Searches for Higgs boson production through decays of heavy resonances at CMS

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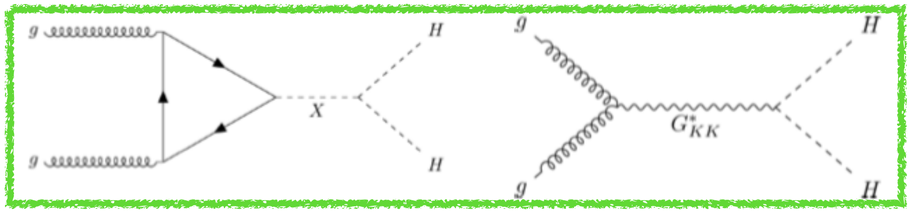
Outline

* Introduction
* HH/HY searches at CMS
* HH/HY projections
* VH searches at CMS
* Summary

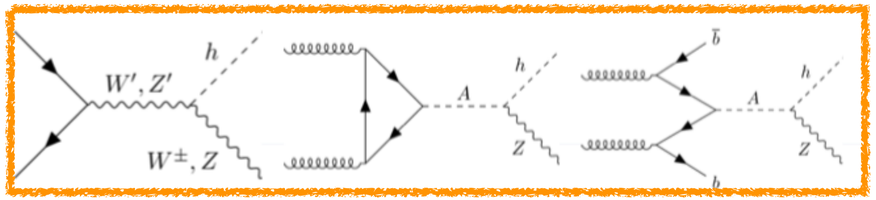
Introduction

Introduction

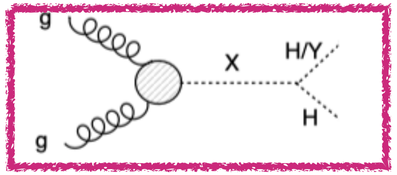
- **Higgs boson could be a probe to explore new physics**
  - Many theories predict new massive resonances that could interact with the SM Higgs boson
    - New heavy resonances could decay into two H(125) bosons ($X \to HH$)
    - New heavy resonances could decay into H(125) boson and a scalar/vector Y/V ($X \to YH(VH)$)
  - Higgs boson production through resonance decay → New physics



- Extended H sectors
- Warped Extra Dimensions (WED)



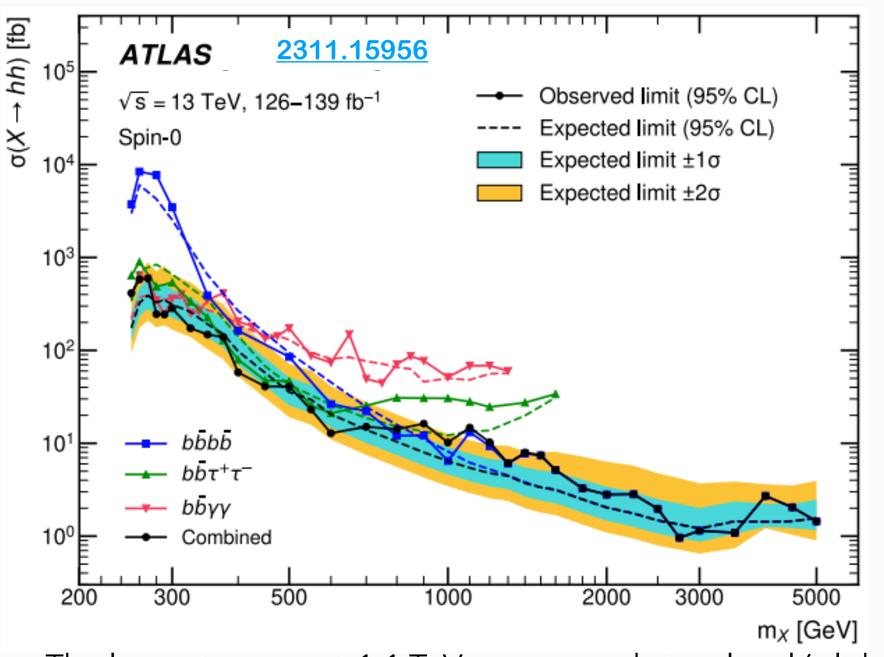
- Extended H sectors
- Heavy Vector Triplet



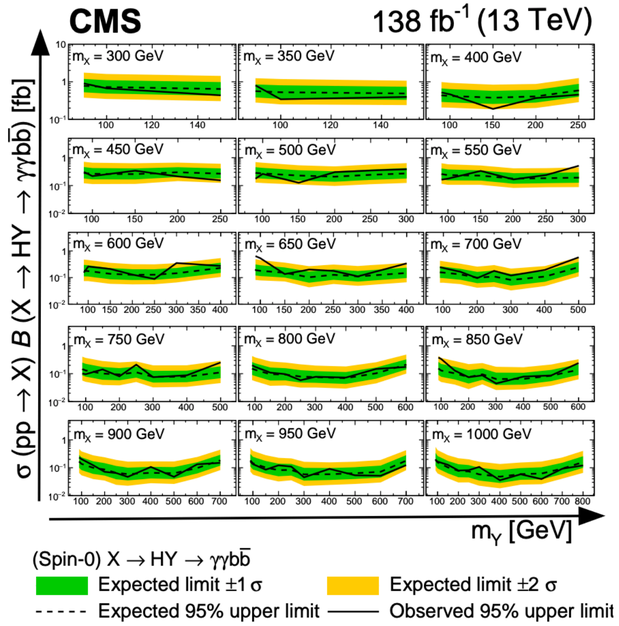
- NMSSM
- TRSM

X → *HH*/*YH* in LHC

- **Heavy resonances were searched for through the HH/HY process in both ATLAS and CMS experiments.**
  - In non-resonant HH searches, the golden channels are bbbb, bbττ, bbγγ
    - The resonant HH searches should also have good sensitivities in these channels
  - For X→YH searches there are no a priori golden channels, since unknown Y branching ratio
  - HH and YH statistical combinations were performed in both ATLAS and CMS
  - Serval excesses were reported in both ATLAS and CMS



The largest excess at 1.1 TeV corresponds to a local (global) significance 3.3σ (2.1σ) in ATLAS HH combination



CMS-PAS-HIG-21-011

The largest excess at (mX,mY) = (650, 90) GeV corresponds to a local (global) significance 3.8σ (2.8σ) in CMS bb$\gamma\gamma$ analysis

HH and HY searches at CMS

CMS Resonant HH/HY analyses overview

- **CMS HH/HY searches and their combination**
  - HH/HY analyses:
    - bbγγ (JHEP), HH+HY and in latest combination
    - bb$\tau\tau$ (JHEP), HH+HY and in latest combination
    - bbbb boosted (PLB), HH+HY an in latest combination
    - Multilepton (JHEP), HH only and in latest combination
    - bbWW resolved (JHEP), HH only and in latest combination
    - bbWW boosted (JHEP), HH only and in latest combination
    - $\tau\tau\gamma\gamma$ (CMS-PAS-HIG-22-012), bbbb resolved(CMS-PAS-HIG-22-012)
    - Ongoing resonant HH/HY analyses (will see more results after Moriond 2025)
      - bbZZ,bbWW,WW$\gamma\gamma$,WW$\tau\tau$...
- **A broad mass range is covered to ensure maximal sensitivity to new physics :**
  - Heavy resonance X: 240GeV to 4.5TeV
  - New scalar Y: 60GeV to 2800 GeV
  - Individual channels search ranges shown in the right table
- **More details about the individual channels could be found in backup**

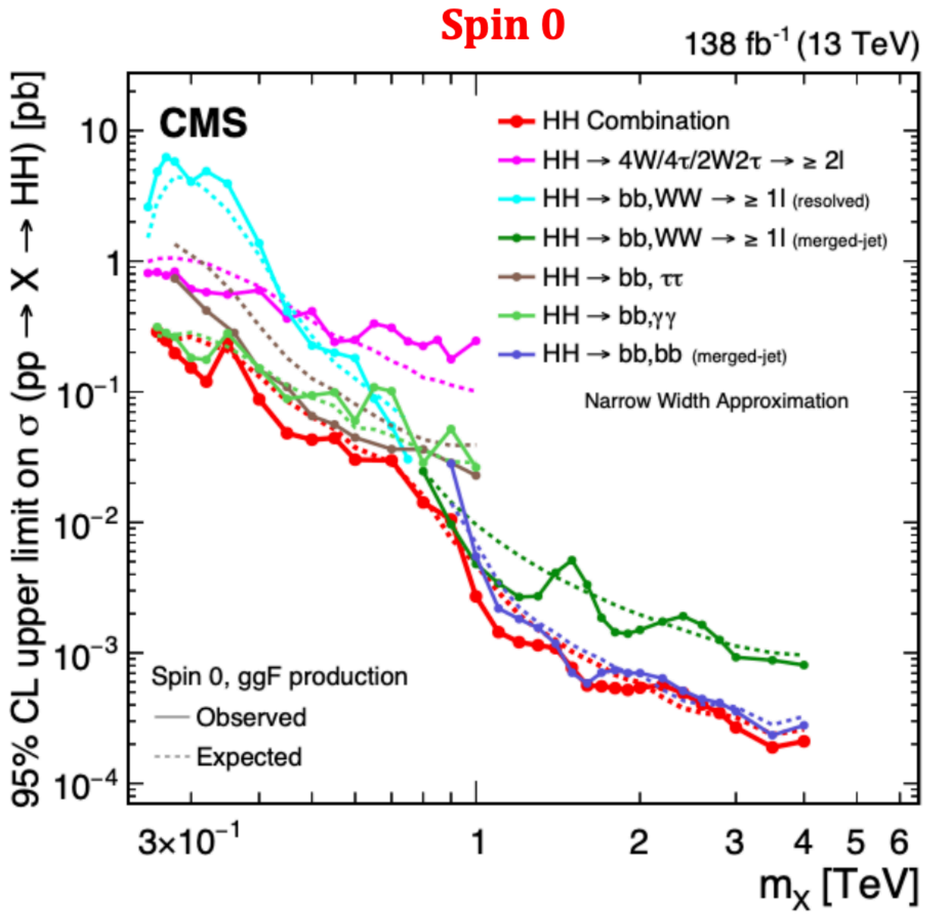
	bb	WW	ττ	ZZ	γγ
bb	33%★				
WW	25%★	4.6%★			
ττ	7.4%★	2.5%★	0.39%★		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%★	0.10%	0.029%	0.013%	0.0005%

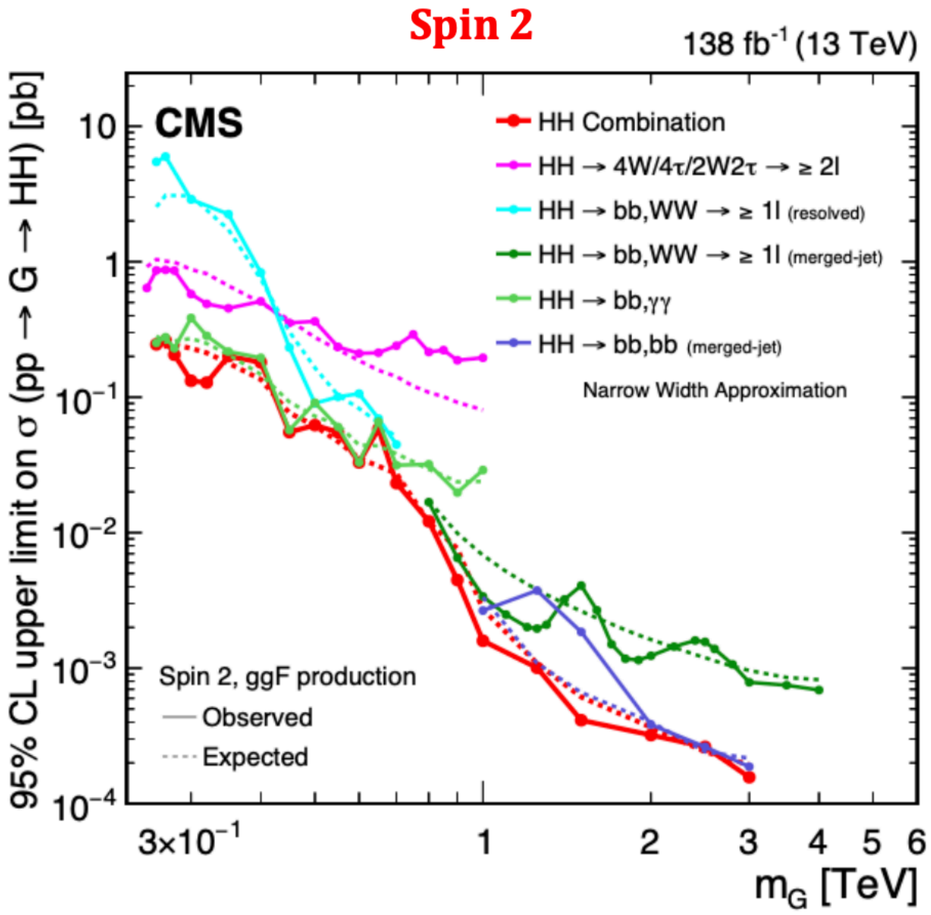
The star marks the channels which included in latest HH combination

H	H	m_X		
b b	W($\ell\nu$)W($\ell\nu + qq$)	250− 900		resolved + semi-merged
b b	W($\ell\nu$)W($\ell\nu + qq$)	800−4500		merged
WW+$\tau\tau$	WW+$\tau\tau$	250−1000		multi-lepton final state
Y	H	m_X	m_Y	
b b	τ τ	240−3000	60−2800	resolved jets and τ leptons
b b	γ γ	300−1000	90− 800	resolved jets and photons
b b	b b	90−4000	60− 600	two merged bb jets

HH searches and combination

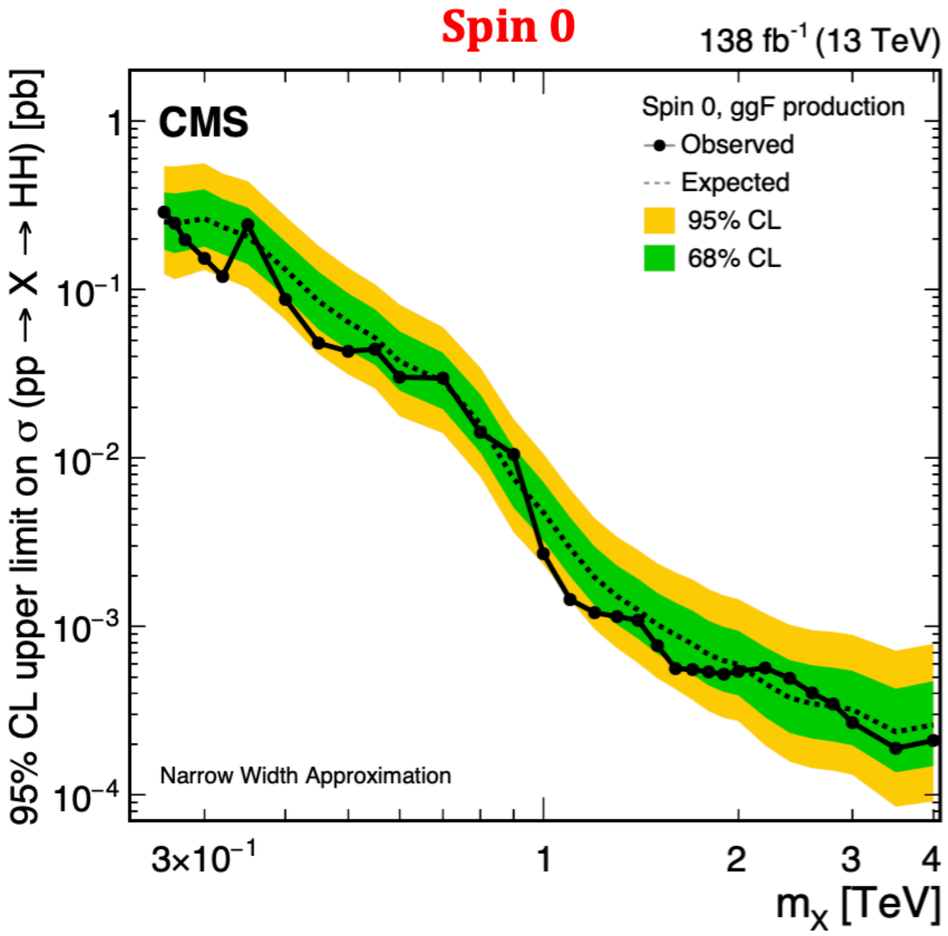
- **HH case: Combination and per channel results**

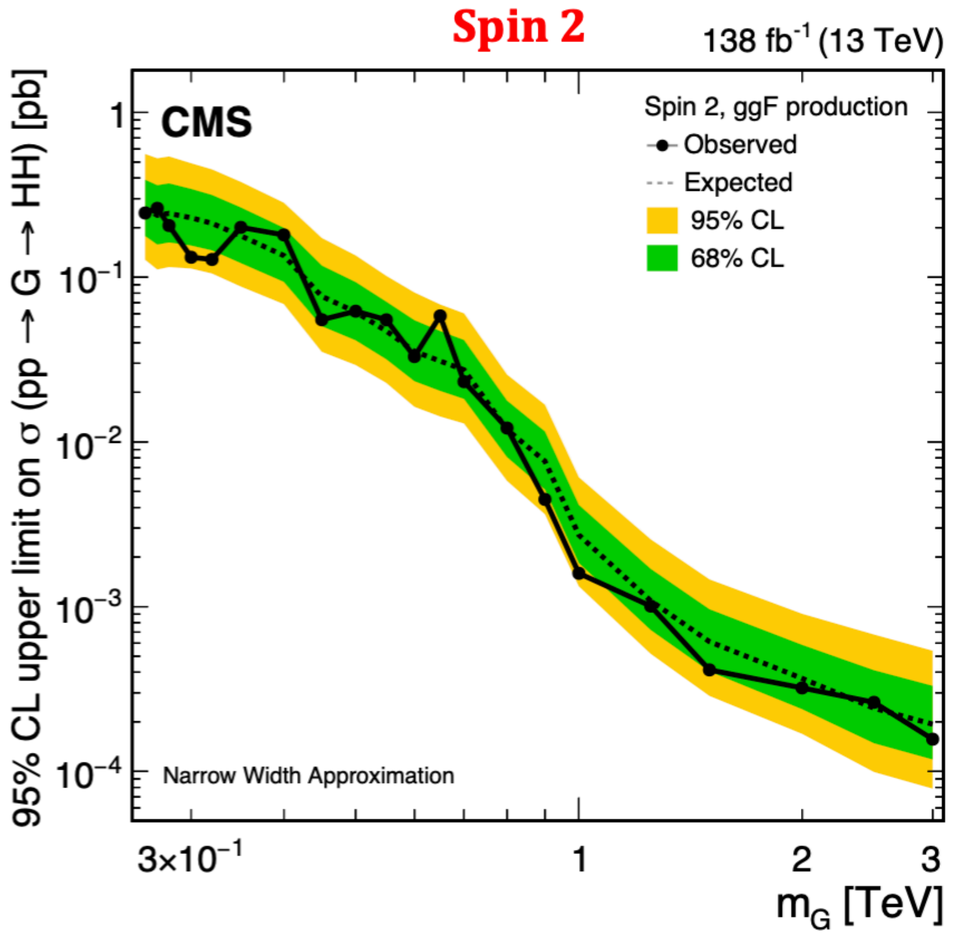




HH combination results

- **HH case: Combination results with expected bands**

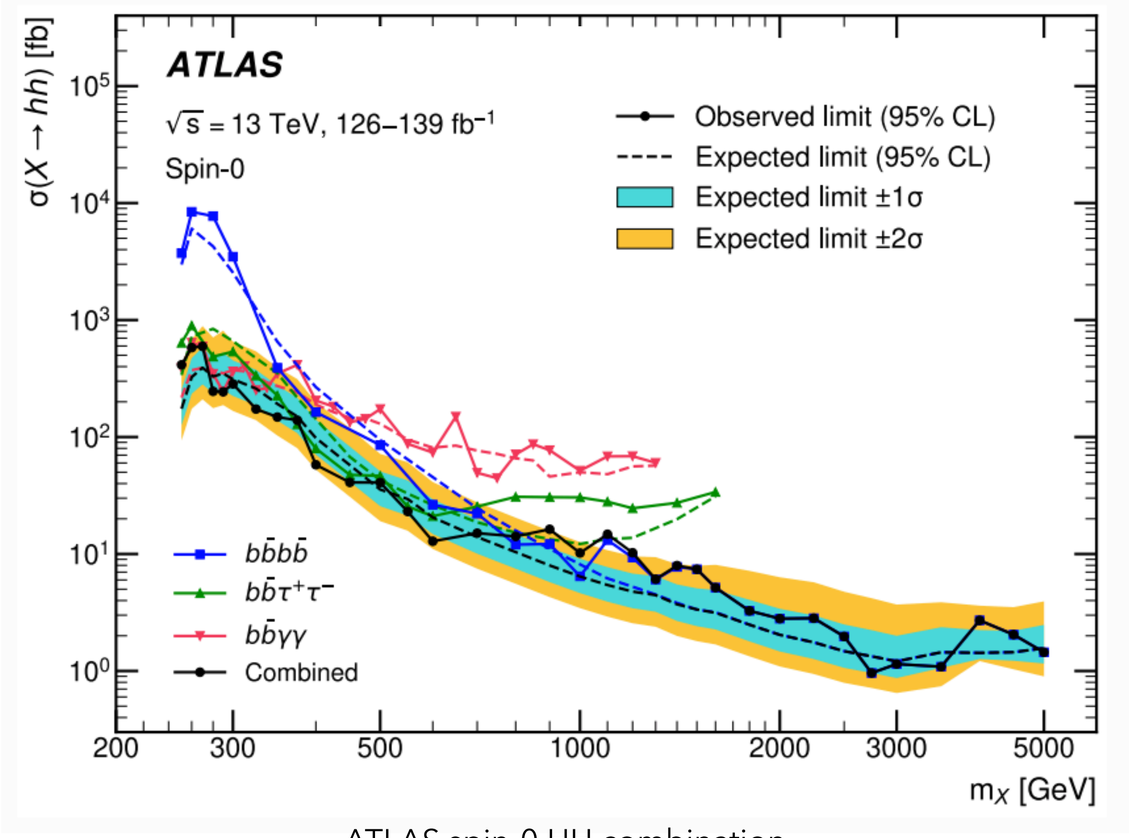




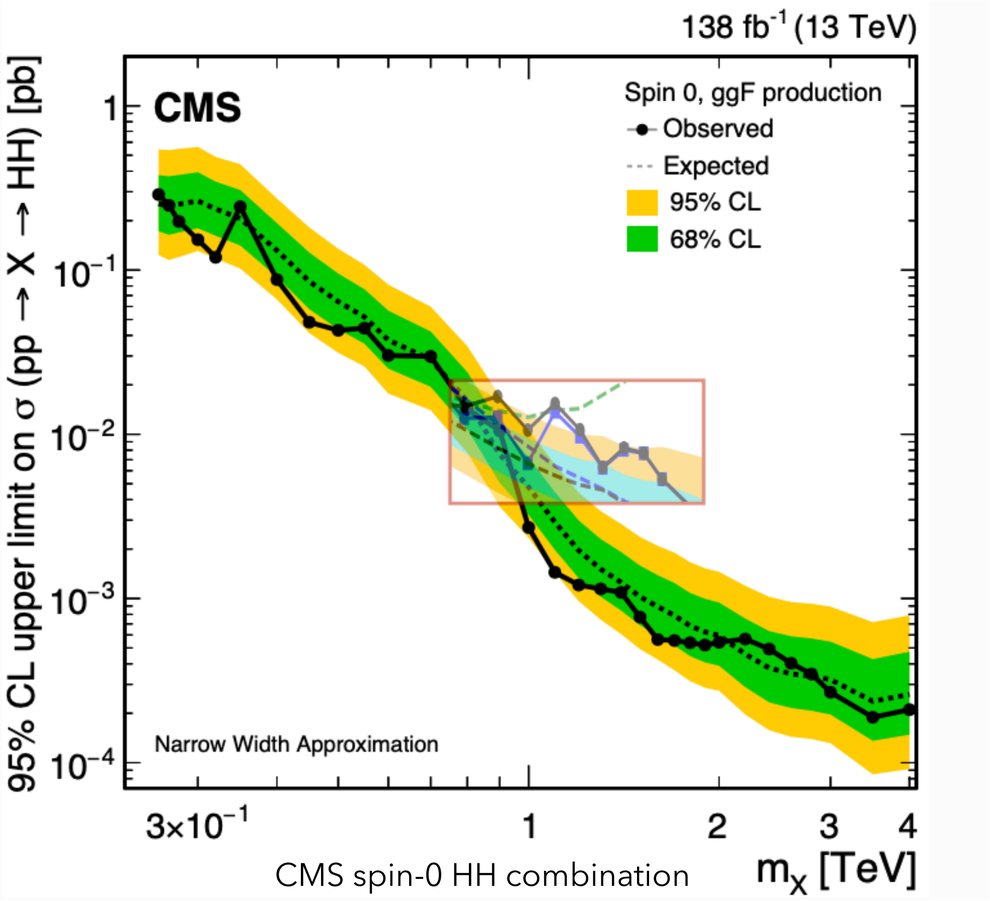
No excess observed, the exclusion in terms of σ B ranges down to 0.2 fb for both spin scenarios probed.

ATLAS results

- **Similar as CMS, bbγγ, bbττ, 4b drives the sensitivity at low / intermediate / high mX**
  - The excess at 1.1TeV was not confirmed by CMS.



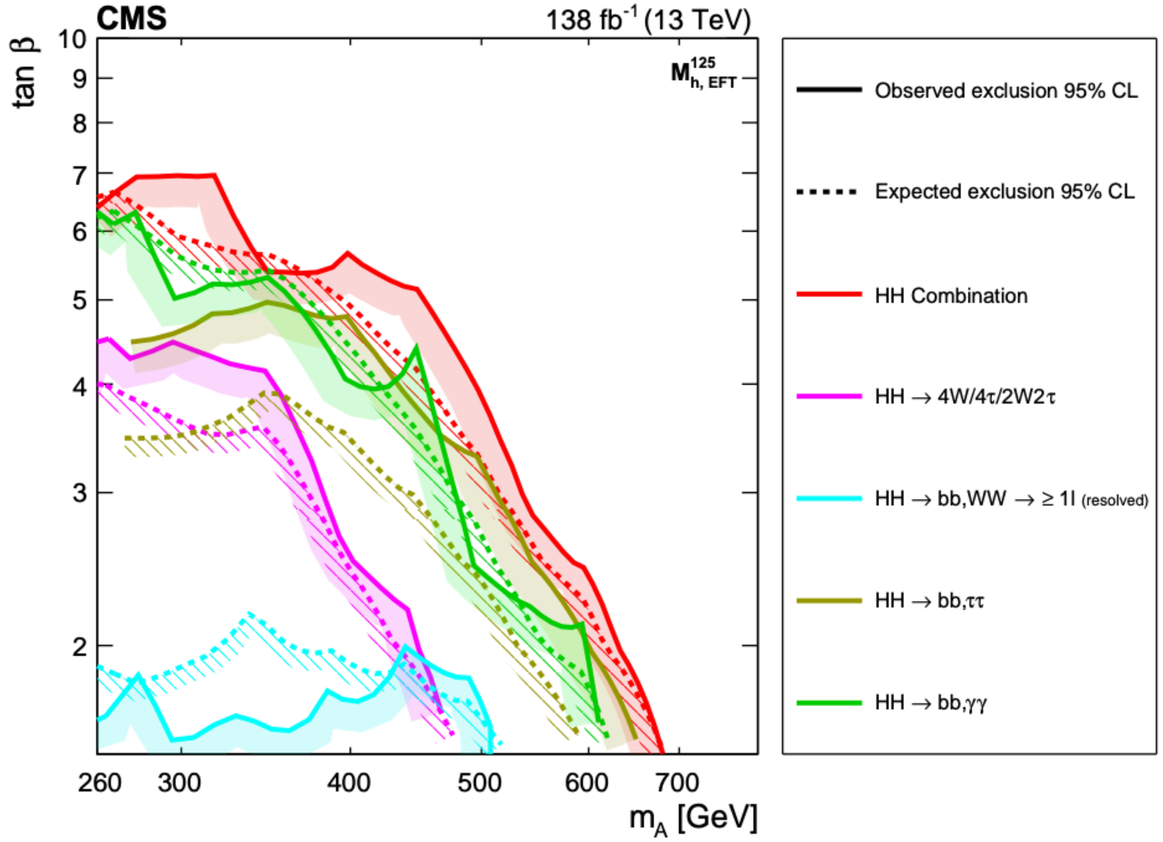
ATLAS spin-0 HH combination

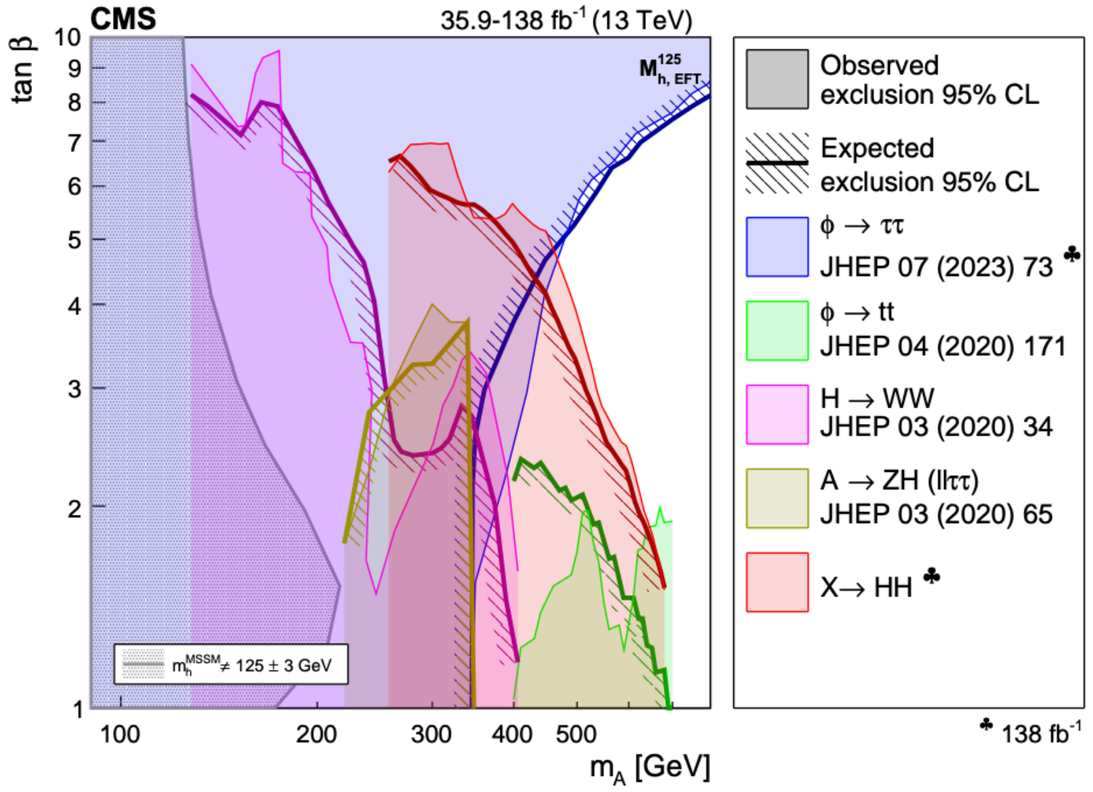


CMS spin-0 HH combination

Interpretations: MSSM model

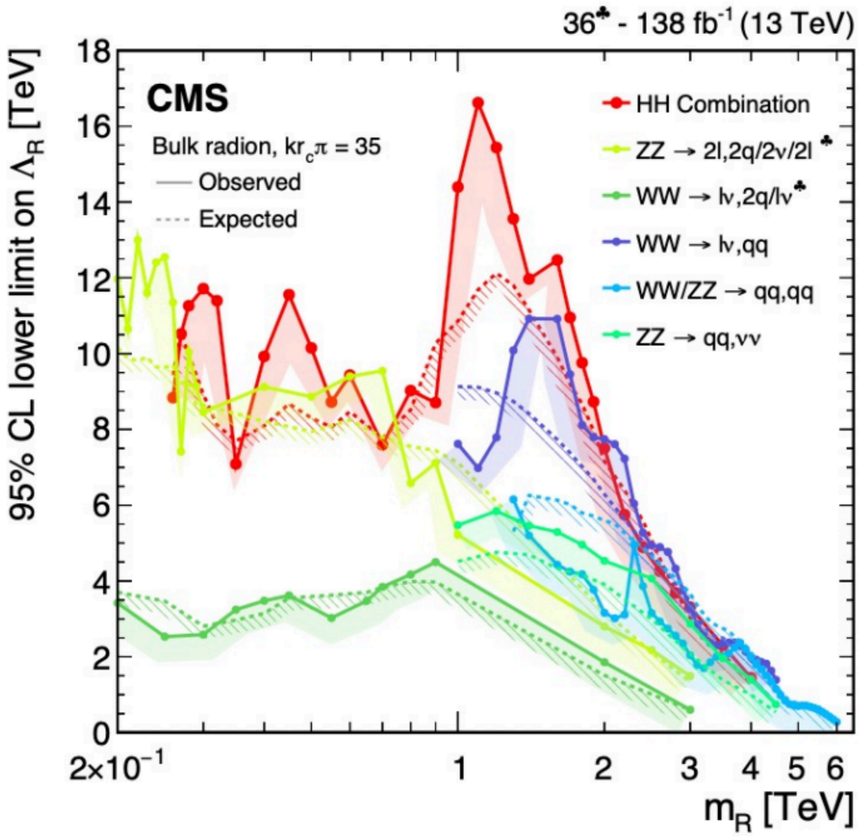
- **Sensitivity gained from HH combination, and shown unique exclusions at mA>400GeV**

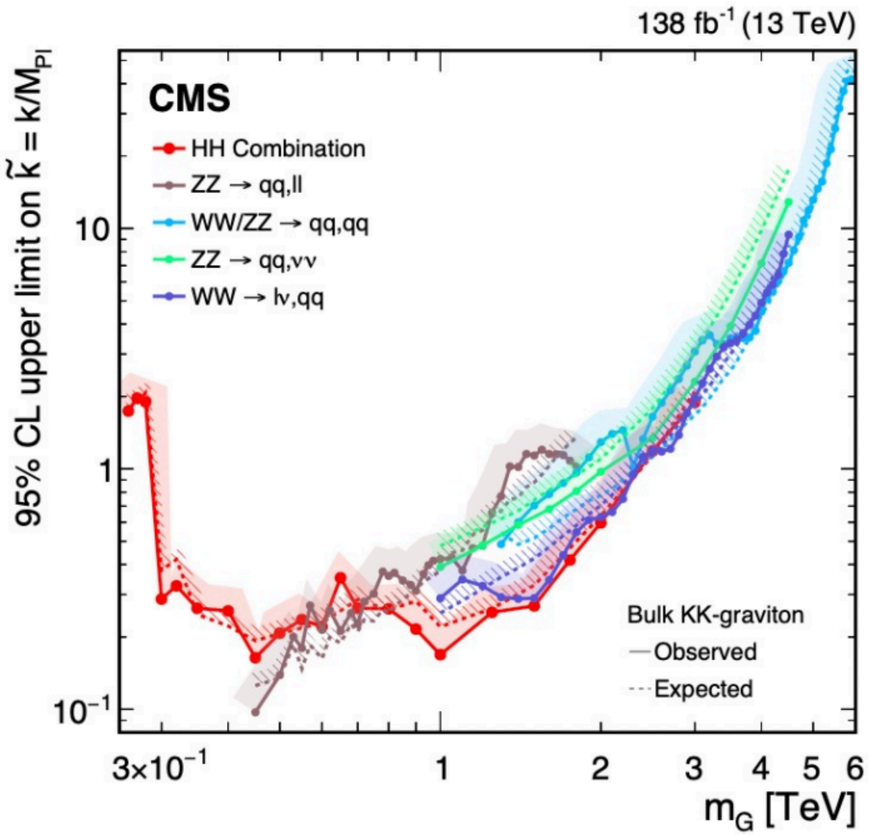




Interpretations: WED model

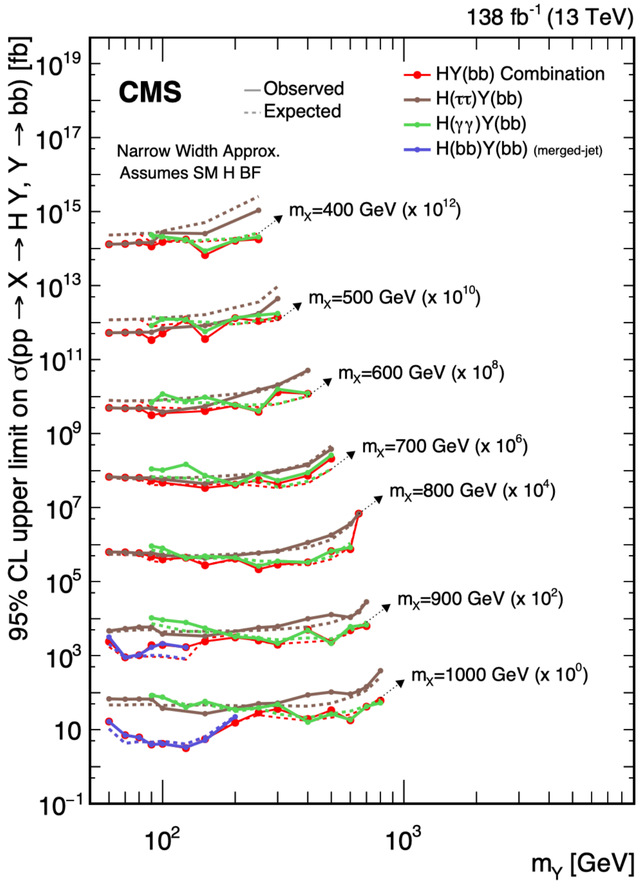
- **Constraints is a complementary to other X → VV analyses in spin-2 case at low mX, and provided best sensitivity at many mass points in spin-0 scenario.**

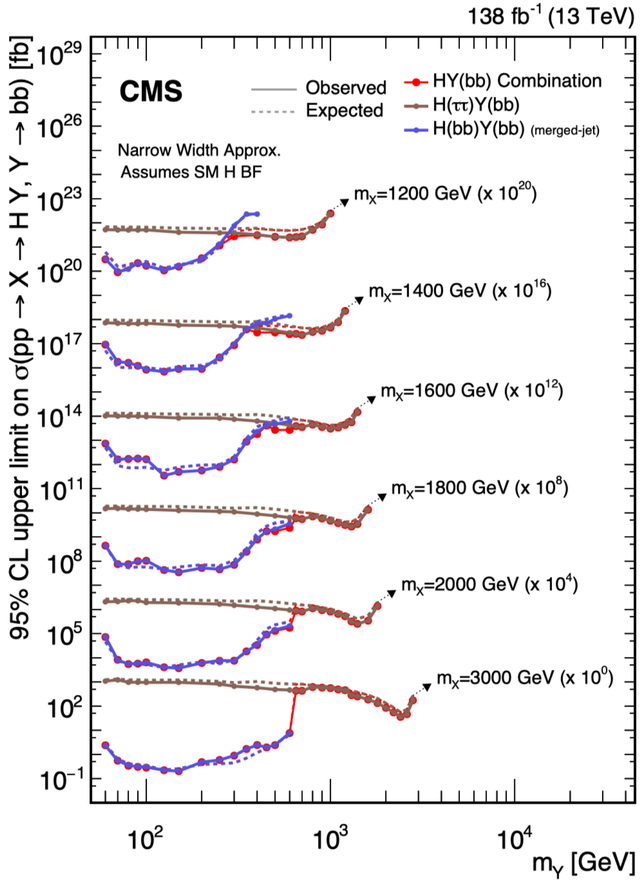




YH searches and combination

YH combination and per-channels results



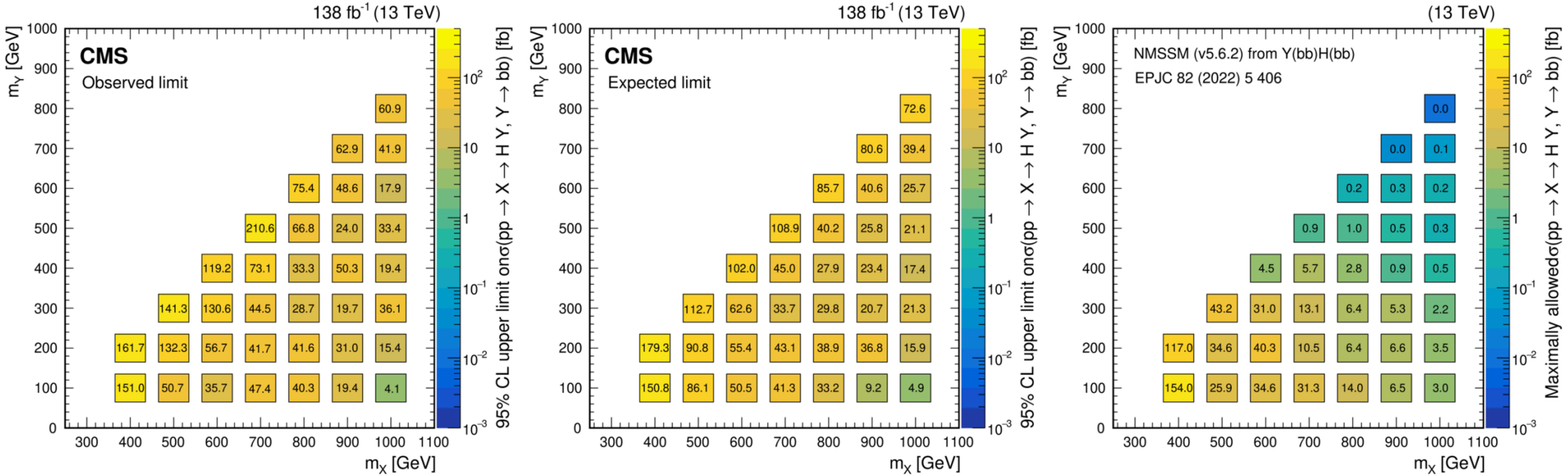


- **At low mX:**
  - The Y(bb)H (ττ) and Y(bb)H (γγ) analyses provide the best sensitivity
- **At mX=1000GeV and higher:**
  - The Y(bb)H (bb) in the merged jet topology dominates for small and medium values of mY
  - At the largest values of mY, the Y (bb)H (bb) sensitivity is reduced, because the boost of the Y is too small, the two b quarks can't merged into one single jets.
- **The typical exclusion upper limits on σxB are about 50, 5, and 0.3 fb for mX = 0.5, 1, and 3 TeV, respectively. No excess observed.**

The results have been achieved by adjusting each channel to the corresponding SM branching fraction of the H boson decay
For the branching fractions of the H → ττ, H → γγ and H → bb decays, the SM values are assumed.

HY model dependent results (NMSSM)

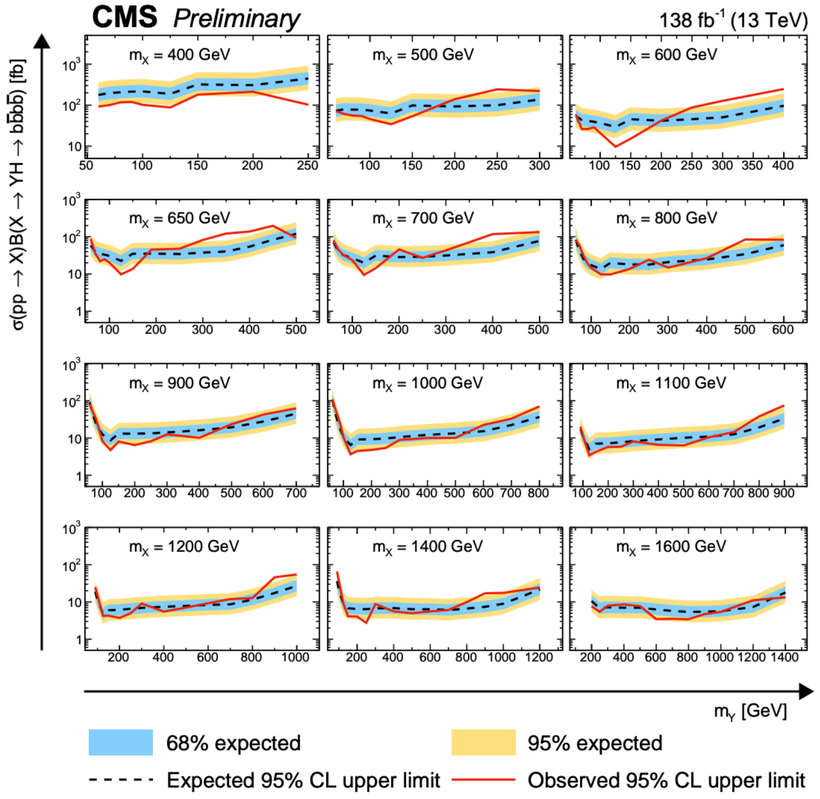
- **Expected and observed limits for the combination of the CMS X → YH analyses is compared to the maximally allowed values in the NMSSM**
  - Only one mass point is excluded in NMSSM by observed limit



2024 new results in CMS

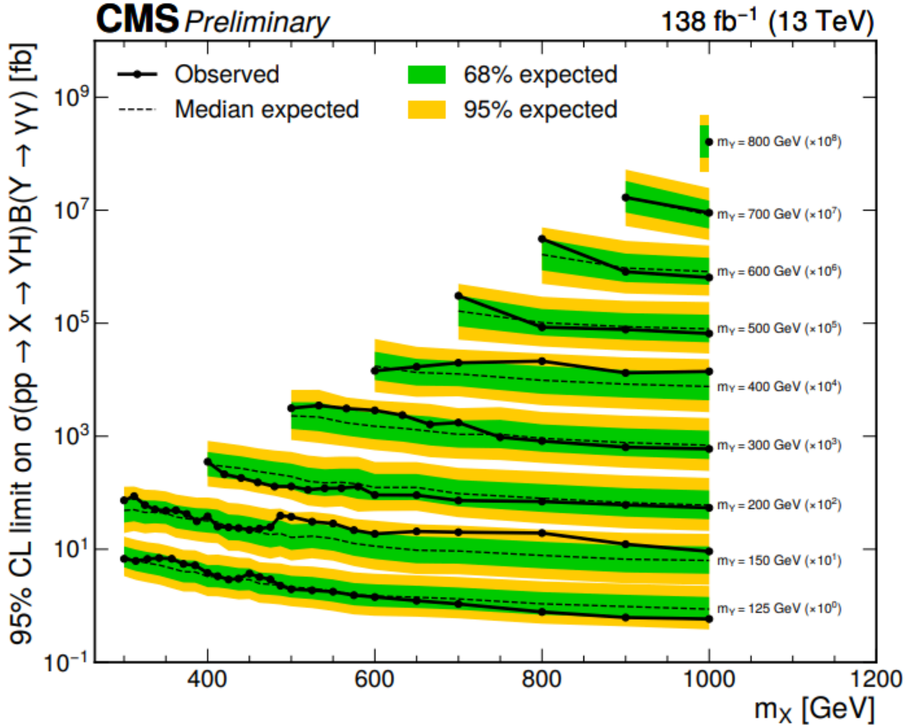
CMS X→YH→4b resolved, CMS-PAS-20-012

- The excess at (mX,mY)=(700,400) GeV with local (global) significance of 4.1(2.8)σ



CMS X→YH→ττγγ, CMS-PAS-22-012

- The excess at (mX,mY)=(525,115) GeV with local significance of 3.4σ



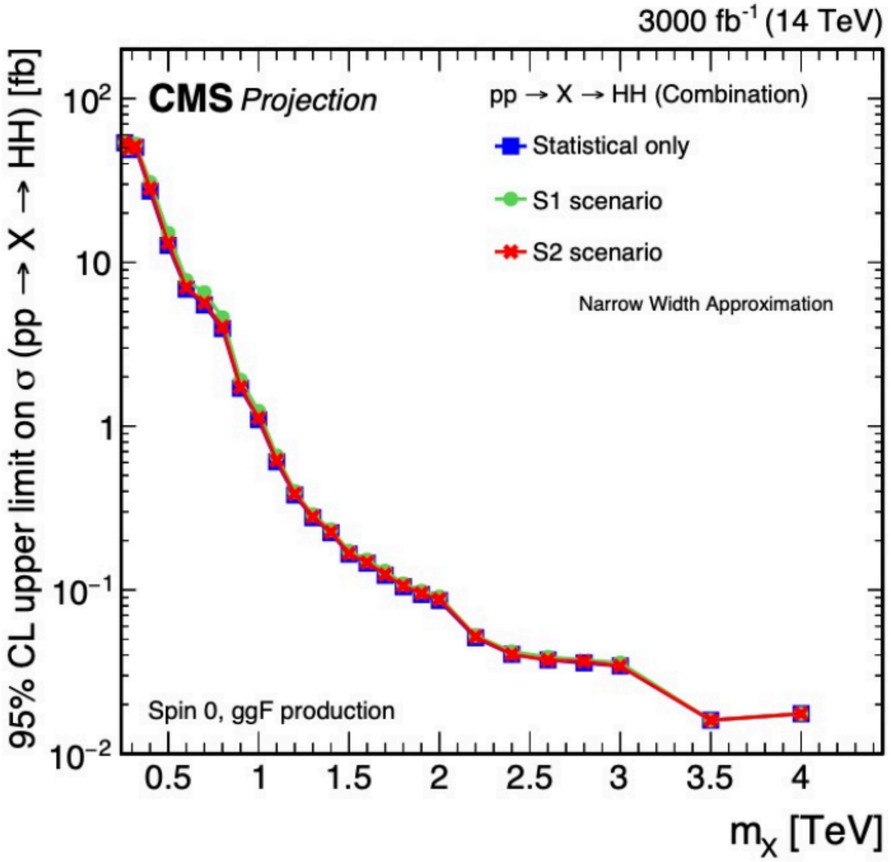
HH/HY projections

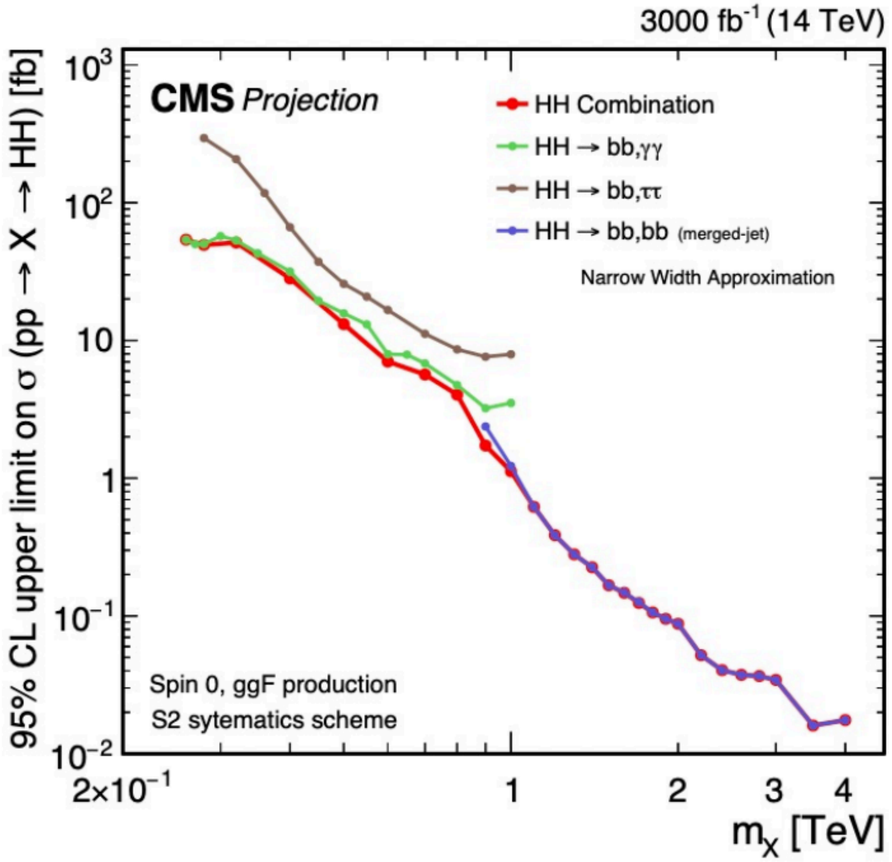
Projection for HL-LHC

- **Signal cross sections have been scaled to the centre-of-mass energy of 14 TeV**
- **Lumi projected to 3000** fb^{-1}
- **Systematics scenarios:**
  - S1: All the systematic uncertainties are assumed to remain the same as in Run 2.
  - S2: The theory uncertainties are halved, while the experimental uncertainties are set according to the recommendations
  - Statistic only
- **Projection of the 3 most sensitive channels :**
  - bb$\gamma\gamma$, bb$\tau\tau$ and bbbb

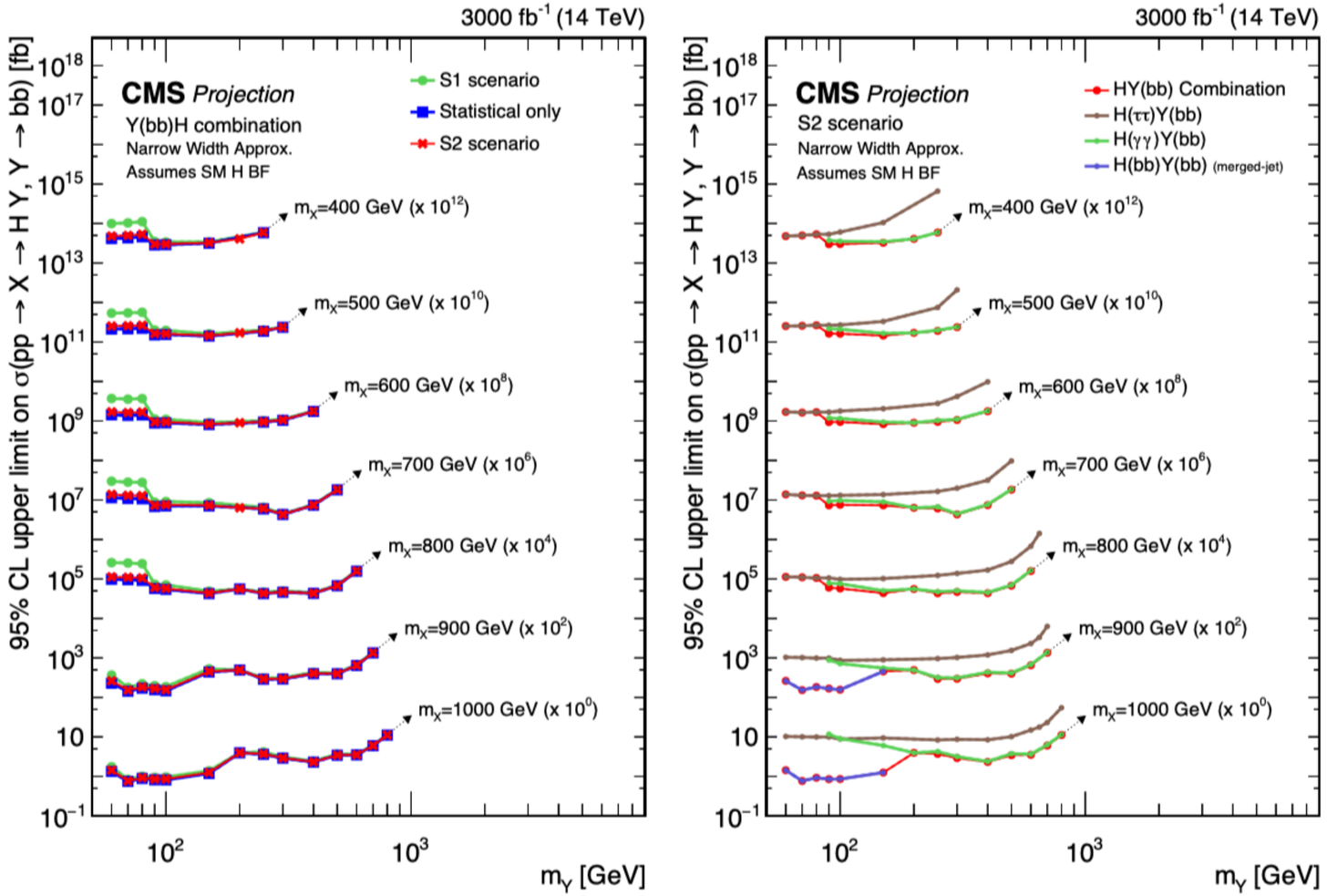
HH Projection

- **The combination still be statistics-dominated**
  - bb$\gamma\gamma$, bbbb dominates the combination





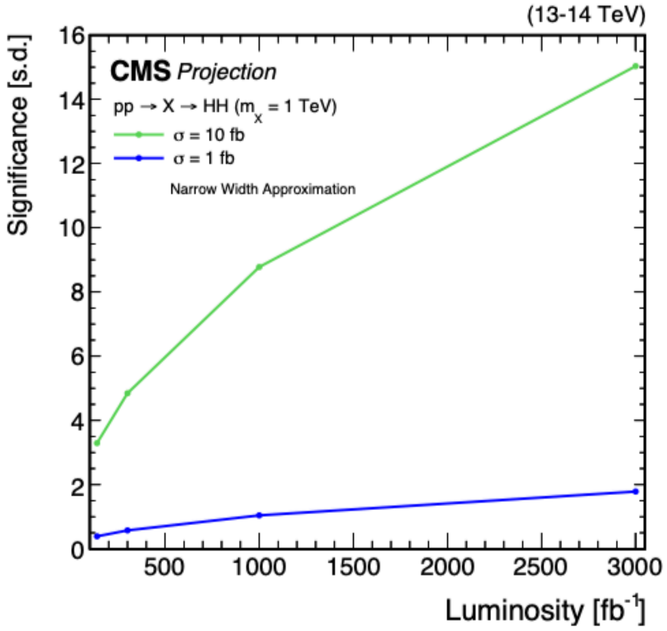
YH Projection



- **The combination gained sensitivity from different channels in different regions**
  - The regions with the largest ratios of mY/mX correspond to a Y particle with low transverse momentum, and can be probed with the bbγγ channel.
  - In the regions with small ratios of mY/mX, the Y particle receives a large Lorentz boost, such that the bbbb boosted channel has the highest sensitivity.
  - In the intermediate region, the bbγγ and bbττ channels provide comparable sensitivity.

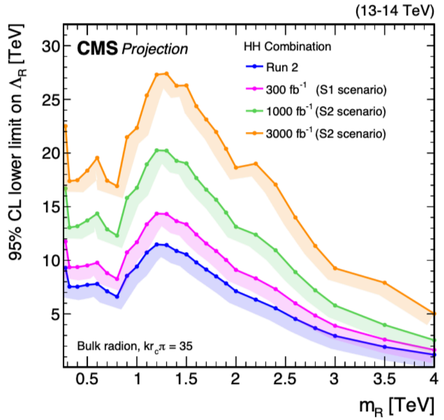
Perspectives for HH/HY searches

- **A signal of X → HH with a cross section of 10 fb would yield 4.8 standard deviations with 300fb^{-1} luminosities**

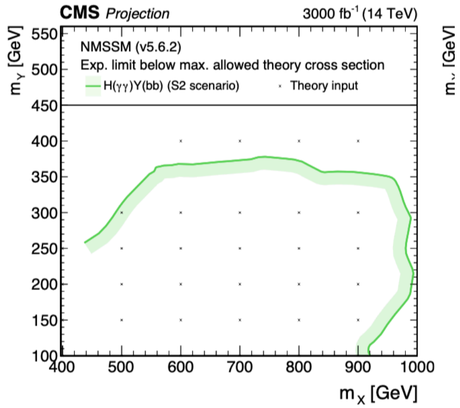


Expected discovery significance for a spin-0 resonance X with mX = 1 TeV and cross sections of 1 and 10 fb

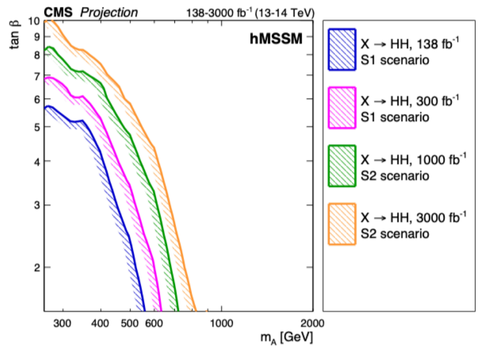
- **The exclusions will also increase a lot in different HH and HY models**



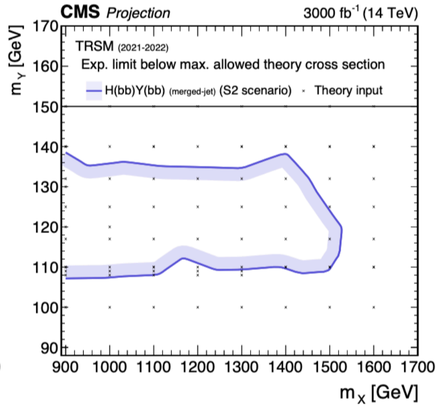
Exclusions in WED



Exclusions in NMSSM



Exclusions in hMSSM



Exclusions in TRSM

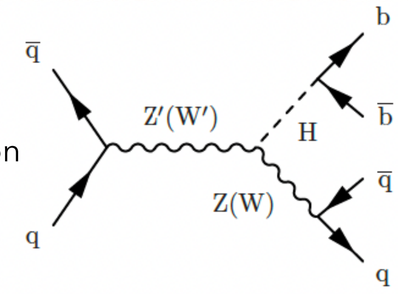
VH searches in CMS

Heavy resonances could also decays into VH

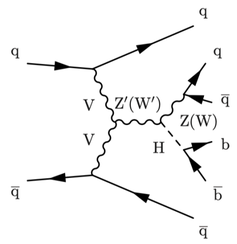
- **Heavy Vector Triplet (W′ and Z′)**
  - Minimal extension of the SM gauge group
    - Additional force-carrying heavy vector bosons, W′ and Z′
    - W′ and Z′ could decays to VH
  - There are two production modes
    - There are 3 typical models based on the couplings:
      - ModelA: with gV=1, cH= −0.556, and cF= −1.316
      - ModelB: with gV=3, cH=−0.976, and cF = 1.024
      - ModelC: with gV=1, cH=1-3, and cF = 0 (VBF only)

        - gV represents the typical strength of the new vector boson interaction. cH scales the couplings to the H/V. cF scales the couplings to fermion

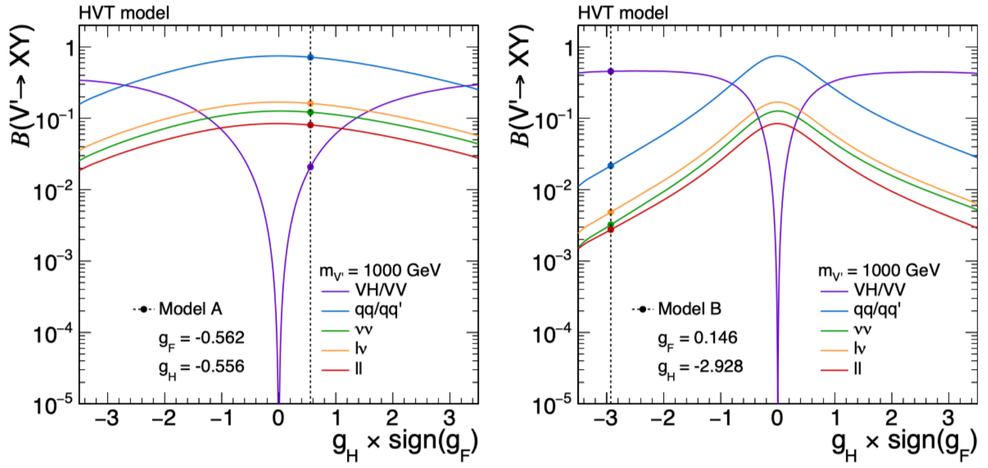
DY production



VBF production



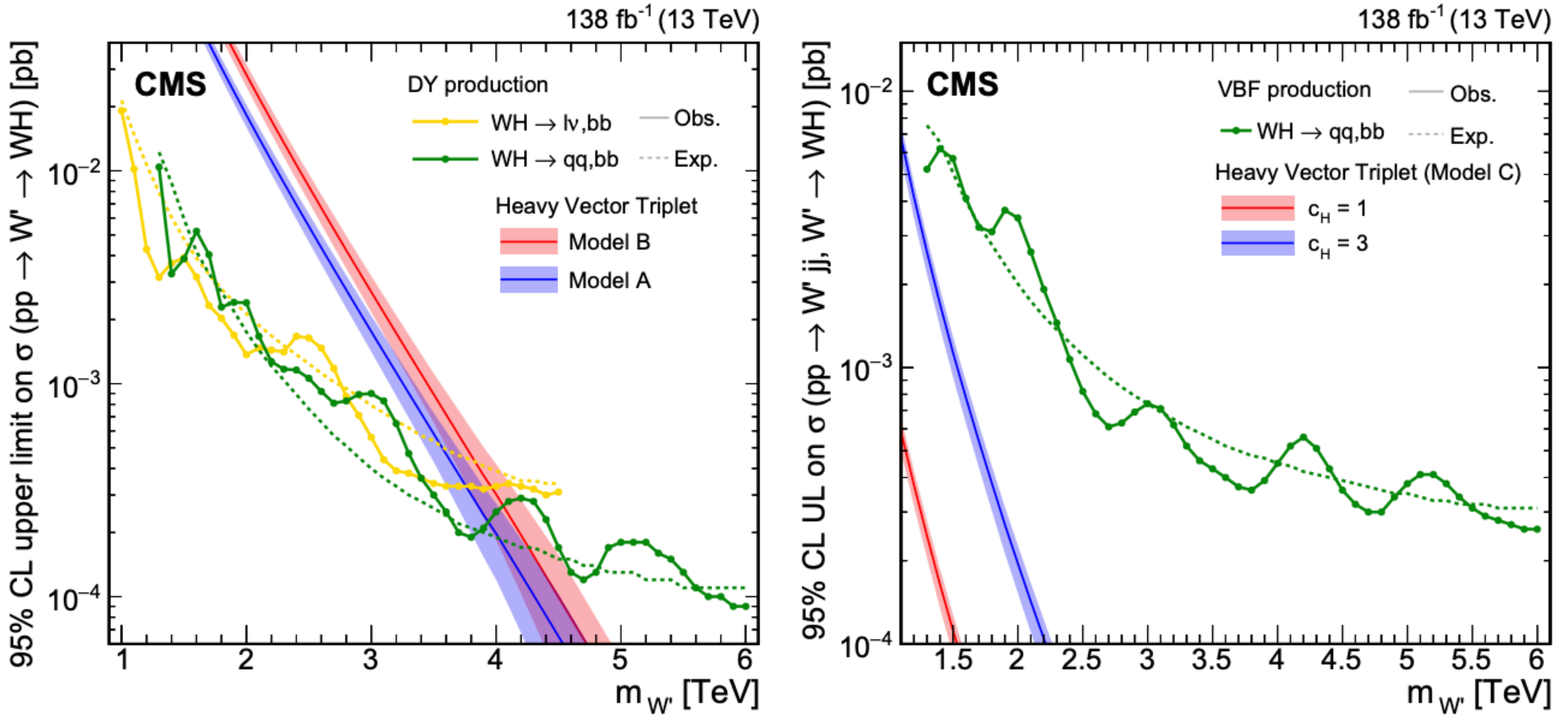
- **Published VH searches in the CMS:**
  - Z(ll)$\tau\tau$ (JHEP)
  - Z(ll+$\nu\nu$)bb (EPJC)
  - Z(ll)bb (EPJC)
  - W/Z(qq)bb (PLB)
  - W(lν)bb (PRD)
  - Z(ll+$\nu\nu$)cc/4q(CMS-PAS-B2G-23-008)
  - Z(ll)$\tau\tau$ (CMS-PAS-HIG-22-004)
- **A combination of VH decay channels is foreseen at a later date as various analyses are still in ongoing**



Branching fractions for heavy vector triplet (HVT) bosons with masses of 1TeV for values of the parameter g F corresponding to models (left) A and (right) B.

VH searches

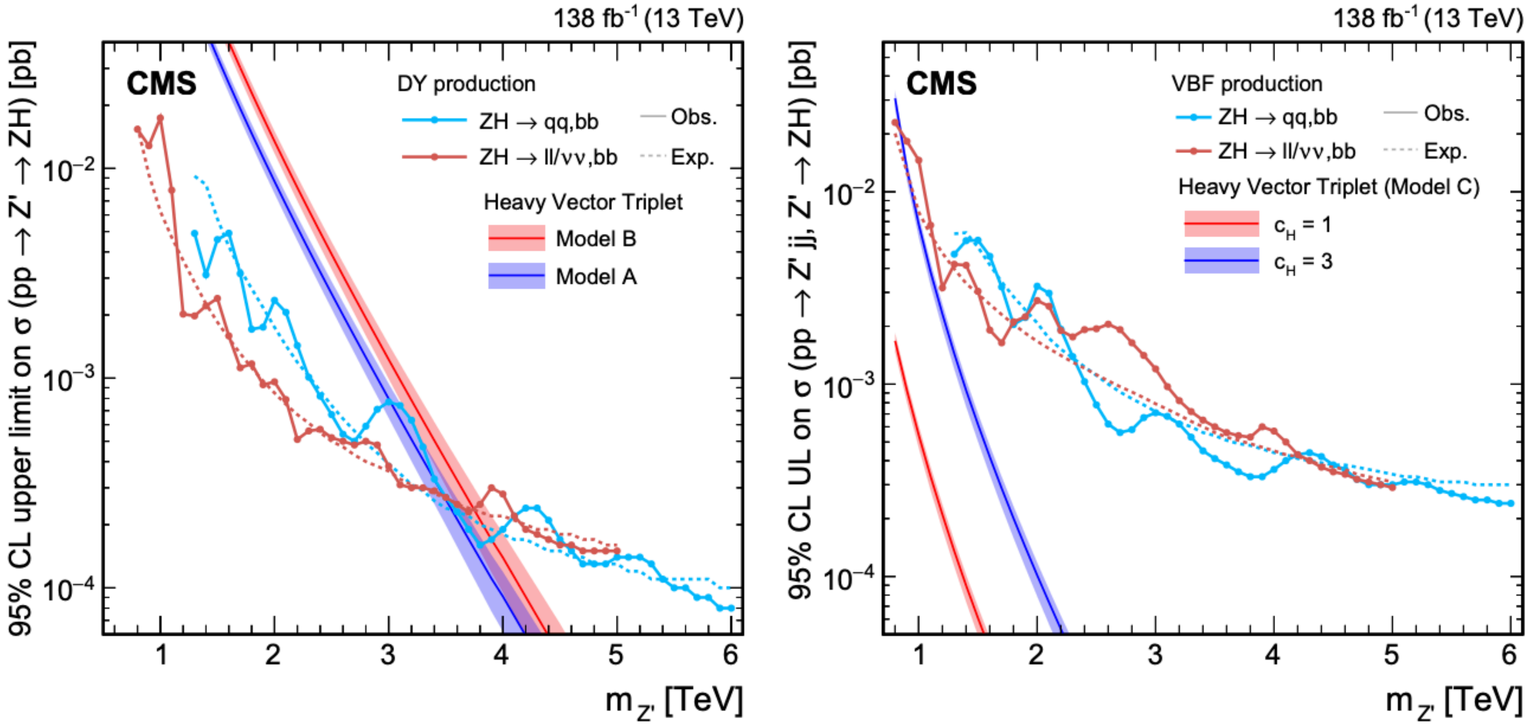
- **Upper limit result:**
  - Upper limits on the production cross section times branching fraction of W’ resonance for the DY (left) and VBF (right) production modes, compared to theory predictions from HVT models. The W’ masses are excluded up to 4.1 TeV in model B interpretations.



The exclusion limits reach values of σB below 0.1 and 0.3 fb for the DY and VBF topologies, respectively.

VH searches

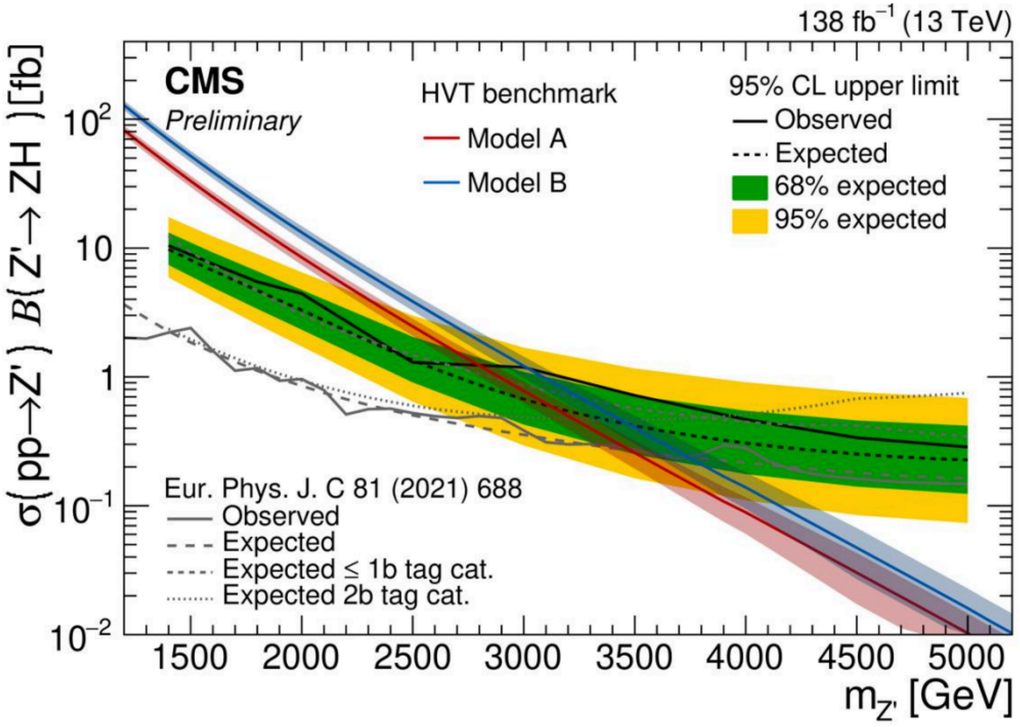
- **Upper limit result:**
  - Upper limits on the production cross section times branching fraction of Z’ resonance for the DY (left) and VBF (right) production modes, compared to theory predictions from HVT models. The Z’ masses are excluded up to 3.9 TeV in model B interpretations.

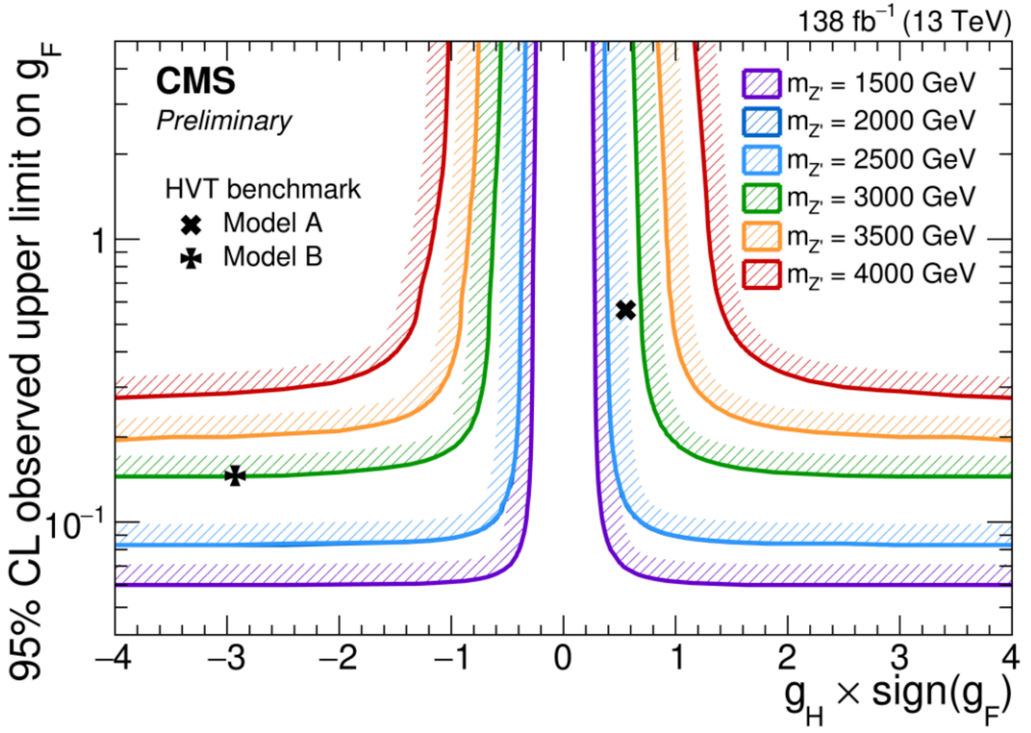


The exclusion limits reach values of σB below 0.1 and 0.3 fb for the DY and VBF topologies, respectively.

2024 new VH results

- **CMS-PAS-B2G-23-008: X → Z(ll/νν) H(cc/4q)**
  - Complement previous CMS analysis targeting H → cc and H → VV*
    → 4q final states exploring the mass range 1.4 TeV < mZ' < 5 TeV





Summary

Summary

- **Resonant HH/HY/VH production predicted in a variety of models**
  - From extended scalar sectors to exotic new physics
- **Many X→HH/HY was performed with full Run2 data in CMS**
  - Included several important channels:
    - bbγγ, bb$\tau\tau$, bbbb boosted, Multilepton, bbWW resolved, bbWW boosted,
  - Combination is a complementarity of the different decay channels
  - New results from bbbb resolved and $\tau\tau\gamma\gamma$ are also presented
- **The HL-LHC HH/HY projection results and the perspectives are presented**
- **Some CMS VH results are also summarized**

Thanks!

backup

Combination procedures

- **Systematics alignment**
  - The systematics that are supposed to behave the same way across analyses are considered a 100% correlated
- **Normalisation for all analysis**
  - Each analysis is normalised to its BR
- **Overlap removal**
  - In multilepton channel, b-veto applied to avoid overlap with other bb related analyses.
  - In bbWW channel, remove the duplicated mass points from bbWW resolved channel, as the sensitivity is lower.
- **Statistic tests**
  - Performed statistical tests to check the sanity of the statistical combination: goodness of fit, pulls and impacts of nuisance parameters , bias test...

Combination: Systematics

- **Systematics alignment**
  - Considering systematics correlations in different analyses
    - Need to align systematics in different analyses to correlate them
  - Theory uncertainties:
    - Followed the naming conventions in HH non-resonant combination

QCD/α_s/PDF:

- No HH/HY signal theory uncertainties
- Applied in all single Higgs processes
- ttbar from Twiki
- Other backgrounds from Twiki
- Single H production from Twiki

Electroweak corrections (ttW, ttZ): Multilepton, bbWW

Branching ratio: Applied in all channels

Combination: Systematics

Systematics alignment

- Experimental uncertainties:

Luminosity:

- Applied in all channels
- Taken values from Lumi POG Recommendations

Systematics	2016	2017	2018
Uncorrelated per era	1.0%	2.0%	1.5%
Correlated among eras	0.6%	0.9%	2.0%
Correlated among 2017 and 2018	-	0,6%	0,2%

Pileup distribution:

- bbbb boosted, bbWW resolved and boosted
- Split by year : multilepton

Pileup Jet ID:

- bbWW resolved
- $bb\gamma\gamma$

Lepton ID /τ scale:

- Considered by the analyses that have this object using different splitting schemes

Combination: Systematics

Systematics alignment

- Experimental uncertainties:

Jet Energy Resolution:

- Split by year: multilepton, $bb\gamma\gamma$, bbbb boosted, bbWW, $bb\tau\tau$
- All eras grouped : bbWW boosted

Jet Energy Scale:

- Split by source: multilepton, bbWW resolved, $bb\tau\tau$
- Split by year:$bb\gamma\gamma$, $bbbb$ boosted
- Grouped in one parameter : bbWW boosted

Jet HEM:

- Multilepton, $bb\gamma\gamma$, bbWW resolved, bbWW boosted

b-tagging:

- Split by sources: multilepton, bbWW resolved
- Other channels are also concerned by b-tagging uncertainties, but split them in different components or use different b-tagging techniques.

Combination: Systematics

Systematics alignment

- Experimental uncertainties:

Unclustered Energy:

- Split by year: multilepton, bbWW resolved
- Split in different components: $bb\tau\tau$
- Grouped: bbWW boosted

ECAL prefiring probability:

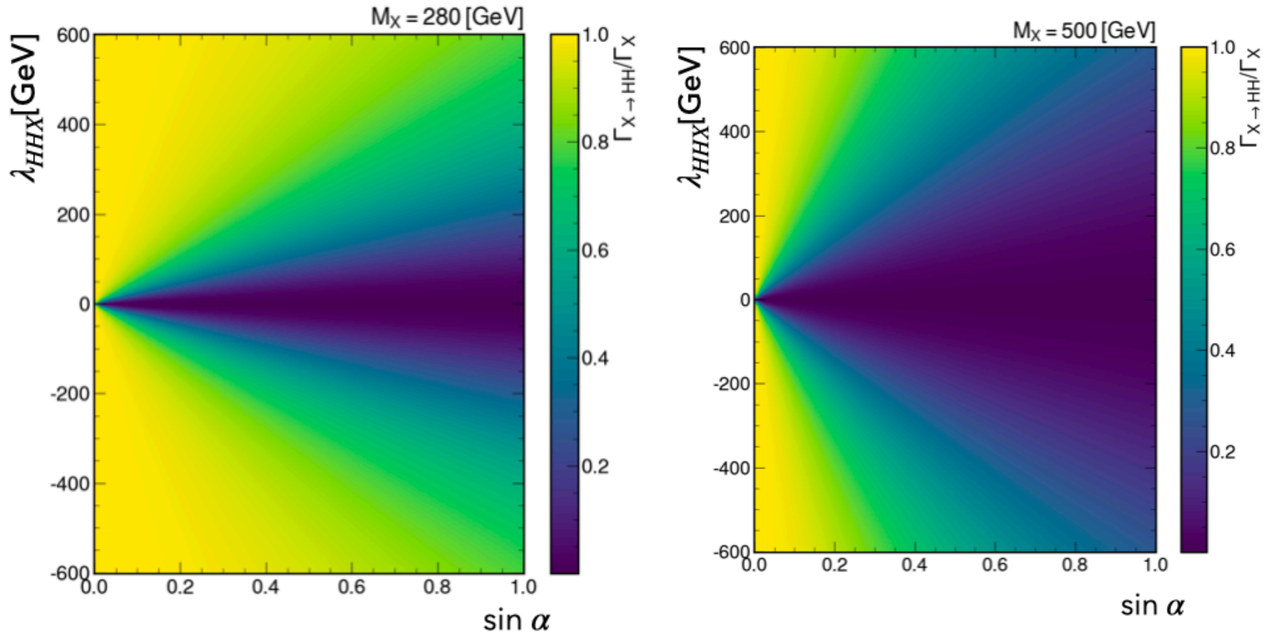
- Split by year: multilepton, $bb\gamma\gamma$, $bbbb$ boosted, bbWW resolved, bbWW boosted
- Grouped in one parameter : $bb\tau\tau$

top $\boldsymbol{pT}$ reweighting:

- bbbb boosted, bbWW resolved
- Split in different components: $bb\tau\tau$

Introduction: Theory background

- **Extended Higgs sectors - additional real singlets**
  - By adding an additional real singlet field, the model leads to one additional scalar X.
    - which can be heavier or lighter than H
  - Using the singlet model for a finite width study

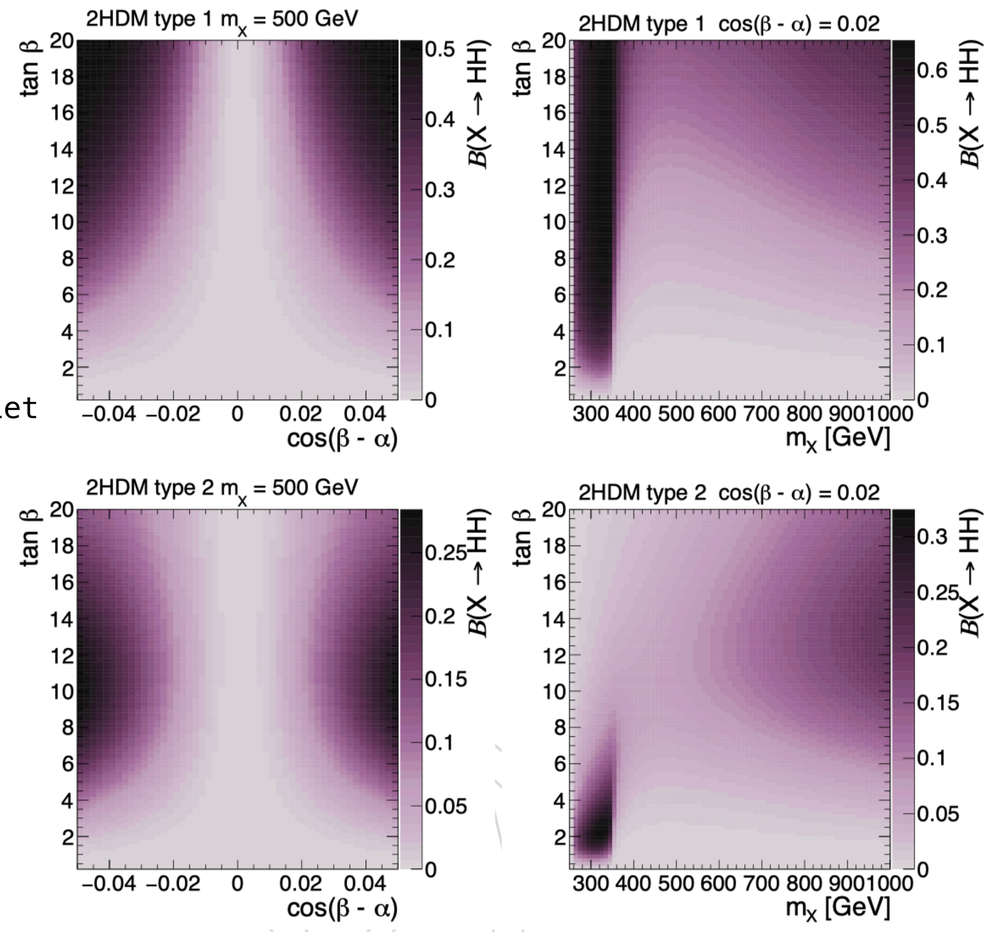


BR to X -> HH in the real singlet model without Z2 symmetry, k_λ is fix to one
(* Plots are only for information, not included in paper)

- Parameters:
  - The ratio of the vacuum expectation values v of the SM complex doublet and of the singlet, ⟨S⟩ , tan β = v/ ⟨S⟩
  - Mixing angle α
  - Masses
  - Deviation from the HHH coupling (k_λ)
  - Coupling between the scalar and HH (λ_{HHX})
- At low sin α the dominant decay mode is HH
- By adding a second real singlet field:
  - Defines the two real singlet model (TRSM)
  - X → YH, X → HH to be possible

Introduction: Theory background

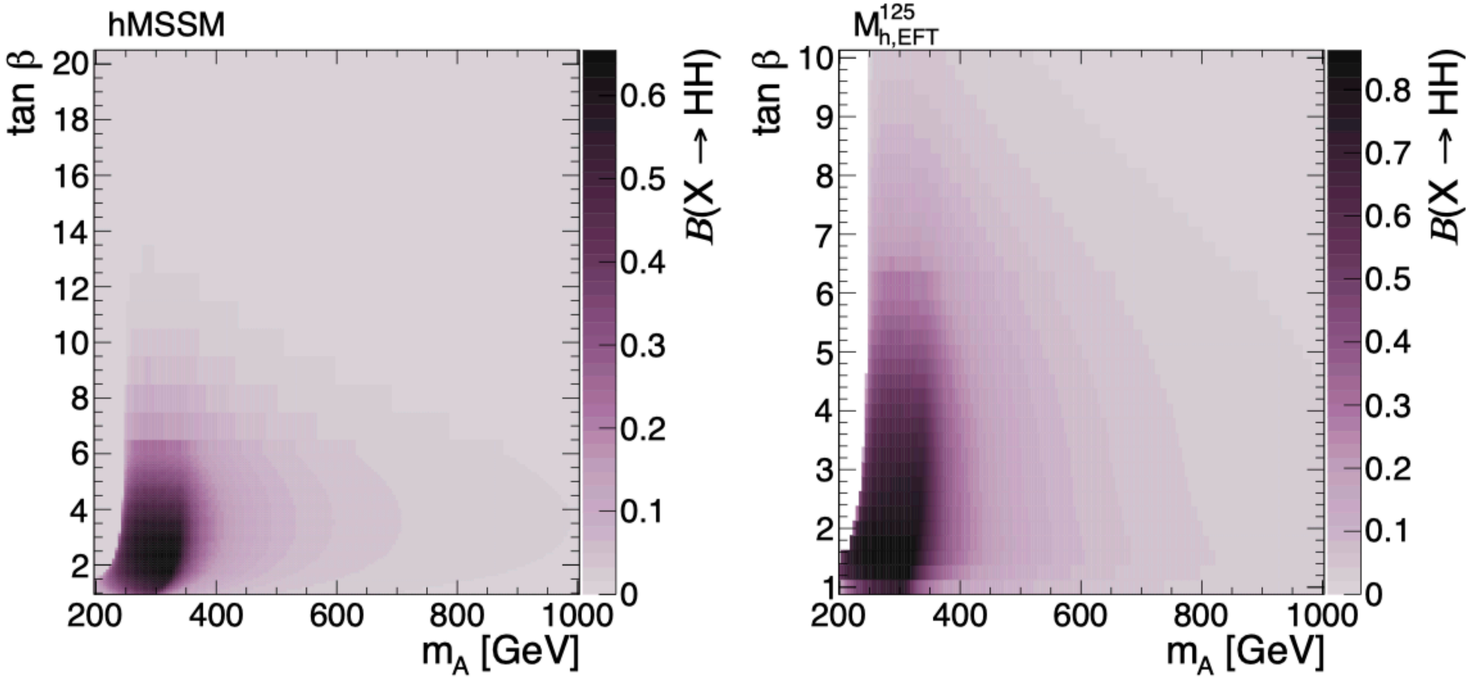
- **Extended Higgs sectors - additional doublets**
  - Leads three neutral and two charged Higgs bosons
  - Parameters:
    - mixing angle (α)
    - a ratio of vev's (tan β)
    - masses
    - by a Z2 symmetry breaking parameter (m_{12})
    - Different types depending on which fermions couple to second doublet
      - Type I: All charged fermions
      - Type II: Only up-type quarks
      - Type X or lepton-specific: Only quarks
      - Type Y or flipped: Only up-type quarks/leptons
- **Heavy Higgs bosons X and A decays in 2HDMs:**
  - X → HH (scalar)
  - A → ZH (CP-odd scalar / pseudoscalar)
- **While adding additional singlet field:**
  - defines the N2HDM.
  - X → YH to be possible



Branching ratios of X → HH in 2HDMs of type I (top) and type II (bottom) in the cos(β−α) - tan β plane for MX= 500 GeV (left), in the m(X)-tan β plane for cos(β−α) = 0.02 (right).

Introduction: Theory background

- **Extended Higgs sectors - Supersymmetric models**
  - The Higgs sector of the minimal supersymmetric standard model (MSSM) has the structure of a Type II 2HDM

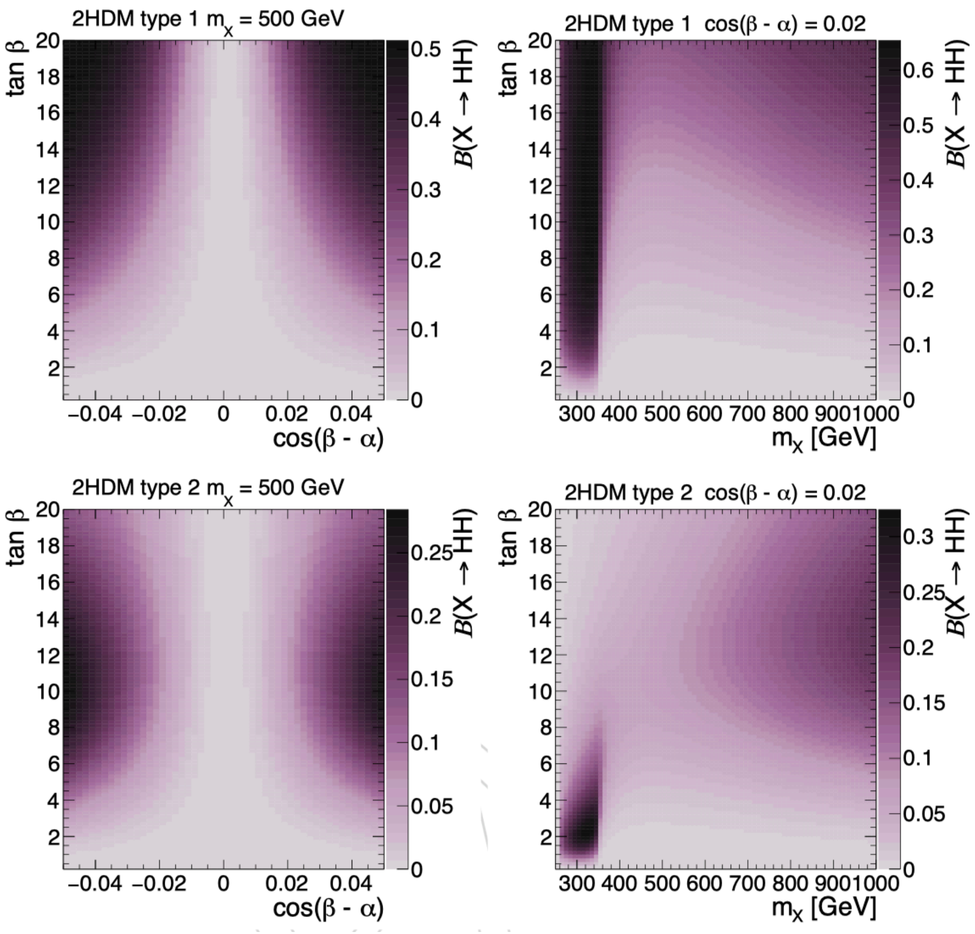


Branching fraction of X → HH in the MSSM, for the hMSSM (left) and the $M_{h,EFT}^{125}$ benchmarks, in the mA-tan β plane

- **Two benchmarks are selected:**
  - hMSSM:
    - Several approximations to simplify the couplings, valid for approximately tanβ < 10
  - $M_{h,EFT}^{125}$ EFT
    - All SUSY particles chosen to be heavy and run in the loops of radiative corrections
    - The meaning of "EFT":
      - Adding light neutralinos/charginos and adjusting the SUSY scale, making the low tan(β) region compatible with MH = 125 GeV
      - Avoids exclusion of low tan-beta in M_h^{125} scenario
  - The X has a decent BR to HH at low tan(β) and MH < 2m_{top}
  - By adding an additional singlet field:
    - Defines next-to-minimal MSSM (NMSSM)

Extended Higgs sectors

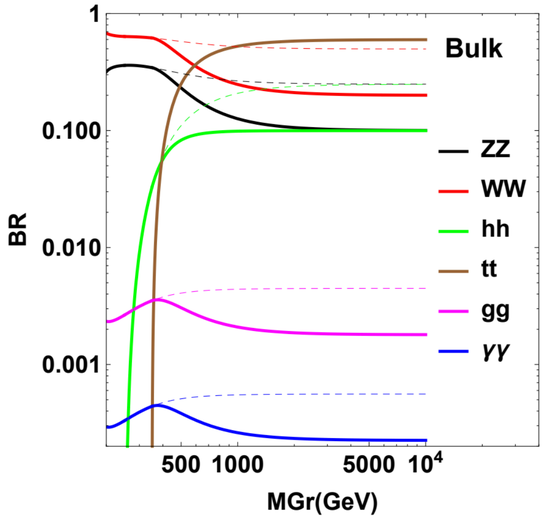
- **Add additional real singlets**
  - By adding an additional real singlet field, the model leads to one additional scalar X.
    - which can be heavier or lighter than H
  - By adding a second real singlet field:
    - Defines the two real singlet model (TRSM)
  - X → HH, X → YH to be possible
- **Add additional doublets**
  - Leads three neutral and two charged Higgs bosons
  - Different types in 2HDM depending on which fermions couple to second doublet
    - Type I: All charged fermions
    - Type II: Only up-type quarks
    - Type X: Only quarks
    - Type Y: Only up-type quarks/leptons
  - X → HH, A → ZH are possible in 2HDM
  - While adding additional singlet field:
    - defines the next-to-minimal 2HDM (N2HDM)
    - X→ YH to be possible

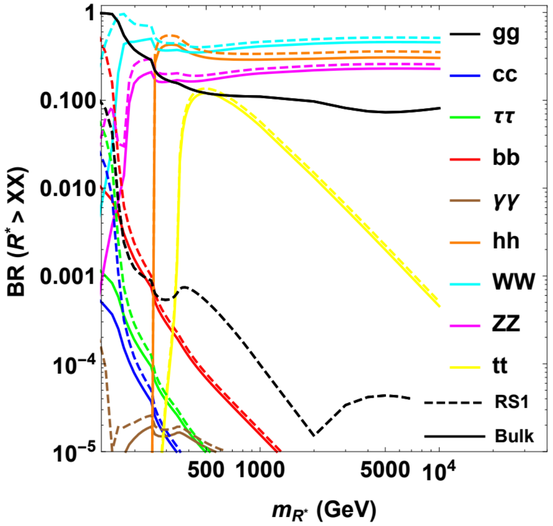


Branching ratios of X → HH in 2HDMs of type I (top) and type II (bottom) in the cos(β−α) - tan β plane for MX= 500 GeV (left), in the m(X)-tan β plane for cos(β−α) = 0.02 (right).

Supersymmetric and WED

- **Supersymmetric models**
  - The Higgs sector of the minimal supersymmetric standard model (MSSM) has the structure of a Type II 2HDM
  - By adding an additional singlet field:
    - Defines next-to-minimal MSSM (NMSSM)
    - X → YH to be possible
- **Warped Extra Dimensions (WED)**
  - The model predicts the existence of a narrow spin-0 (Radion) and a spin-2 (KK-Graviton) particles
    - Parameters:
      - Dimensionless quantity $k/\overline{M_{pl}}$ (k is warp factor, $\overline{M_{pl}}$ is reduced Planck mass) when referring to the KK-Graviton
      - The mass scale Λ_R when referring to the radion
        - interpreted as the ultraviolet cutoff of the model
    - By given more spatial dof to the SM fields defines bulk scenario
    - The BR to HH is among the dominant on the Bulk scenario

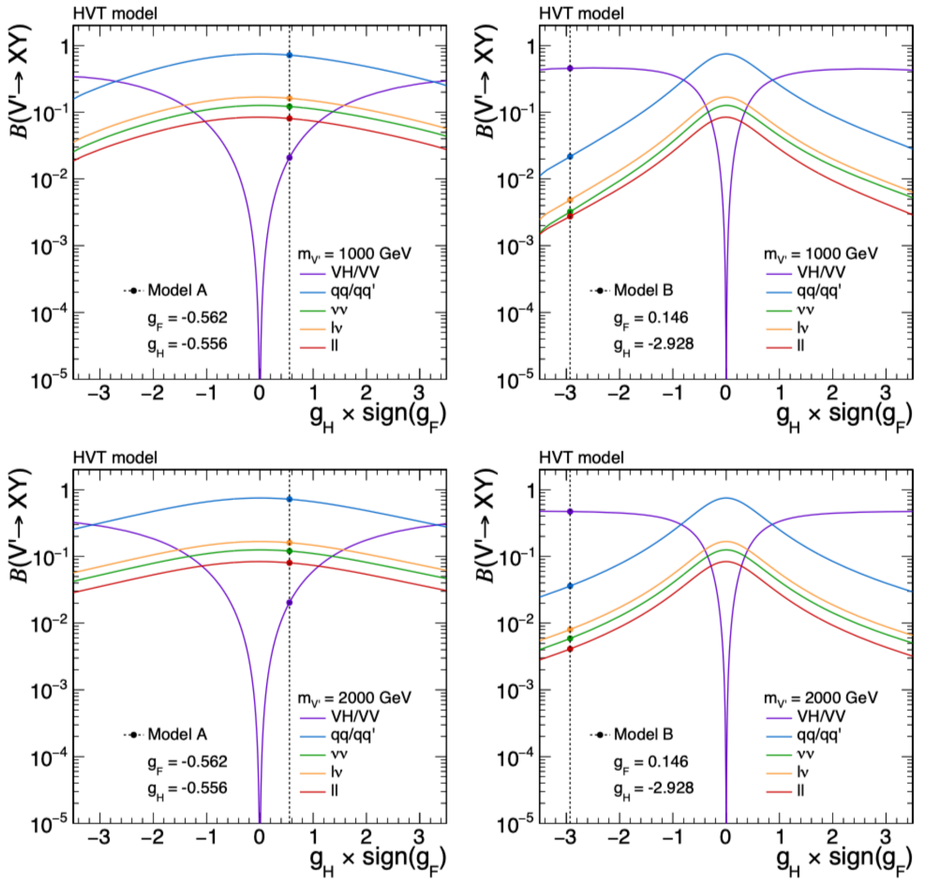




Branching ratios of graviton and radion

Heavy Vector Triplet benchmarks

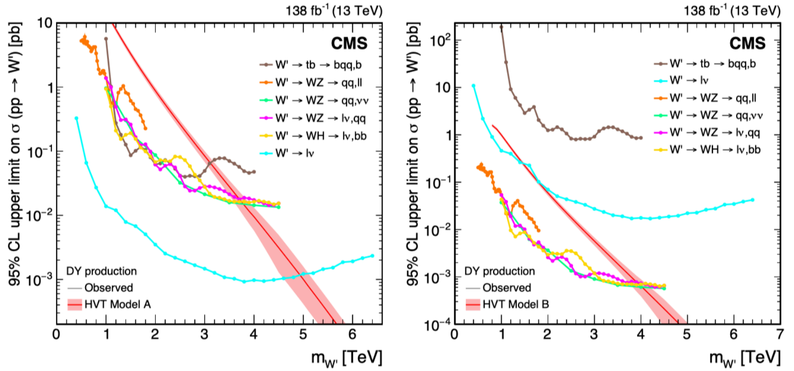
- **Heavy Vector Triplet (W′ and Z′)**
  - Minimal extension of the SM gauge group
    - Additional force-carrying heavy vector bosons, W′ and Z′
  - The W’ and Z’ coupling is proportional to:
    - gF = $g^2 c_F / g_V$, to fermions, g is the SU(2) Lgauge coupling, cF scales the W′ and Z′ couplings to fermions, gV represents the typical strength of the new vector boson interaction.
    - gH = $g_V c_H$, to both H and W/Z
  - There benchmarks are considered:
    - Model A, with gV= 1, cH= −0.556, and cF= −1.316, corresponding to gF=−0.562 and gH = −0.556. This scenario reproduces a model with a weakly coupled extended gauge theory.
    - Model B, with gV=3, cH=−0.976, and cF = 1.024, corresponding to gF=0.146 and gH = −2.928. It mimics a minimal strongly coupled composite Higgs model.
    - Model C, with gV=1, cH=1 − 3, and cF = 0, is a model where couplings to fermions are suppressed, such that no production via a Drell–Yan (DY) process is possible at the LHC and the production of W′ and Z′ bosons happens exclusively via VBF.
  - For large values of gH , the bosonic decay modes dominate the branching fractions, indicating that the searches for VH resonances have the best sensitivity together with searches for VV resonances.



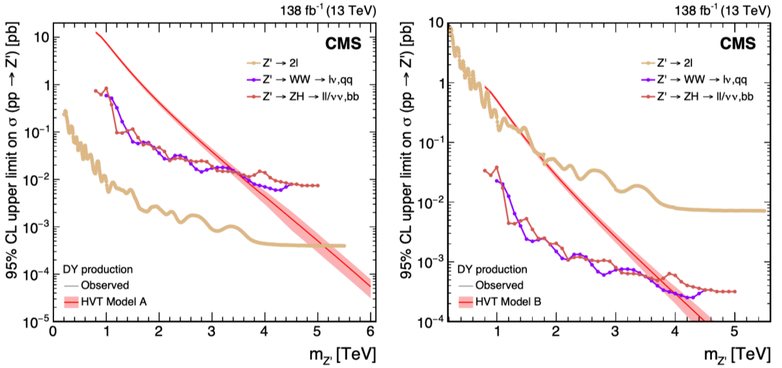
Branching fractions in model A and B in mV'=1000 and 2000GeV

Heavy vector triplet models

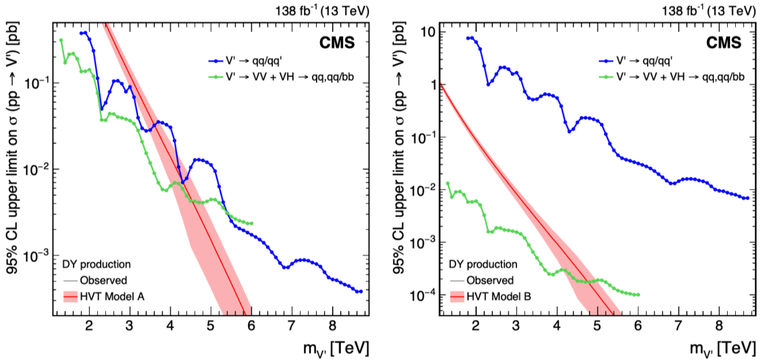
- Upper limits on the DY production cross section of W', Z' and combined V' spin-1 resonances assuming branching fractions of HVT model A (left) and model B (right)
- Theory predictions from HVT models A and B are also shown.
- The all-jets channels are sensitive to both W ′ and Z ′ production and are thus interpreted in combined V ′ production. While in model A, searches for fermion pair production dominate the sensitivity, in model B, where couplings of V′ to bosons are large, the VV and VH searches are most sensitive.
- In the scenario of model C, where V' is produced exclusively via VBF, the data set is not sufficient to exclude couplings below gH = 3.



DY production of W'



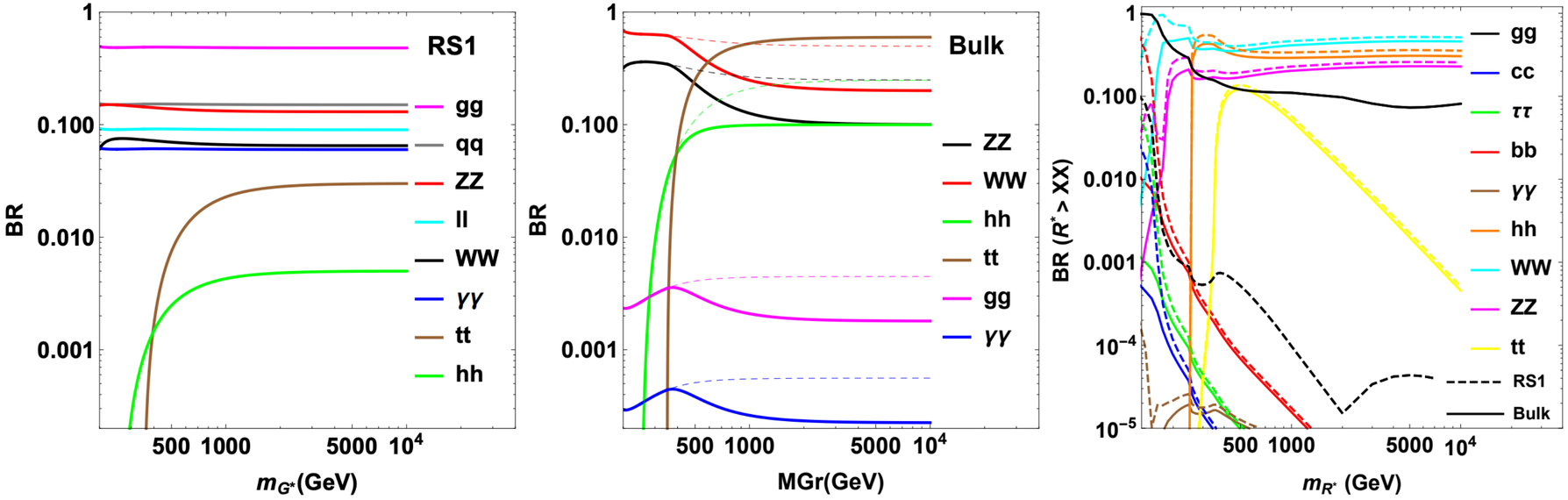
DY production of Z'



DY production of V'

Introduction: Theory background

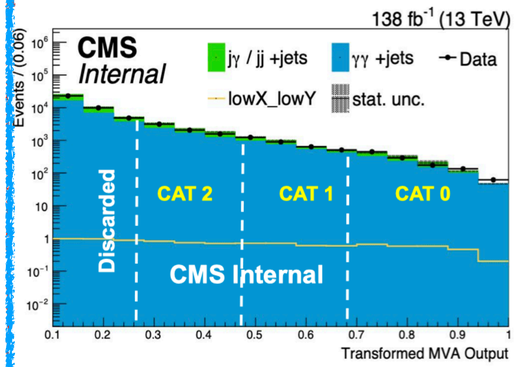
- **Warped Extra Dimensions (WED)**
  - The model predicts the existence of a narrow spin-0 (Radion) and a spin-2 (KK-Graviton)
    - Parameters:
      - Dimensionless quantity $k/\overline{M_{pl}}$ (k is warp factor, $\overline{M_{pl}}$ is reduced Planck mass) when referring to the KK-Graviton
      - The mass scale Λ_R when referring to the radion
        - interpreted as the ultraviolet cutoff of the model
    - Different benchmarks are typically considered:
      - RS1 (original)
      - Bulk – more spatial dof are given to the SM fields
    - The BR to HH is among the dominant on the Bulk scenario



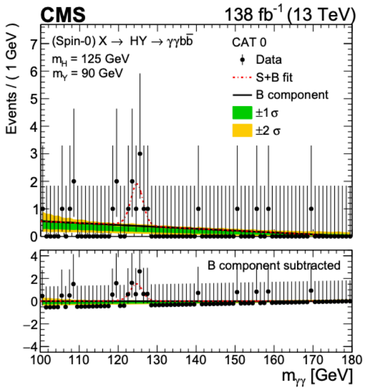
The decay branching fractions of a RS1 graviton (left), bulk graviton (middle), radion (right)

bb$\gamma\gamma$ (HIG-21-011)

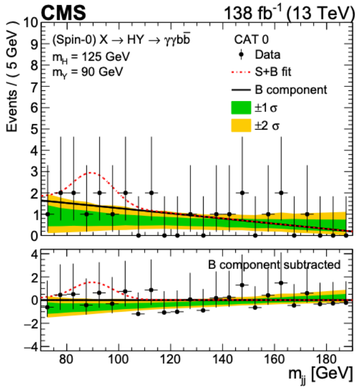
- **Characteristics of bb$\gamma\gamma$ channel :**
  - Low branching ration, but clean final states.
  - HH and HY analysis
    - For HY results, Higgs decays to $\gamma\gamma$, Y decays to bb
- **Main backgrounds:**
  - photon+Jets, diphoton+Jets, single Higgs
- **Analysis strategy:**
  - Standard Higgs to $\gamma\gamma$ tagger.
  - Select two b-jets with highest b-score
  - Training BDT to reject non-resonant backgrounds
  - Applied 4-body mass selection and dedicated ttH killer to reject single Higgs
  - Categorise events based on MVA output
- **Signal extraction:**
  - 2D fits for di-photon and di-jet mass
- **Results: both HH and HY were included**
  - Excess of 3.8 (2.8)σ found at M_X= 650 GeV and M_Y = 90 GeV



MVA outputs and categorisation

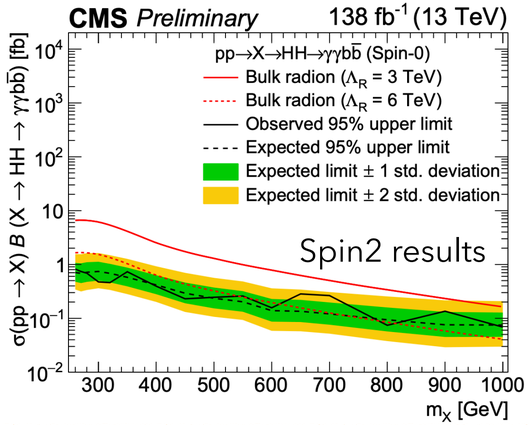


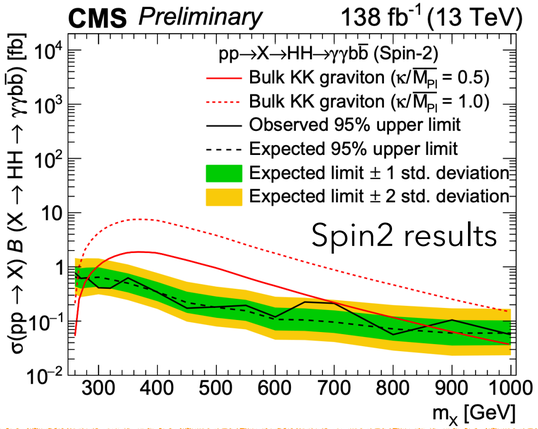
Diphoton-mass fits

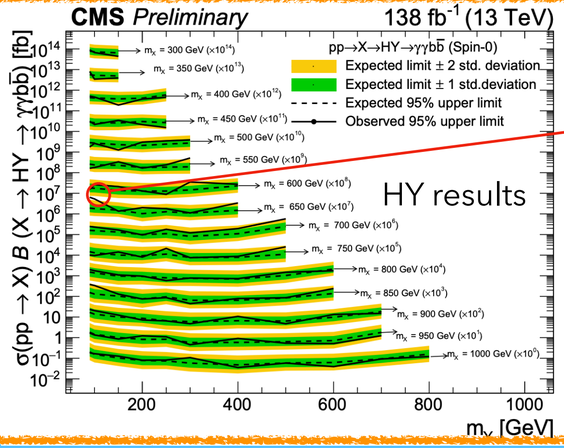


Dijet mass fits

Plot source



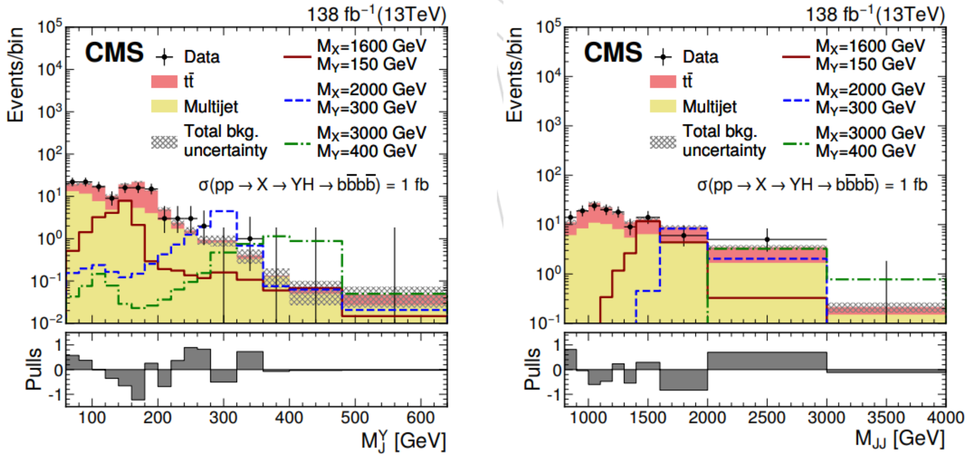




Excess of 3.8 (2

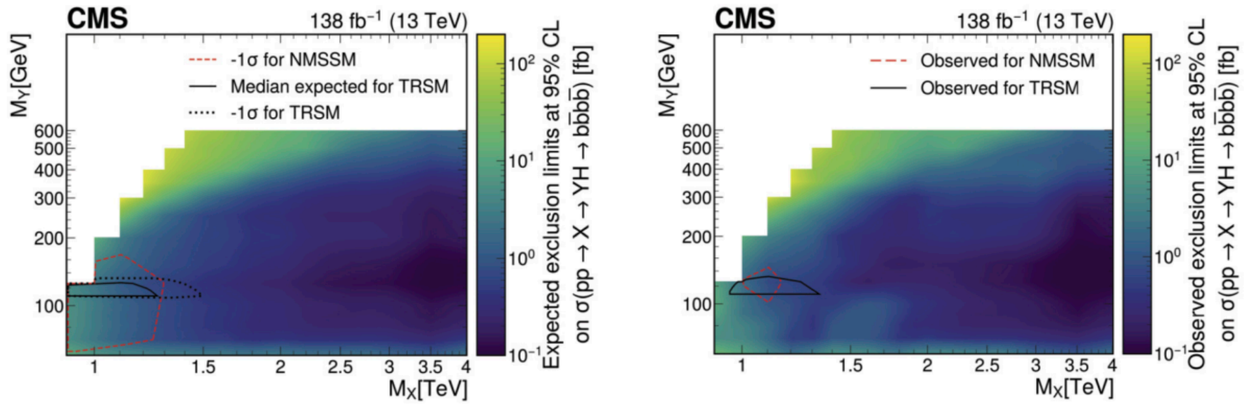
bbbb boosted (B2G-21-003)

- **Characteristics of bbbb boosted channel :**
  - Largest branching ratio. Low backgrounds
  - At very high M_X, because of the boost, the two b-jets might merged to a fat-jet
  - Explored both HH and HY scenarios, Y decays to bb, H decays to bb
- **Main backgrounds:**
  - $t\bar{t}$, QCD multijets, single Higgs
- **Analysis strategy:**
  - Applied Particle-Net fat b-jet tagging to discriminate the decays of a boosted H boson to a pair of b quarks against a background of other jets
- **Signal extraction:**
  - 2D M_{jj}/M_j^Y fits
- **Results:**
  - Both HH and HY were included



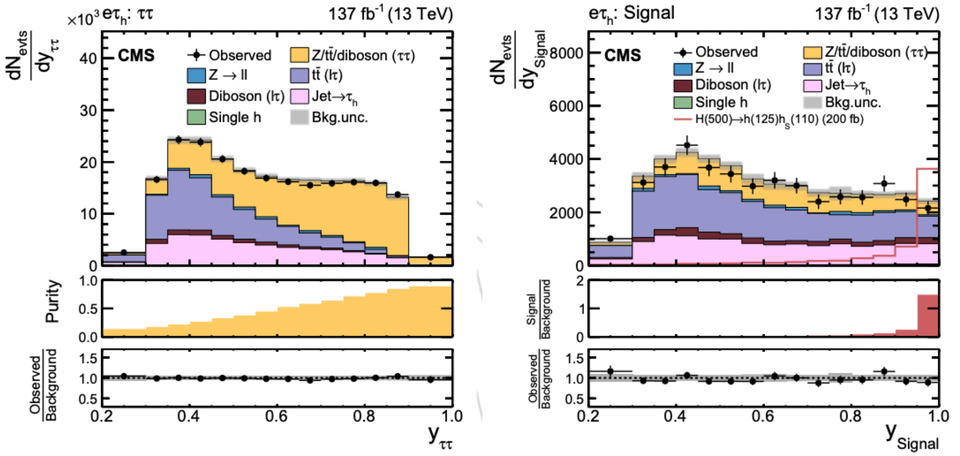
Distributions of M Y J (left) and MJJ (right) in the high-purity signal region of the Y(bb)H(bb) analysis in the merged jet topology

Plot source



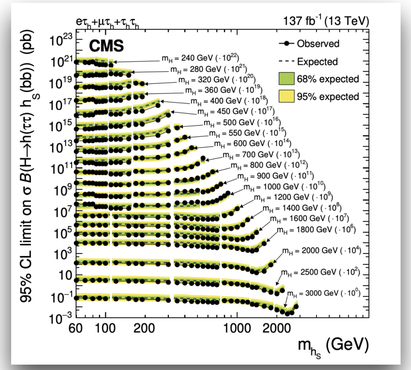
bb$\tau\tau$ (HIG-20-014)

- **Characteristics of bb$\tau\tau$ channel :**
  - Select events with a reconstructed tau lepton pair in the final states $\tau_h\tau_h$, eτ_h, $\mu\tau_h$ (Covered ~88% $\tau\tau$ decays)
  - HY only analysis, Higgs decays to $\tau\tau$, Y decays to bb
- **Main backgrounds:**
  - Z,$t\bar{t}$, diboson, WJets, fake τ, QCD, single Higgs
- **Analysis strategy:**
  - Select a least (b jet + jet) + 1 $\tau\tau$ pair
  - Train multi-classification neural-network to separate signal from:
    - Genuine ττ
    - Remaining top-quark pairs
    - Jet→τ h misidentified
    - Miscellaneous smaller backgrounds: Z→$\ell\ell$, diboson, single top and single Higgs
- **Signal extraction:**
  - Maximum likelihood fits on neural-network outputs
- **Results:**
  - Only HY results, emulate HH results for combination
- **Direct HH(125GeV) searches are ongoing (CMS-B2G-24-011)**

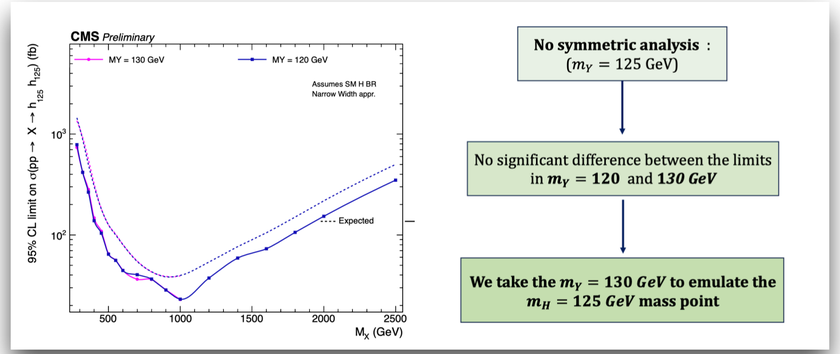


Distributions of the NN output scores , in different event categories after NN classification

Plot source



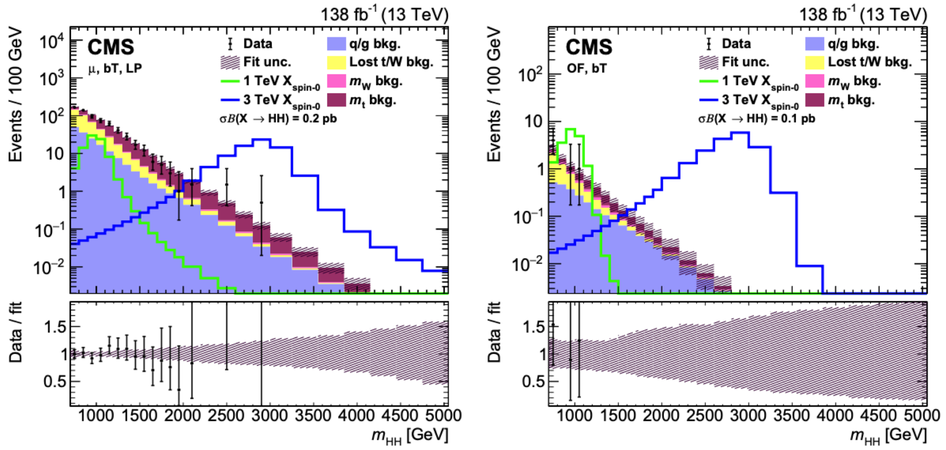
Original HY results



Emulation of HH results

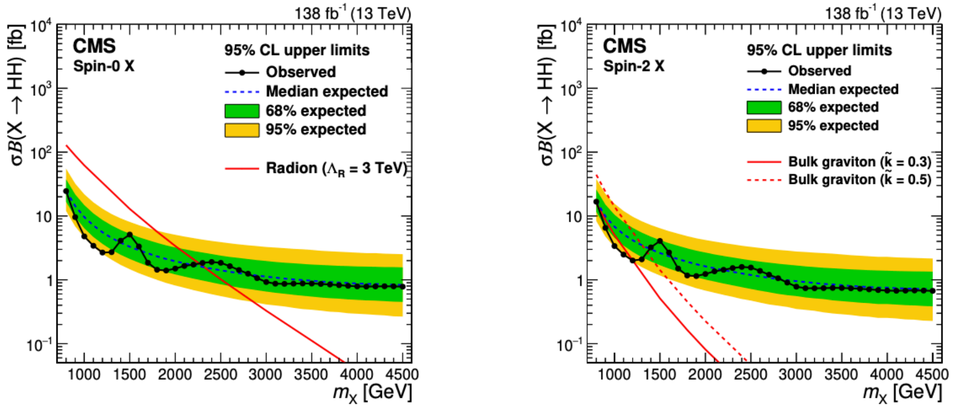
bbVV boosted (B2G-20-007)

- **Characteristics of bbbb boosted channel :**
  - 2nd Largest branching ratio
  - bbWW leptonic and bb$\tau\tau$ HH decay modes
  - Explored HH scenario only
- **Main backgrounds:**
  - $t\bar{t}$, QCD multijets, single Higgs
- **Analysis strategy:**
  - One AK8 jet ($H \rightarrow bb$)
  - Semi-leptonic: 1 lepton + 1 more AK8 jet in bbWW
  - Di-leptonic: 2 leptons final states of bbWW and bbττ
  - Categorise events into different cats base on the flavor of the leptons, the purity of the H→WW, and the working points of H→bb.
  - Aditional b-tagged AK4 jets (DeepJet) are vetoed
- **Signal extraction:**
  - Fit to the 2D mX/mbb distribution with 4 background and 1 signal template
- **Results:**
  - Only HH results



The mHH distributions in data and the estimated background from SM processes in selected SL (left) and DL (right) categories

Plot source

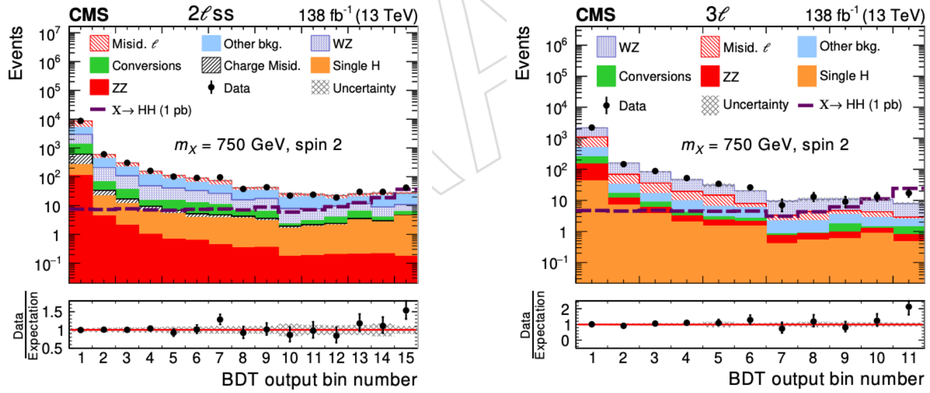


Spin-0 results

Spin-2 results

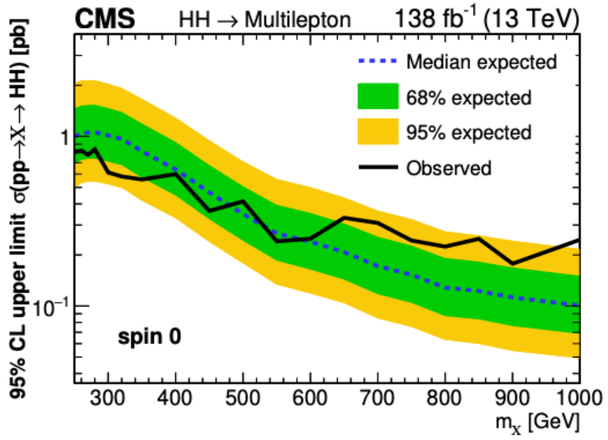
Multilepton(HIG-21-002)

- **Characteristics of bb$\gamma\gamma$ channel :**
  - Includes $WWWW, WW\tau_h\tau_h$ and $\tau_h\tau_h\tau_h\tau_h$ decay modes
    - 7% coverage in HH branching ratios
  - HH only analysis
- **Main backgrounds:**
  - WZ, ZZ, Misidentified lepton, Conversion electrons, single Higgs …
- **Analysis strategy:**
  - Separate 7 sub-channels based on the number and the flavour of leptons
  - Training BDT to distinguish non-resonant signal, resonant spin-0 signal and resonant spin-2 signal from the backgrounds
  - For HY scan, trained parametric MVA by using resonant mass as inputs.
  - Applied b-veto to remove overlap
- **Signal extraction:**
  - Simultaneous maximum likelihood fits of BDT outputs
- **Results:**
  - Only HH results, HY not included.

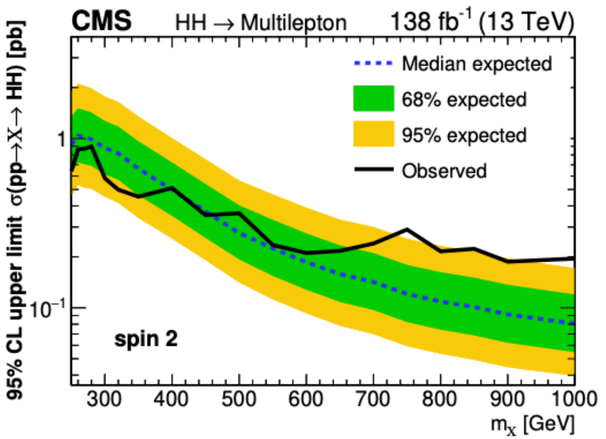


Distribution in BDT classifier output for resonances of spin 2 and mass 750 GeV in the 2lss (left) and 3l (right) categories.

Plot source



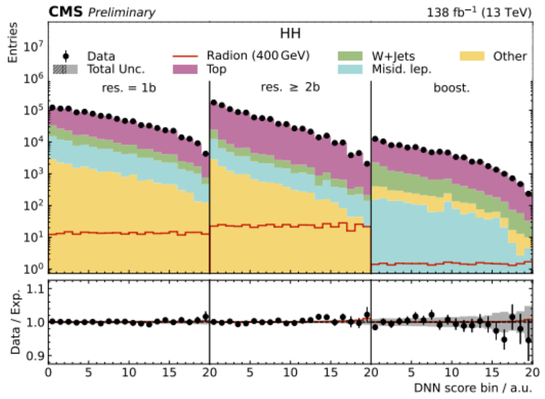
Spin0 result



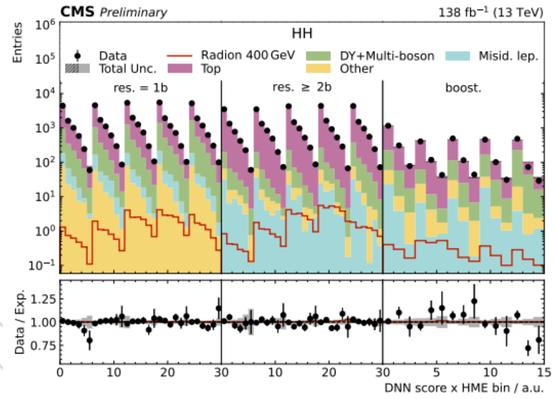
Spin2 result

bbWW resolved (HIG-21-005)

- **Characteristics of bbbb boosted channel :**
  - 2nd Largest branching ratio
  - Include semi-leptonic and di-leptonic decays of H→WW
  - Explored HH scenario only
- **Main backgrounds:**
  - top related bkg , QCD multijets, W+Jets, DY+Multiboson, misidentified lepton, single Higgs
- **Analysis strategy:**
  - b-jets selection:DeepJet (AK4 jets) DeepCSV (AK8 subjets)
  - Training DNN to classify the events
    - The signal categories are further divided into sub-categories according to the b-jet topology and multiplicity
  - In di-leptonic channel, designed a Heavy Mass Estimator (HME) to reconstruct the resonance.
- **Signal extraction:**
  - Fit to the DNN outputs
- **Results:**
  - Only HH results

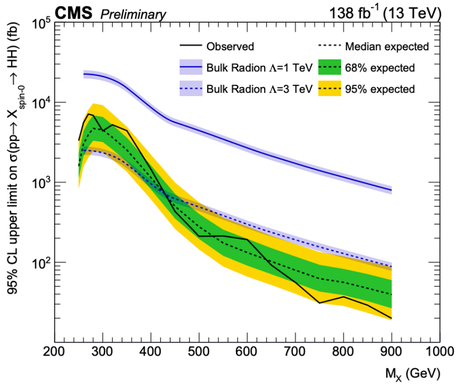


DNN output in semi-leptonic channel

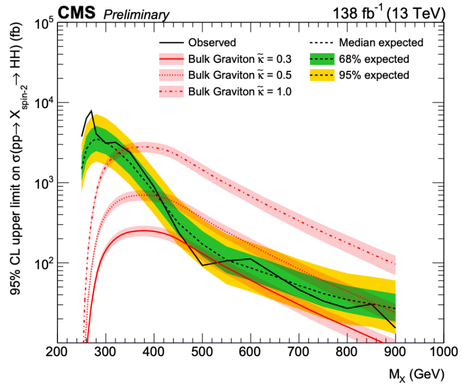


DNN output in di-leptonic channel

Plot source



Spin-0 results

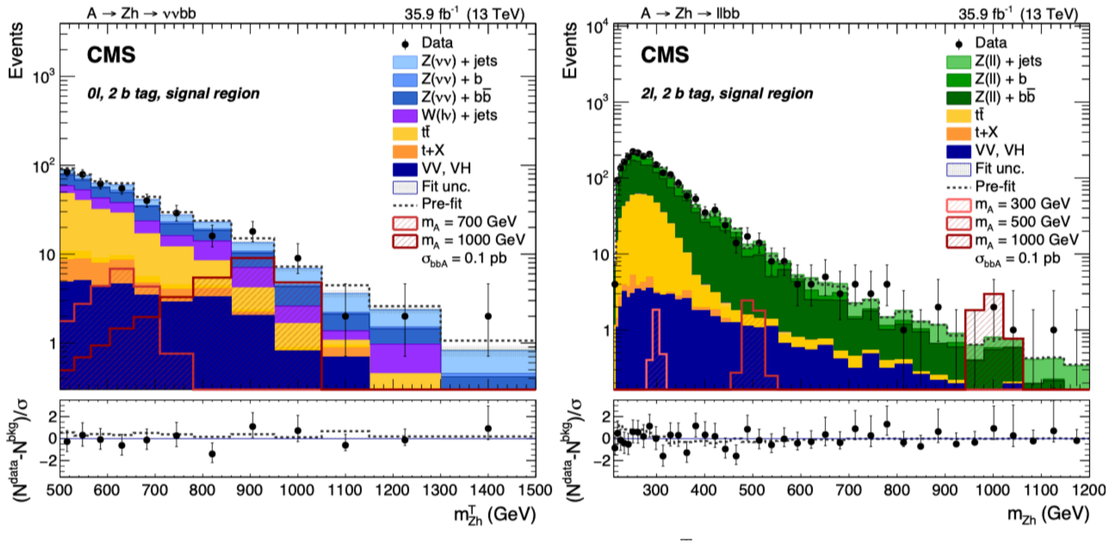


Spin-2 results

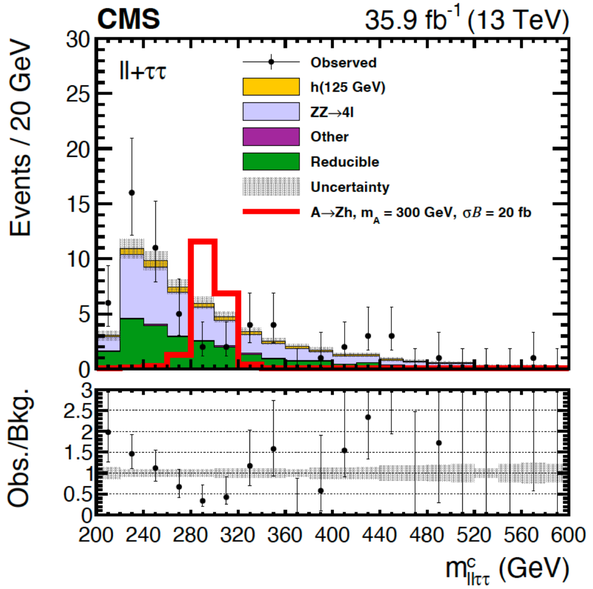
VH searches: sub-TeV mass region

- **Search for Higgs bosons through A→ZH decay mode, in the mass range below 1 TeV**
- **Based on 2016 data only**
  - H→bb decay channel,Z→ee,μμ,$\nu\nu$
  - H→$\tau\tau$ decay channel, Z→ee or μμ

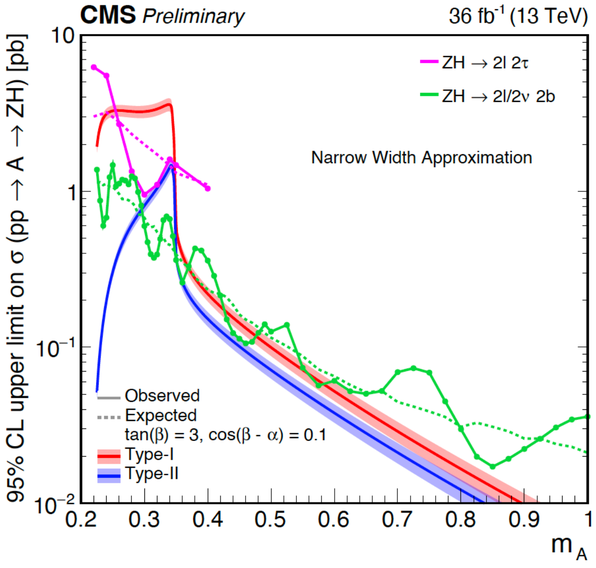
$$m_{\mathrm{ZH}}^{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}^{\mathrm{H}} \left[1 - \cos\Delta\phi(\mathrm{H}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})\right]}$$



A→Z(vv)H(bb)　　A→Z(ee or μμ)H(bb)



A→Z(ee or μμ)H($\tau\tau$)



upper limits compared to 2HDM Type-I and Type-II models

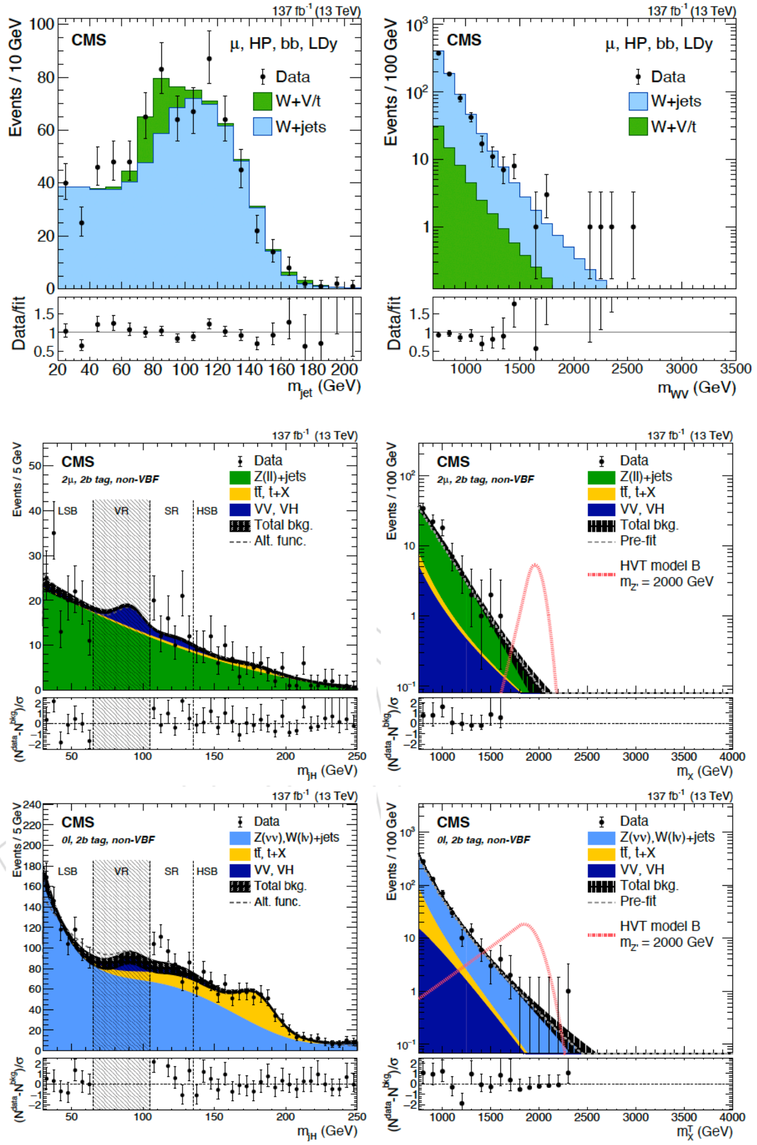
VH searches: high mass region

- **Leptonic V boson decays:**
  - presence of an isolated electron (muon) with pT >115 (55) GeV
    - W(lv) channel: + pT(miss) > 80 (40) GeV in the electron (muon) case
    - Z(ll) channels: + a second lepton with pT> 20 GeV and with the same flavour as the first lepton
  - Z(vv) channel: absence of leptons, pT(miss)> 250 GeV
- AK8 jet as H→bb candidate

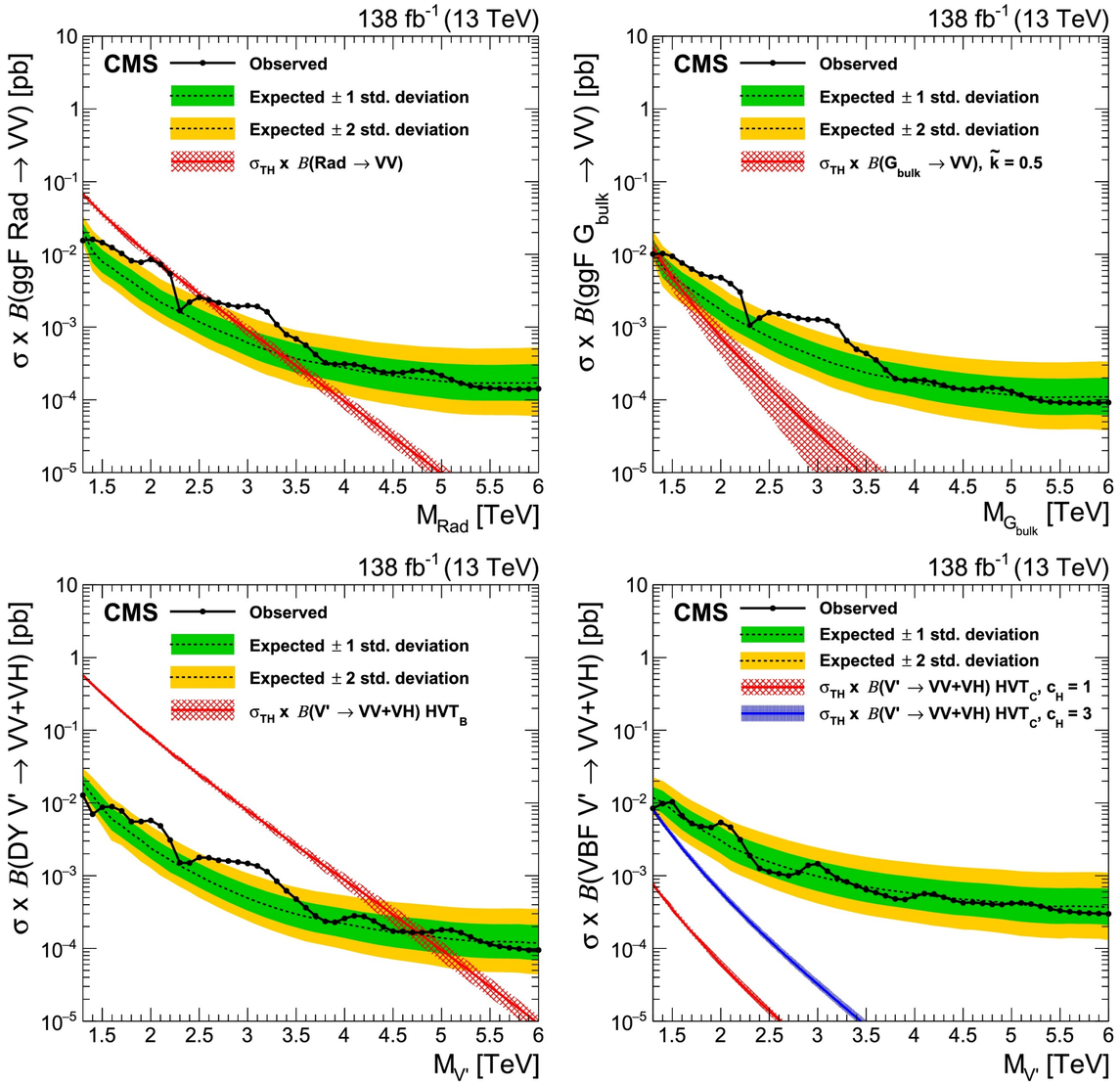
W(lv)H(bb) channel

Z(ll)H(bb) channel

Z(vv)H(bb) channel



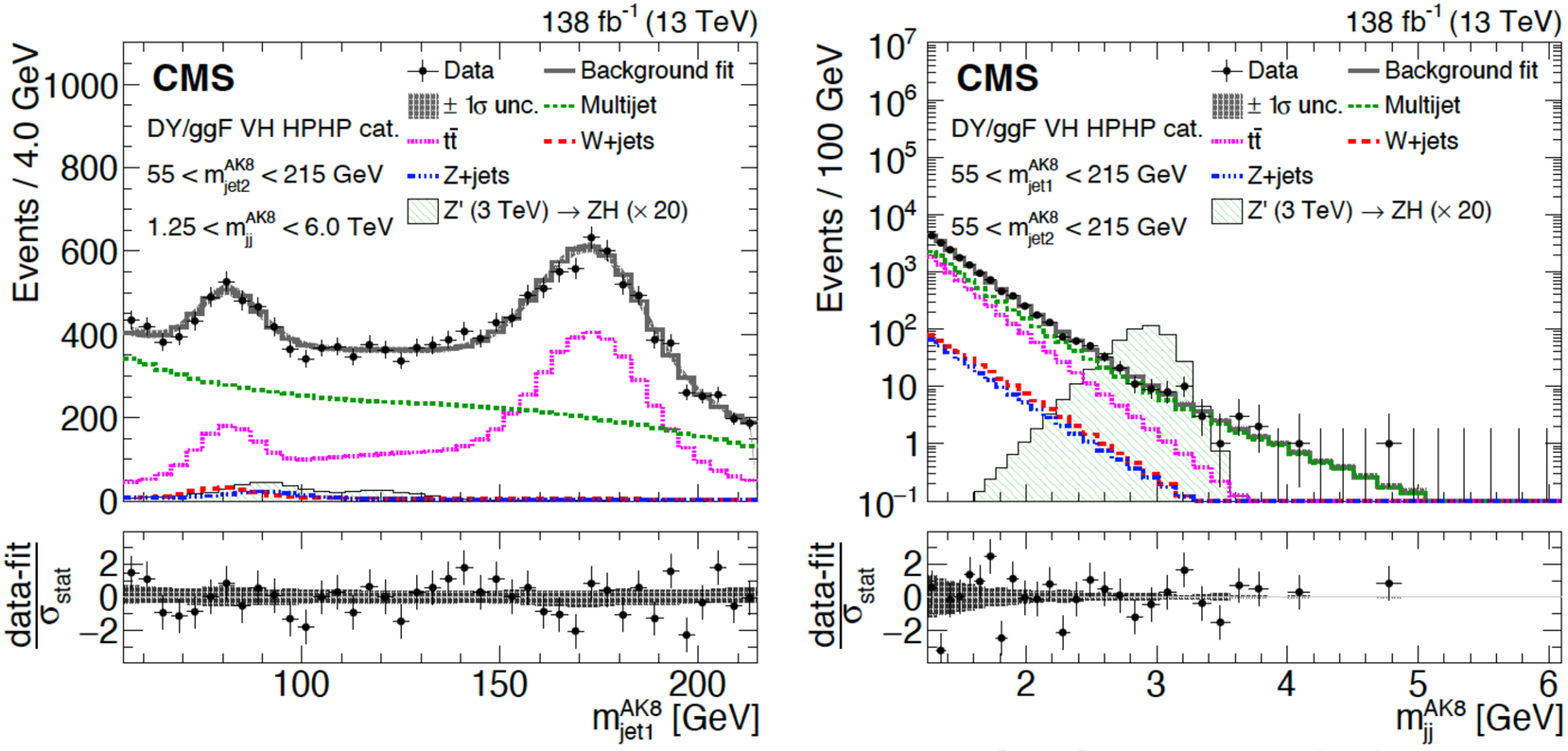
VH search results



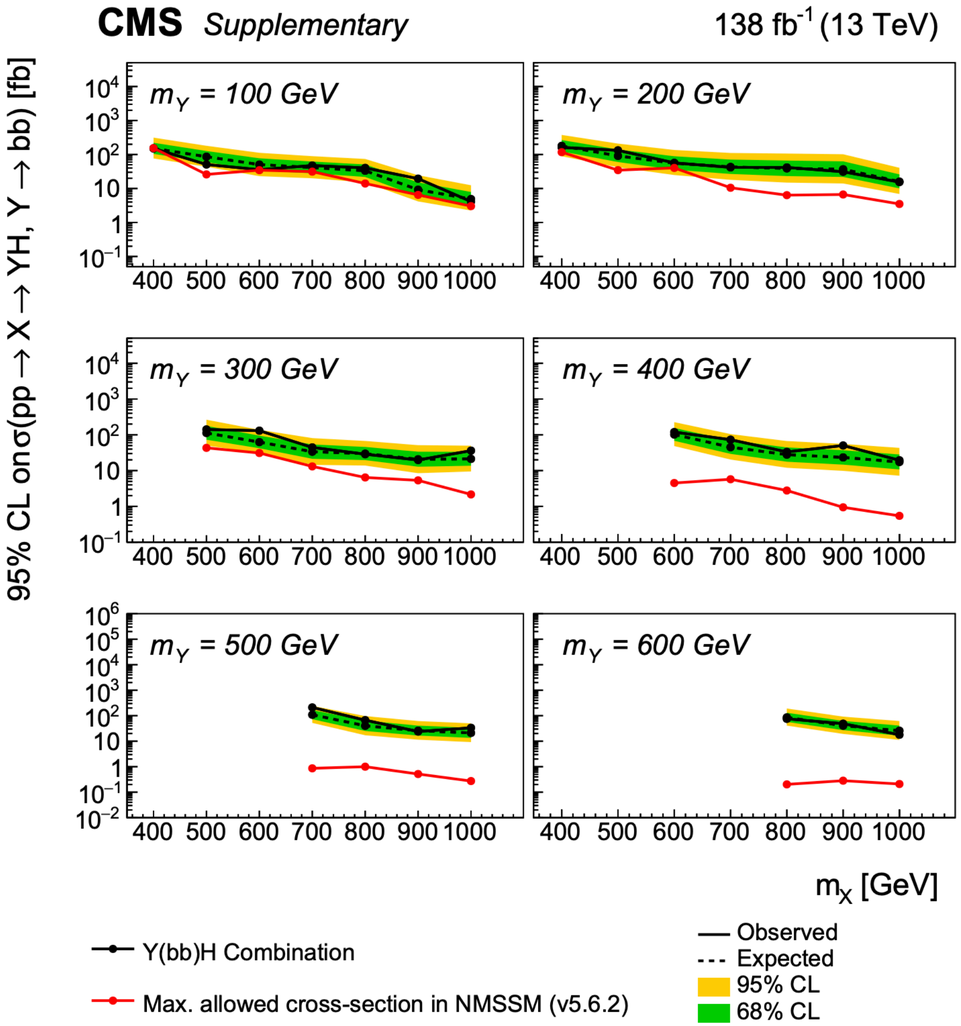
A maximum local significance of 3.6 standard deviations from the standard model prediction, corresponding to a global significance of 2.3 standard deviations, is observed at masses of 2.1 and 2.9 TeV.

VH searches: high mass region

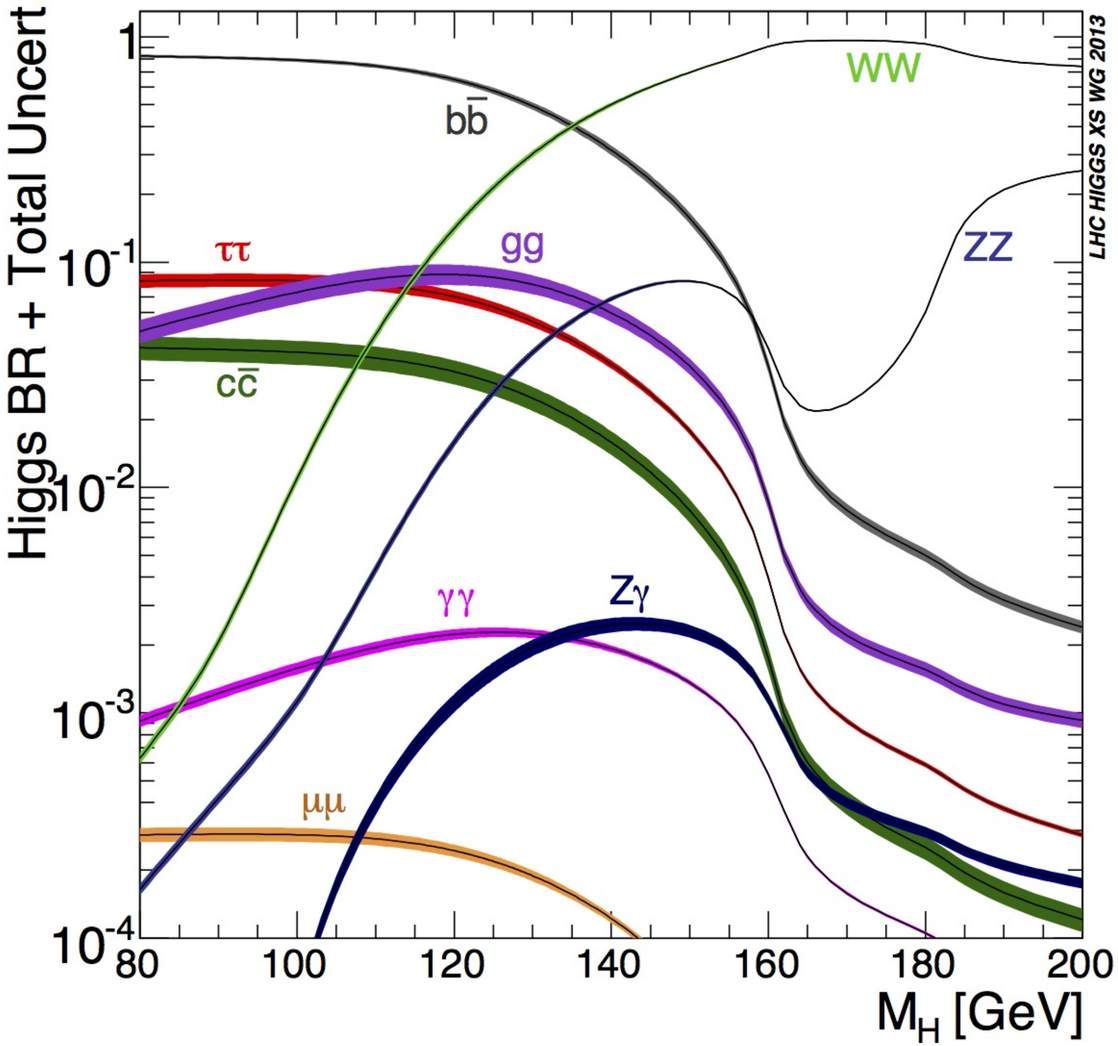
- **Hadronic V boson decays:**
  - Presence of two AK8 jets with pT > 200 GeV
  - invariant mass of the selected AK8 jets > 1250 GeV



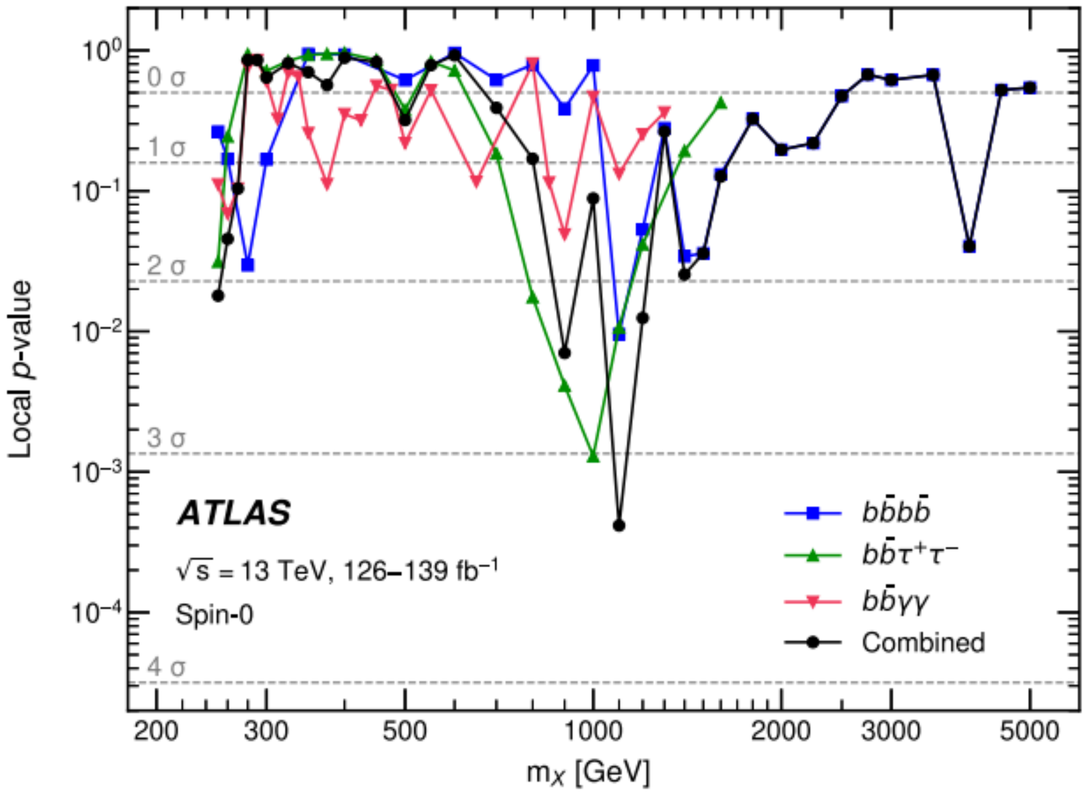
NMSSM comparison

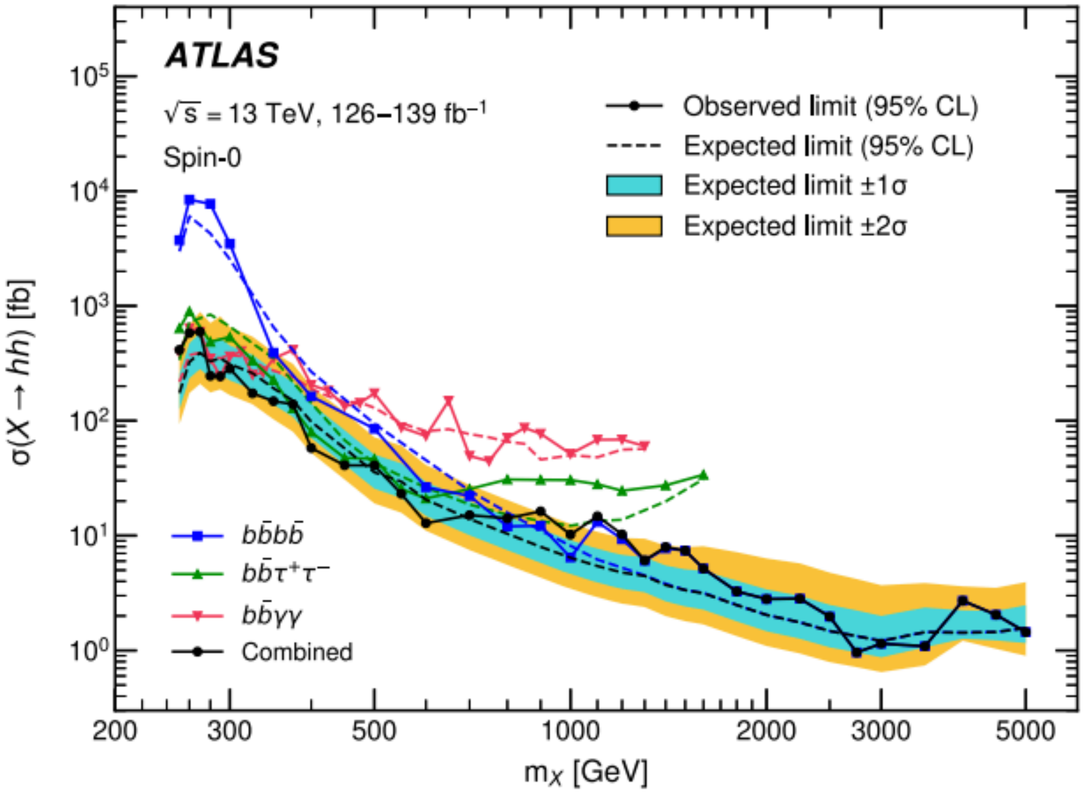


Higgs branching ratio



ATLAS HH combination results



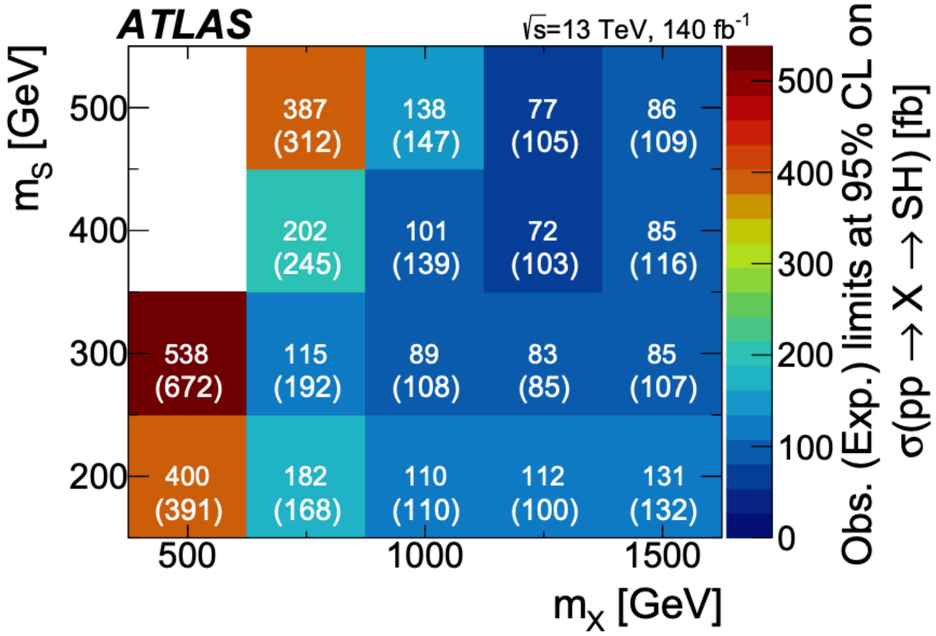


The largest deviation is observed at 1.1 TeV and corresponds to a local significance of 3.3σ, which is driven mainly by the bb⁻ ττ– channel. The global significance of this excess is estimated to be 2.1σ

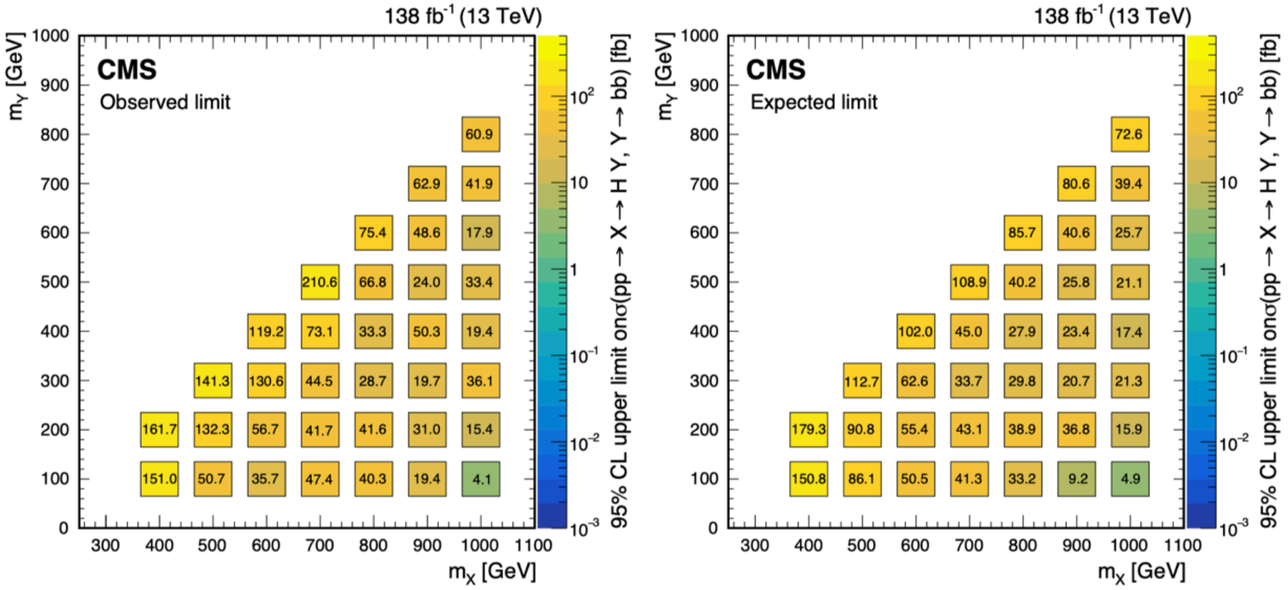
Below masses of 0.32 TeV and above 0.8 TeV, this combination gives the strongest observed limits to date on resonant HH production.

ATLAS combination results

- **ATLAS vs CMS**



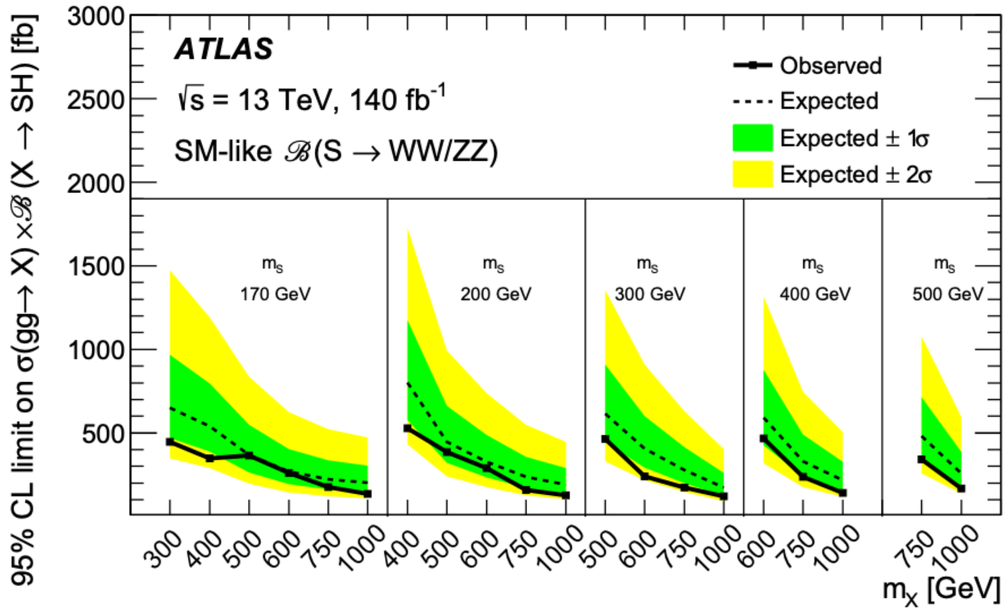
ATLAS results



CMS results

ATLAS VV$\gamma\gamma$ results

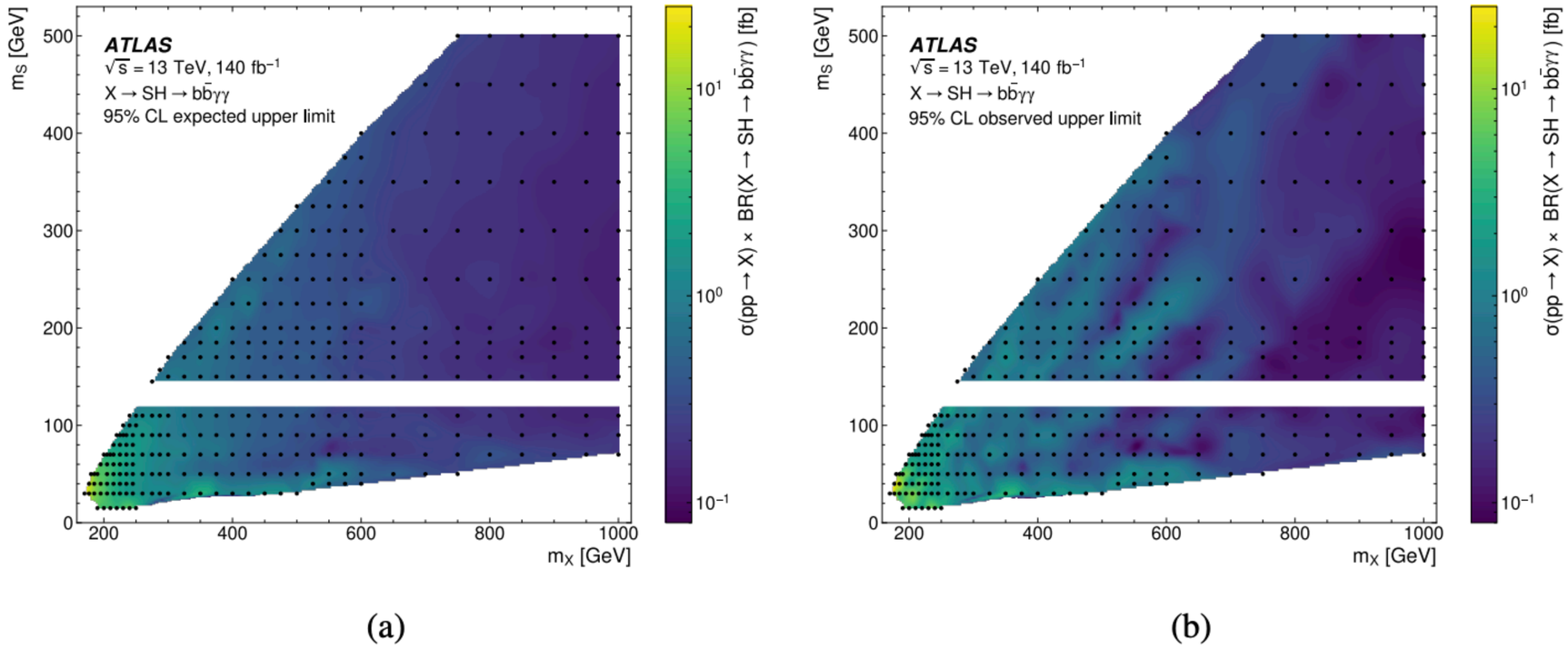
- The observed (expected) upper limits lie in the range of 530 – 120 fb (800 – 170 fb) under the assumption that $\mathcal{B}$(S→ WW/ZZ) corresponding to those the SM Higgs boson would have at the mass of the particle.



link

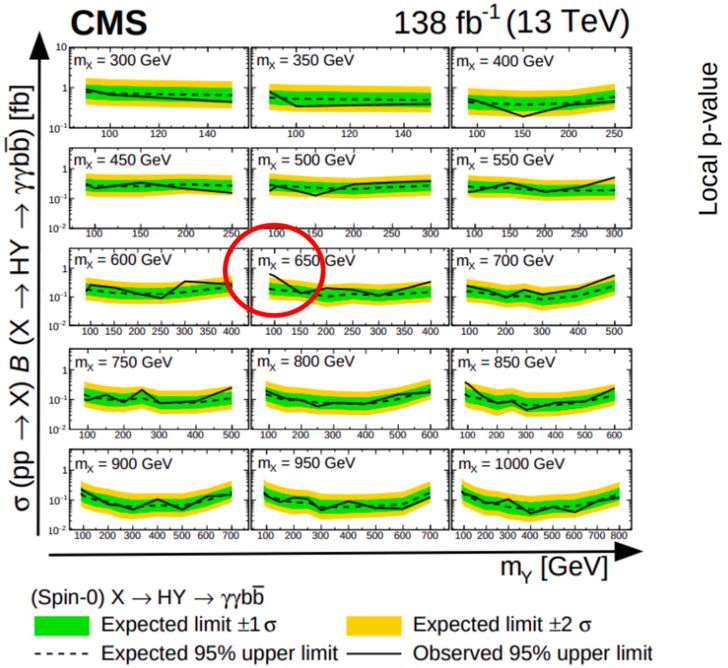
ATLAS bbγγ

- **The largest deviation from the background-only expectation occurs for (mX, ms) = (575, 200) GeV with a local (global) significance of 3.5 (2.0) standard deviations.**

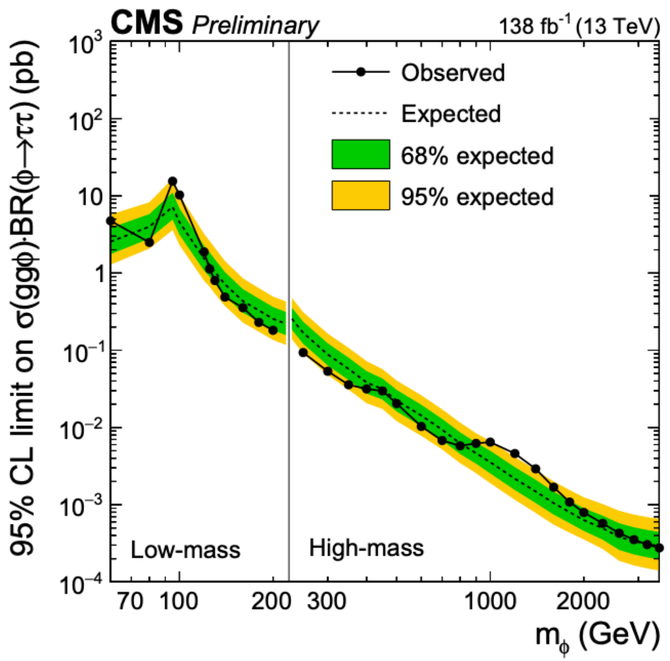


plot source

CMS excess

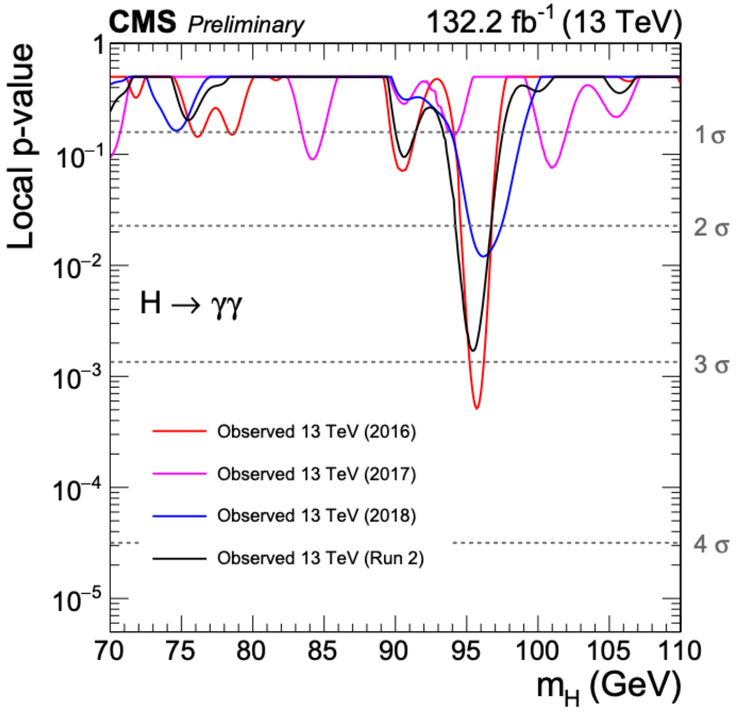


Local (global) significances (mX,mY) = 650, 90 GeV: 3.8 (2.8)



[Additional Higgs search]

The largest deviation from the expectation is observed for ggϕ production at mϕ = 100 GeV with a local (global) p-value of 3.1 (2.7) standard deviations (s.d.)

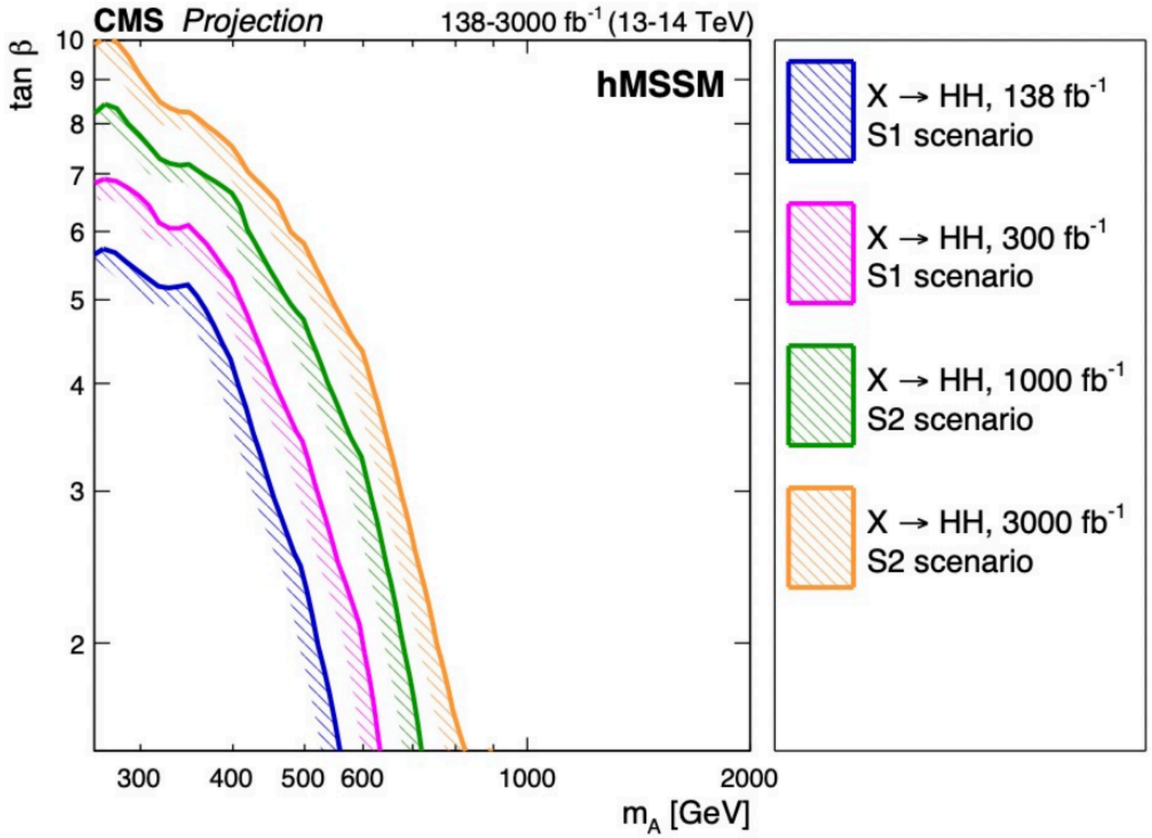


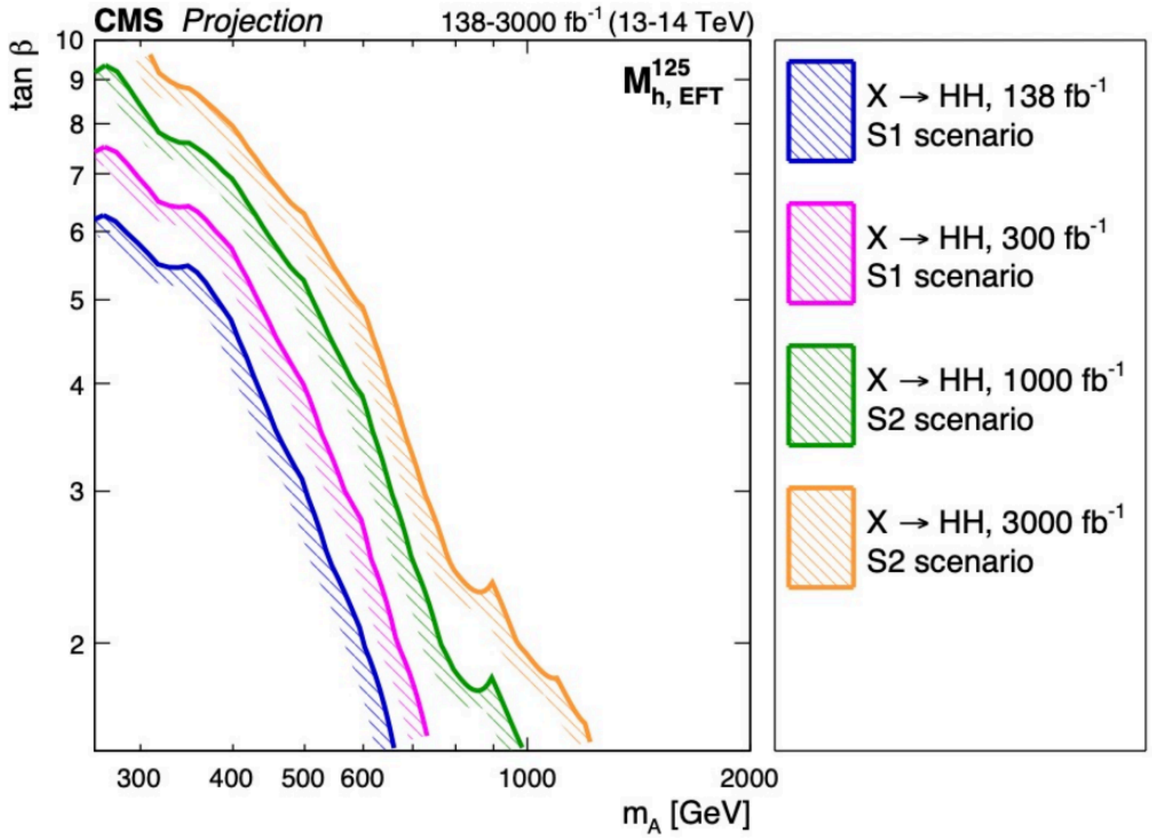
[Low mass Higgs search]

At 95.4 GeV with a local (global) significance of 2.9 (1.3) standard deviations

NMSSM exclusions in Projection results

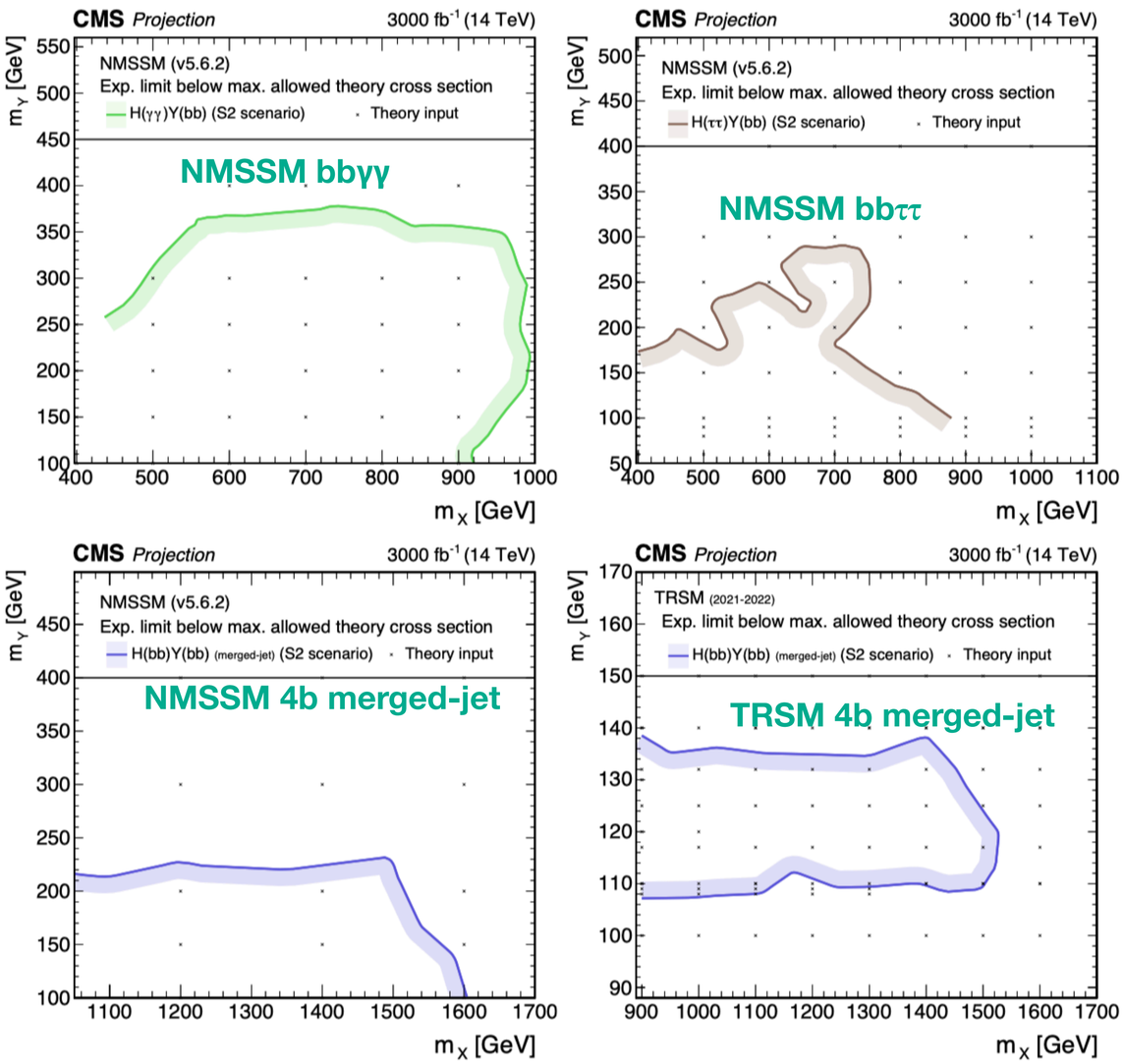
- **Exclusion from the resonant HH searches will complement the searches for X decaying to a pair of fermions or vector bosons.**





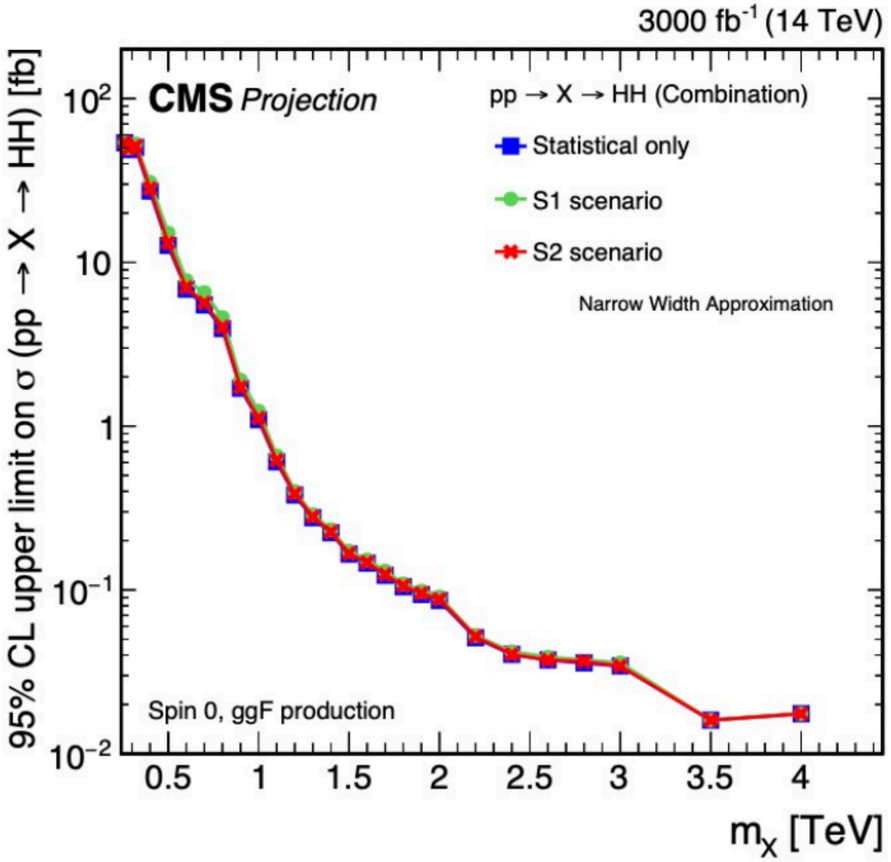
NMSSM and TRSM exclusions in Projection results

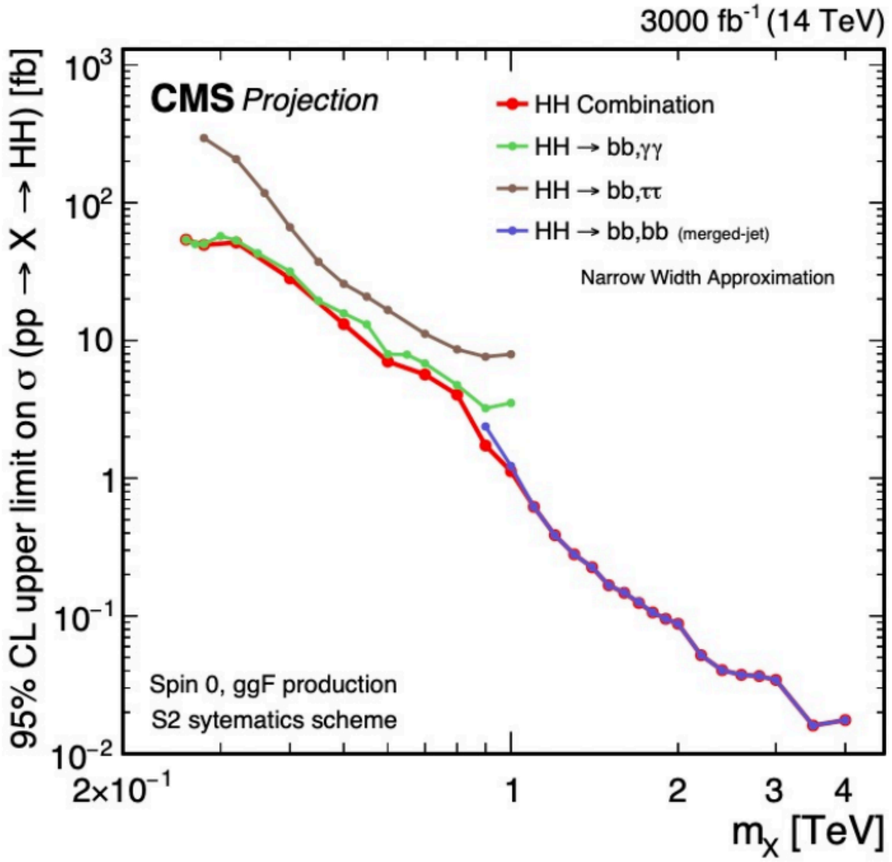
- **Exclusion contours obtained with interpolation: areas where the projected upper limit is lower than the maximally allowed cross section in the model.**



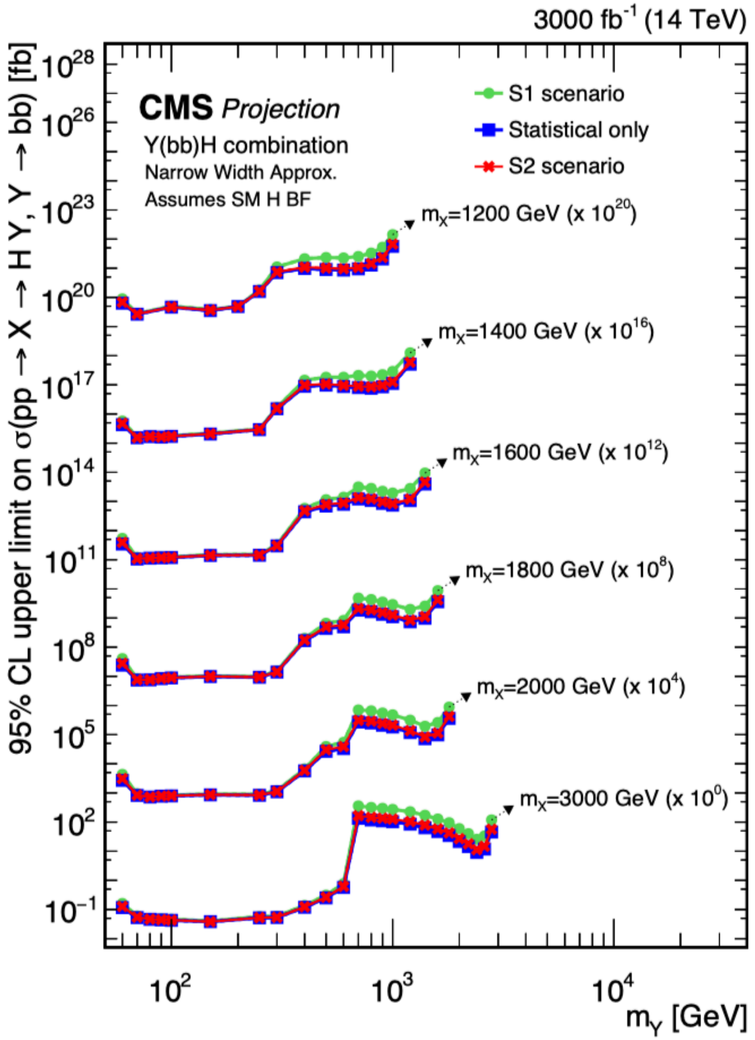
HH Projection

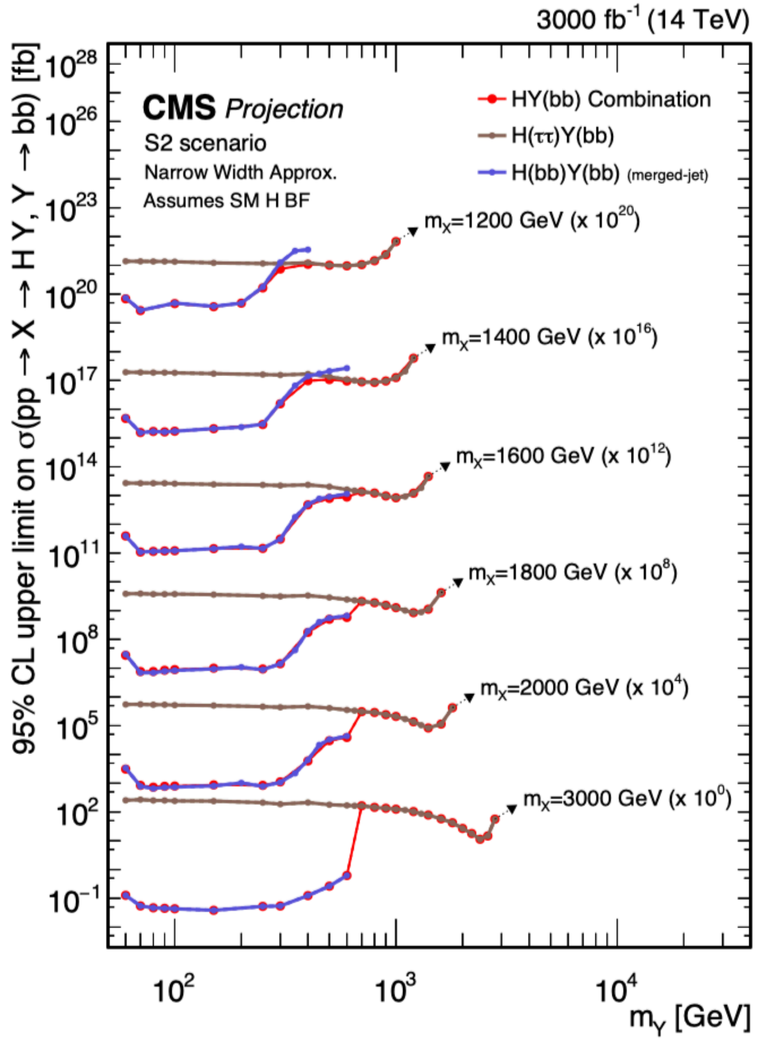
- **The combination still be statistics-dominated**
  - bb$\gamma\gamma$, bbbb dominates the combination





YH Projection (mX<1000GeV)

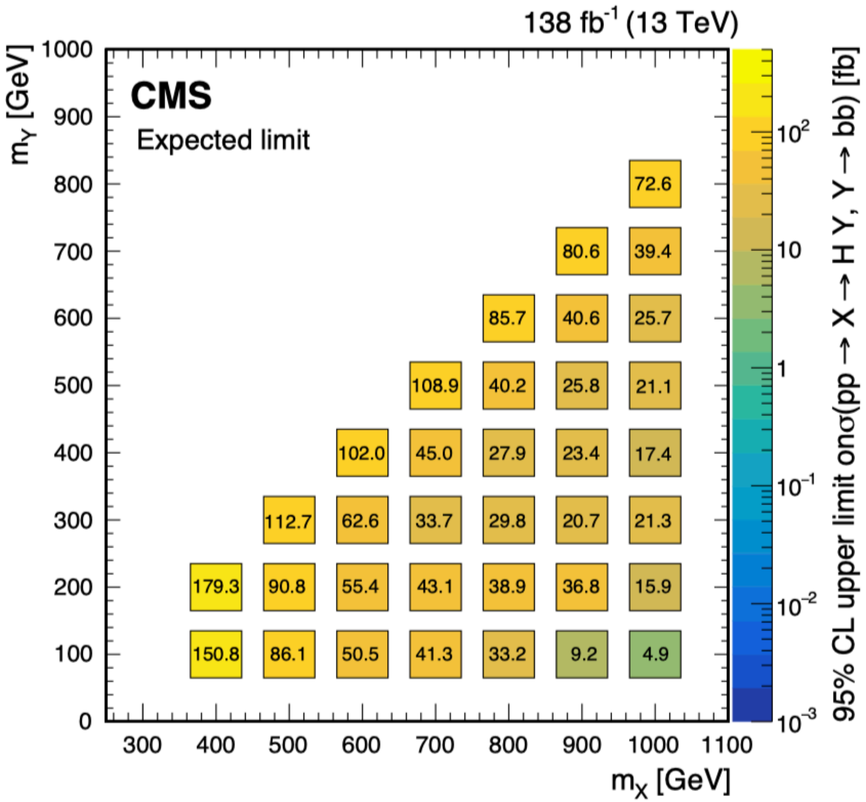




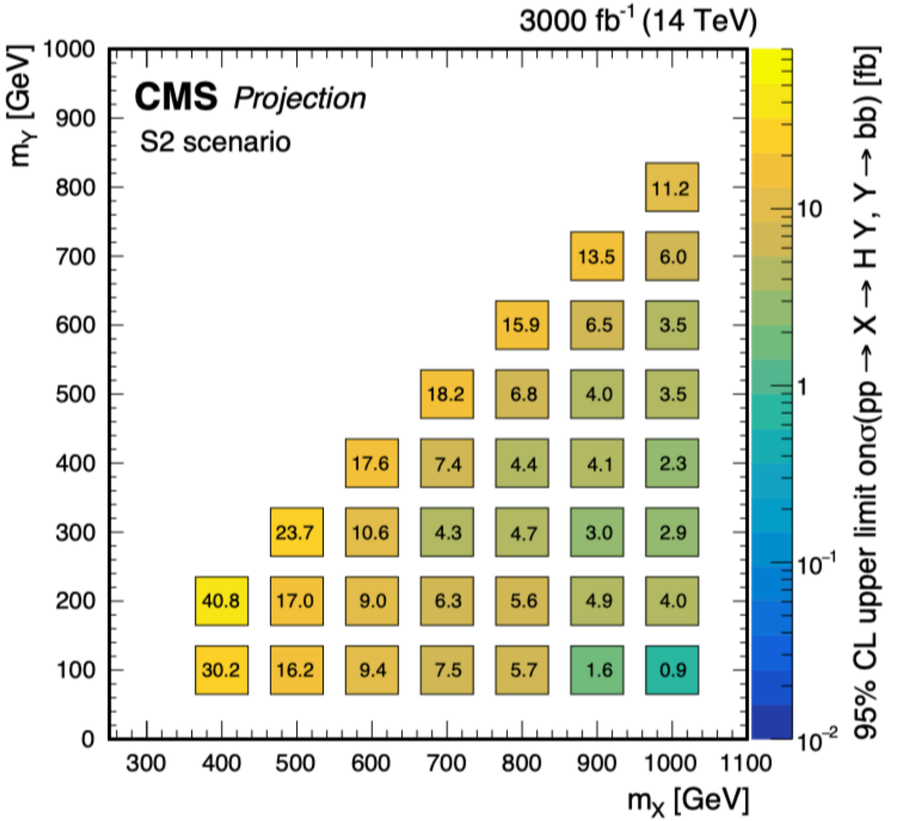
- **The combination gained sensitivity from different channels in different regions**
  - The regions with the largest ratios of mY/mX correspond to a Y particle with low transverse momentum, and can be probed with the bbγγ channel.
  - In the regions with small ratios of mY/mX, the Y particle receives a large Lorentz boost, such that the bbbb boosted channel has the highest sensitivity and only this final state is considered.
  - In the intermediate region, the bbγγ and bbττ channels provide comparable sensitivity.

YH Projection

- **Selected bins of expected upper limit projections of the YH combination presented as a function of m_X and m_Y**



Run2 results



Projection results

Interpretations: hMSSM model

- **hMSSM is a benchmark designed to produce 125GeV mass for the lightest MSSM scalar**
  - There is a unique sensitivity of the X → HH searches for mA ≳ 450 GeV and tan β < 5. It can also be a complement to $\tau\tau$ analysis