Search for new resonances decaying into two Higgs bosons at CMS

18 – 24 July 2024, Prague, Czech Republic

Chayanit Asawatangtrakuldee (Chulalongkorn University)

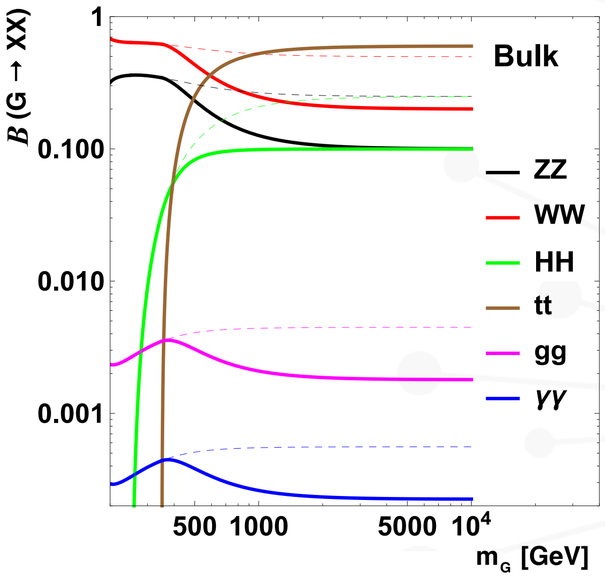
on behalf of the CMS Collaboration

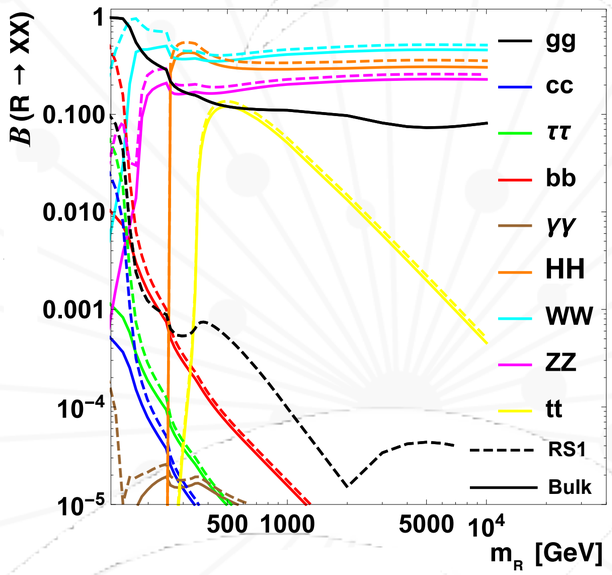
Introduction

- **12 years since the discovery, properties & couplings of the SM Higgs boson extensively studied at the LHC**
  - present data compatible with a scalar particle spin 0 and even parity of mass $m_H \sim 125.2$ GeV
  - several open questions require a deeper understanding of the Higgs boson

- **Large amount of LHC data exploited since Run 2 and now Run 3 is more than half-way recorded**
  - Higgs boson could be a probe to explore new physics
  - opens new window in exploration of the Higgs sector

- **Many BSM theories predicted resonant HH production**
  - Warped Extra Dimension (WED)
    - a narrow spin-0 (Radion) a spin-2 (KK-Graviton)
  - Extended Higgs Sector : 2HDM, 2HDM+S, TRSM
    - Supersymmetric Models : MSSM, NMSSM



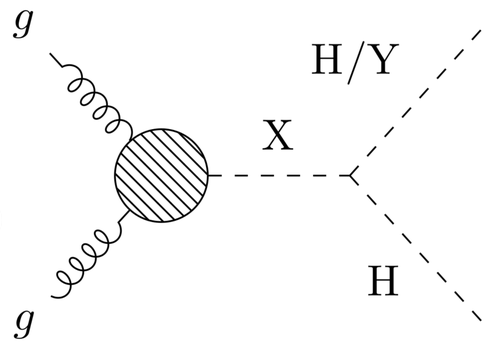


X → HH/YH → $\gamma\gamma\tau\tau$

new

CMS PAS HIG-22-012

- Motivated by Warped Extra Dimensions and Extended Higgs sector models
  - heavy Higgs can decay to lighter Higgs

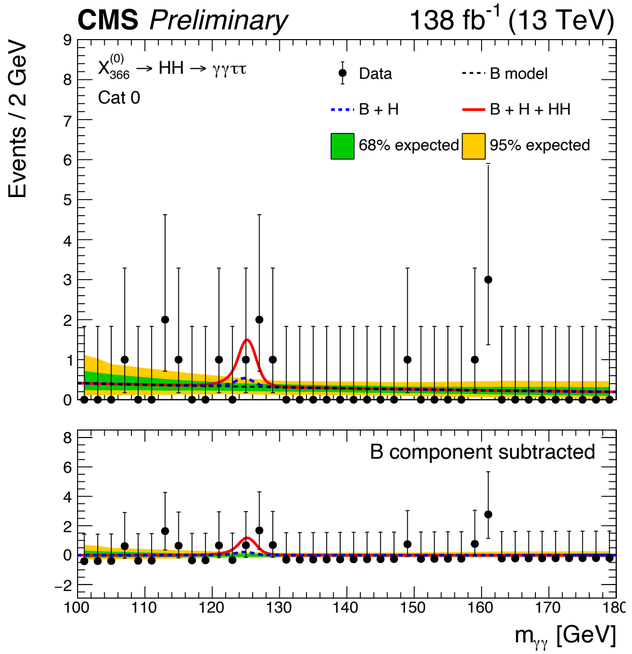


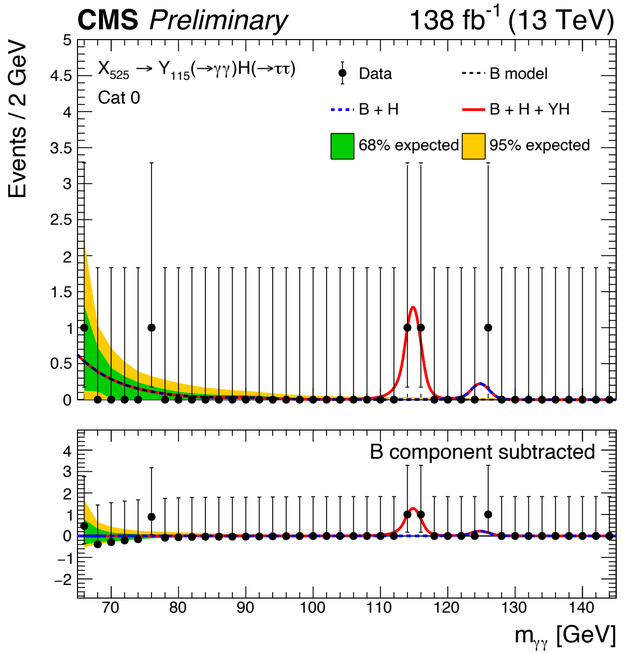
- HH → $\gamma\gamma\tau\tau$ has small branching fraction but clean signatures (*non-resonant not included here*)
  - four channels: $\mathrm{X}^{(0)} \to \mathrm{HH}$, $\mathrm{X}^{(2)} \to \mathrm{HH}$, $\mathrm{X} \to \mathrm{Y}(\tau\tau)\mathrm{H}(\gamma\gamma)$, $\mathrm{X} \to \mathrm{Y}(\gamma\gamma)\mathrm{H}(\tau\tau)$

- Narrow width resonance searches
  - $\mathrm{X} \to \mathrm{HH}$ for 260 < m_{X} < 1000 GeV
  - $\mathrm{X} \to \mathrm{Y}(\tau\tau/\gamma\gamma)\mathrm{H}(\gamma\gamma/\tau\tau)$ for 50/70 < m_{Y} < 800 GeV

- Parametric NN is trained using multiple mass hypotheses vs backgrounds for each search channel
  - pNN output served for event categories

- Signal extraction is performed on $m_{\gamma\gamma}$ distribution



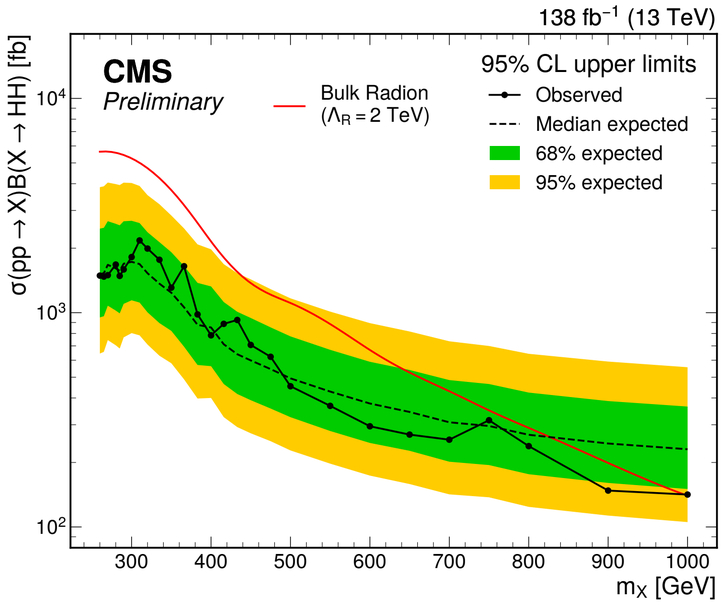


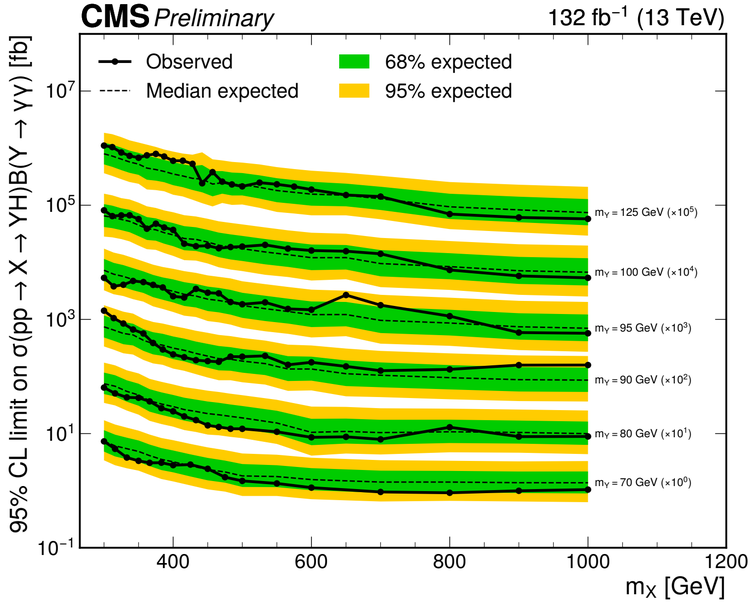
X → HH/YH → $\gamma\gamma\tau\tau$

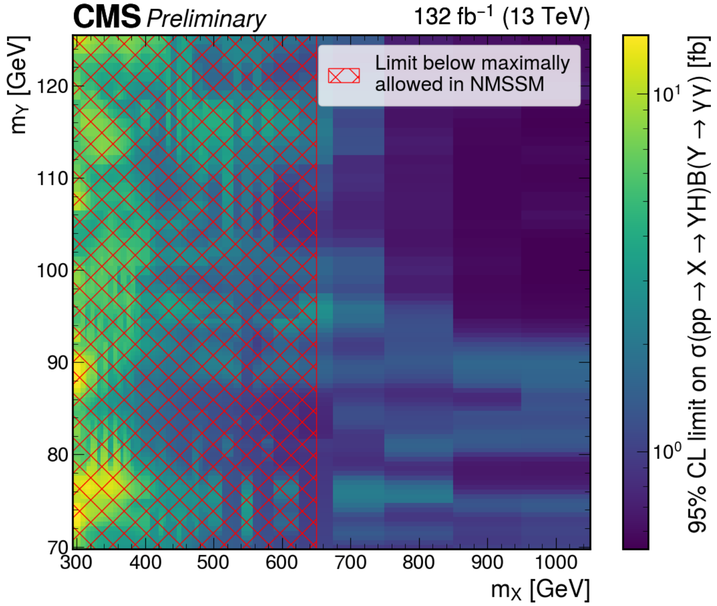
new

CMS PAS HIG-22-012

- Main backgrounds from $\gamma\gamma$+jets (non-resonant) and single-H production (resonant)
- A maximum likelihood fit on $m_{\gamma\gamma}$ distribution is done for each probed mass and event category
- Some deviations from background-only hypothesis are observed in $\mathrm{X} \rightarrow \mathrm{YH}$ channels
  - $\mathrm{X} \rightarrow \mathrm{Y}(\tau\tau)\mathrm{H}(\gamma\gamma)$: 2.6σ (2.2σ) local (global) significance at (m_{X}, m_{Y}) = (320, 60) GeV
  - $\mathrm{X} \rightarrow \mathrm{Y}(\gamma\gamma)\mathrm{H}(\tau\tau)$: 3.4σ (0.1σ) logal (global) significance at (m_{X}, m_{Y}) = (525, 115) GeV





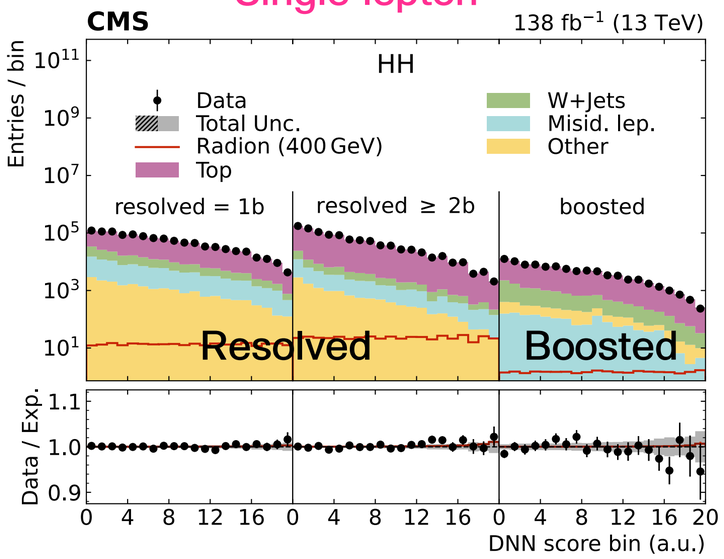


X → HH → bbWW

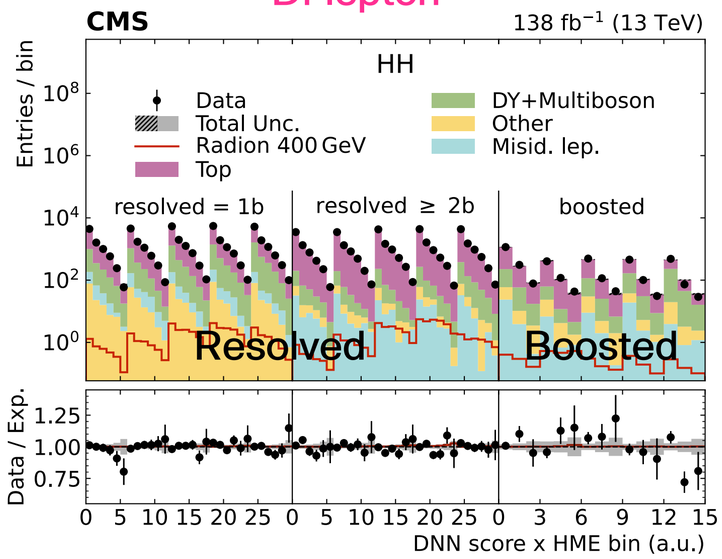
arXiv:2403.09430

- Motivated by Warped Extra Dimensions and Extended Higgs sector models
- HH → bbWW channel has the second largest combined branching fraction
  - single-lepton ($b\bar{b}\ell\nu q\bar{q}$) and di-lepton ($b\bar{b}\ell\nu\ell\nu$) final states (*non-resonant not shown here*)
- Narrow width resonances for mass 250 – 900 GeV
- Multi-class DNN to classify events according to processes
- Signal extraction by simultaneous fit to DNN discriminant distributions

Single-lepton



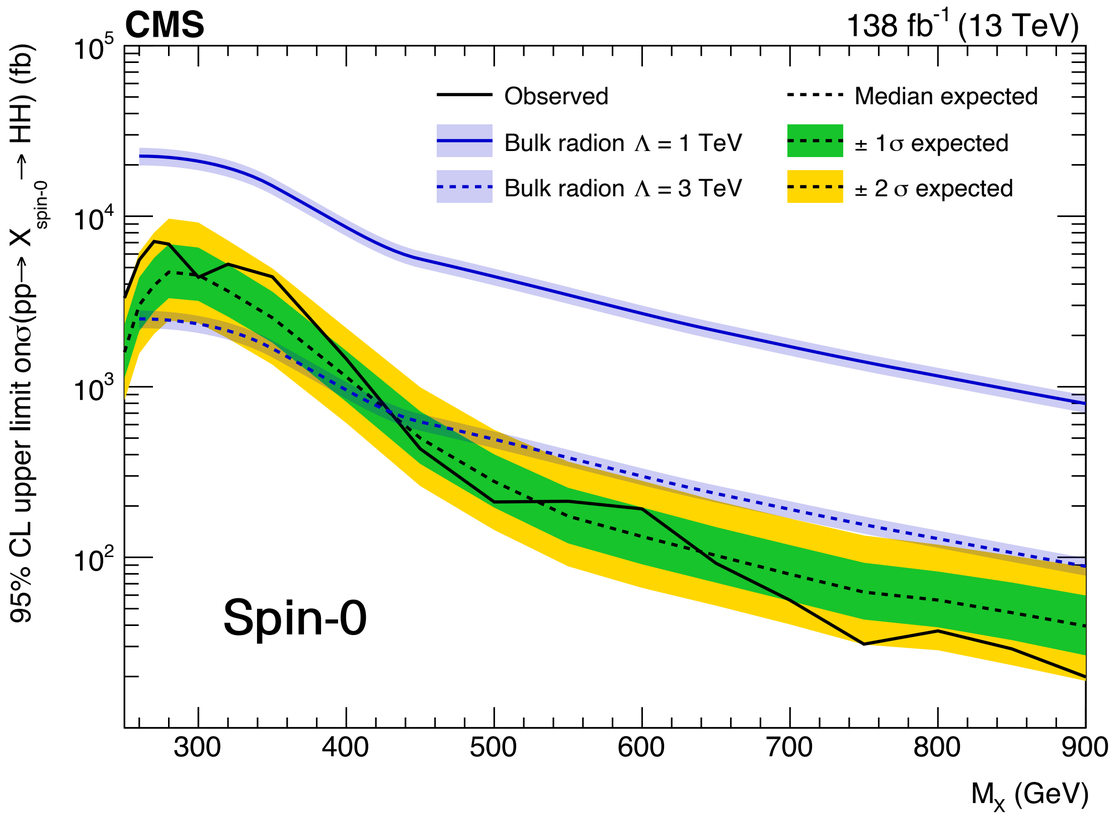
Di-lepton

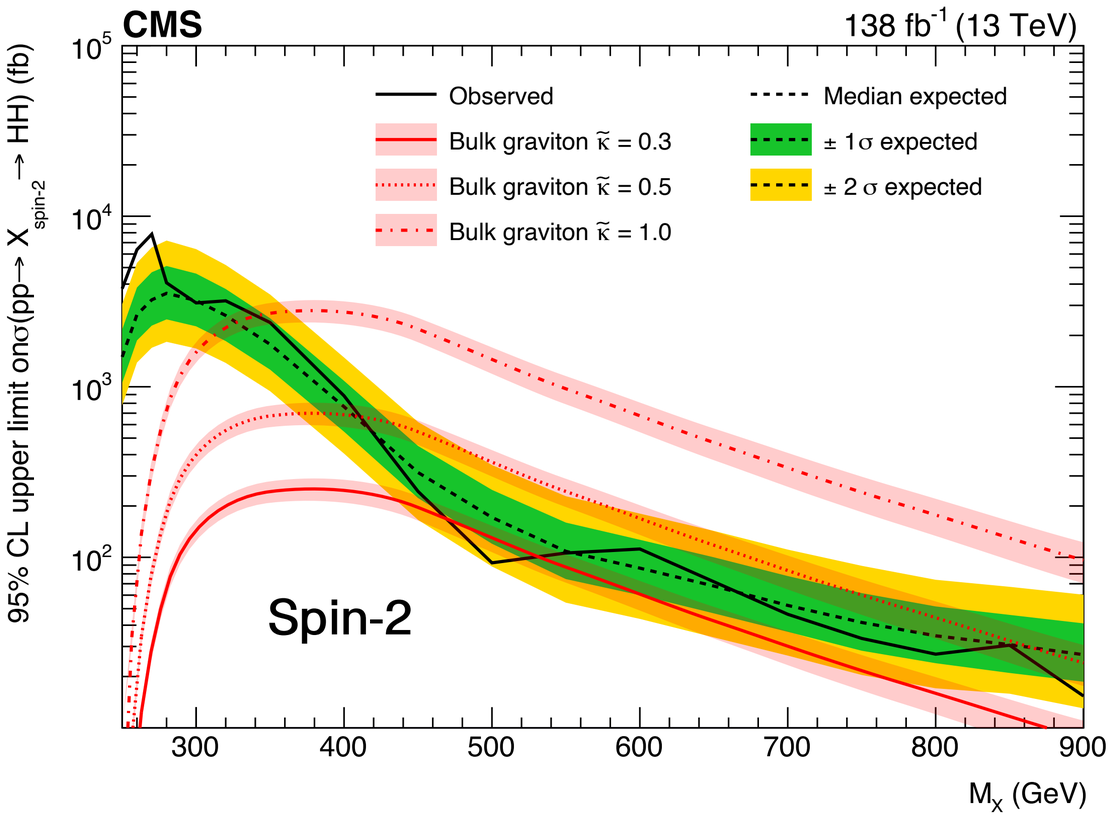


X → HH → bbWW

arXiv:2403.09430

- Upper limits for X → HH cross section between 250 – 900 GeV for spin-0 and spin-2 assumption
- Compared to Warped Extra Dimension models (bulk radion and graviton)





X → HH/YH → bb$\gamma\gamma$

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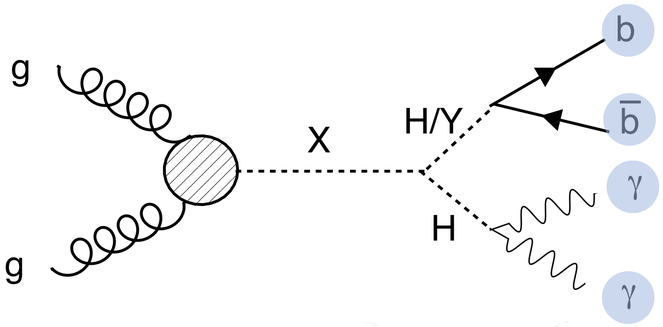
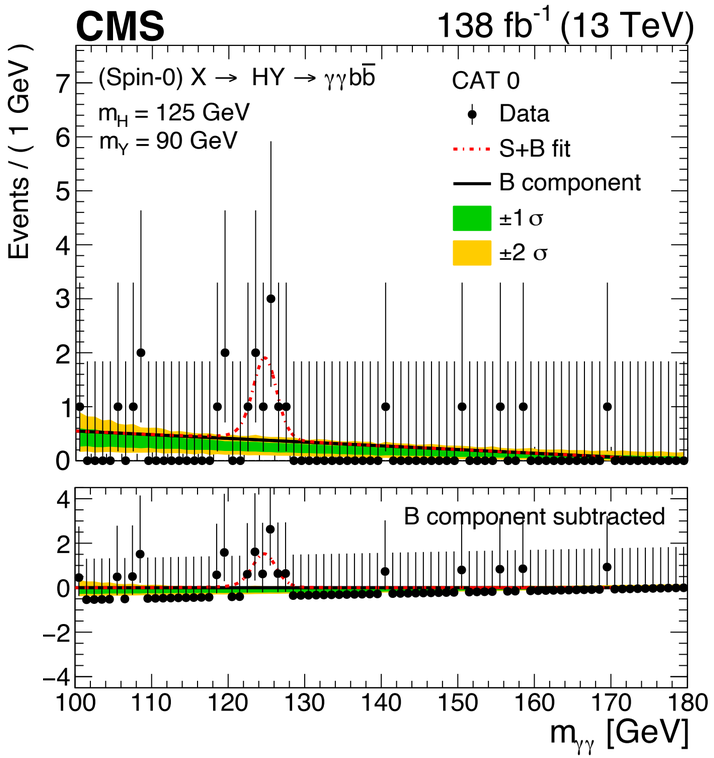
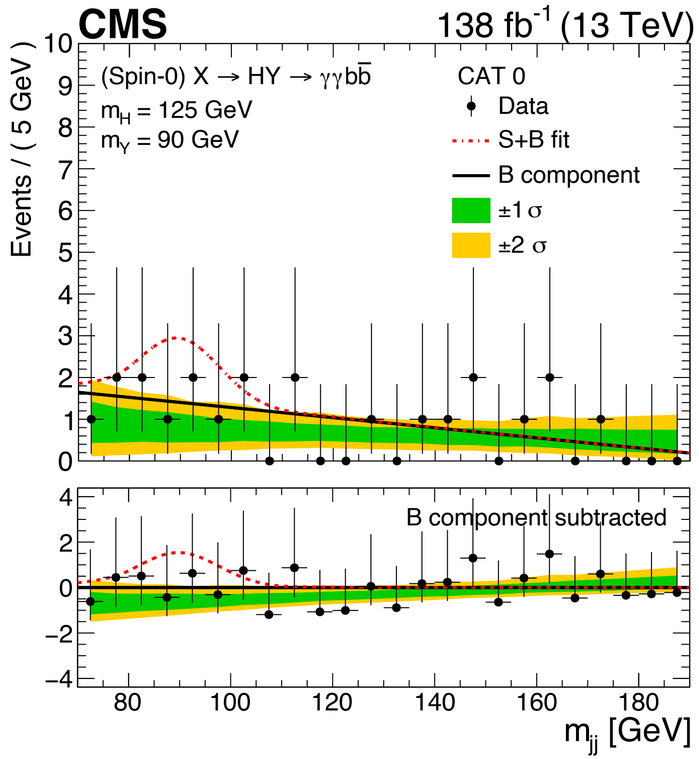
- Motivated by **NMSSM**: MSSM extended by one more complex singlet, **TRSM**: SM extended by two real singlet fields, and **WEDs** models (HH resonance)

- Signal extraction is performed on **($m_{\gamma\gamma}$, m_{jj})** plane







- BDT (NN) scores to separate signals and non-resonant (resonant) backgrounds

- Six BDT training accounts for different signal m_X-m_Y mass ranges
  - 3 event categories based on BDT output

X → HH/YH → bb$\gamma\gamma$

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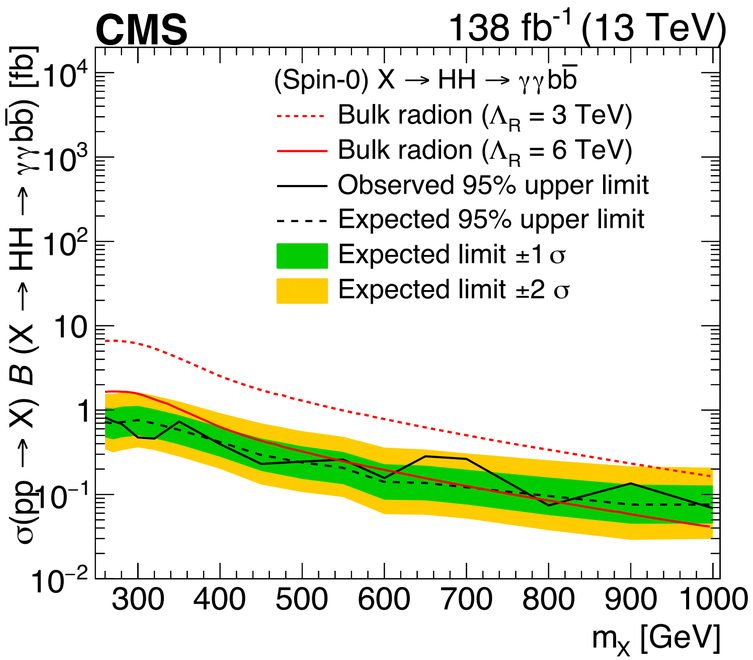
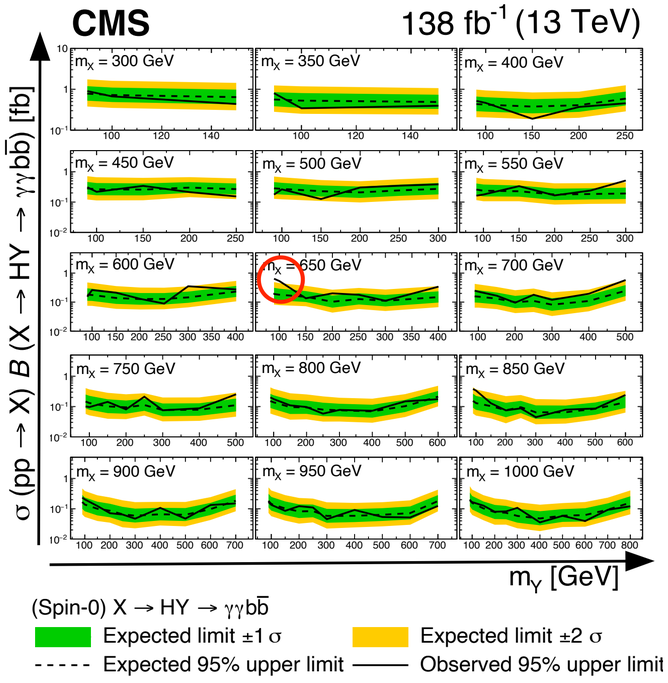
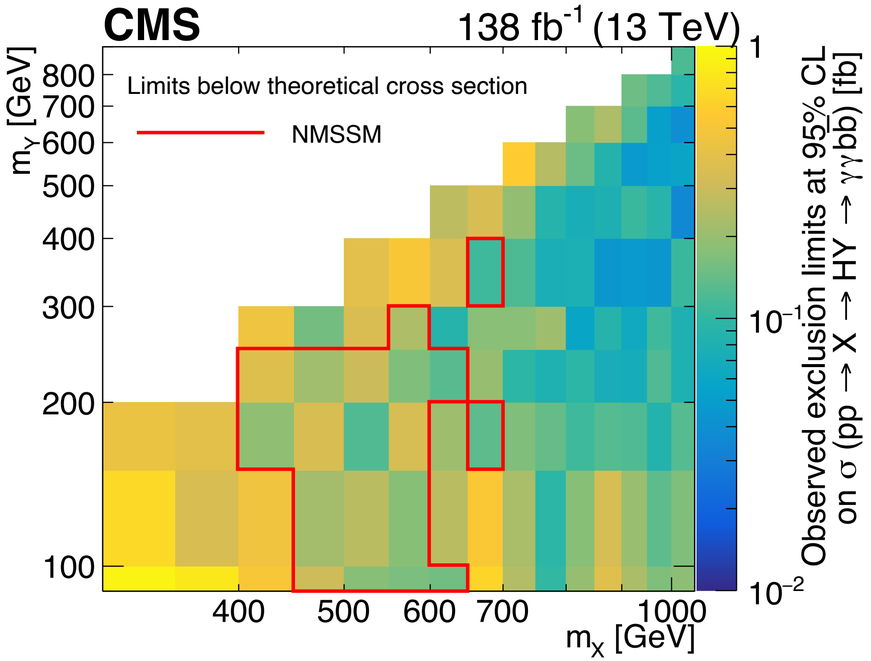
- A simultaneous two-dimensional (2D) fit to **($m_{\gamma\gamma}$, m_{jj})** system in all categories
- The largest deviation from background-only hypothesis with local (global) significance of 3.8σ (2.8σ) is observed for m_X **= 650 GeV** and m_Y **= 90 GeV**
  - coincides with a similar excess observed in H → $\gamma\gamma$ (arXiv:2405.18149)







Combination of X → HH/YH

arXiv:2403.16926

- All searches are performed by assuming narrow-width approximation

Model	Process	Links
Warped Extra Dimension Spin-0 radion Spin-2 graviton **&** **Extended Higgs Sector**	X → HH → 2b 2W (resolved)	arXiv:2403.09430 *(submitted to JHEP)*
	X → HH → 2b 2W (merged)	JHEP 05 (2022) 005
	X → HH → multileptons	JHEP 07 (2023) 095
	X → HH/YH → 2b 2τ	JHEP 11 (2021) 057
	X → HH/YH → 2b 2γ	JHEP 05 (2024) 316
	X → HH/YH → 2b 2b	Phys. Lett. B 842 (2023) 137392
Extended Higgs Sector	A → ZH → 2ℓ 2τ	JHEP 03 (2020) 065
	A → ZH → $2\ell/2\nu$ 2b	EPJC 79 (2019) 564

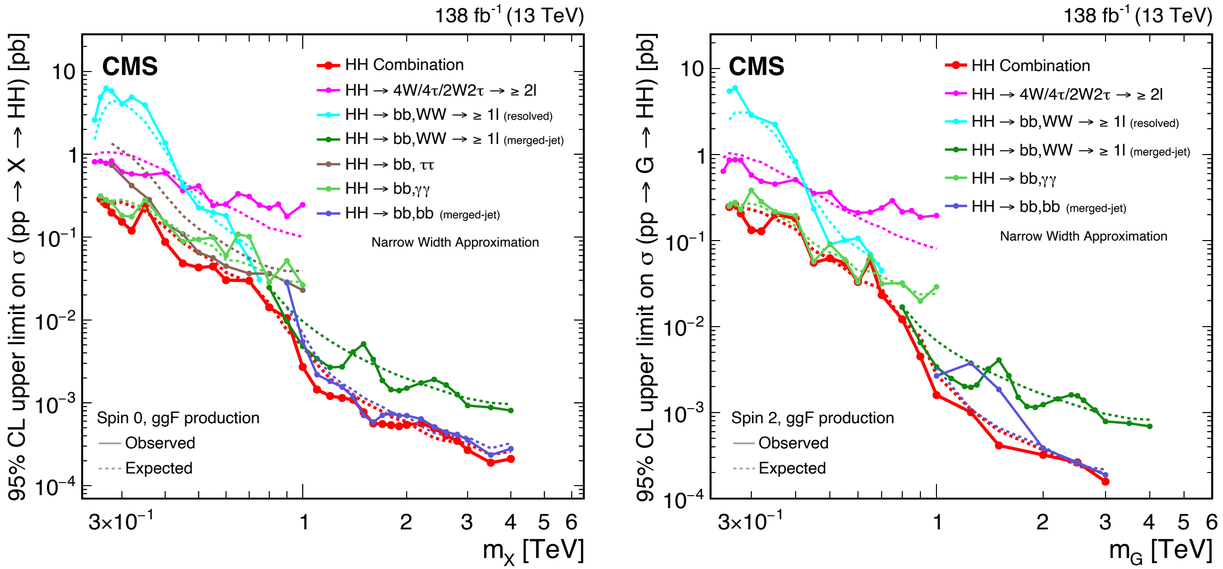
X → VH already covered by Daniel Hundhausen (previous talk)

Combination of X → HH/YH

https://www.hepdata.net/record/146897

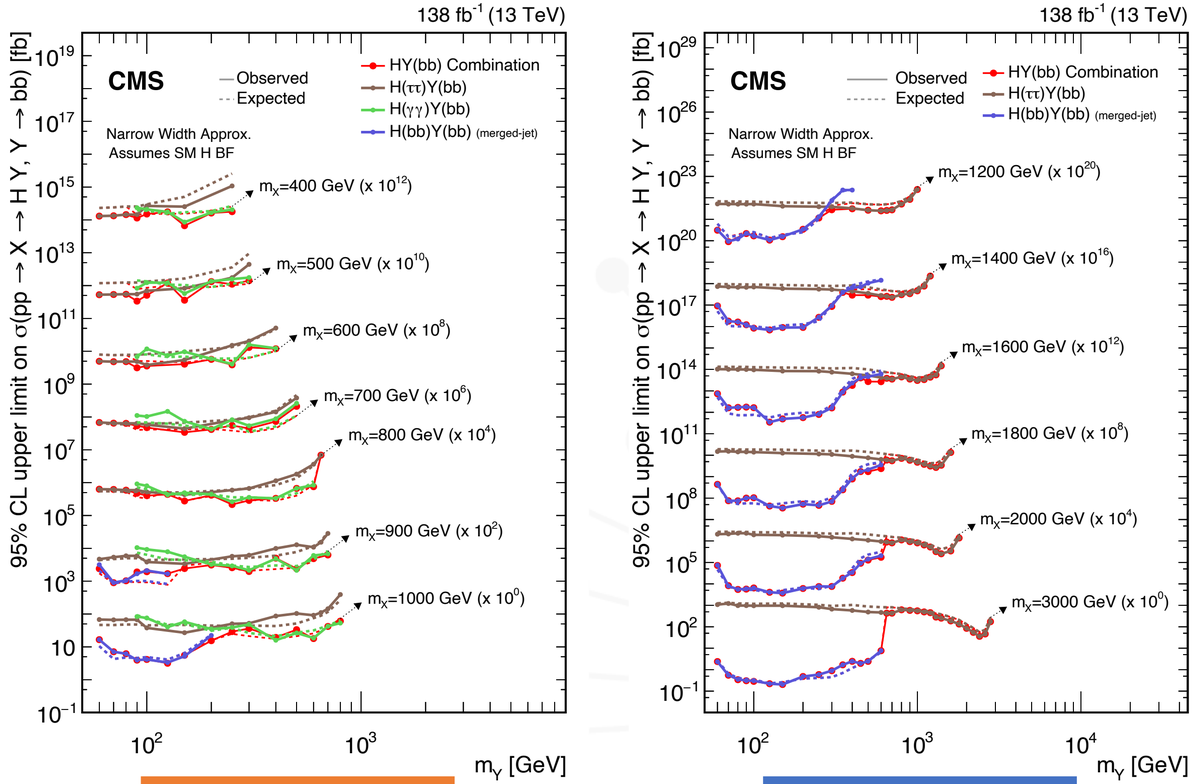
- X denotes as spin-0 radion in WED and new scalar boson in extended Higgs sector models
- G denotes as spin-2 graviton in WED
- Y denotes as additional boson in NMSSM/TRSM

X → HH



- Six searches for $X \rightarrow HH$ and their combination (red curve)
- The strongest observed limits to date on resonant HH production below masses of 320 GeV and above 800 GeV

X → YH

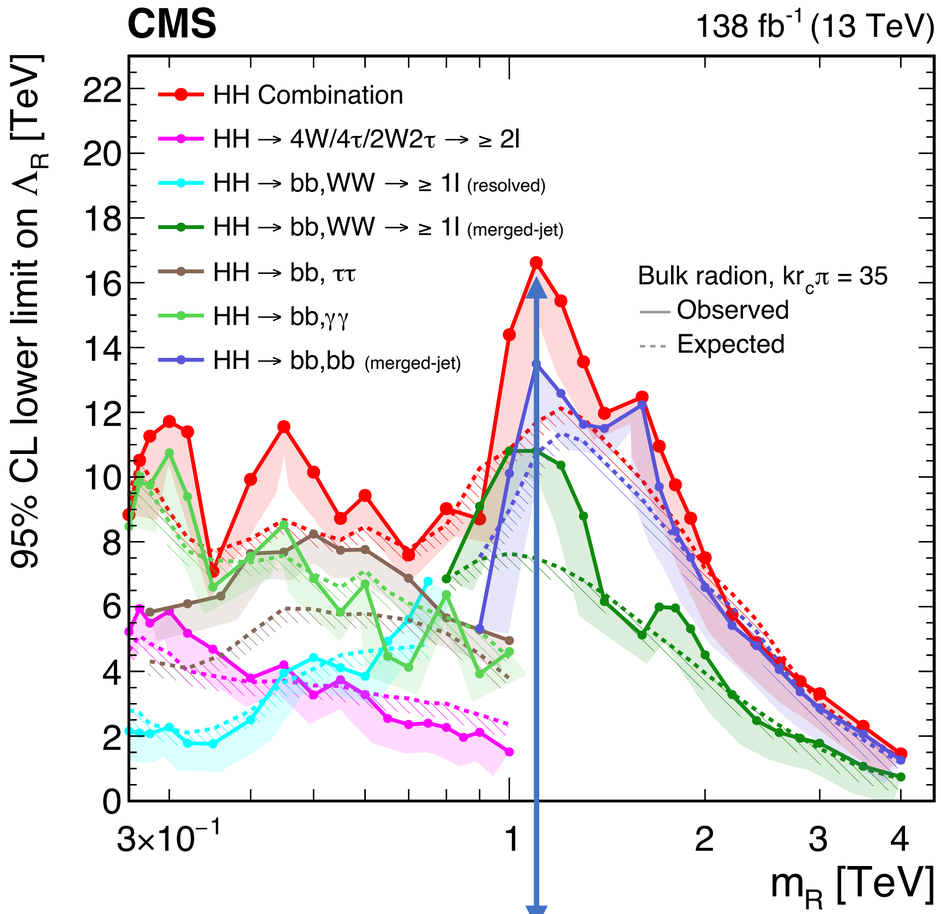


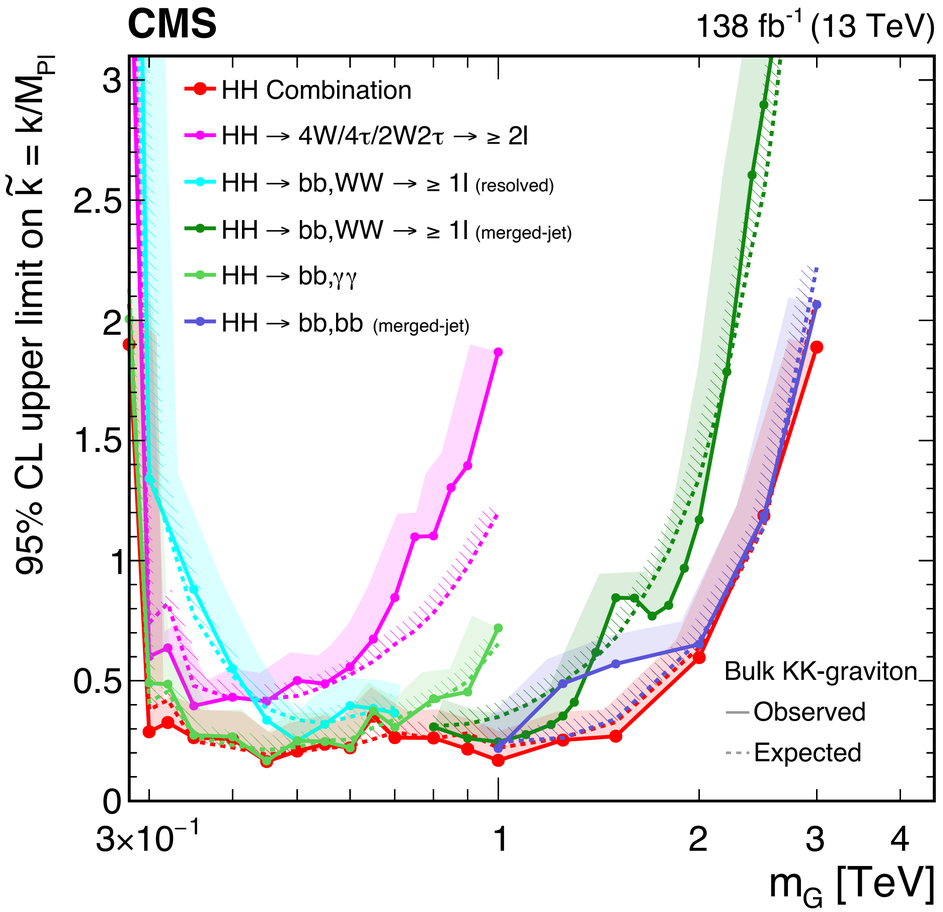
$m_X \leq 1000$ GeV

$m_X \geq 1200$ GeV

Interpretations - Warped Extra Dimension

arXiv:2403.16926



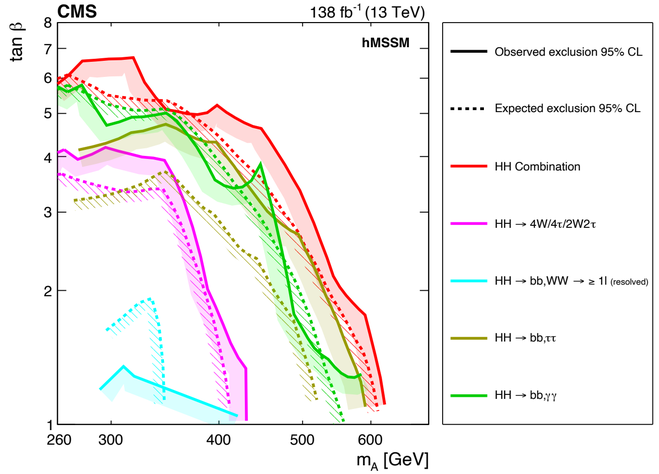


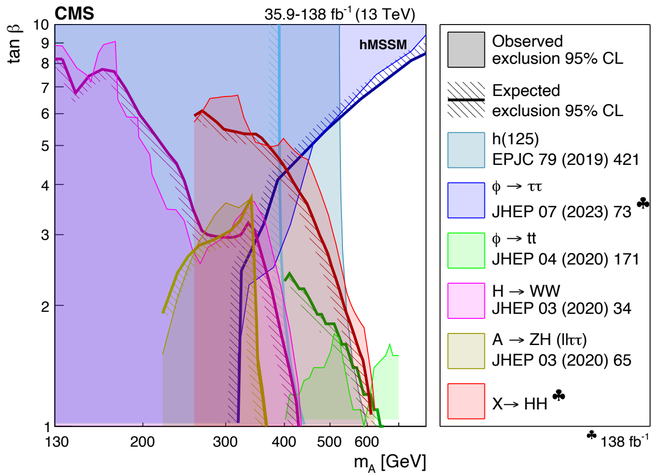
The strongest exclusion limits of about 12 TeV expected and 16 TeV observed are reached near $m_R = 1.2$ TeV

The combination excludes values of $\tilde{k}$ larger than about 0.3 at 95% CL for the large mass range $0.3 < m_G < 1.5$ TeV

Interpretations - Extended Higgs Sector

MSSM – hMSSM

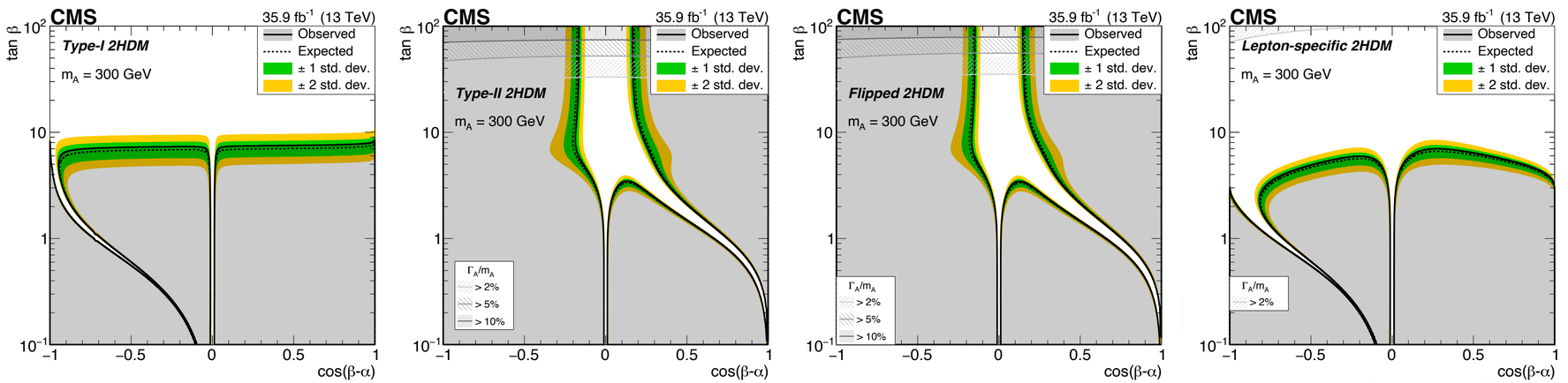




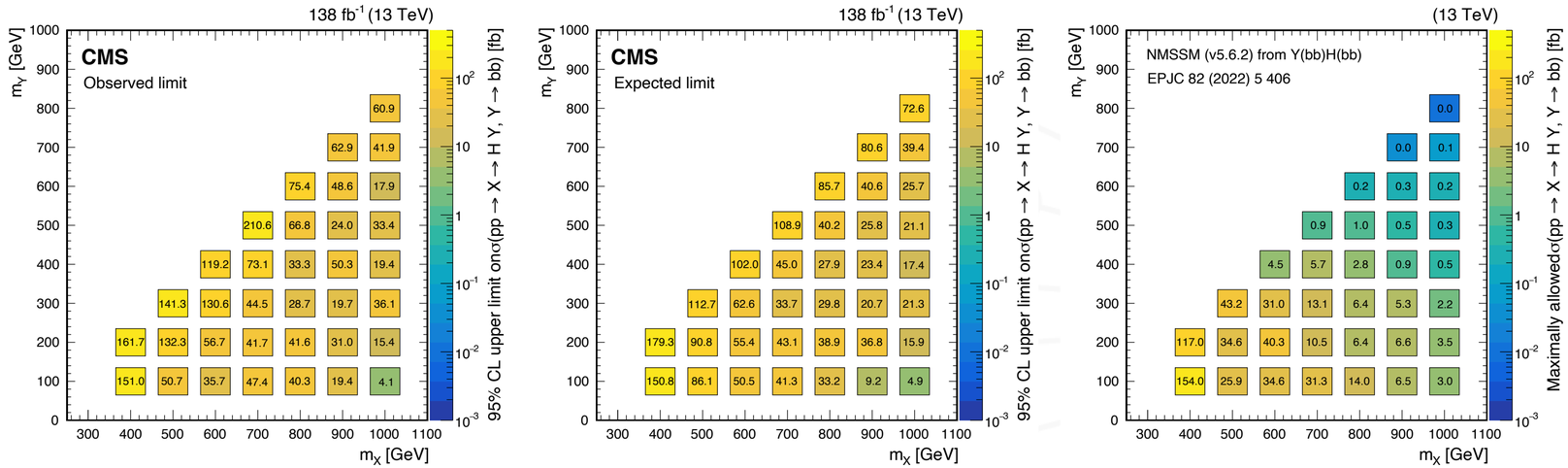
Results for M_{h}^{125} are available in backup.

2HDM (from $A \to ZH$ decay)

arXiv:2403.16926



NMSSM and TRSM (from $X \to YH$ decay)

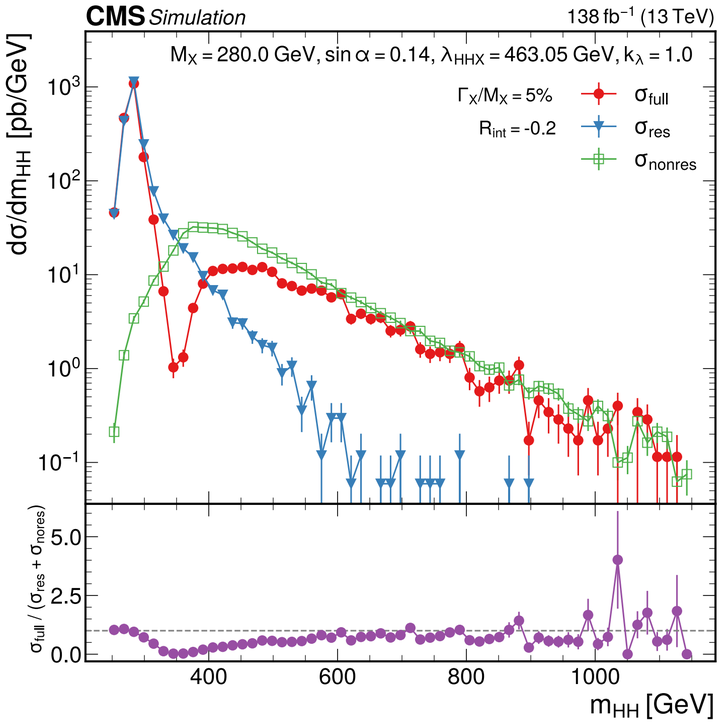


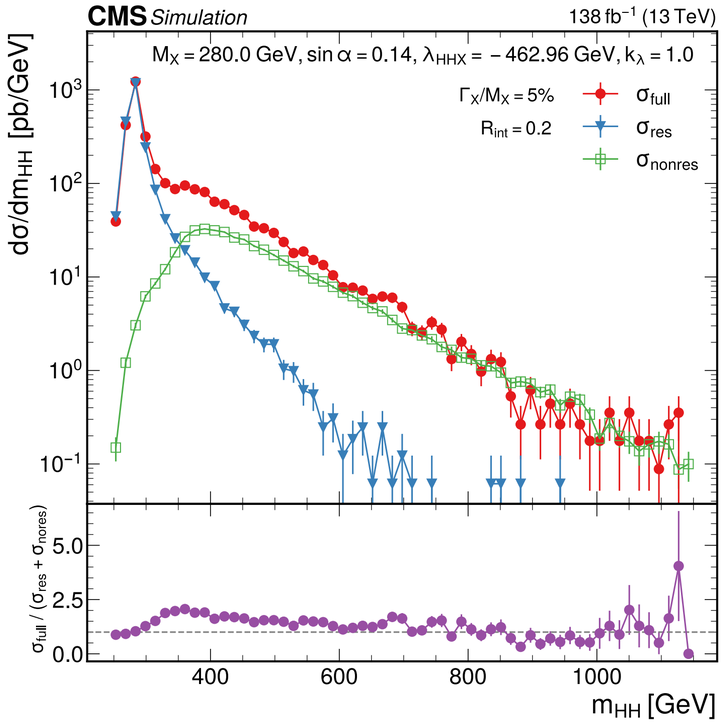
Effects of finite width and interference

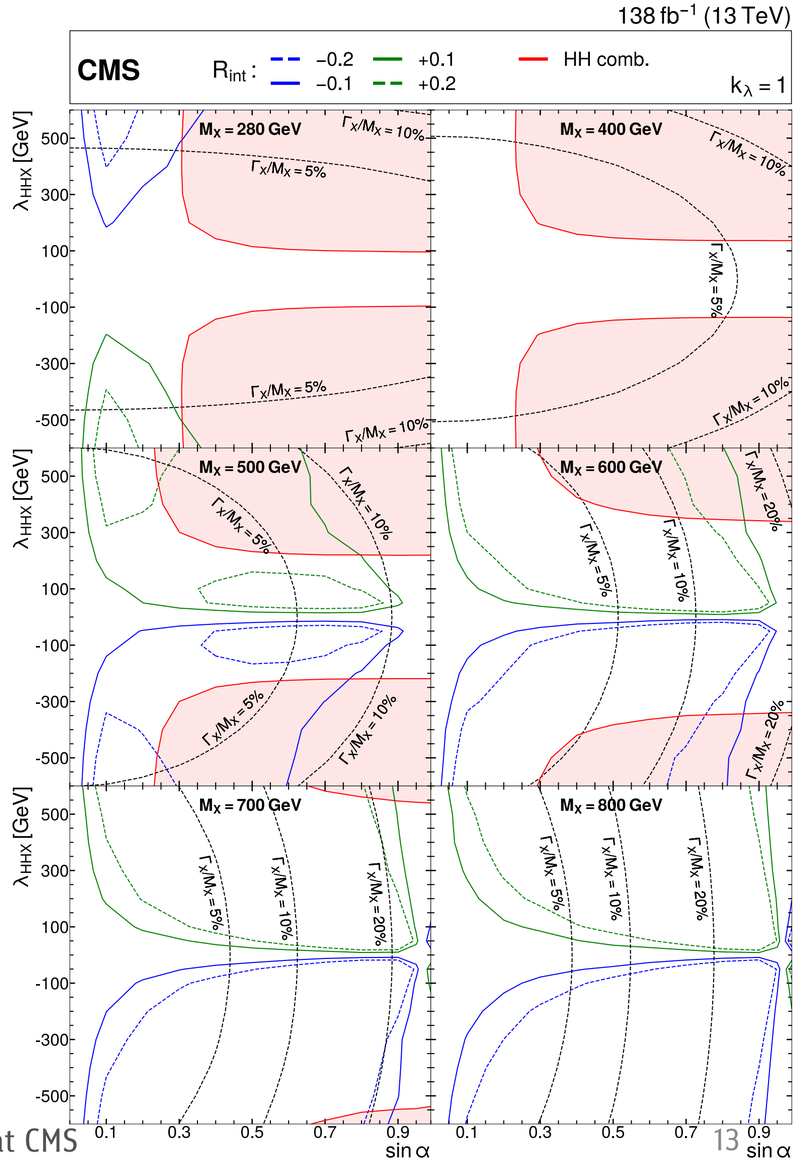
arXiv:2403.16926

- Based on **the real-singlet model**, perform a parameter scan in m_X, $\sin\alpha$, and λ_{HHX} of the interference ratio

$$R_{\text{int}} = \frac{\sigma^{\text{full}} - \left(\sigma^{\text{resonant-only}} + \sigma^{\text{nonresonant}}\right)}{\sigma^{\text{resonant-only}} + \sigma^{\text{nonresonant}}}$$







Summary

- CMS has published many results on

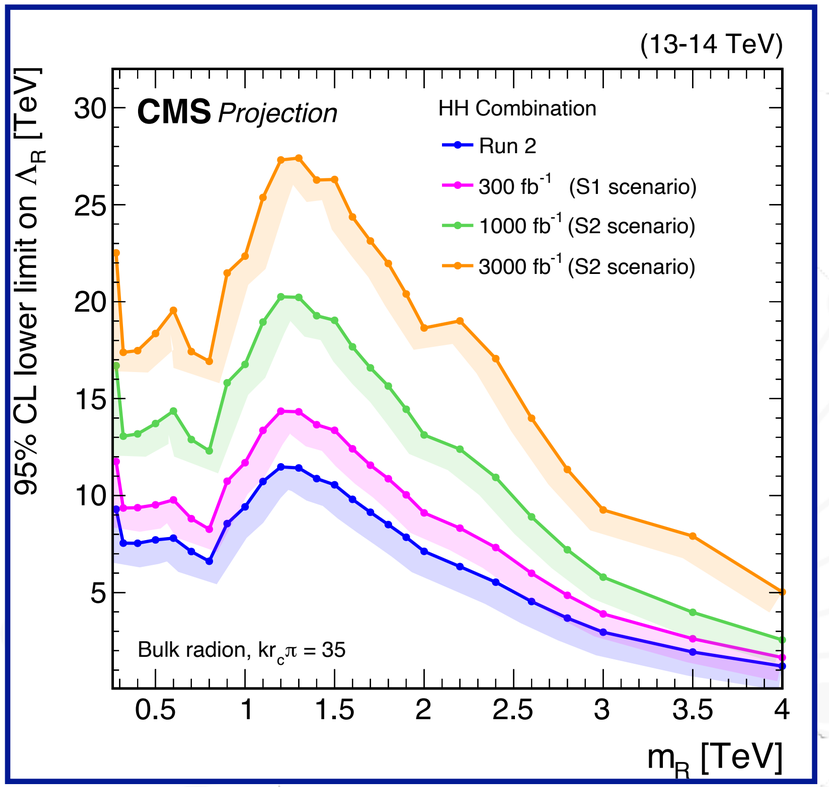
“Search for new resonances decaying into two Higgs bosons"

arXiv:2403.16926

- Machine learning techniques play crucial role in various aspects
  - object reconstruction (DeepJet, DeepTau, ParticleNet,…)
  - signal vs background discriminants
  - etc.

- Small excess observed but no strong deviation from SM
  - more data will be needed to clarify their nature

- Many more results to come — **Stay Tuned for Run 3 analyses!**



Backup

Extended Higgs Sector

Extend SM with *singlets*

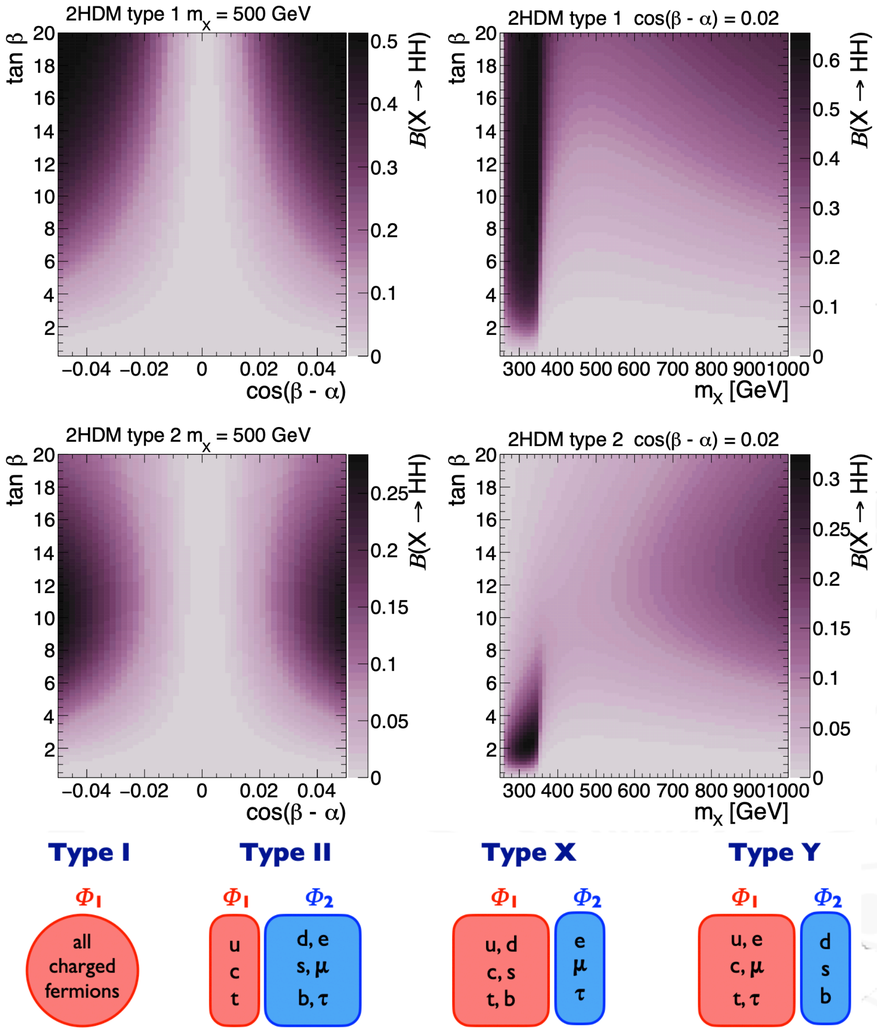
- Additional **one real singlet** leads to new scalar X ($m_{\mathrm{X}} \geq$ or $\leq m_{\mathrm{H}}$)
  - using the singlet model for a finite width study in this report
  - three free parameters (Z_2 symmetry) : tanβ, mixing angle α, and m_{X}
  - At low sinα, $\mathrm{X} \to \mathrm{HH}$ is dominant

- **Two real singlets (TRSM)**
  - second new scalar Y
  - $\mathrm{X} \to \mathrm{HH}$, $\mathrm{X} \to \mathrm{YH}$, and $\mathrm{X} \to \mathrm{YY}$ become possible

Extend SM with *doublets*

- **Two Higgs doublet models (2HDMs)**
  - 5 Higgs bosons : $\mathrm{H}^{\pm}$, A (CP-odd), X and H (CP-even)
  - 4 types (Type I, Type II (MSSM), Type X, Type Y) with natural flavor and CP conservation, depending on how two doublets couple to the SM particles
  - Heavy Higgs bosons X and A decays in 2HDMs :
    - $\mathrm{X} \to \mathrm{HH}$ (scalar)
    - $\mathrm{A} \to \mathrm{ZH}$ (CP-odd scalar)
- **Adding additional singlet or doublet:**
  - defines the N2HDMs and 2HDM+S
  - $\mathrm{X} \to \mathrm{YH}$ and $\mathrm{X} \to \mathrm{YY}$ are dominant

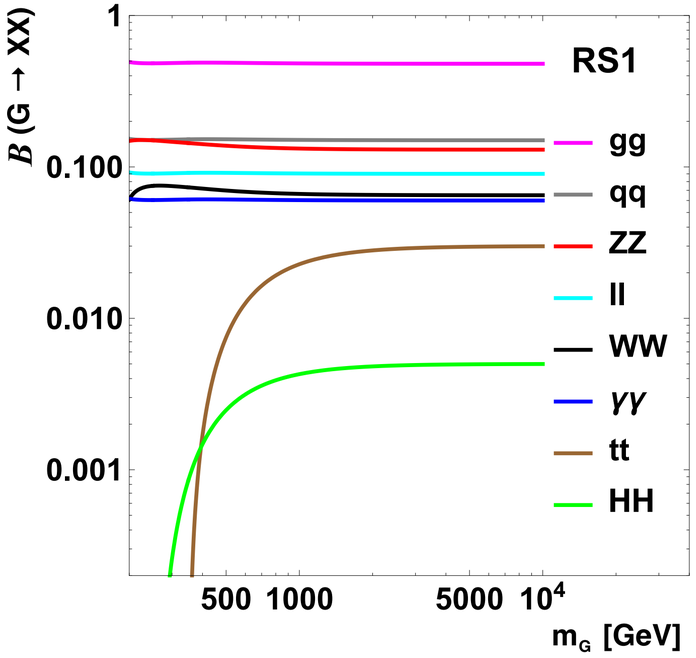
arXiv:2403.16926 *(submitted to Physics Reports)*

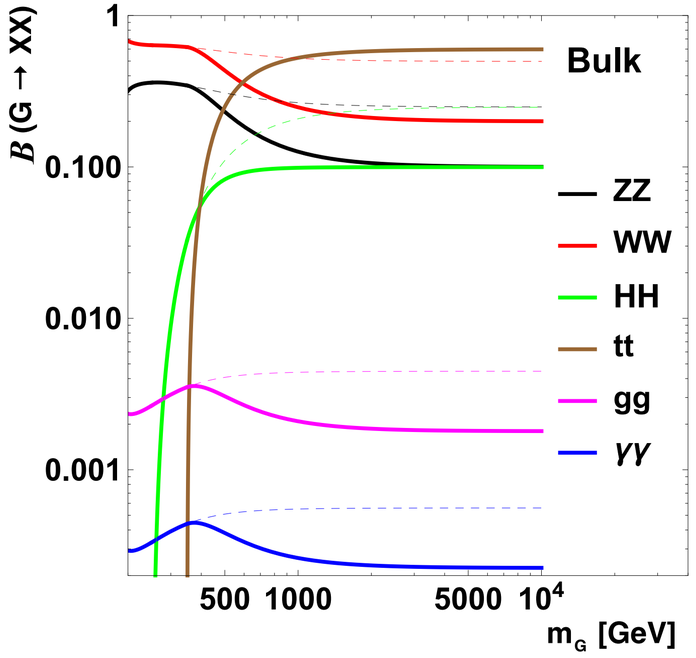


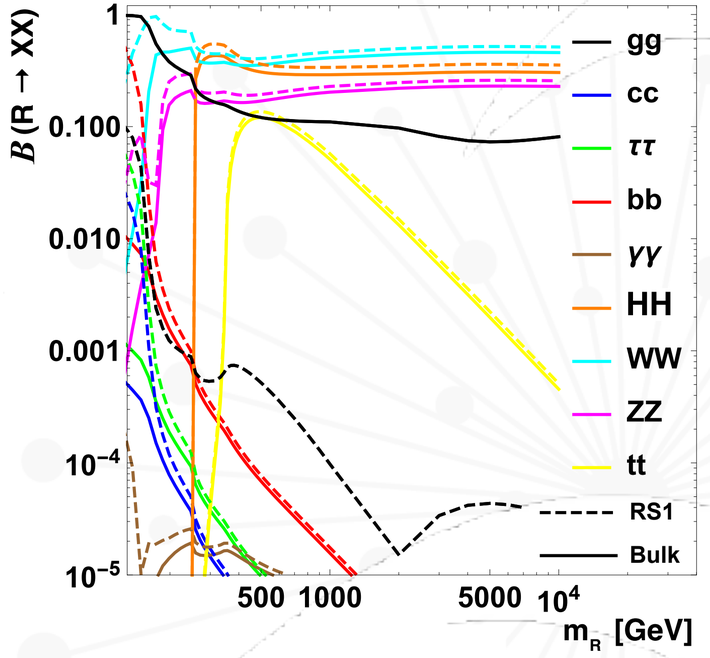
Warped Extra Dimension (WED)

- The model predicts the existence of a narrow spin-0 (Radion) and a spin-2 (KK-Graviton)
- Different benchmarks are considered for KK-Graviton : **RS1 and bulk-RS**
  - the BR to HH is among the dominant on the bulk-RS scenario
- For large radion masses, the branching fraction to HH is approximately 25%

arXiv:2403.16926 *(submitted to Physics Reports)*

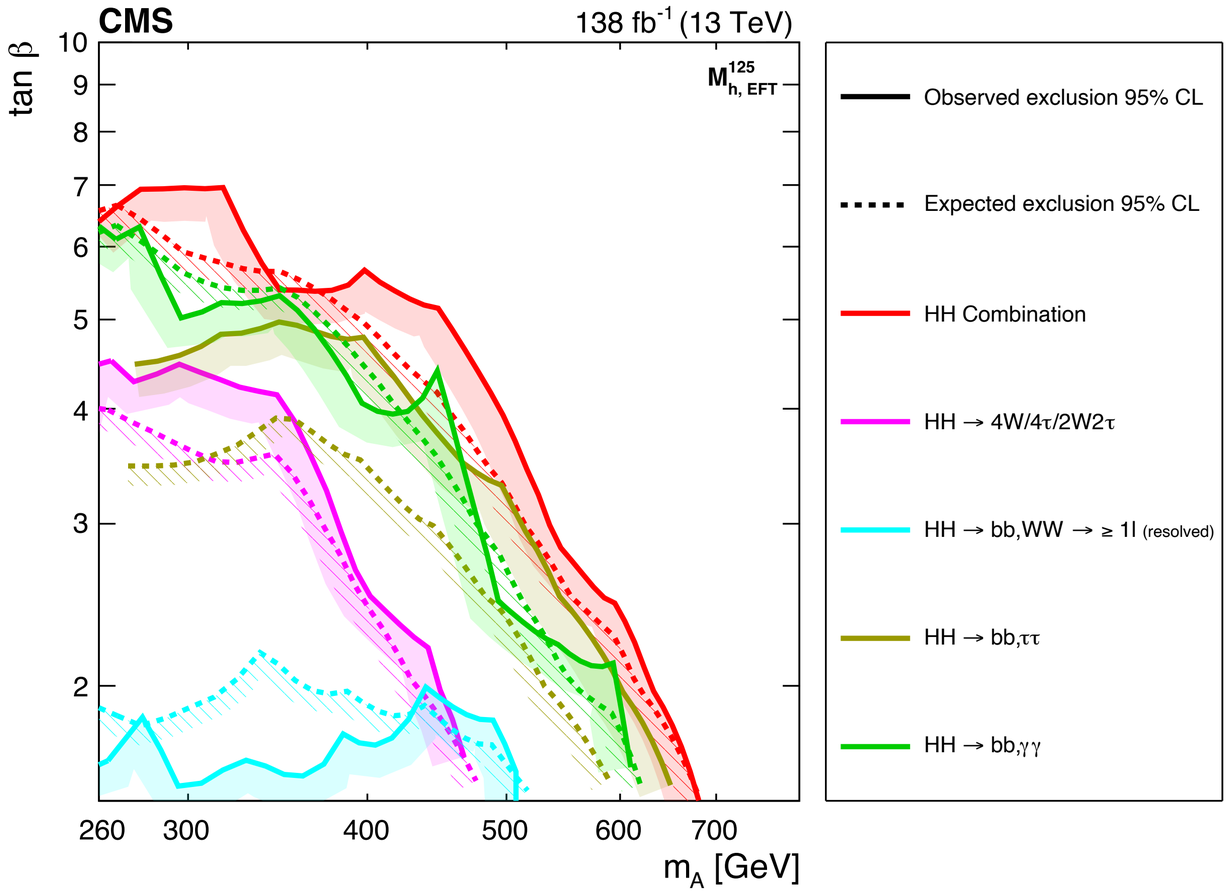


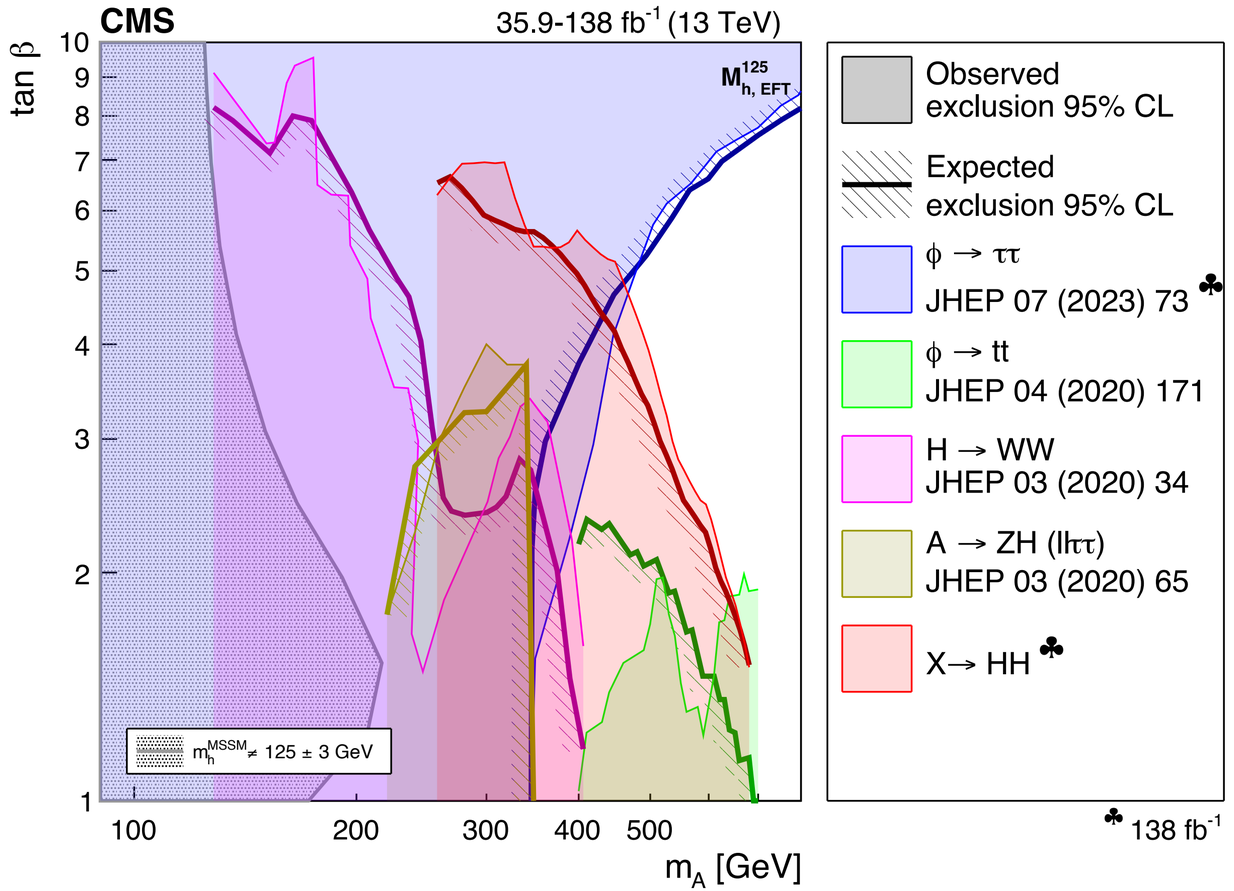




Interpretations - Extended Higgs Sector

- M_{h}^{125} scenarios





Effects of finite width and interference

- m_X = 500 GeV, sinα = 0.03, λ_{HHX} = -600 GeV, κ_λ =1.0, and R_{int} = ±10%