavor violating Higgs decays



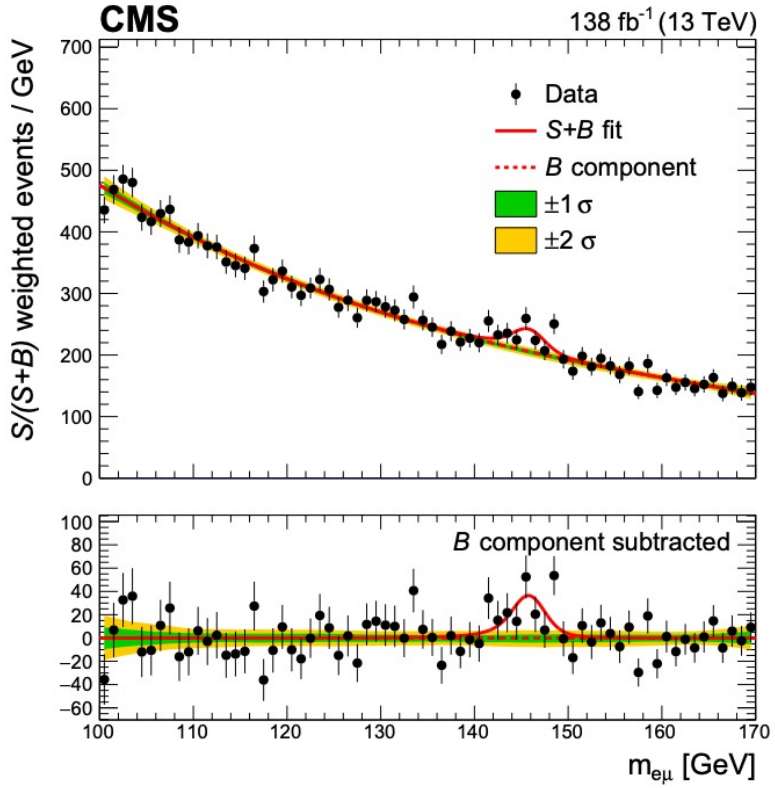
H_{125} (or additional X) → eμ 2305.18106 (submitted to Phys. Rev. D) *(2023 result)*

Consider both SM Higgs and BSM Higgs with mass 110 < m_X < 160 GeV

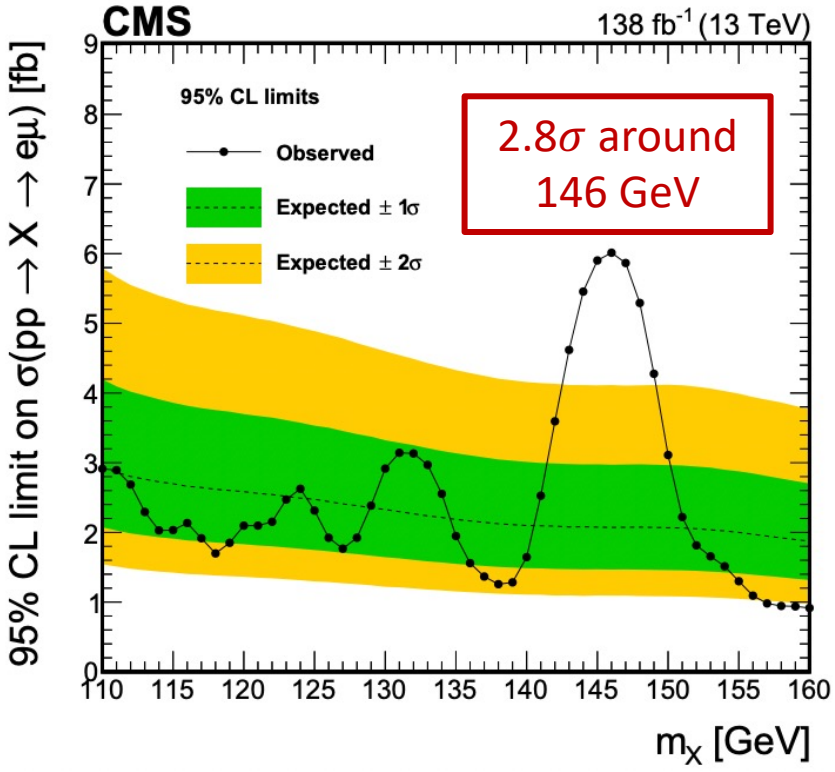
- Train BDT per ggH/VBF mode for event categorization
- Signal extracted from $m_{e\mu}$ (100-170 GeV)
- More details to be covered in the next talk by Gilson Correia Silva



BDT score in ggH category



$m_{e\mu}$ with the S+B fit at m_X = 146 GeV



Limits on σ(pp → X → $e\mu$)

Summary

- Large Run 2 datasets of ~140 fb^{-1} @ 13 TeV being probed for searching exotic decays of the Higgs boson (+ combinations with Run 1 datasets)
- No significant deviation from the SM prediction is observed
- Improved sensitivity leads to tighter BSM constraints beyond simple luminosity increase
  - Mostly driven by the use of ML in various stages (object reconstruction, S/B separation, etc.)

➢ Looking ahead to Run 3 and beyond (HL-LHC)

  ➢ Unprecedentedly larger volume of collision data at higher energy (+ combination with current data)

  ➢ More ML integration to be expected to further drive sensitive improvement

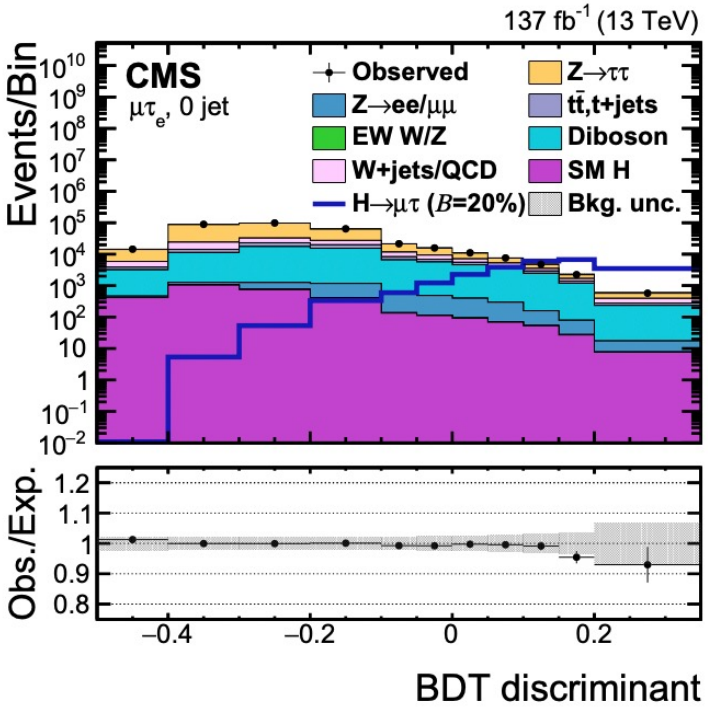
Thank you!

Backup

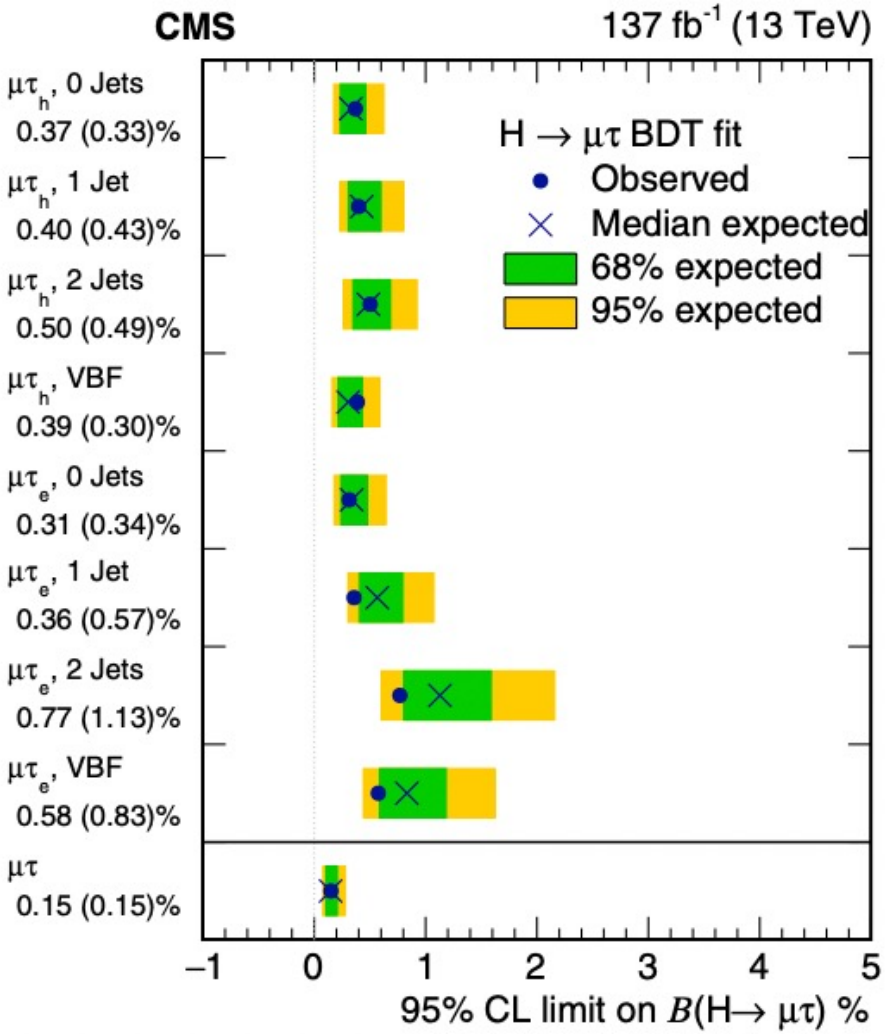
$H_{125} \rightarrow \mu\tau/e\tau$ Phys. Rev. D 104, 032013 (2021) *(2021 result)*

Consider $\{\tau \rightarrow \tau_e/\tau_h$ in $\mu\tau\}$ and $\{\tau \rightarrow \tau_\mu/\tau_h$ in $e\tau\}$

- Train BDT per channel for event categorization
- Set limits
  - B(H $\rightarrow \mu\tau$) < 0.15 (0.15 expected)%
  - B(H $\rightarrow e\tau$) < 0.22 (0.16 expected)%



BDT score in $\mu\tau_e$ 0 jet category



Limits on B(H $\rightarrow \mu\tau$) with channel breakdown