

Overview of searches for $X \rightarrow hh$ or $X \rightarrow Yh$ at CMS

LHC HH subgroup meeting

28 September 2022

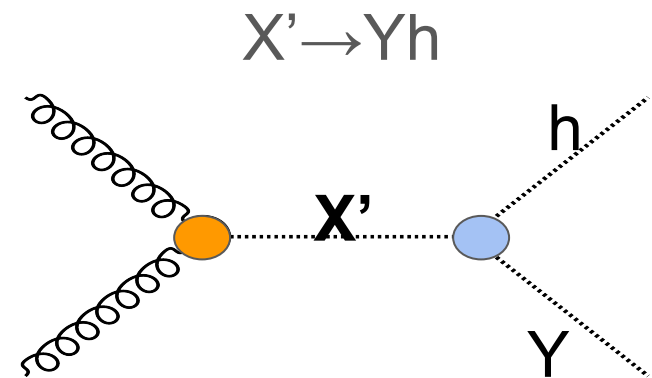
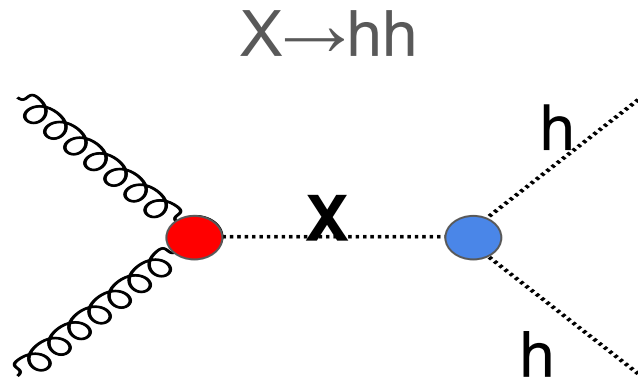
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on behalf of the CMS HH team

¹ IHEP CAS

² Vilnius university

Considered interpretations



- Spin 0 resonances
 - Randall-Sundrum radion
 - 2 H doublets models (2HDM)
- Spin 2 resonances
 - Randall-Sundrum KK graviton

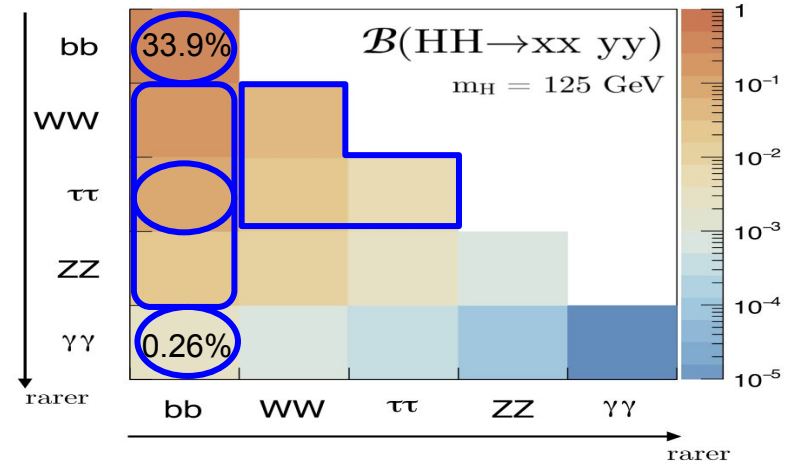
- Spin 0 resonances
 - Next-to-minimal supersymmetry models (NMSSM) [JHEP07\(2008\)](#)
 - Two-real-scalar-singlet extension of the SM (TRSM) [E.P.J.C80,151\(2020\)](#)

- Assuming resonances with narrow decay widths
- No interference effects

Explored final states

- $h \rightarrow bb$: large SM BR & bkg rejection from heavy-flavour jet ID
- h final states with leptons, γ , or T_h : efficient bkg rejection

Available $X \rightarrow hh$ (or Yh) searches with full Run 2 data from CMS

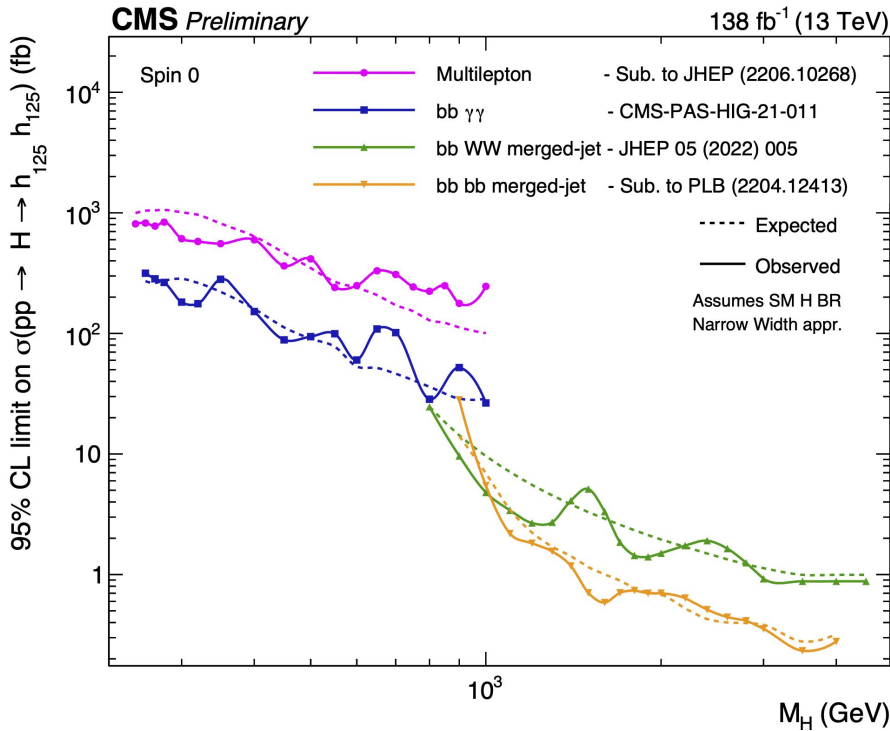


Decay channel	Interpretations		
	spin 0 $X \rightarrow hh$	spin 0 $X \rightarrow Yh$	spin 2 $X \rightarrow hh$
bbbb CMS-PAS-B2G-20-004 , arXiv:2204.12413	✓	✓	✓
bb+leptons JHEP 2205 (2022) 005	✓		✓
bbTT JHEP11(2021)057		✓	
bb $\gamma\gamma$ CMS-PAS-HIG-21-011	✓	✓	✓
multileptons arXiv:2206.10268	✓	✓	

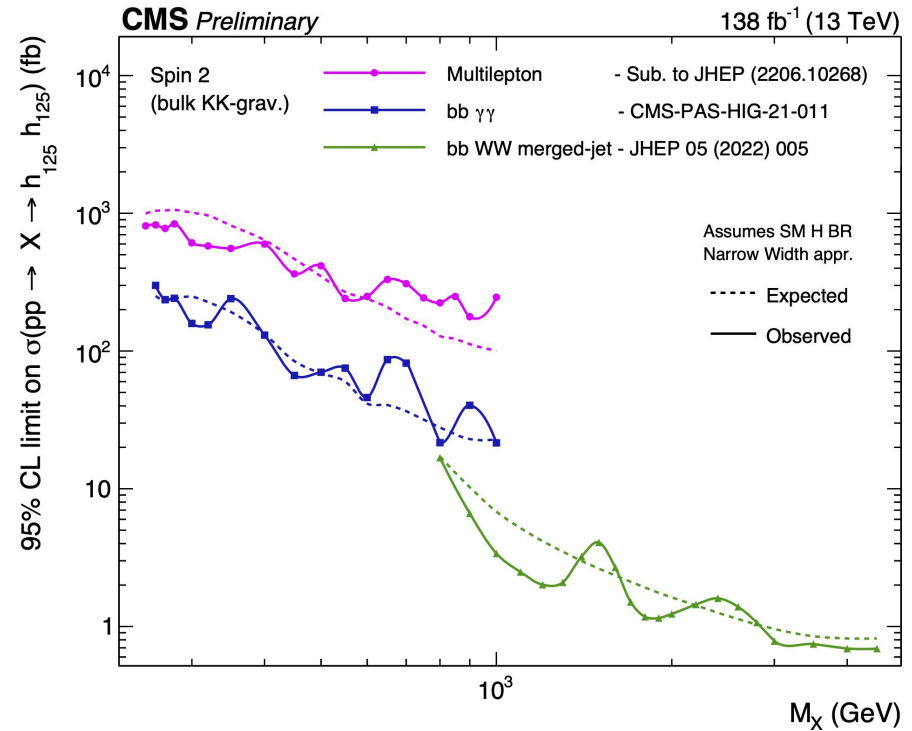
X→hh search in Run 2 data

Upper limit on $\sigma(pp \rightarrow X \rightarrow HH)$

spin 0 resonance

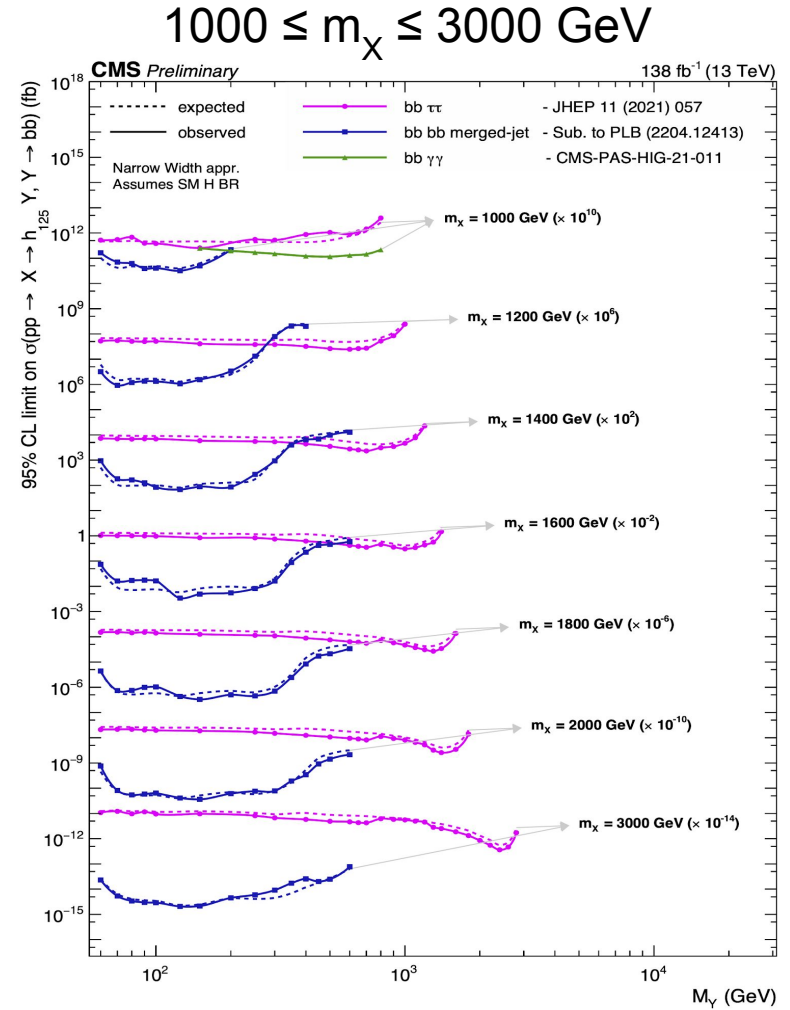
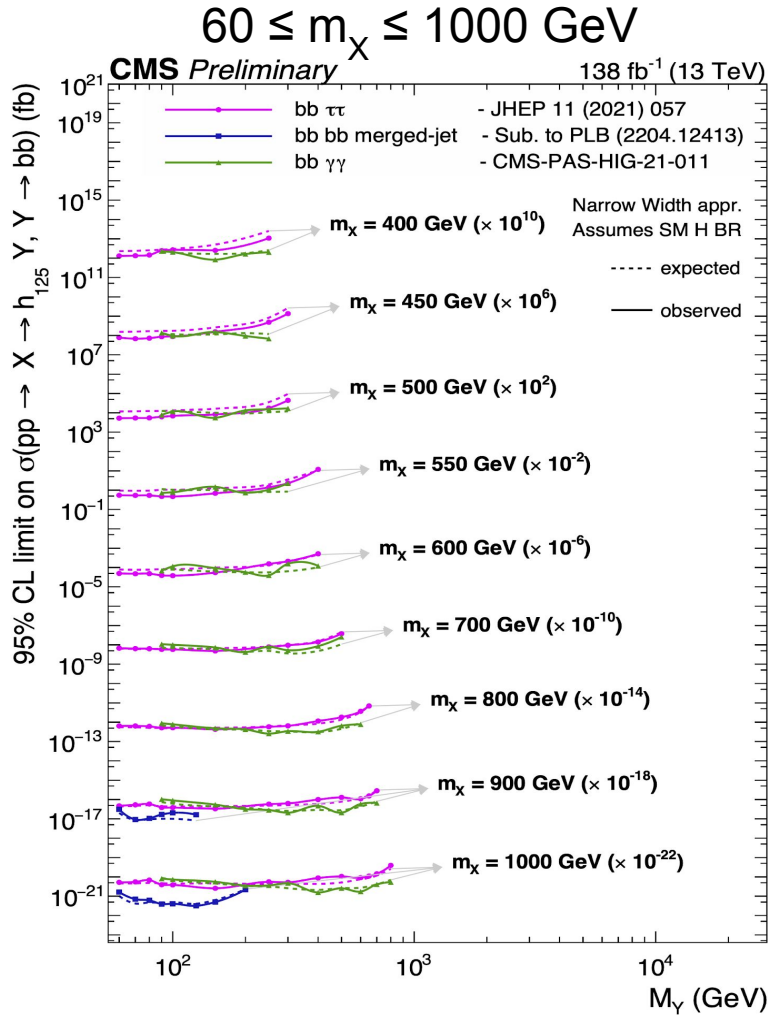


spin 2 resonance



➤ No significant deviations from SM observed

X → Yh search in Run 2 data

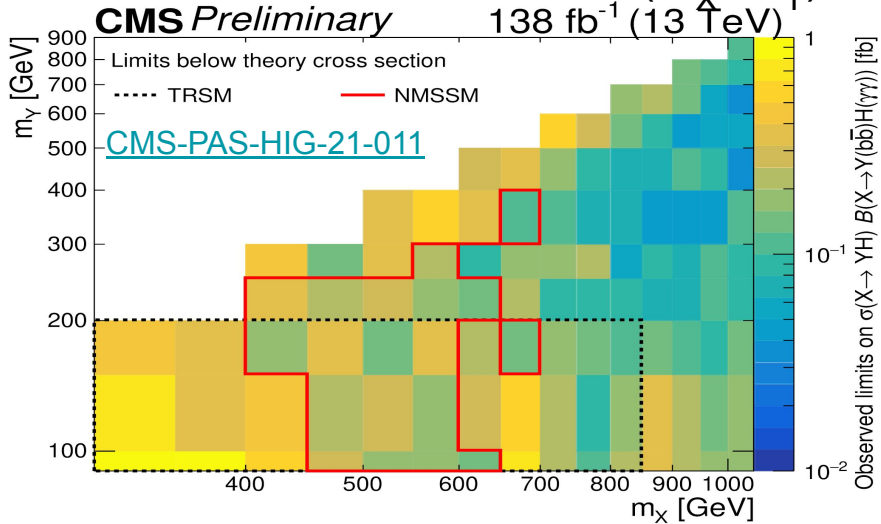


- Excess with local(global) significance of 3.8(2.8) σ for (m_X, m_Y) = (650, 90) GeV in bby $\gamma\gamma$

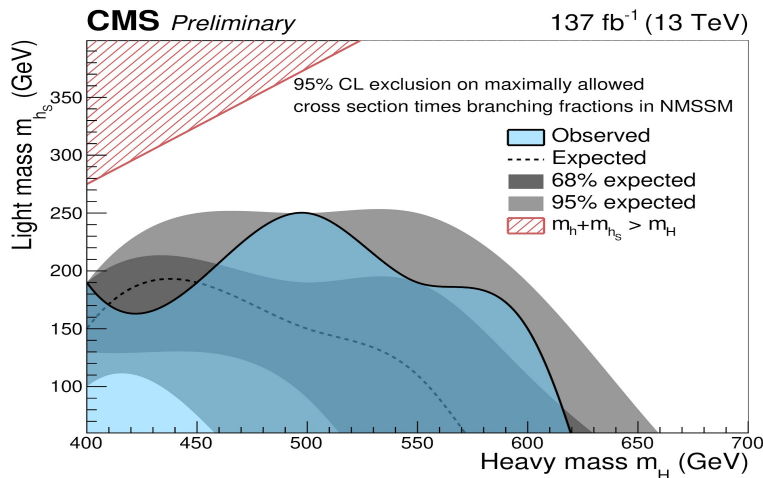
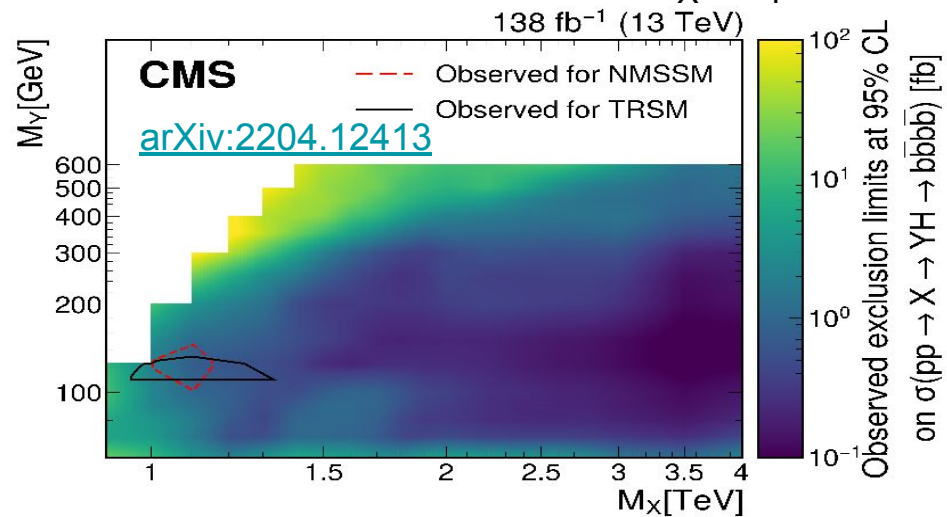
NMSSM and TRSM interpretations of $X \rightarrow Yh$ searches

- Assuming maximally allowed NMSSM and TRSM XS's

Observed limits on $\sigma(pp \rightarrow X \rightarrow YH \rightarrow b\bar{b}\gamma\gamma)$ at 95% CL as a function of (M_X, M_Y)



Observed limits on $\sigma(pp \rightarrow X \rightarrow YH \rightarrow 4b)$ at 95% CL as a function of (M_X, M_Y)



Obs. and exp. limits on $\sigma(pp \rightarrow X \rightarrow YH \rightarrow b\bar{b}\tau\tau)$ at 95% CL as a function of (M_X, M_Y)

BACKUP

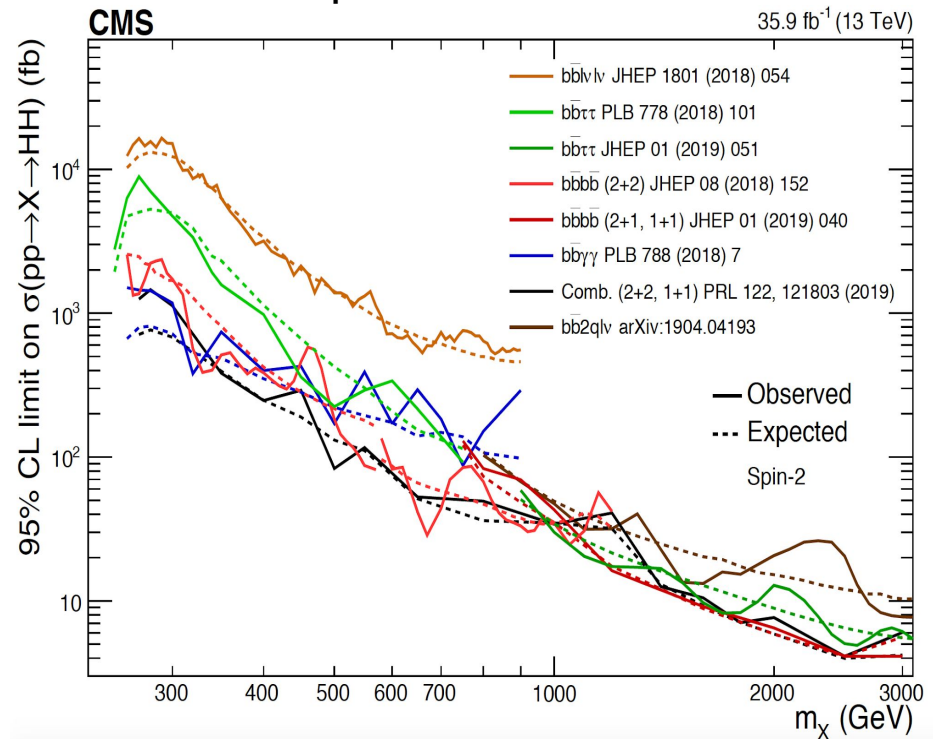
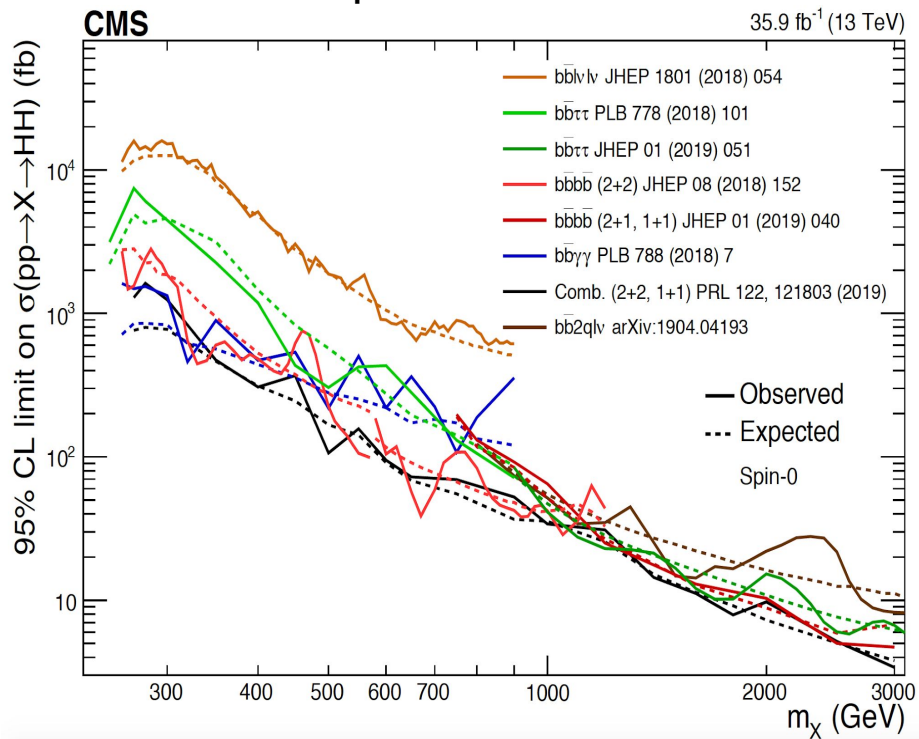
$X \rightarrow hh$ comb with 2016 data ($\sim 36 \text{ fb}^{-1}$)

- No significant excess found

Upper limit on $\sigma(pp \rightarrow X \rightarrow hh)$

spin 0 resonance

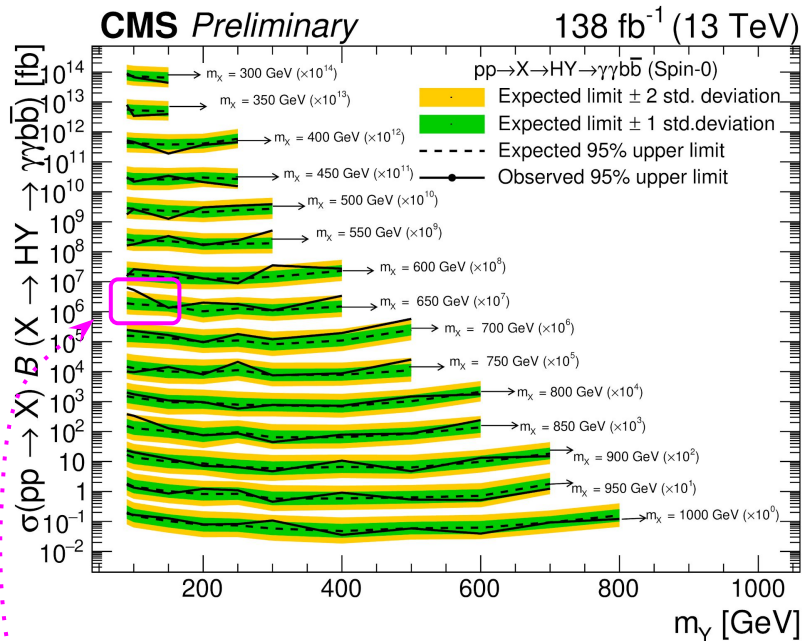
spin 2 resonance



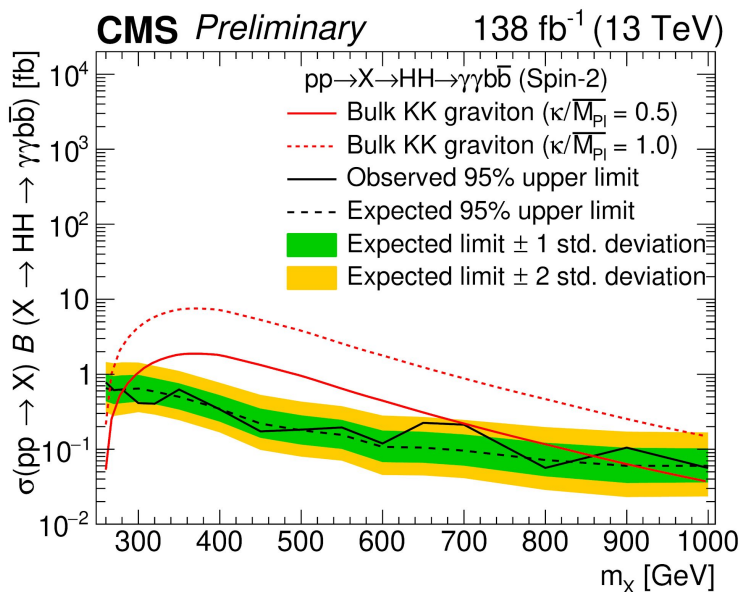
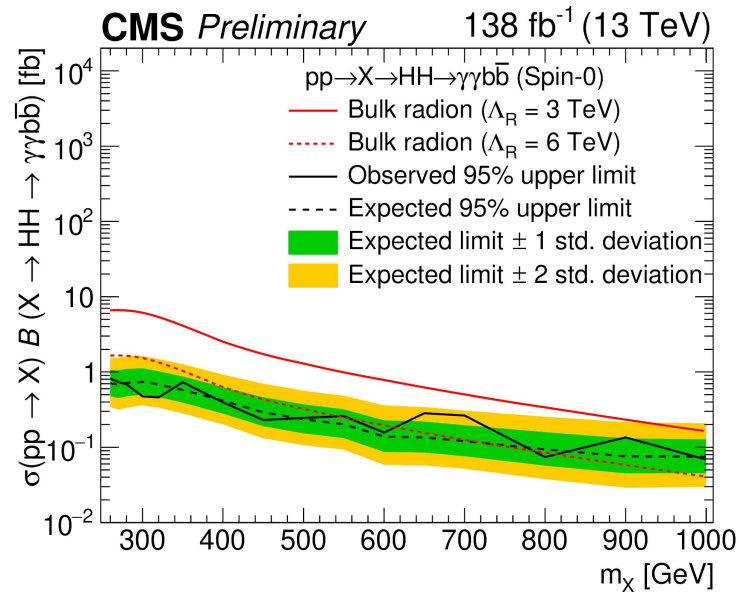
$X \rightarrow hh \rightarrow bby\gamma$ and $X \rightarrow Yh \rightarrow bby\gamma$ - overview

- Clean but rare final state
 - γ pair + b-jets pair resonant on m_H
 - bkg from jets(+ $\gamma\gamma$) \rightarrow γ and b-jet ID requirements
- MVA strategy to optimize signal-bkg separation
 - BDT's to separate sig from $\gamma(\gamma)$ +jets
 - DNN to separate HH from $ttH(\gamma\gamma)$
- Sensitivity optimized to different m_X & m_Y hypotheses
 - BDT's trained in six separate intervals of $m_X/(m_Y+m_h)$ and used to define three analysis categories
 - For each probed m_X , selection on $m_{bby\gamma}^* = M_{\gamma\gamma jj} - M_{\gamma\gamma} - M_{jj} + 250$ GeV to keep $\sim 60\%$ of signal
- Signal extraction from simultaneous fit of $m_{\gamma\gamma}$ and m_{bb}

$X \rightarrow hh \rightarrow bby\bar{y}$ and $X \rightarrow Yh \rightarrow bby\bar{y}$ - results



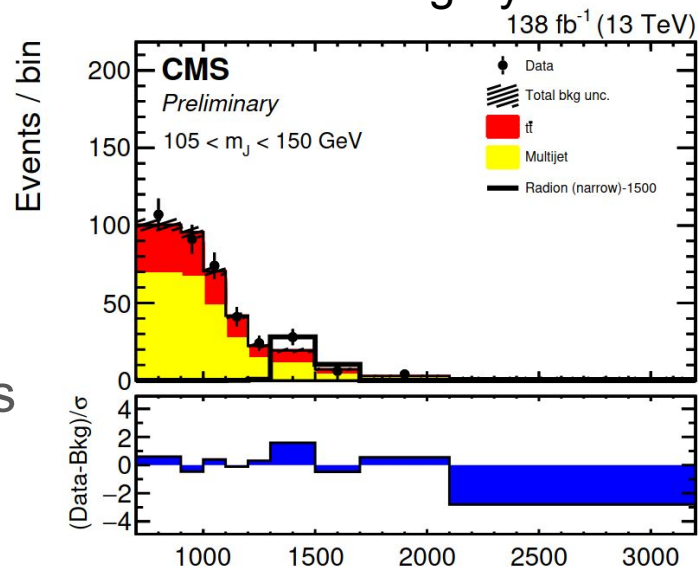
- Excess with local(global) significance of 3.8(2.8) σ for $(m_X, m_Y) = (650, 90)$ GeV



X → hh → 4b - overview

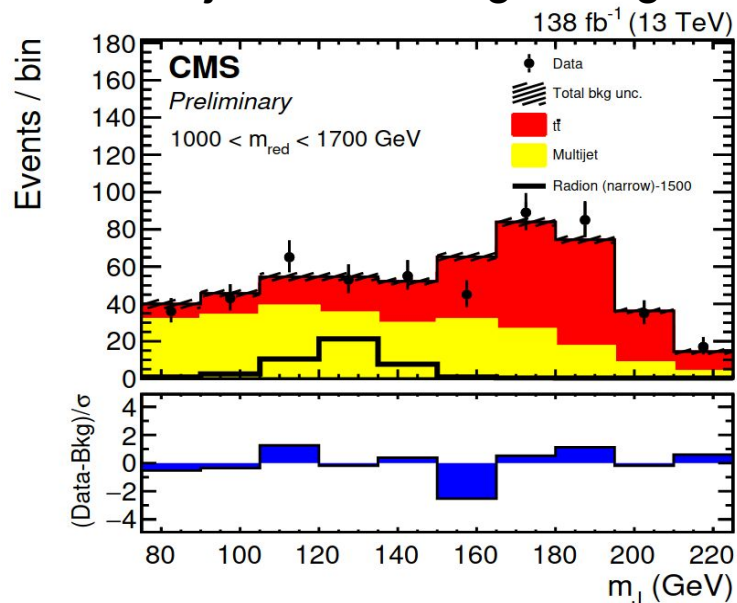
- $m_X \in [1, 3]$ TeV and spin 0 or 2
- Final states with 1 or 2 boosted H
 - 2 AK8 jets, or 1 AK8 + 2 AK4 jets
- main bkg from QCD and tt
 - b-jet ID based on DNN discriminators
 - modeling from data assisted by MC

m_{HH}^* in high b-tag scores category



$$m_{HH}^* = m_{HH} - m_{H1} - m_{H2} + 250 \text{ GeV}$$

lead AK8 jet mass in high b-tag scores cat'



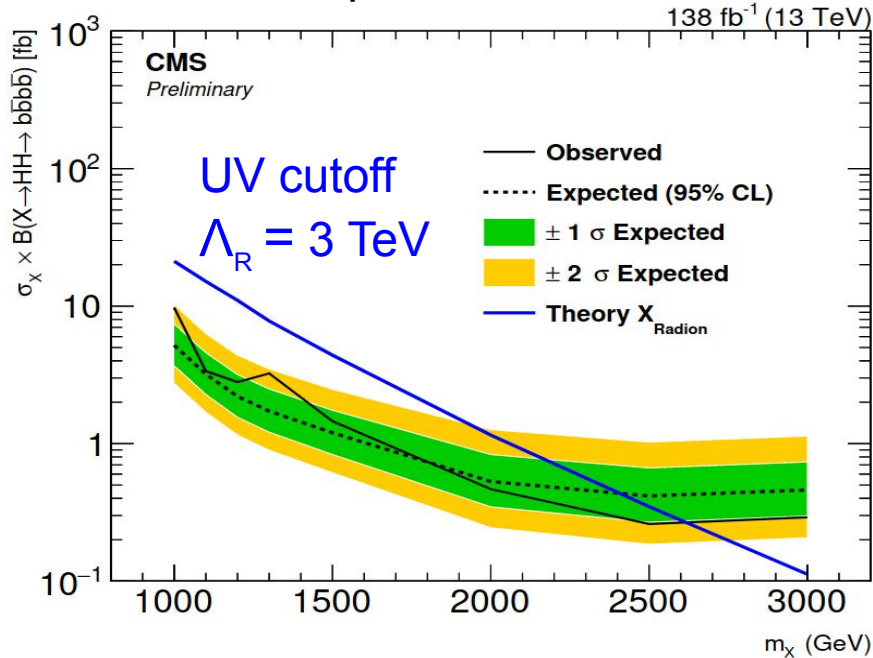
- One category for semi-boosted + two cat's for fully-boosted based on the b-tag scores
- Signal extraction from fit to m_{HH}^* and leading AK8 jet mass

$X \rightarrow hh \rightarrow 4b$ - results

- No significant excess found in the 1-3 TeV m_X range

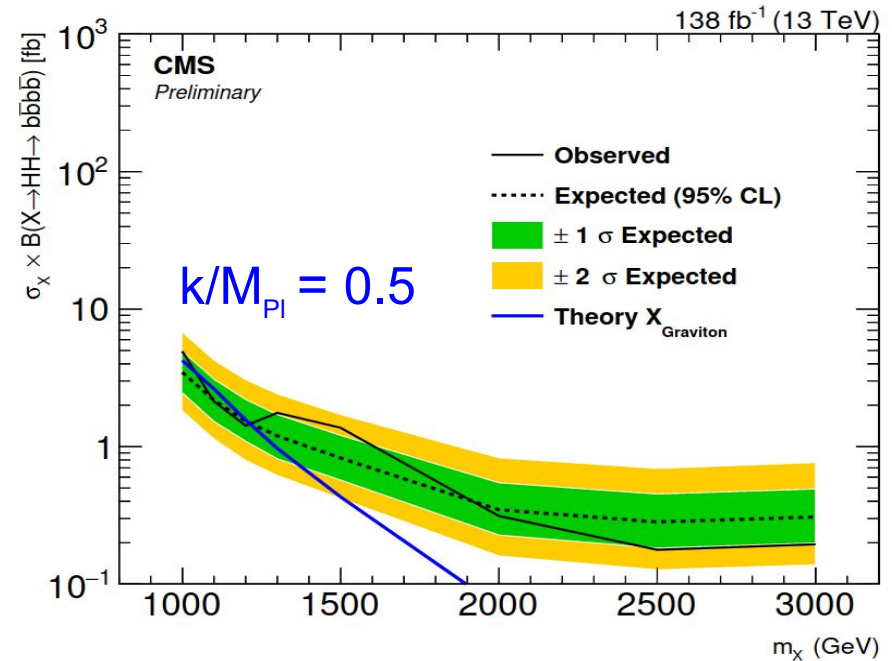
Upper limit on $\sigma(pp \rightarrow X \rightarrow hh \rightarrow 4b)$

spin 0 resonance



limits from 4.94 to 0.19 fb

spin 2 resonance



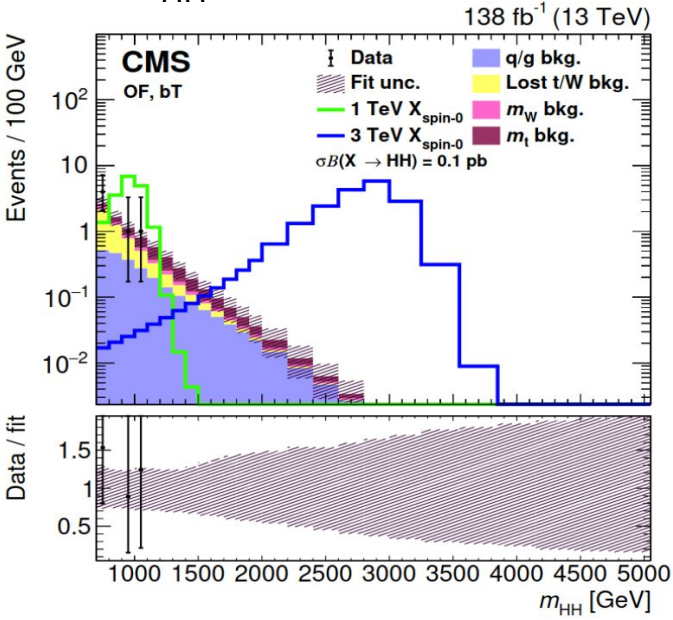
limits from 9.74 to 0.29 fb

- For $\Lambda_R = 3$ TeV & $k/M_{Pl} = 0.5$, radion with $m \in [1, 2.6]$ TeV and graviton with $m \in [1, 1.2]$ TeV excluded @95% CL

X→hh→bb+leptons boosted - overview

- Resonance with $m_X \in [0.8, 4.5]$ TeV and spin = 0 or 2
- Target HH decays $bb\overline{WW}(qq\ell\nu) + bb\overline{\tau\tau}(2\ell 4\nu) + bb\overline{VV}(2\ell 2\nu)$
 single-lepton (SL) final state = large radius jet + nearby lepton + p_T^{miss} di-lepton (DL) final state = 2 leptons + p_T^{miss}
 + H→bb reconstructed as a large radius heavy-flavored jet
- Main bkg from tt and Z+jets modeled with simulation

m_{HH} in one DL category



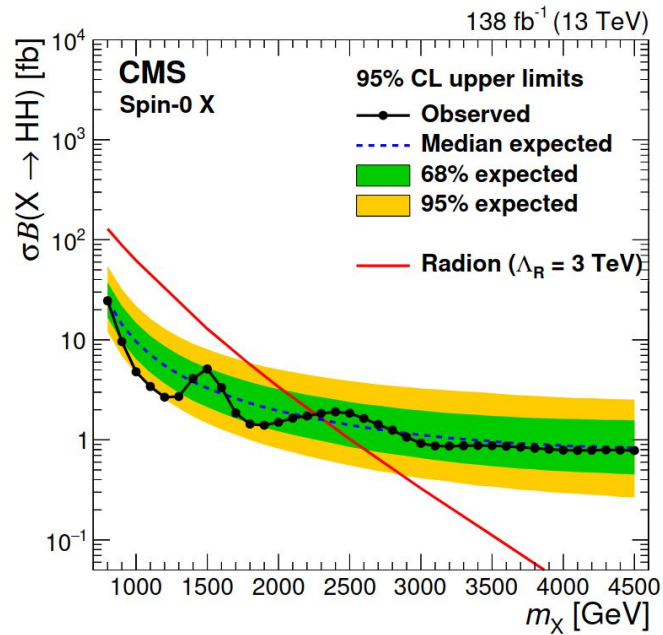
- Event categorization on lept. flavour, b-tag score, and other variables providing good sig-bkg separation
 - 8 SL categories + 4 DL categories
- 2D fit to (m_{HH}, m_{bb})

$X \rightarrow hh \rightarrow bb + \text{leptons}$ boosted - results

- No significant excess found

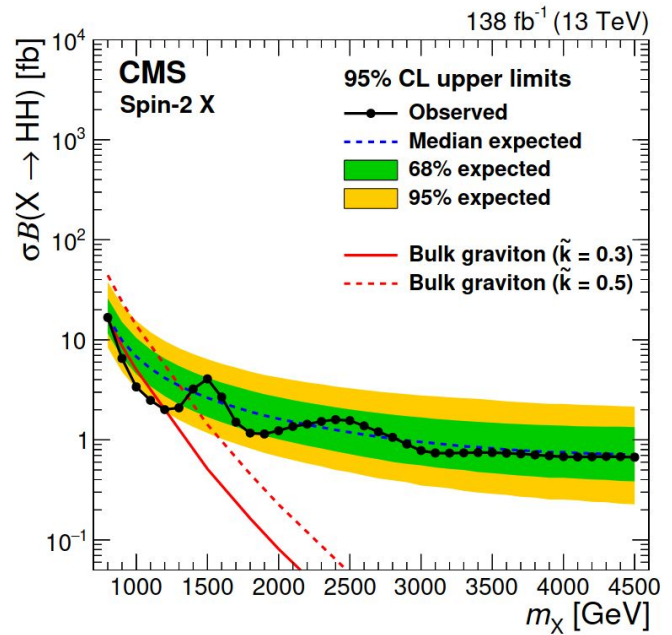
Upper limit on $\sigma(pp \rightarrow X \rightarrow HH)$

spin 0 resonance



Upper limits from 24.5 to 0.78 fb

spin 2 resonance

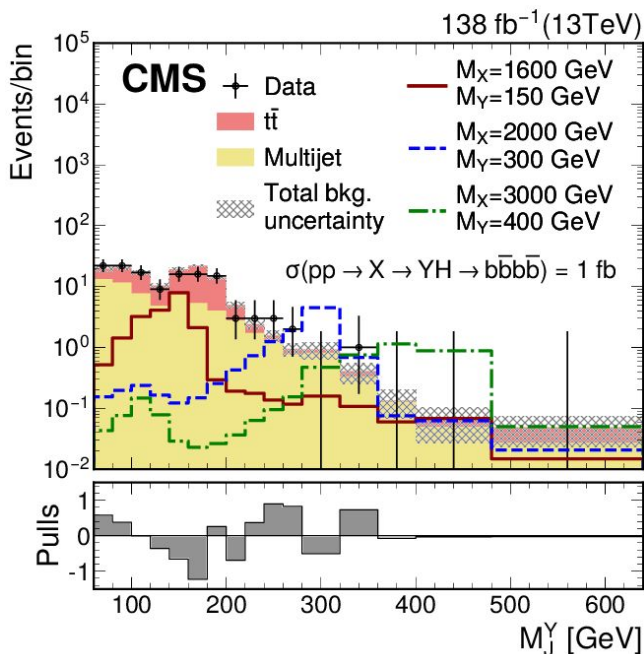


Upper limits from 16.7 to 0.67 fb

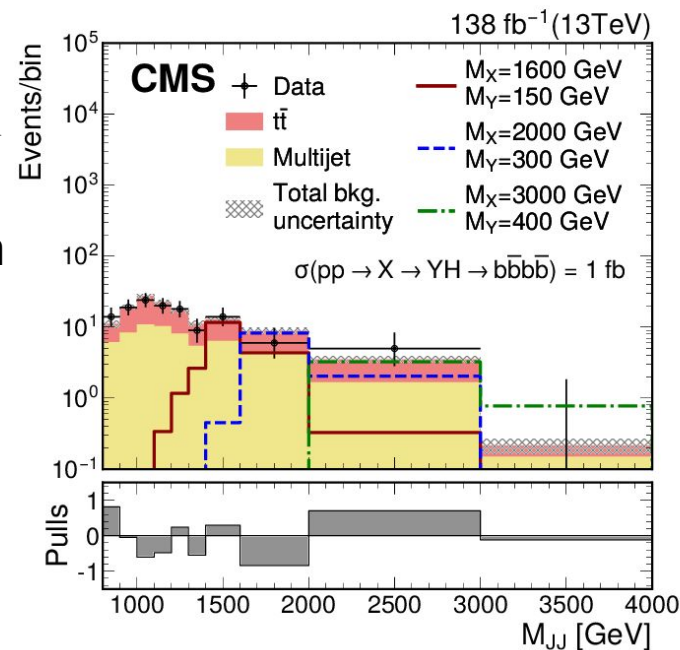
➤ Sensitivity similar to search for $X \rightarrow HH \rightarrow 4b$

$X \rightarrow Yh \rightarrow 4b$ boosted - overview

- $m_X \in [0.9, 4]$ TeV and $m_Y \in [60, 600]$ GeV \rightarrow boosted H & Y
- Similar final state and bkg of boosted non-resonant HH(4b)
 - Similar ParticleNet-based strategy for H(bb) ID, m_{bb} regression and event categorization
- Modeling of QCD bkg from data and of tt from simulation
 - Data control regions for validation & to improve data/MC agreement
- 2D fit to reconstructed m_X and m_Y of signal candidates



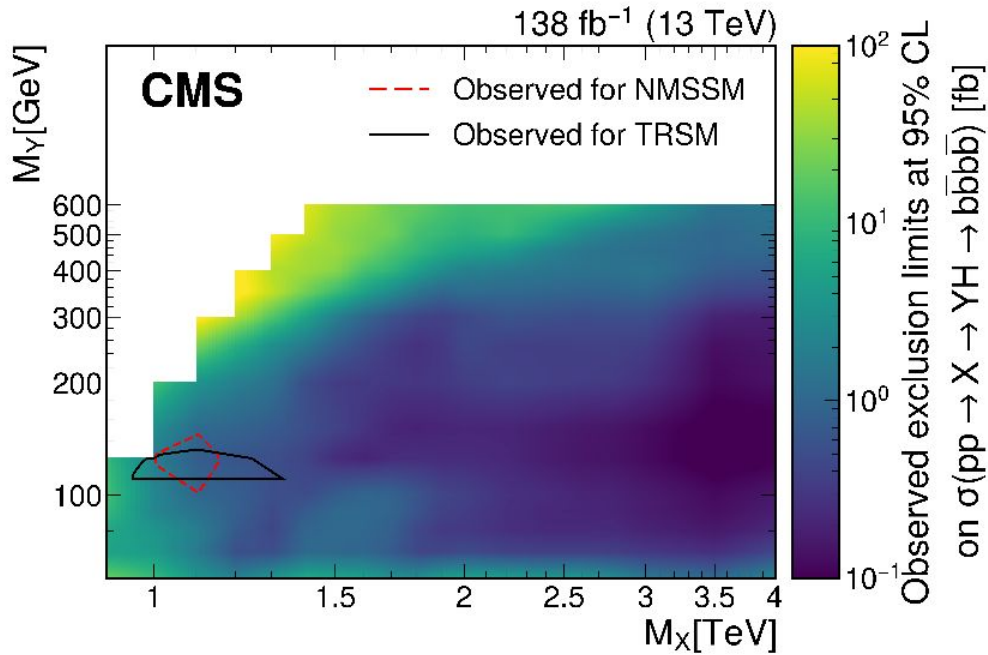
reco m_Y and m_X in
the highest
ParticleNet score
category



$X \rightarrow Yh \rightarrow 4b$ boosted - results

- No significant excess found

Observed limits on $\sigma(pp \rightarrow X \rightarrow YH \rightarrow 4b)$
at 95% CL as a function of (M_X, M_Y)

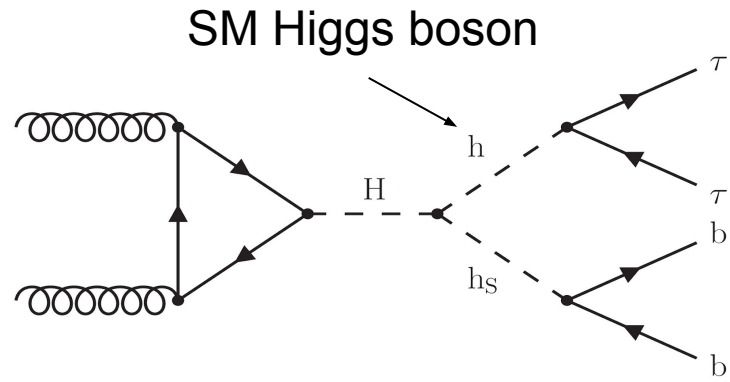


➤ Limits range from 0.1 fb to 150 fb

Assuming maximally allowed NMSSM and TRSM XS's

- NMSSM excluded within $M_X \in [1, 1.15]$ TeV and $M_Y \in [101, 145]$ GeV
- TRSM excluded within $M_X \in [0.95, 1.33]$ TeV and $M_Y \in [110, 132]$ GeV

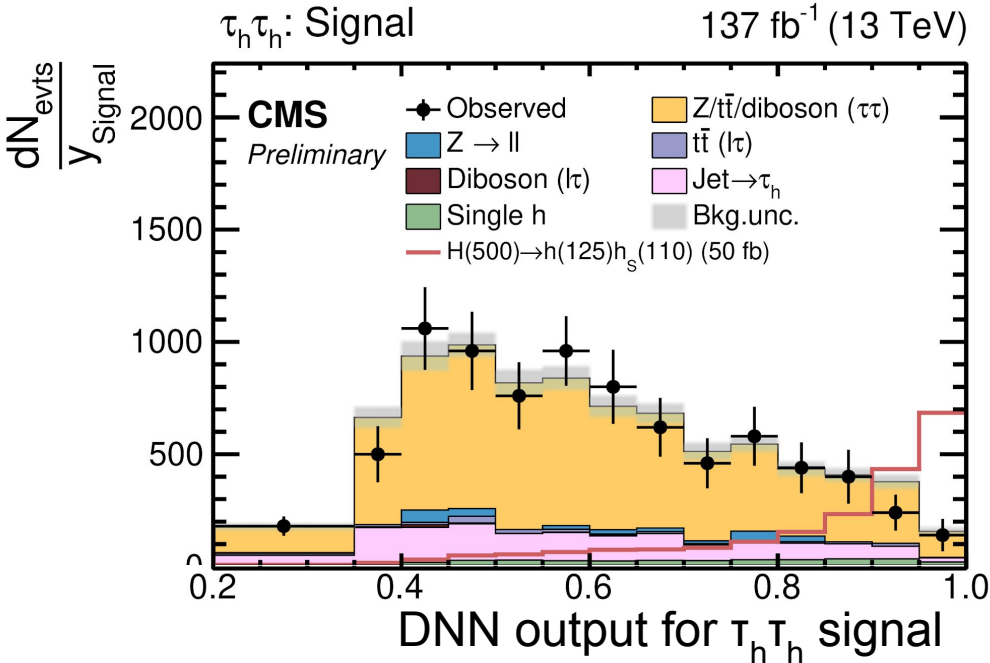
H → h_S h → bbττ (= X → Yh → bbττ) - overview



Online+offline selections targeting $\tau_h \tau_h$, $e\tau_h$, $\mu\tau_h$

Require ID of exactly 1 or 2 b-jets

- Main backgrounds from QCD, tt, and Z+jets



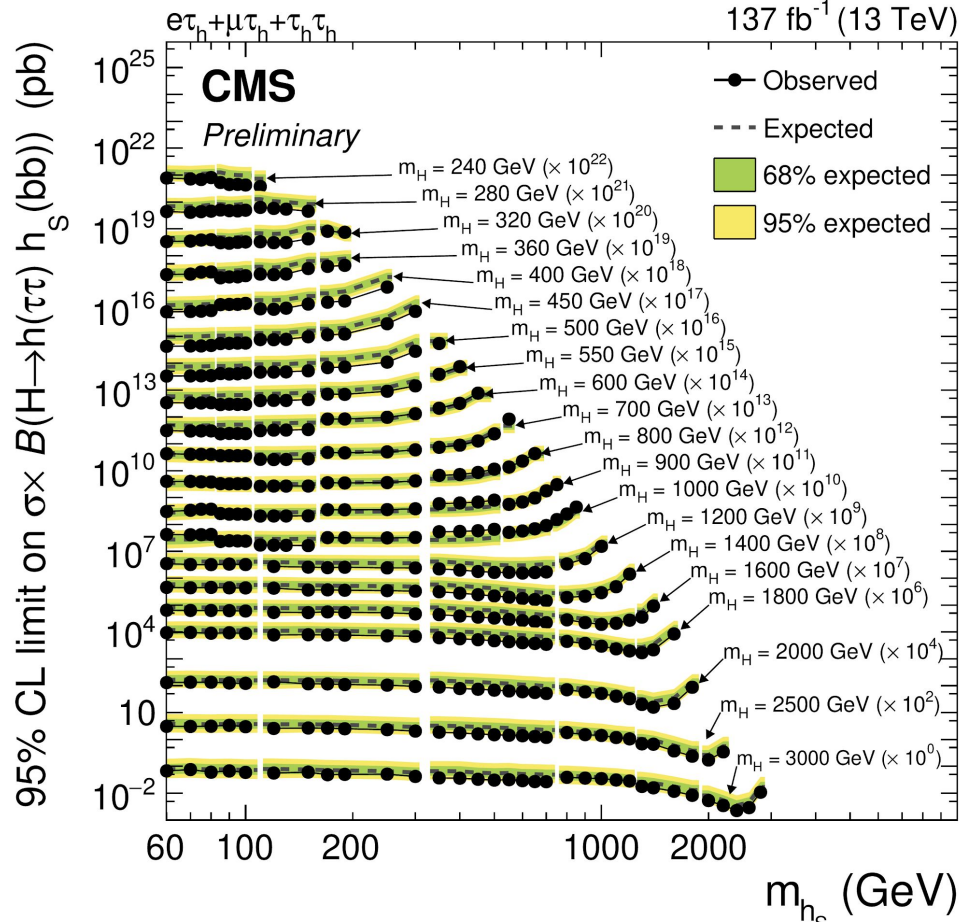
➤ Optimize signal vs bkg separation with NN multiclassifier

- Signal region dominated by events with genuine τ_h

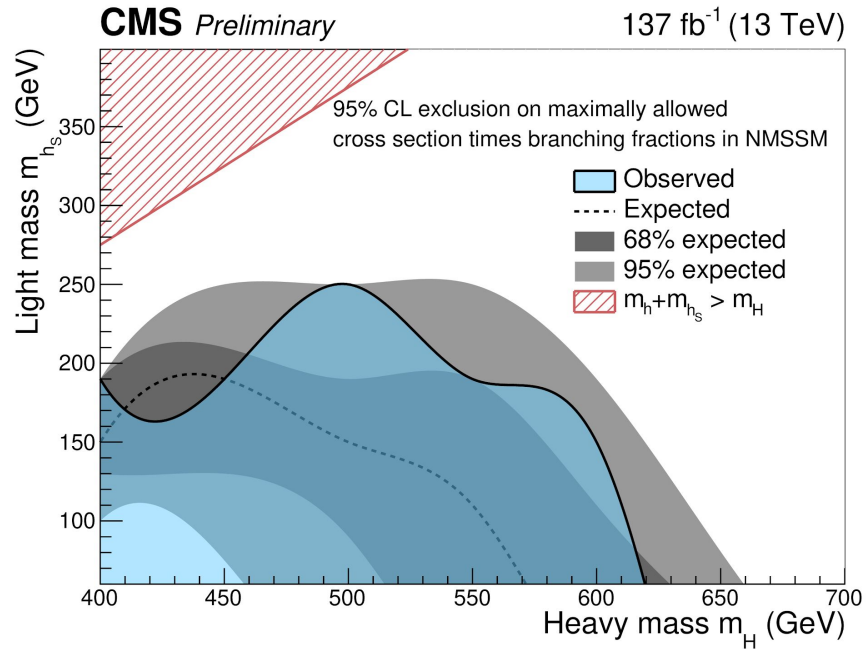
H → h_s h → bbττ (= X → Yh → bbττ) - results

- No deviations from SM observed
 - Upper limits from 125 fb (m_H = 240 GeV) to 2.7 fb (m_H = 3 TeV)

model-independent limit on H → hh_s XS vs h_s mass for different m_H hypotheses



NMSSM interpretation



- Exclude m_H up to ~620 GeV
- Exclude m_{h_s} up to ~250 GeV