University of Colorado Boulder

Recent CMS searches for resonances decaying to HH and SH pairs

Davide Zuolo – University of Colorado Boulder

Outline

I will present the most recent public results on HH and SH searches performed by CMS using the LHC Run 2 dataset

- CMS-PAS-HIG-22-012 - Search for the nonresonant and resonant production of a Higgs boson in association with an additional scalar boson in the γγττ final state
- CMS-PAS-B2G-23-008 - Search for a heavy resonance decaying into ZH in events with an energetic jet and two electrons, two muons, or missing transverse momentum
- B2G-23-002 - Combination of searches for Higgs boson production through decays of heavy resonances
- CMS-PAS-HIG-20-012 - Search for a new heavy scalar boson decaying into a Higgs boson and a new scalar particle in the four b-quarks final state

CMS-PAS-HIG-22-012

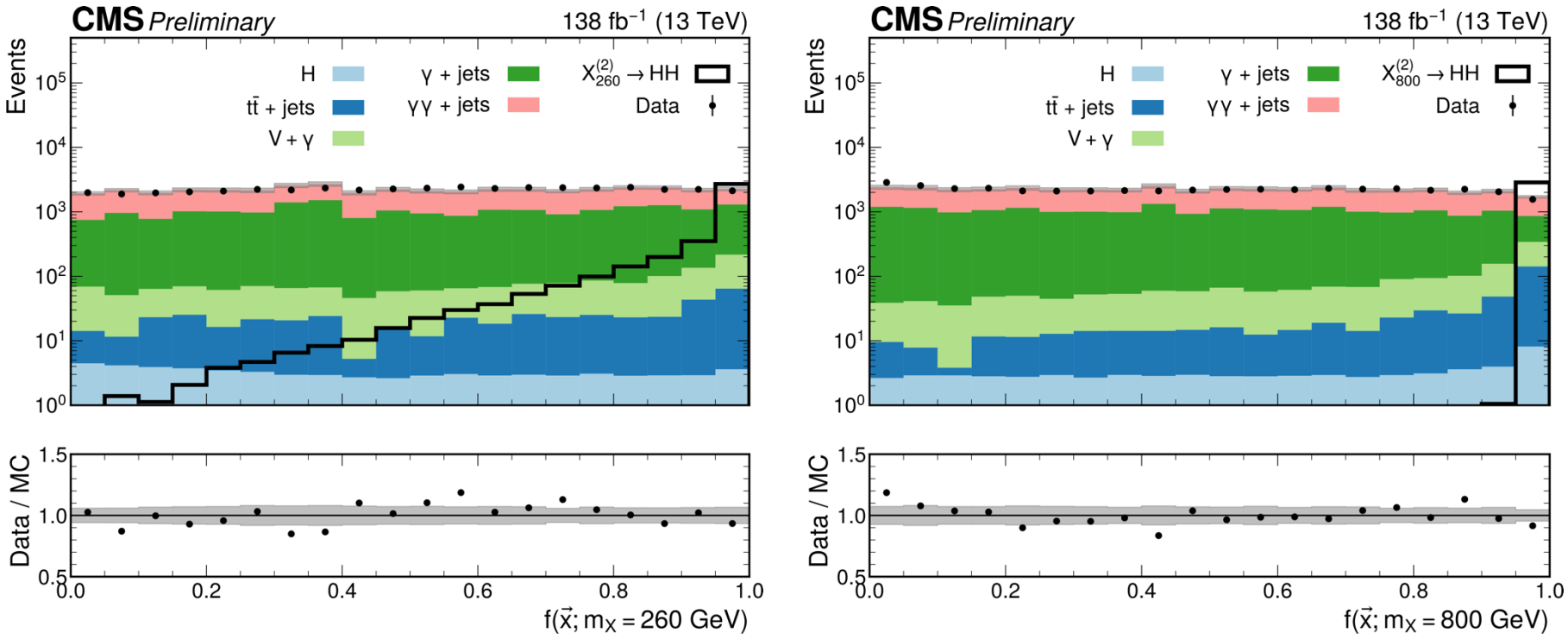
γγττ analysis – intro

- First CMS analysis targeting this final state
- Small branching fraction but clean diphoton signature for trigger
- Nonresonant and resonant production modes via gluon fusion are studied
  - X → HH with 260 GeV < m_X < 1000 GeV, both spin-0 (Radion) and spin-2 (Graviton) resonances as predicted in the Randall-Sundrum bulk model [1]
  - X → Y(ττ)H(γγ) and X → Y(γγ)H(ττ) following the NMSSM model [2]
    - 300 GeV < m_X < 1000 GeV and $m_X > m_Y + m_H$ in both cases
    - 50 GeV < m_Y < 800 GeV in X → Y(ττ)H(γγ)
    - 70 GeV < m_Y < 125 GeV in X → Y(γγ)H(ττ) low mass
    - 125 GeV < m_Y < 800 GeV in X → Y(γγ)H(ττ) high mass
  - large variations in trigger efficiency and event kinematics for different Y(γγ) masses → analysis split in two mass ranges

γγττ analysis – details

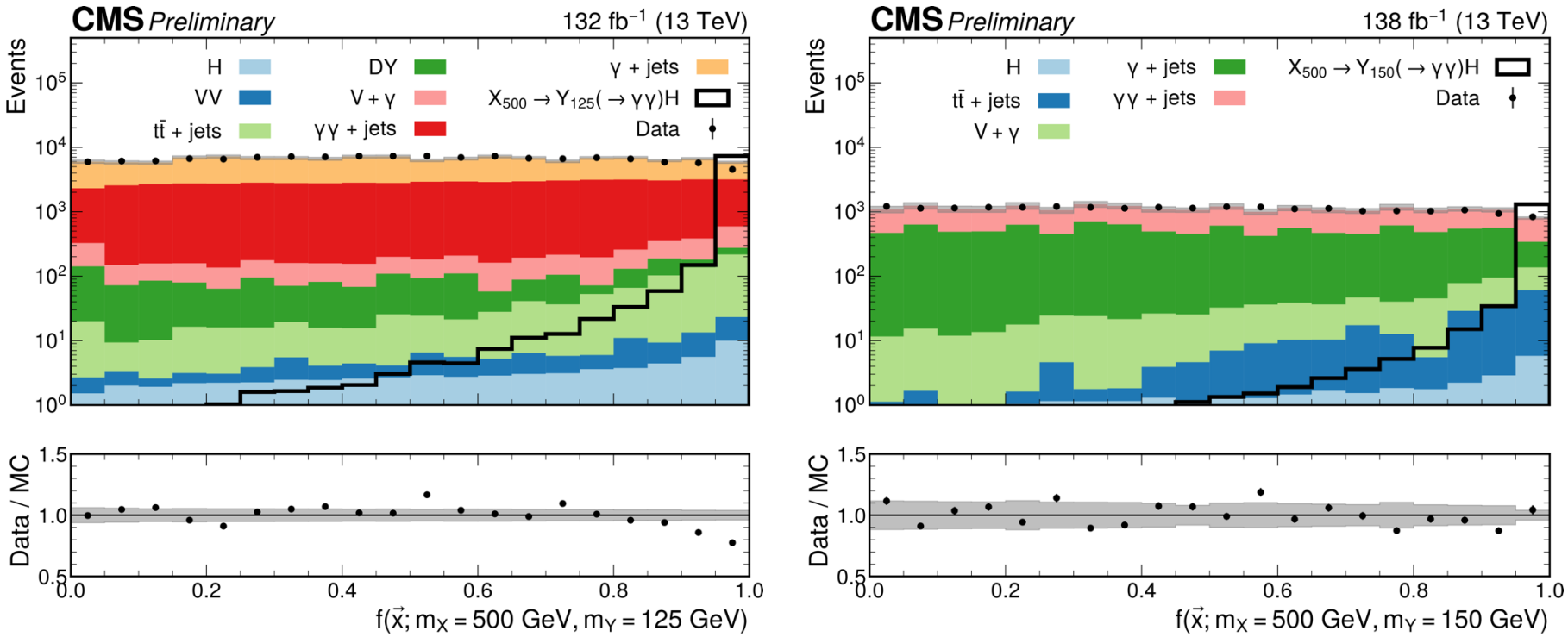
- Online trigger selections: two isolated photons, p_T >30 GeV and p_T >18 GeV
- Offline selections: kinematics, identification, $m_{\gamma\gamma}$ > 100 GeV (65 GeV for low mass Y(γγ)H(ττ))
- All the possible decays of tau pairs are considered offline ($e\tau_h$,$\mu\tau_h$,$\tau_h\tau_h$,ee,μμ,eμ)
- Main backgrounds: γγ + jets (irreducible) and γ + jets (reducible), single Higgs production considered as resonant background
- Modeling: signal and single H are modeled using Double Crystal Ball functions while falling background is modeled using discrete profiling in $m_{\gamma\gamma}$ sidebands
- Categorization based on parametric Neural Network (pNN) [3] output
  - m_X and m_Y treated as conditional parameters
  - Category boundaries based on the number of expected background events
    - Optimization based on S/B leaded to insufficient number of data events to model background
- Signal extraction from maximum likelihood fit to $m_{\gamma\gamma}$

γγττ analysis – pNN – X → HH



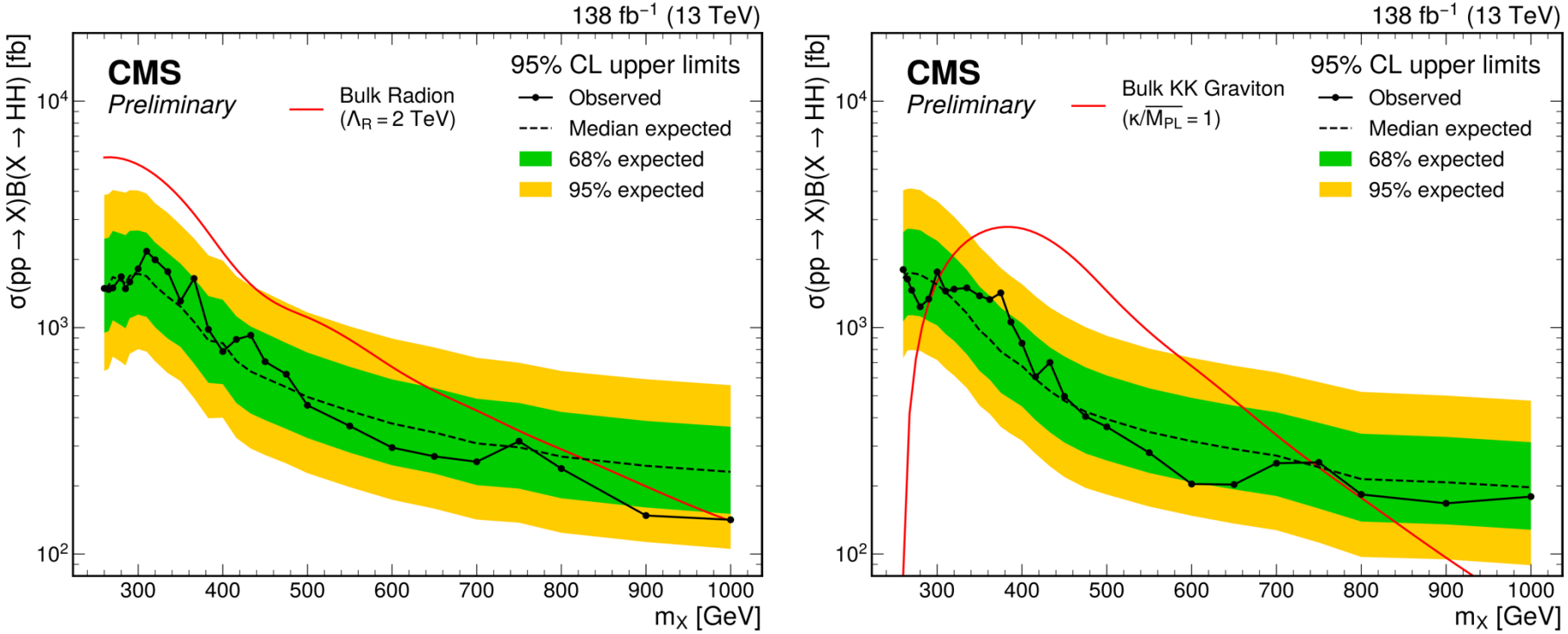
The classification problem evolves with m_X → it's easier to discriminate a high m_X signal from background and the background itself changes

γγττ analysis – pNN – X → YH



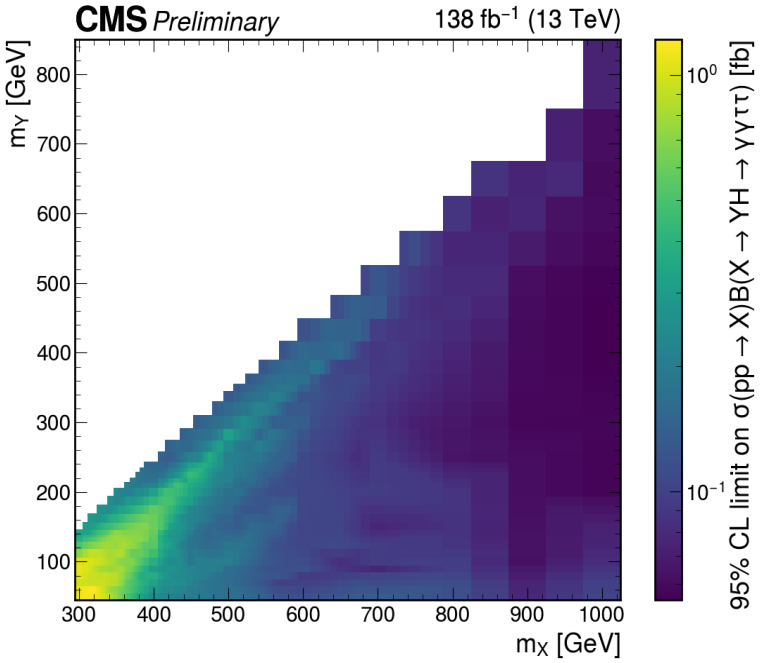
Please note the different legend (background composition) for low mass(left) and high mass(right) → low mass region has a DY contribution from photon misId

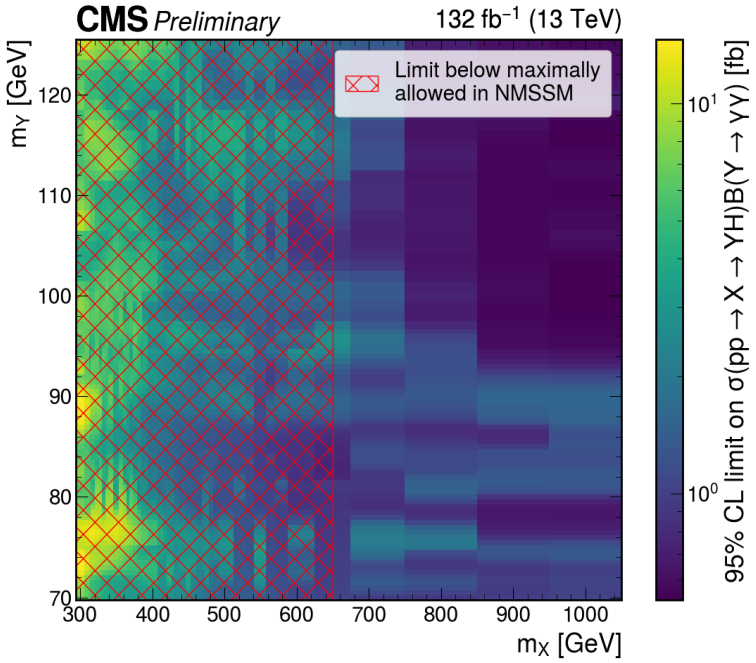
γγττ analysis – results – X → HH

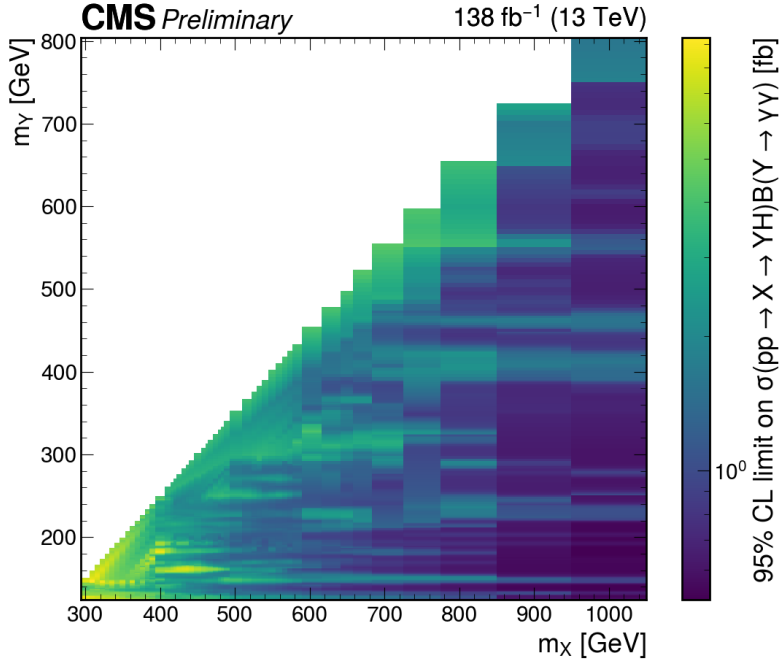


Left: spin-0 – Right: spin-2

γγττ analysis – results – X → YH







Left: X → Y(ττ)H(γγ) – Middle: low mass X → Y(γγ)H(ττ) – Right: high mass X → Y(γγ)H(ττ)
Observed limits below the maximally allowed can be used to provide tighter constraints on NMSSM

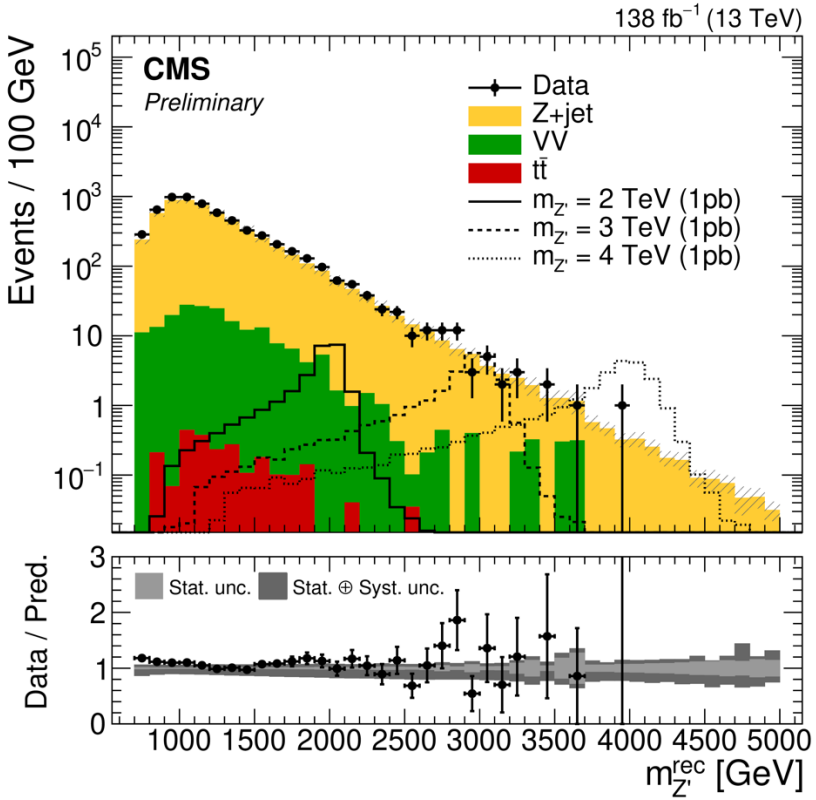
CMS-PAS-B2G-23-008

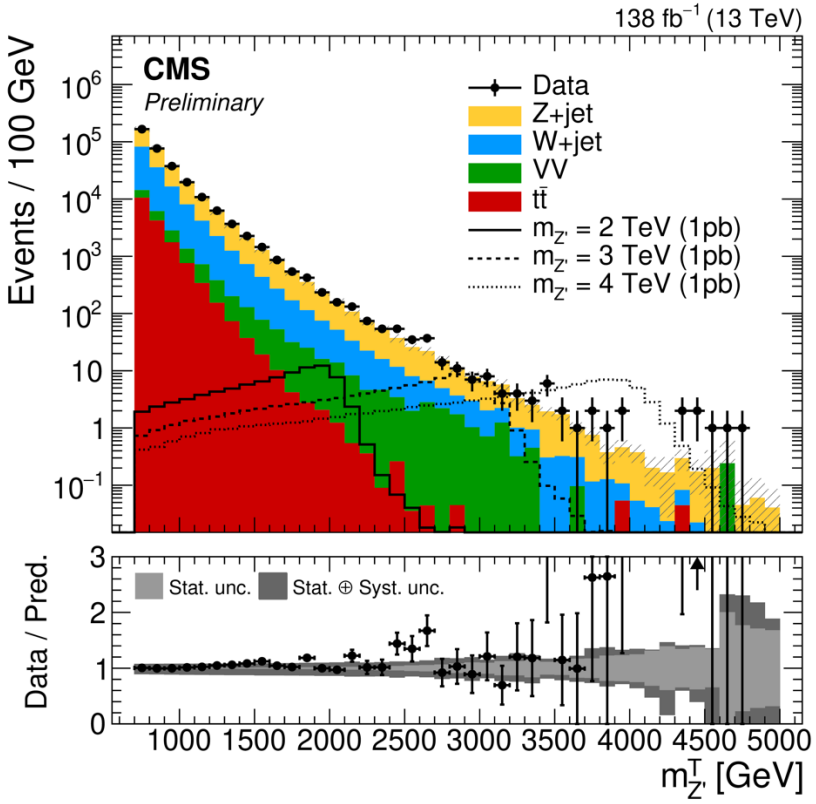
Z' → ZH analysis – intro

- Complement previous CMS analysis targeting H → cc and H → VV* → 4q final states exploring the mass range 1.4 TeV < $m_{Z'}$ < 5 TeV
- Z' signal as described in the Heavy Vector Triplet (HVT) model [4]
- Online trigger selections: single lepton or large p_T^{miss}
- Offline selections:
  - Z: opposite sign lepton pairs (ee and μμ) with 81 GeV < m_{ll} < 101 GeV; $p_{T,ll}$ > 200 GeV; $\Delta R(l_1,l_2)$ < 0.45 OR no charged leptons and p_T^{miss} > 250 GeV
  - H: 1 large-radius jets with p_T > 200 GeV and $\Delta\phi(H,Z)$ > 2, Tagged using ParticleNet [5]
  - events with 2 b-tagged subjets are rejected to ensure orthogonality to previous analysis
- Main backgrounds: V(W,Z) + jets, modeled fitting a one-dimensional function to the observed data

Z' → ZH analysis – observables

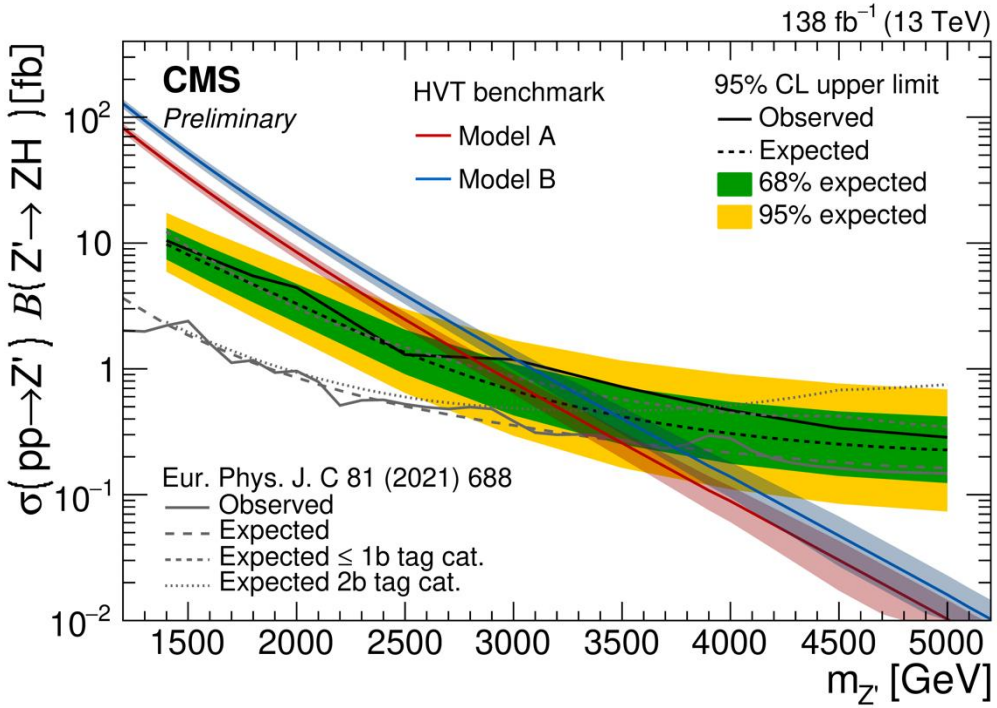
- Signal is extracted from fit to ZH system invariant mass (ee and μμ channels, left) or transverse mass (neutrino channel, right)

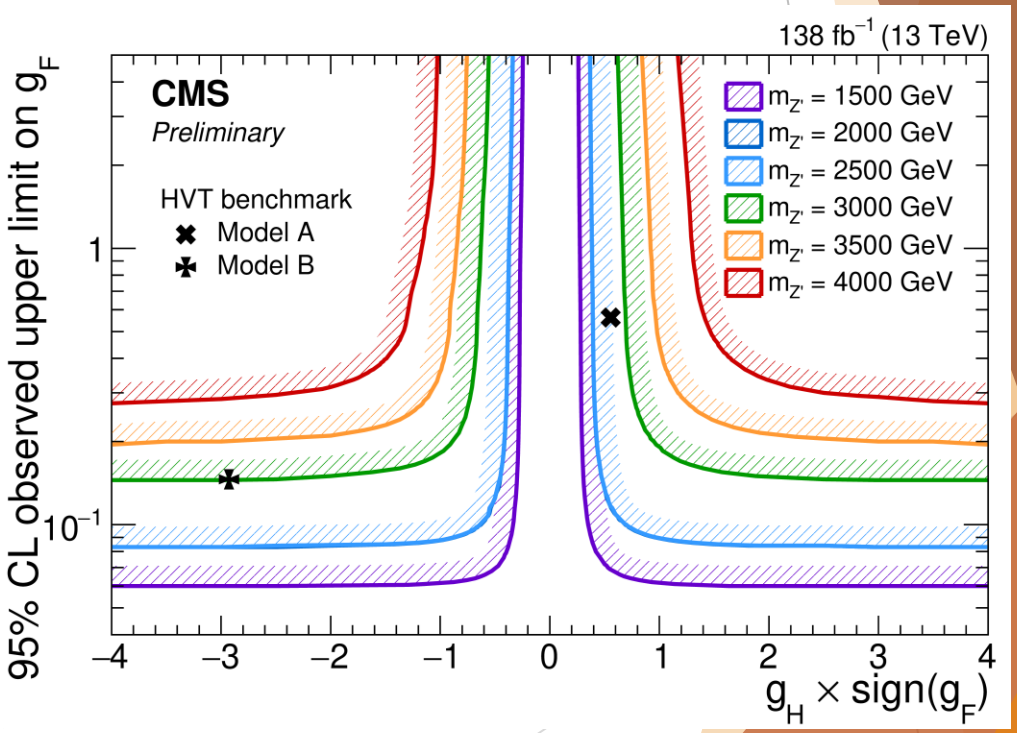




Z' → ZH analysis – results

- Upper limits on cross sections are shown on left, compared to previous CMS analysis (grey lines) and two HVT benchmarks (red and blue lines)
- Two dimensional upper limits on the coupling parameters for fermions and bosons in the HVT model are shown on the right for different Z' masses





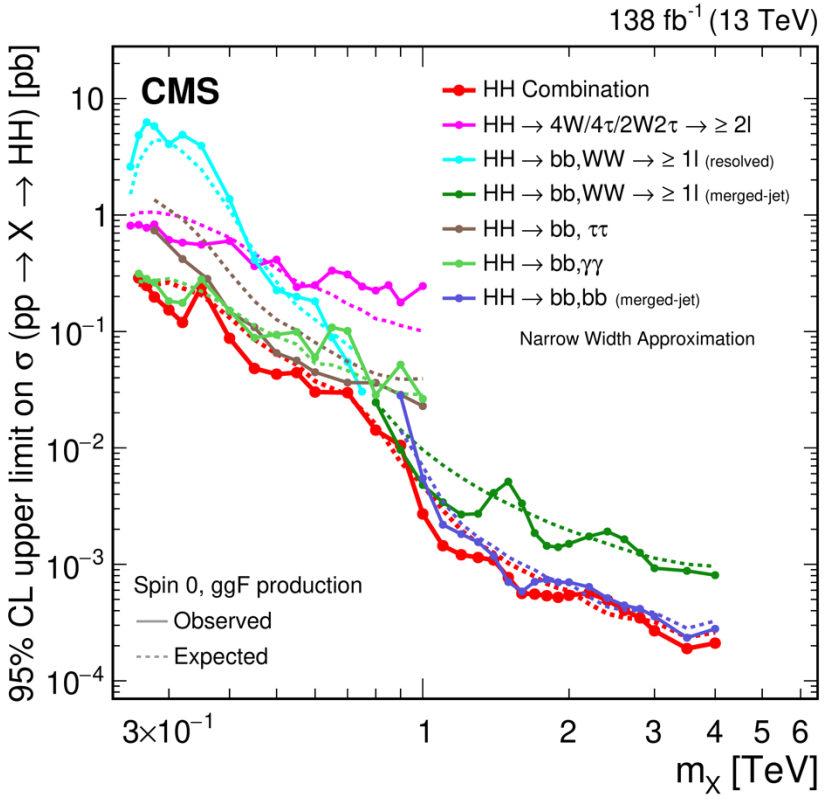
B2G-23-002

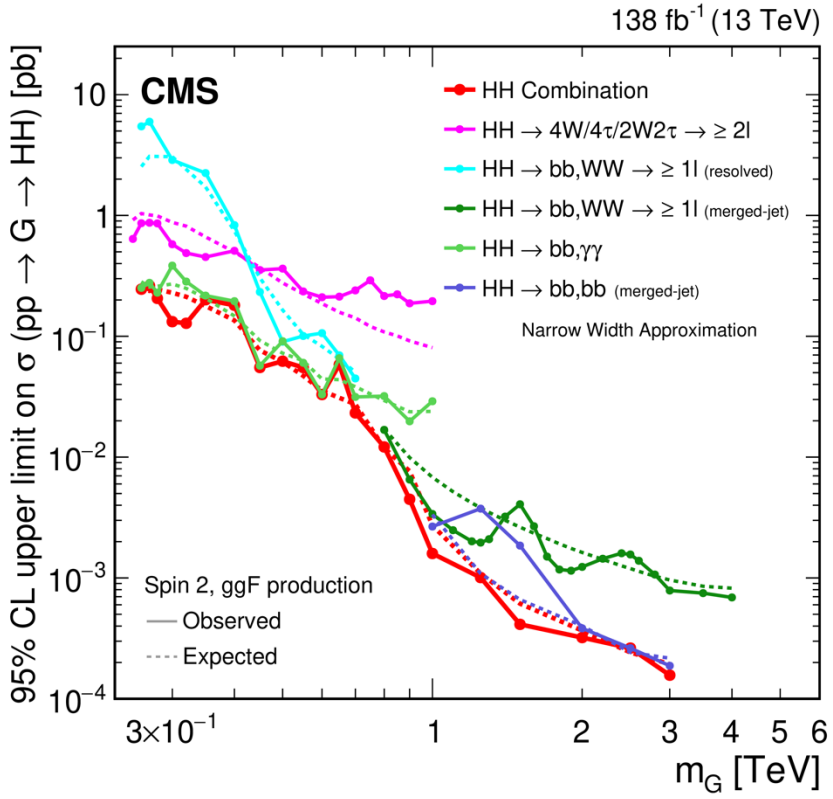
Combination

Target final state		Ref.	Mass coverage (GeV)		Comment
V	H		m_X		
$Z(\ell\ell)$	$\tau\tau$	[107]	220 – 400		
$Z(\ell\ell + \nu\nu)$	bb	[108]	225 – 1000		resolved jets
$W(\ell\nu)$	bb	[109]	1000 – 4500		$W \to \ell\nu$ and merged bb jet
$Z(\ell\ell)$	bb	[110]	800 – 4600		$Z \to \ell\ell/\nu\nu$ and merged bb jet
$Z(qq)$	bb	[111]	1300 – 6000		two merged jets
H	H		m_X		
bb	$W(\ell\nu)W(\ell\nu + qq)$	[112]	250 – 900		resolved + merged
bb	$W(\ell\nu)W(\ell\nu + qq)$	[113]	800 – 4500		merged
$WW + \tau\tau$	$WW + \tau\tau$	[114]	250 – 1000		multilepton final state
Y	H		m_X	m_Y	
bb	$\tau\tau$	[115]	240 – 3000	60 – 2800	resolved jets and τ leptons
bb	$\gamma\gamma$	[116]	300 – 1000	90 – 800	resolved jets and photons
bb	bb	[117]	900 – 4000	60 – 600	two merged bb jets

NB: The result for m_Y = 130 GeV of the Y(bb)H(ττ) is used to estimate the result for HH production

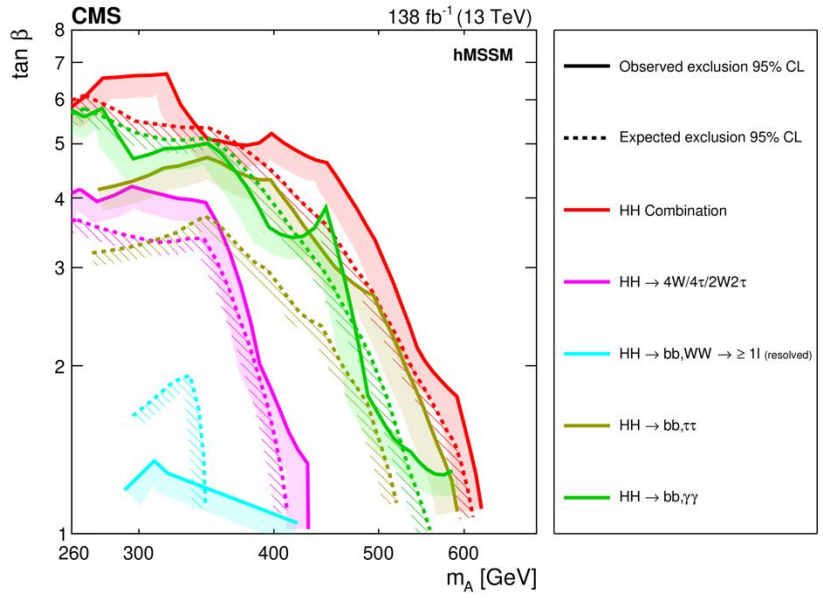
X → HH – model independent results

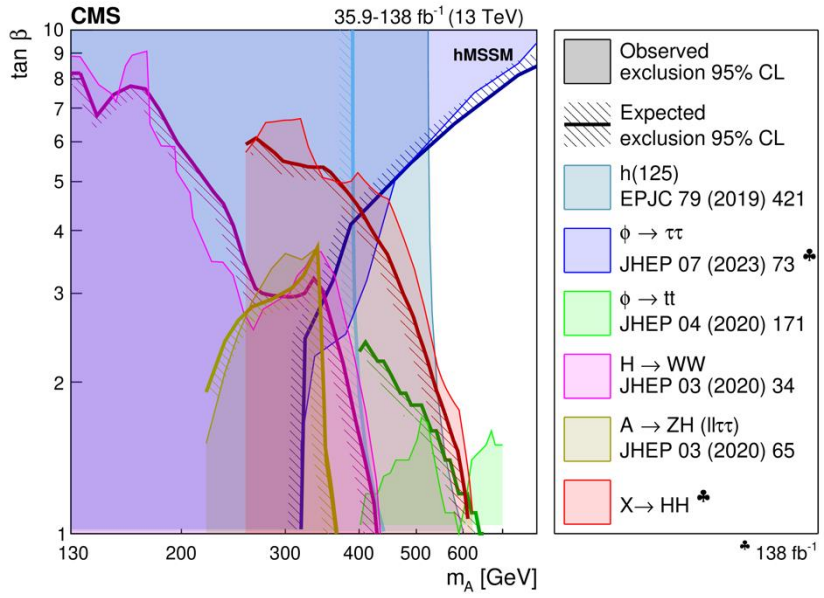




Highest sensitivity at low resonance mass comes from the bbγγ channel while at high mass the best results come from the bbbb channel (merged jet topology)

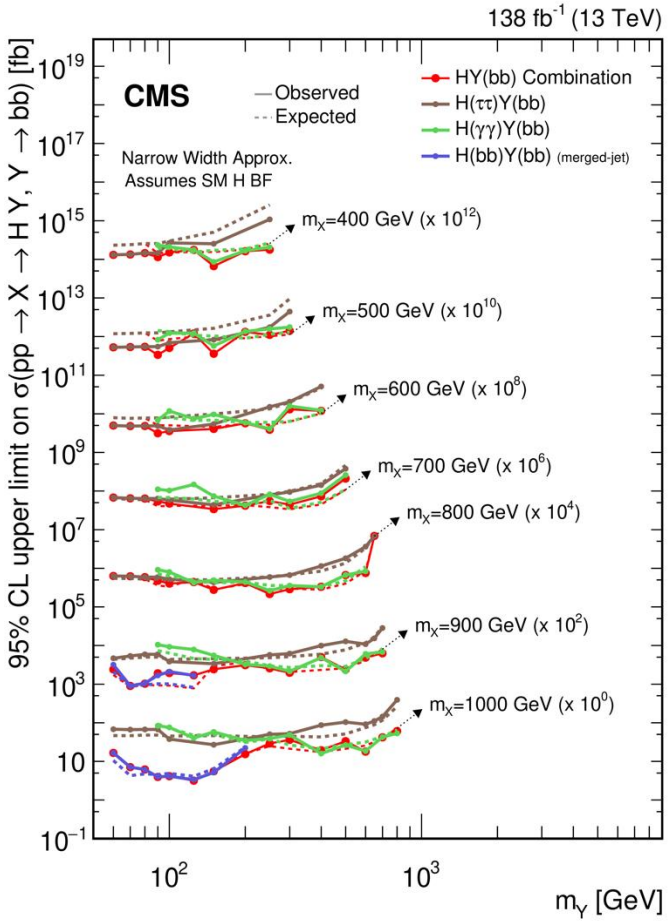
X → HH – model dependent results (hMSSM)

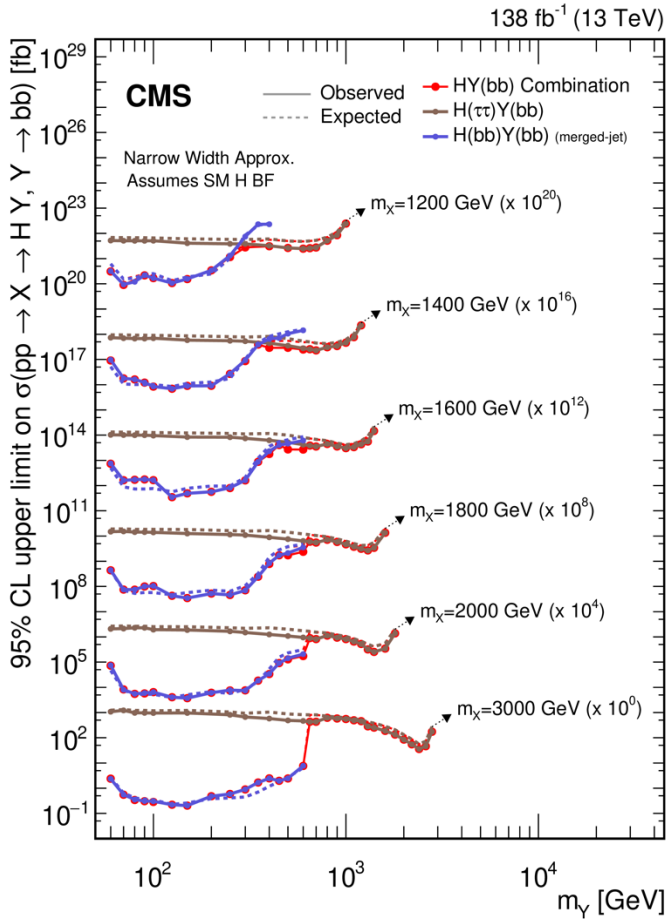




Constraints from HH searches are competitive with other searches for m_A < 350 GeV (tt threshold)

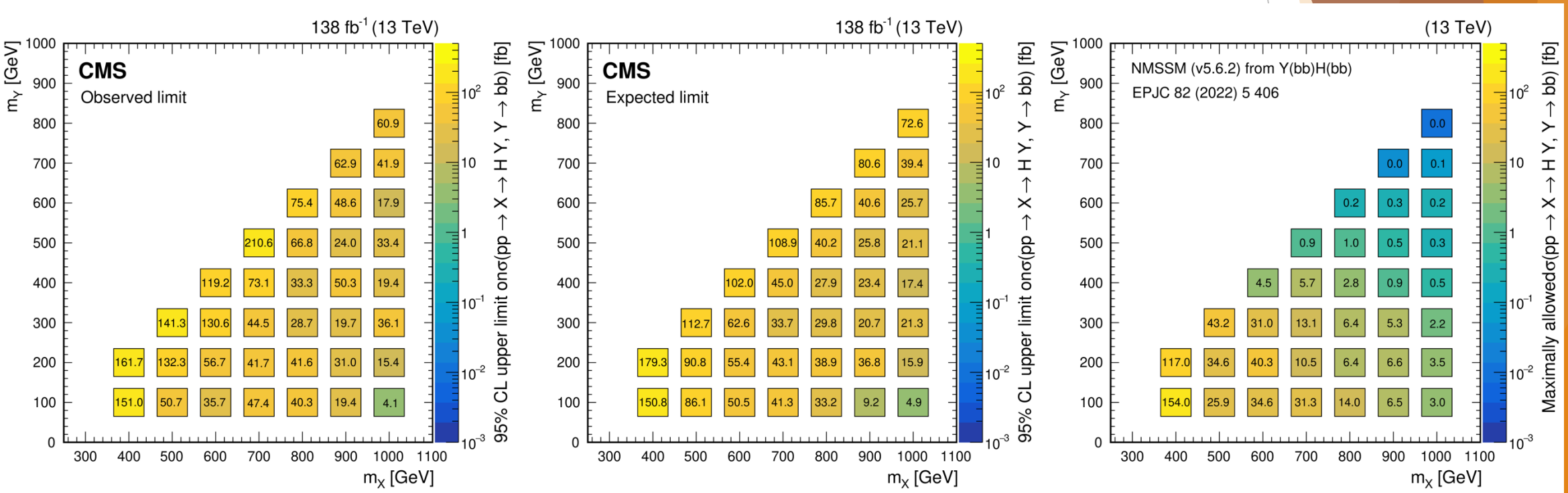
X → YH – model independent results





For presentation purposes, the limits have been scaled in successive steps by two order of magnitude, each. For each set of graphs, a black arrow points to the m_X related legend. Again, the bbbb channel (merged jet topology) drives the sensitivity at high m_X

X → YH – model dependent results (NMSSM)



Expected and observed limits for the combination of the CMS X → YH analyses is compared to the maximally allowed values in the NMSSM

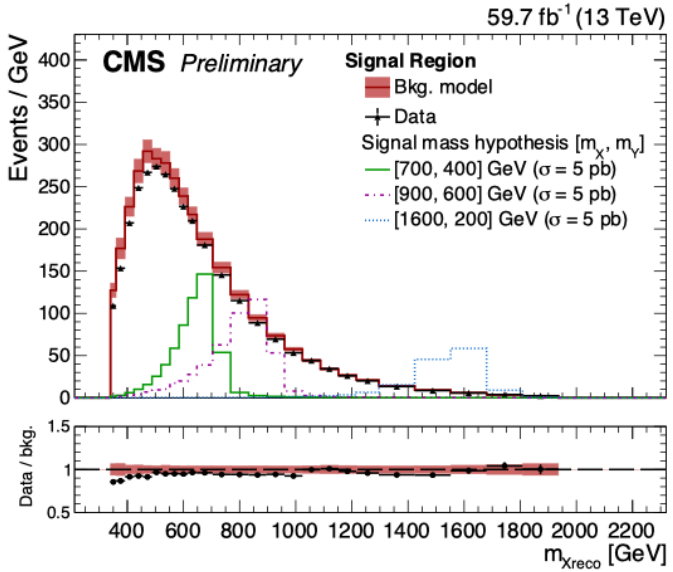
CMS-PAS-HIG-20-012

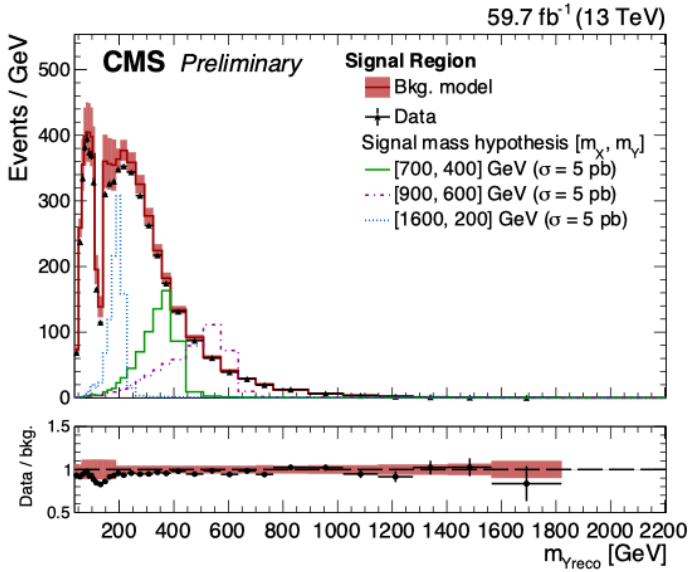
4b analysis - intro

- X → YH with 400 GeV < m_X < 1600 GeV and 60 GeV < m_Y < 1400 GeV
- Online trigger selections: 4 jets (3 tagged) OR high H_T (scalar sum of the transverse momentum of all jets in the event)
- Offline selections:
  - 4 (3) small radius jets tagged using the DeepJet [6] algorithm for signal dataset (control dataset)
  - H → bb from highest invariant mass pair of jets
  - Three regions for background estimation
    - signal region (SR): $|m_{H,reco} - 125\ GeV| < 20\ GeV$
    - validation region (VR): $20\ GeV < |m_{H,reco} - 125\ GeV| < 30\ GeV$
    - control region (CR): $30\ GeV < |m_{H,reco} - 125\ GeV| < 60\ GeV$

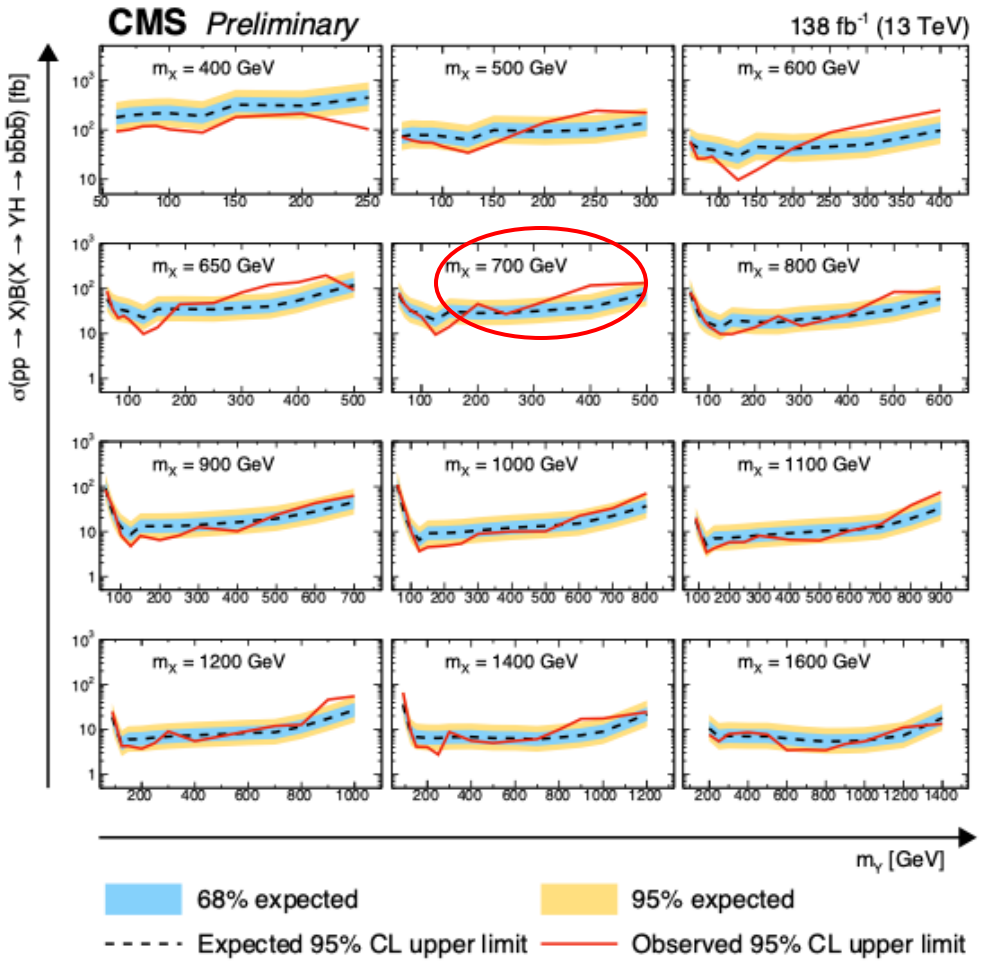
4b analysis - details

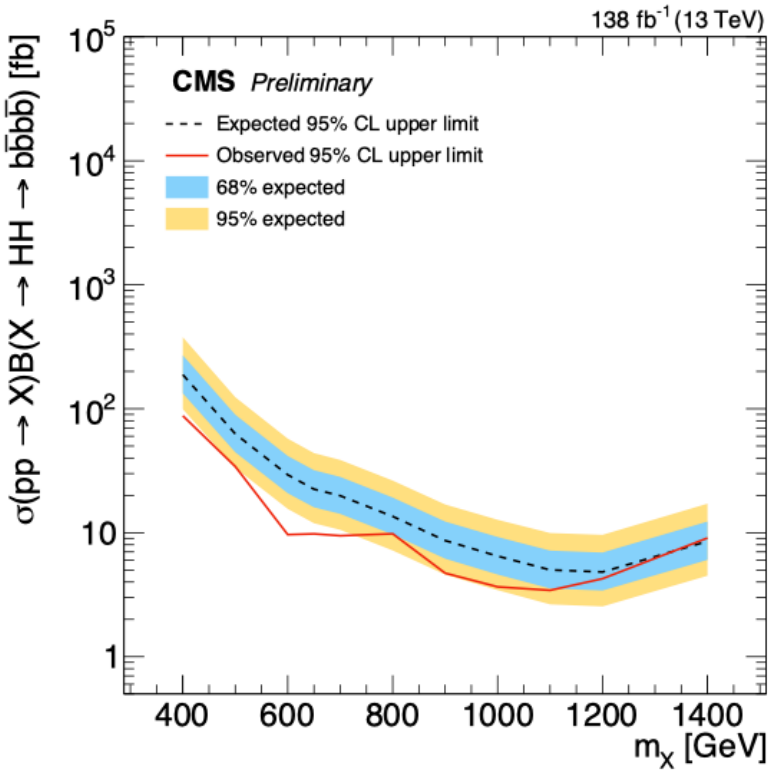
- Data-driven background estimation via BDT reweighting [7]
  - model the difference between the 3b and 4b samples as a function of multiple observables
  - trained with collision data in the CR(3b) and CR(4b)
  - the orthogonal distance of the event in the $m_{X,reco}$ - $m_{Y,reco}$ plane from the diagonal defined by $m_{X,reco} - m_{Y,reco} = 125$ GeV is used as input to provide correlated $m_{X,reco}$ and $m_{Y,reco}$ to the BDT
- Two-dimensional fit using the reconstructed masses of the X and Y scalars





4b analysis - results





Average improvement of 30% for $m_X \leq 1000$ GeV w.r.t. the combination.
Largest excess with a local (global) significance of 4.1 (2.8) standard deviations for $m_X = 700$ GeV and $m_Y = 400$ GeV

Conclusions

- I presented here the most recent CMS searches for resonances decaying to HH and SH pairs
- A combination of these searches has been submitted to Physics Reports as part of a series of papers proposed by the journal to CMS and ATLAS collaborations
- The paper presents many more interpretations, studies of finite width resonances and interference with non-resonant production
- Projections of the results to HL-LHC integrated luminosity are also included
- CMS is currently wrapping up analyses using the LHC Run 2 dataset, and more results are expected to be made public during the winter

Thanks for your attention!