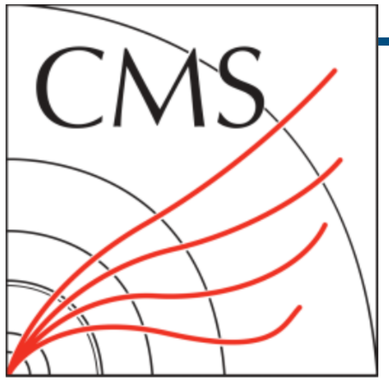

Search for HH and YH resonances in CMS

Shaowei Song on behalf of CMS HH/YH combination

16th France-China Particle Physics Network/Laboratory workshop (FCPPN/L 2025)

21-25 July, 2025

Haitian Grand Theatre Hotel, Qingdao

中國科學院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Over 20 institutes/universities contributed to this paper

- IP2I, IHEP, and PKU made important contributions to this paper, reflecting strong and effective collaboration throughout the work.

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Searches for Higgs boson production through decays of heavy resonances

The CMS Collaboration ✉

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Searches for Higgs boson production through decays of heavy resonances

The CMS Collaboration*

Abstract

The discovery of the Higgs boson has led to new possible signatures for heavy resonance searches at the LHC. Since then, search channels including at least one Higgs boson plus another particle have formed an important part of the program of new physics searches. In this report, the status of these searches by the CMS Collaboration is reviewed. Searches are discussed for resonances decaying to two Higgs bosons, a Higgs and a vector boson, or a Higgs boson and another new resonance, with proton-proton collision data collected at $\sqrt{s} = 13$ TeV in the years 2016–2018. A combination of the results of these searches is presented together with constraints on different beyond-the-standard model scenarios, including scenarios with extended Higgs sectors, heavy vector bosons and extra dimensions. Studies are shown for the first time by CMS on the validity of the narrow-width approximation in searches for the resonant production of a pair of Higgs bosons. The potential for a discovery at the High Luminosity LHC is also discussed.

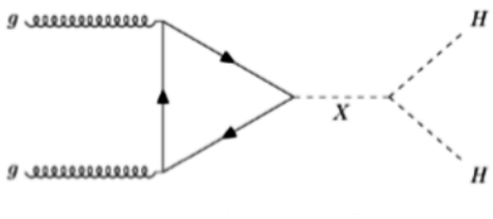
Outline

1. Introduction
2. HH/YH combination in CMS
3. HH/YH Interpretation
4. HH/YH Projection
5. Summary

Introduction

Higgs boson could be a probe to explore new physics

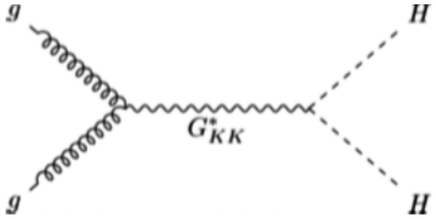
- Many BSM theories predict new massive resonances that could interact with the SM Higgs boson.
  - New heavy resonance could decay to two SM Higgs bosons
  - New heavy resonance could decay to one SM Higgs boson + one vector boson
  - New heavy resonance could decay to one SM Higgs boson + one scalar

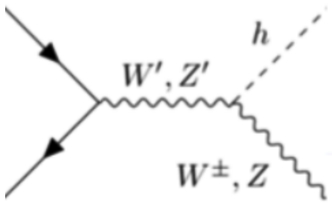


Extended Higgs Sectors

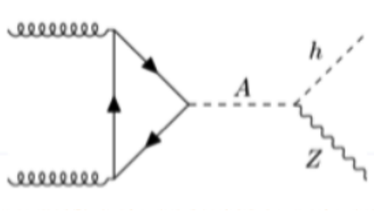
Warped Extra Dimensions

Scalar



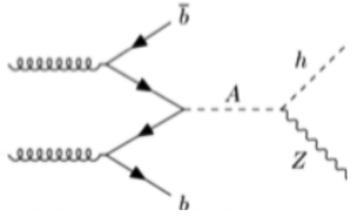


Vector bosons



Extended Higgs Sectors

Heavy Vector Triplet



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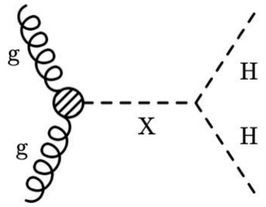


NMSSM

TRSM

Nomenclature

H: the 125 GeV SM Higgs boson

X: a scalar BSM resonance

Y: a scalar BSM resonance

G: a spin-2 BSM resonance

A: heavy pseudoscalar boson

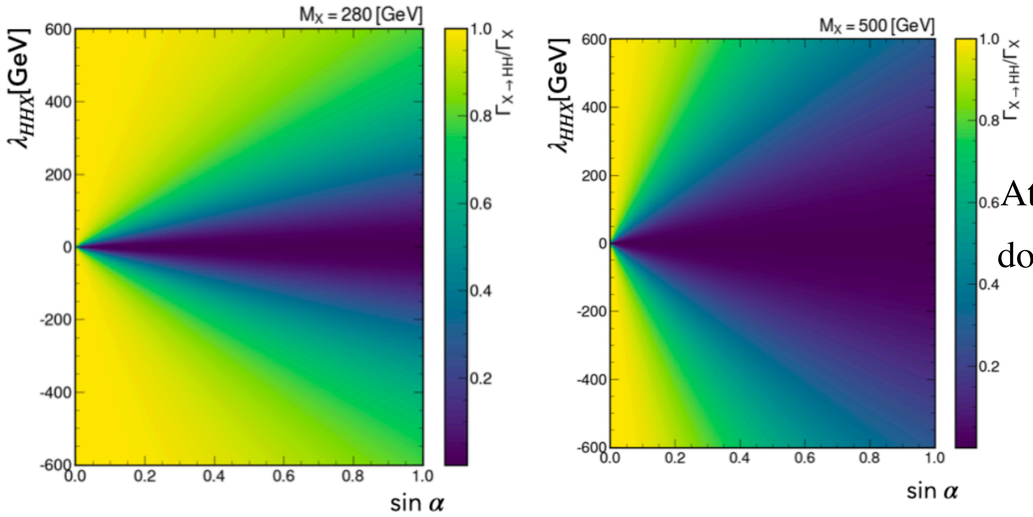
W'/Z': charge/neutral new force-carrying heavy vector bosons

Extended Higgs Sectors

- Additional real singlet
  - Parameters:
    - ✦ tanβ (ratio of the vacuum expectation values(vevs) v /<S>)
    - ✦ Mixing angle α
    - ✦ Masses
    - ✦ Deviation from HHH coupling k_λ
    - ✦ Coupling between the scalar and HH λ_{HHX}
  - Adding an additional real singlet field, leading to a new scalar X
    - ✦ X->HH (scalar) possible
  - Adding one more real singlet (Two Real Singlet Model, TRSM)
    - ✦ X->YH (scalar) possible
- Additional doublet: 2HDM
  - Parameters:
    - ✦ tanβ, α, masses, m_{12} (Z2 symmetry breaking parameter)
  - 3 neutral and 2 charged Higgs bosons
    - ✦ X->HH (scalar) and A->ZH (pseudo-scalar/CP-odd scalar) possible
      - ✦ Type I: All charged fermions
      - ✦ Type II: Only up-type quarks
      - ✦ Type X or leptonic-specific: Only quarks
      - ✦ Type Y or flipped: Only up-type quarks/leptons

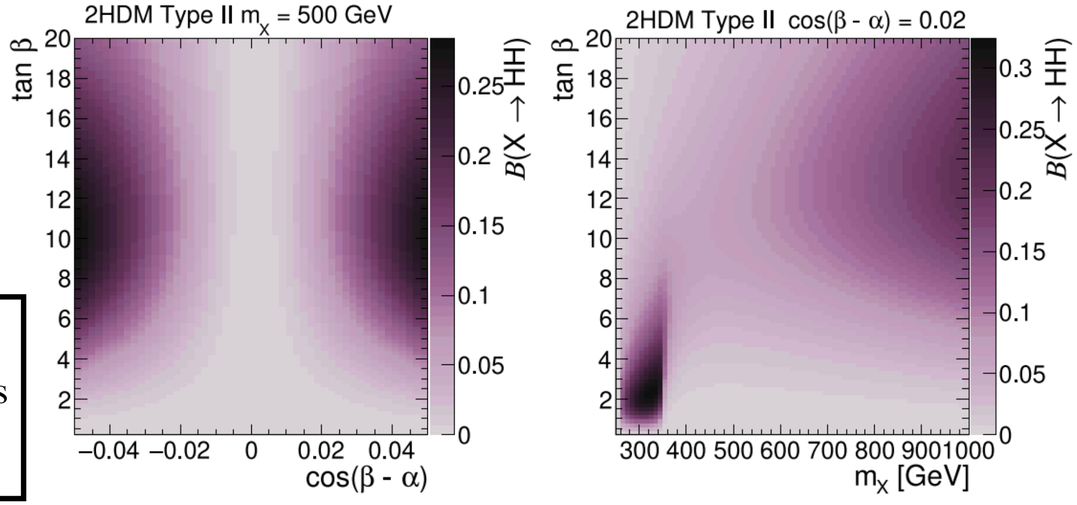
Four different types depends on which fermions couple to second doublet

  - While adding an additional real singlet field(Next-to-minimal 2HDM, N2HDM)
    - ✦ X->YH (scalar) possible



At low sinα, the dominated decay mode is HH

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)



BR to X->HH in 2HDM of Type II in cos(β-α) - tanβ plate for MX = 500GeV(left) and mX-tanβ plate(right)

Warped Extra Dimensions Model

- Predict exist spin-0 Radion and spin2 KK-Graviton.
  - Parameters:
    - ✦ Dimensionless quantity $k/\bar{M}_{pl}$ (k is warp factor, is reduced Planck mass) when referring to the KK-Graviton.
    - ✦ The mass scale Λ_R when referring to the Radion.
  - 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

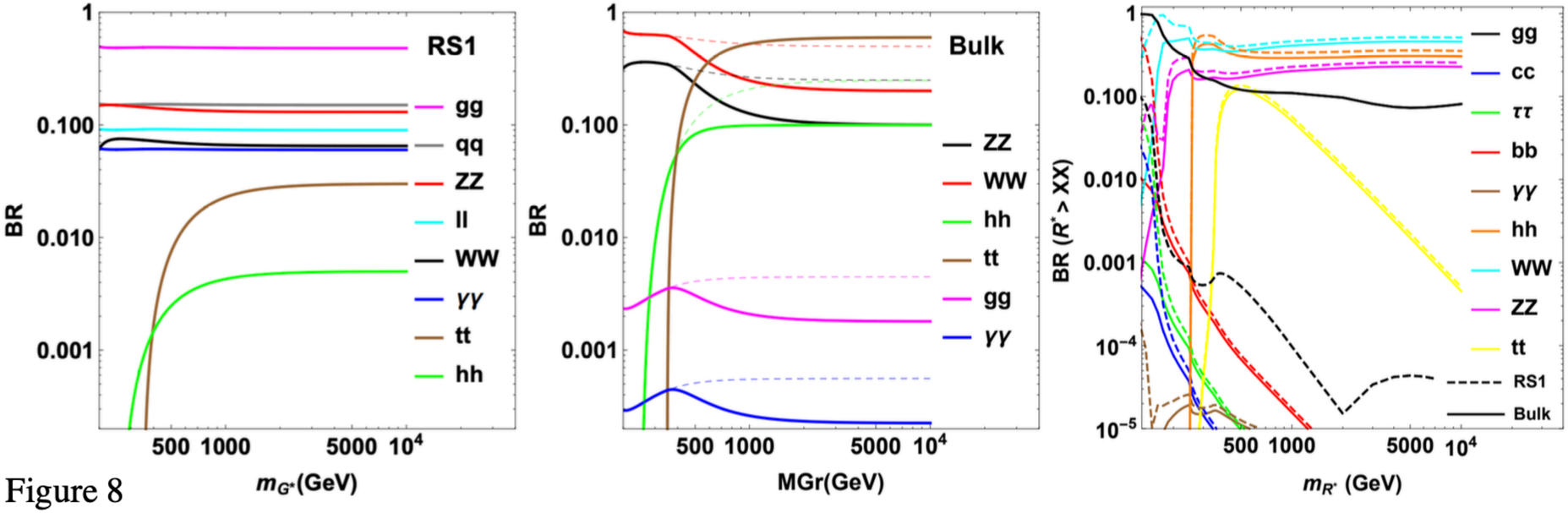
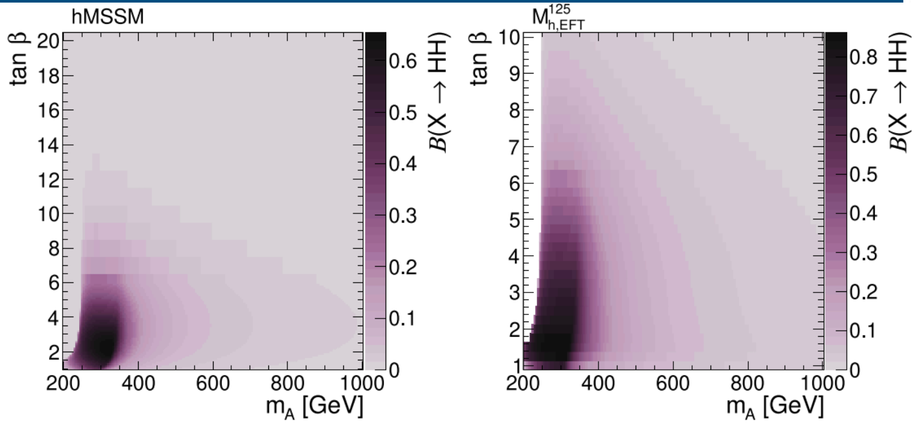


Figure 8

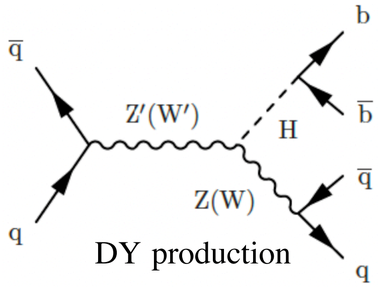
The decay branching fractions of a RS1 graviton (left), bulk graviton (middle), radion (right)

Supersymmetric and Heavy Vector Triplet Models

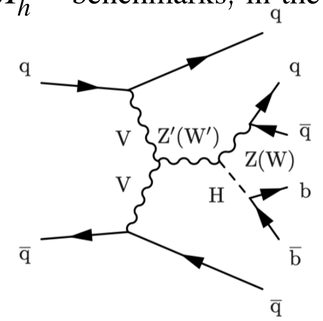
- Supersymmetric models
  - The Higgs sector of the minimal supersymmetric standard model (MSSM) has the structure of a Type II 2HDM
  - Adding an additional singlet field (Next-to-minimal MSSM, NMSSM)
    - ✦ X->YH possible
- Heavy Vector Triplet (W′ and Z′)
  - Minimal extension of the SM gauge group
    - ✦ Additional force-carrying heavy vector bosons, W′ and Z′
  - W′ and Z′ could decays to VH
  - Parameters:
    - ✦ The mass of W′ and Z′ resonances
    - ✦ a coefficient c_F, which scales the couplings of the additional gauge bosons to fermions
    - ✦ c_H, which scales the couplings to the Higgs boson and longitudinally polarized SM vector bosons
    - ✦ gv, representing the typical strength of the new vector boson interaction.



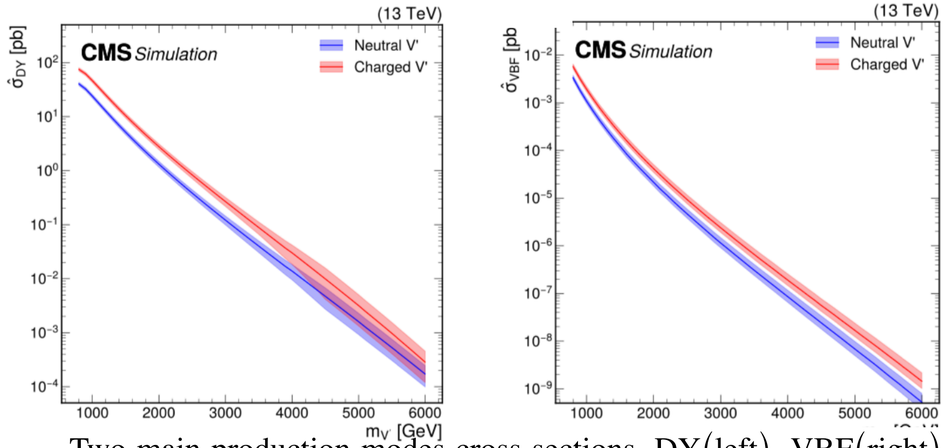
Branching fraction of X → HH in the MSSM, for the hMSSM (left) and the M_h^{125} benchmarks, in the mA−tan β plane



DY production



VBF production



Two main production modes cross sections, DY(left), VBF(right)

Heavy Vector Triplet benchmarks

- 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

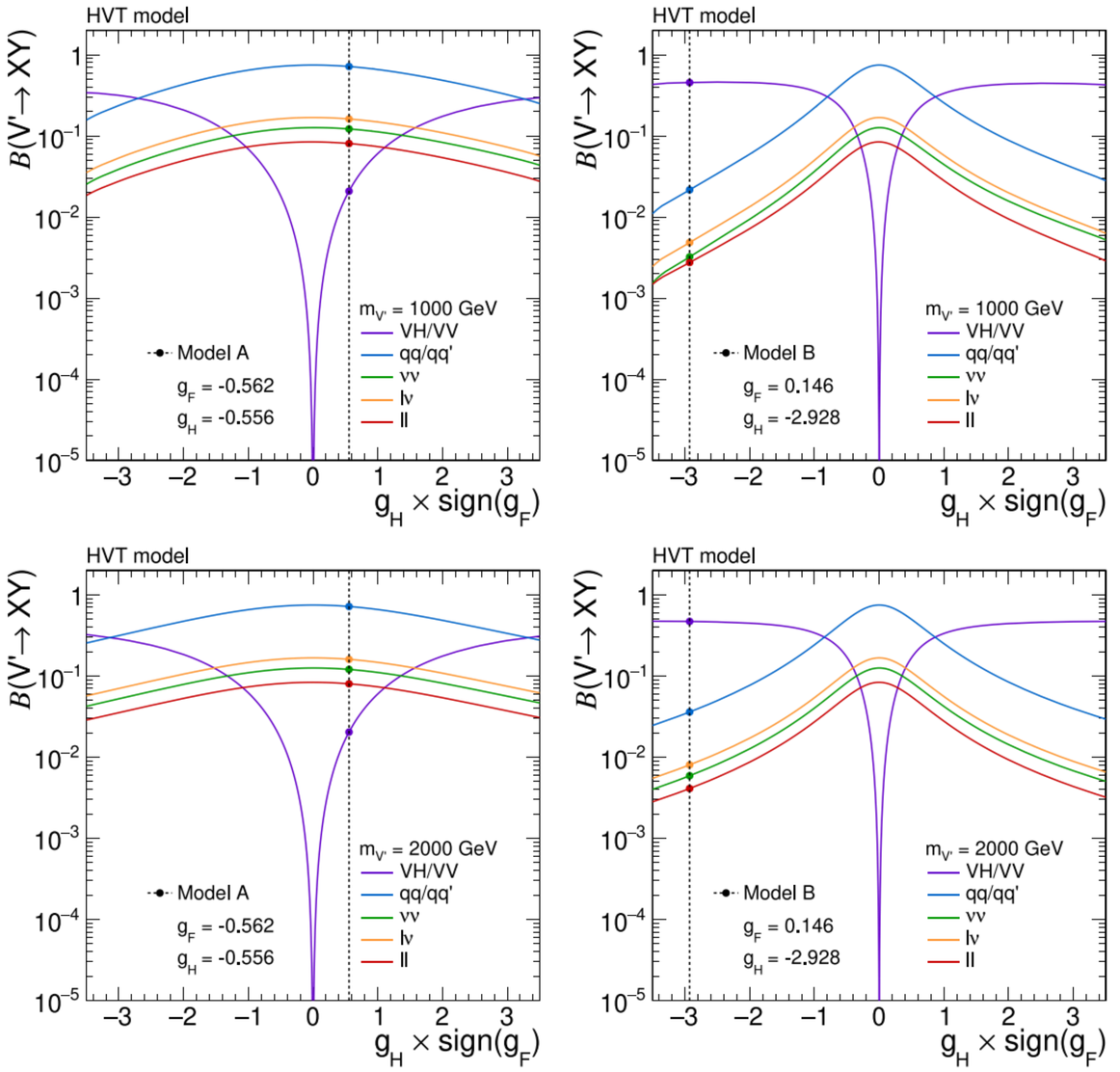


Fig. 11. Branching fractions for heavy vector triplet (HVT) bosons with masses of (upper) 1 and (lower) 2 TeV for values of the parameter g_F corresponding to models (left) A and (right) B. The exact branching fractions of each model are indicated by the crossing points of the individual curves with the dashed vertical lines.
Source: Calculations are based on the work of Ref. [30].

HH/YH combination in CMS

- HH/YH searches in CMS:
  - bbγγ (JHEP), in combination
  - bbττ (JHEP), in combination
  - bbbb boosted (PLB), in combination
  - multilepton (JHEP), only HH in combination
  - bbWW (JHEP,JHEP), only HH in combination
  - ττγγ (CMS HIG-22-012)....
- Search ranges:
  - Heavy resonance X: 240GeV to 4.5TeV
  - New scalar Y: 60GeV to 2800 GeV
  - Individual channels search ranges shown in the right table
- Combining different analyses will result in a **more senstive** final result

Table 1 — In paper

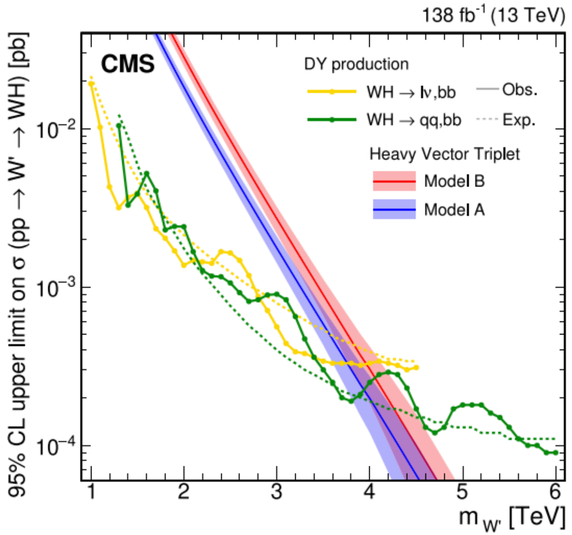
H	H		m_X		
b b	W($\ell\nu$)W($\ell\nu + qq$)	[115]	250– 900		resolved + semi-merged
b b	W($\ell\nu$)W($\ell\nu + qq$)	[116]	800–4500		merged
WW+$\tau\tau$	WW+$\tau\tau$	[117]	250–1000		multi-lepton final state
Y	H		m_X	m_Y	
b b	$\tau\ \tau$	[118]	240–3000	60–2800	resolved jets and τ leptons
b b	$\gamma\ \gamma$	[119]	300–1000	90– 800	resolved jets and photons
b b	b b	[120]	90–4000	60– 600	two merged bb jets

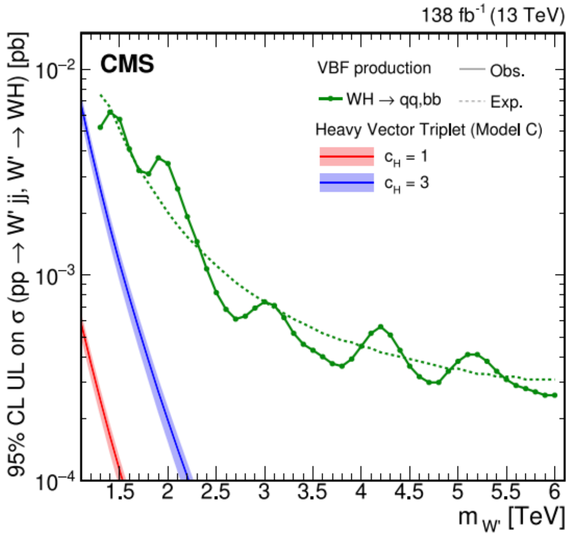
	bb	WW	ττ	ZZ	γγ
bb	33%★				
WW	25%★	4.6%★			
ττ	7.4%★	2.5%★	0.39%★		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%★	0.10%	0.029%	0.013%	0.0005%

Most channels take advantage of the high b-quark Branching ratio

VH analysis in CMS

- VH searches in the CMS:
  - Z(ll) (JHEP)
  - Z(ll+)bb (EPJC)
  - W(l)bb (PRD)
  - Z(ll)bb (EPJC)
  - W(qq)bb (PLB)

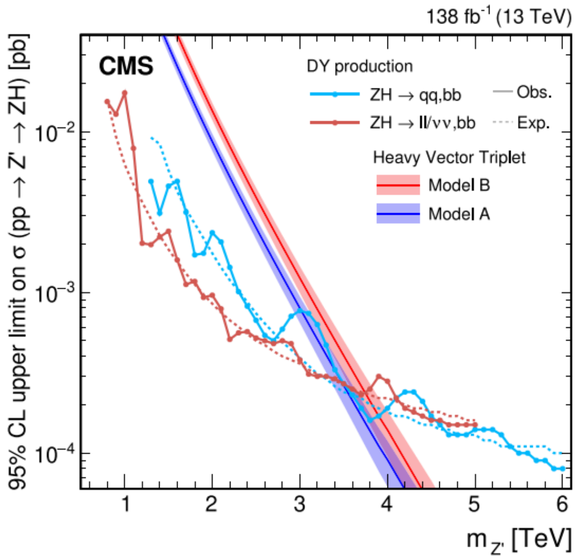


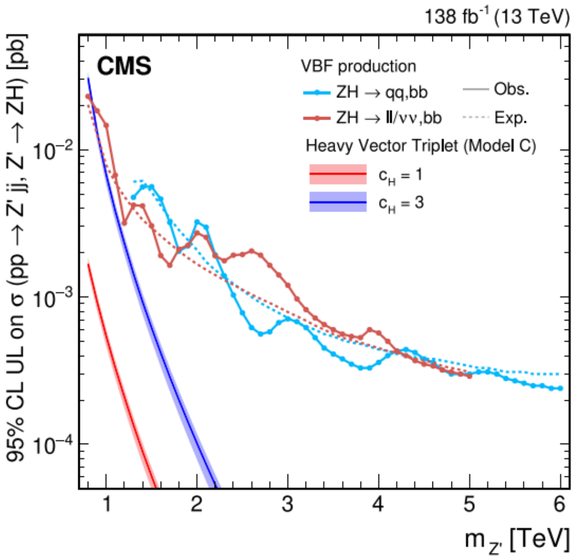


Upper limits on the production cross section times branching fraction of W' and Z' spin-1 resonance for the DY and VBF production modes, compared to theory predictions from HVT models.

- Search ranges :
  - Heavy resonance X: 220GeV to 6TeV

V	H	m_X	
Z($\ell\ell$)	$\tau\tau$	220 – 400	
Z($\ell\ell + \nu\nu$)	bb	225 – 1000	resolved jets
W($\ell\nu$)	bb	1000 – 4500	W → $\ell\nu$ and merged bb jet
Z($\ell\ell$)	bb	800 – 4600	Z → $\ell\ell/\nu\nu$ and merged bb jet
Z(qq)	bb	1300 – 6000	two merged jets





Combination procedure

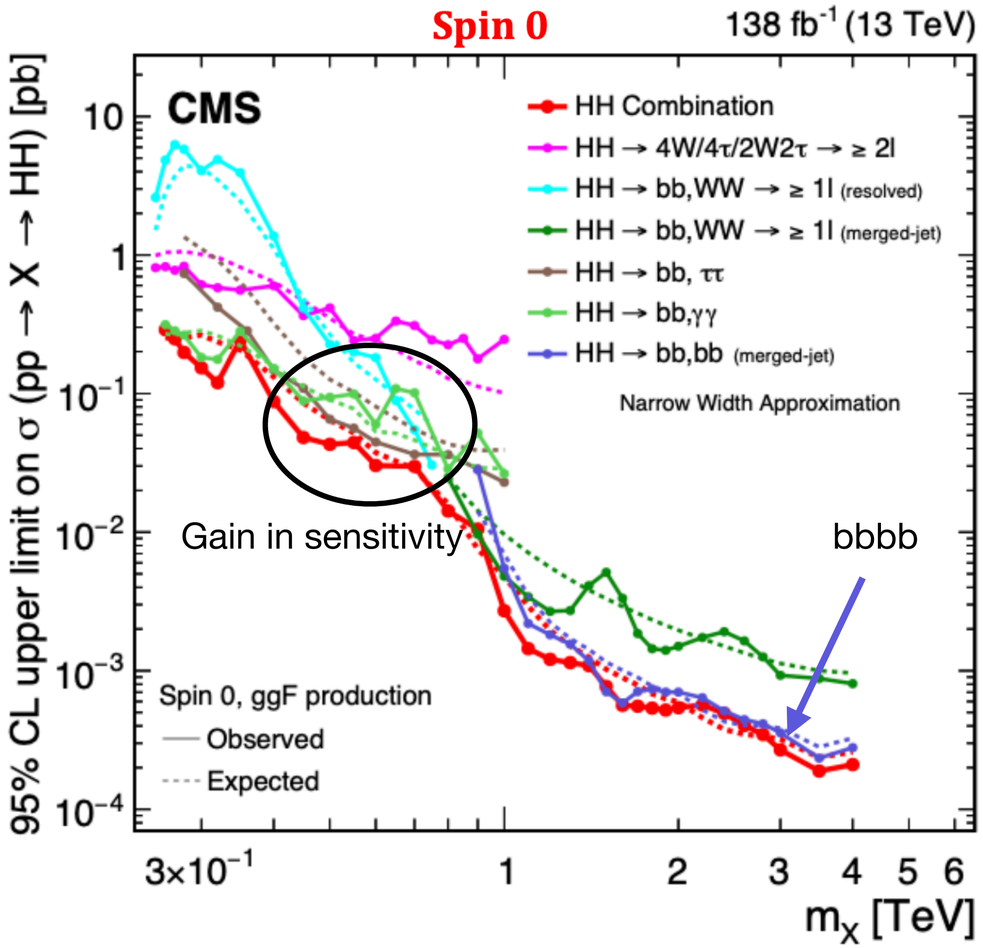
1. Overlap removal:
   - one event can't appear in two analyses.
2. Systematics alignment:
   - The systematics that are supposed to behave the same way across analyses are considered a **100% correlated**
3. Each analysis is normalized to its branch ratio.
4. Statistical test:
   - check the sanity of the statistical combination — goodness of fit, pulls and impacts of nuisance parameters , bias test

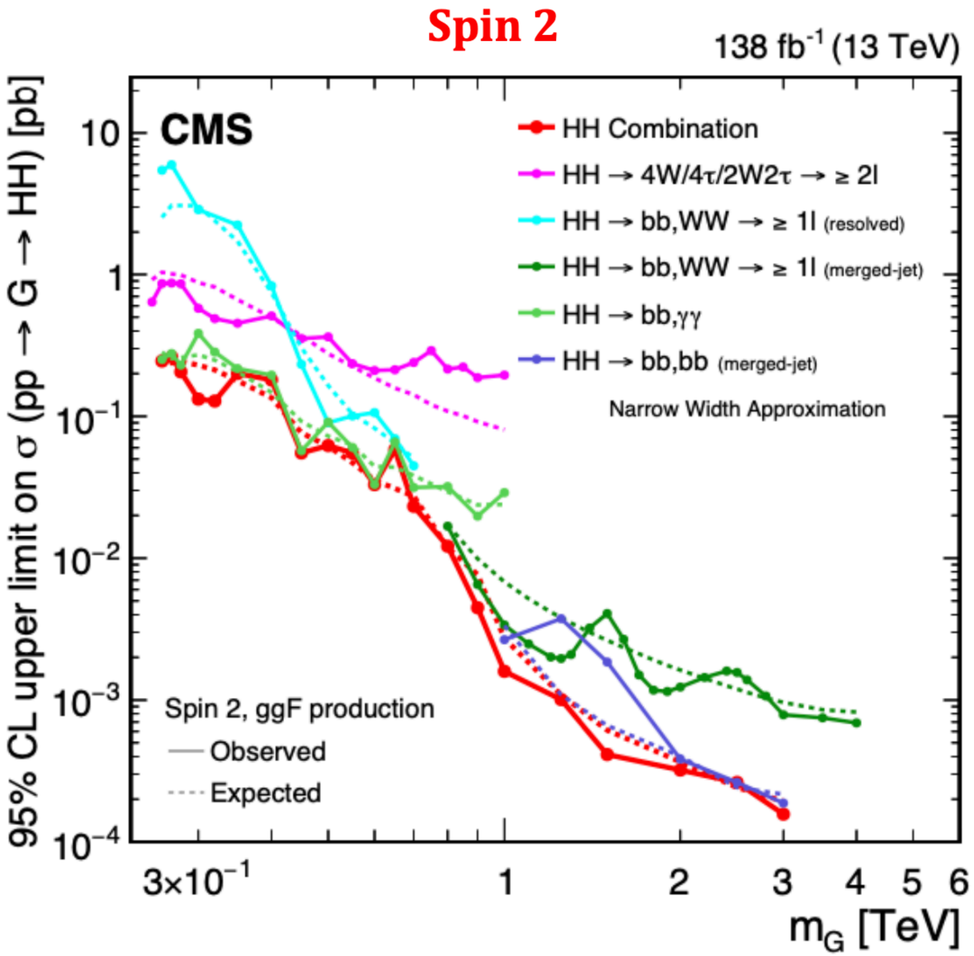
- For YH combination, **only final states with Y → bb are considered.**
  - In order to stay as model-independent as possible, a correction is only done for the branching fraction of the H boson.
- The combination includes only those **mass points that are common to all analyses considered**.

HH combination results

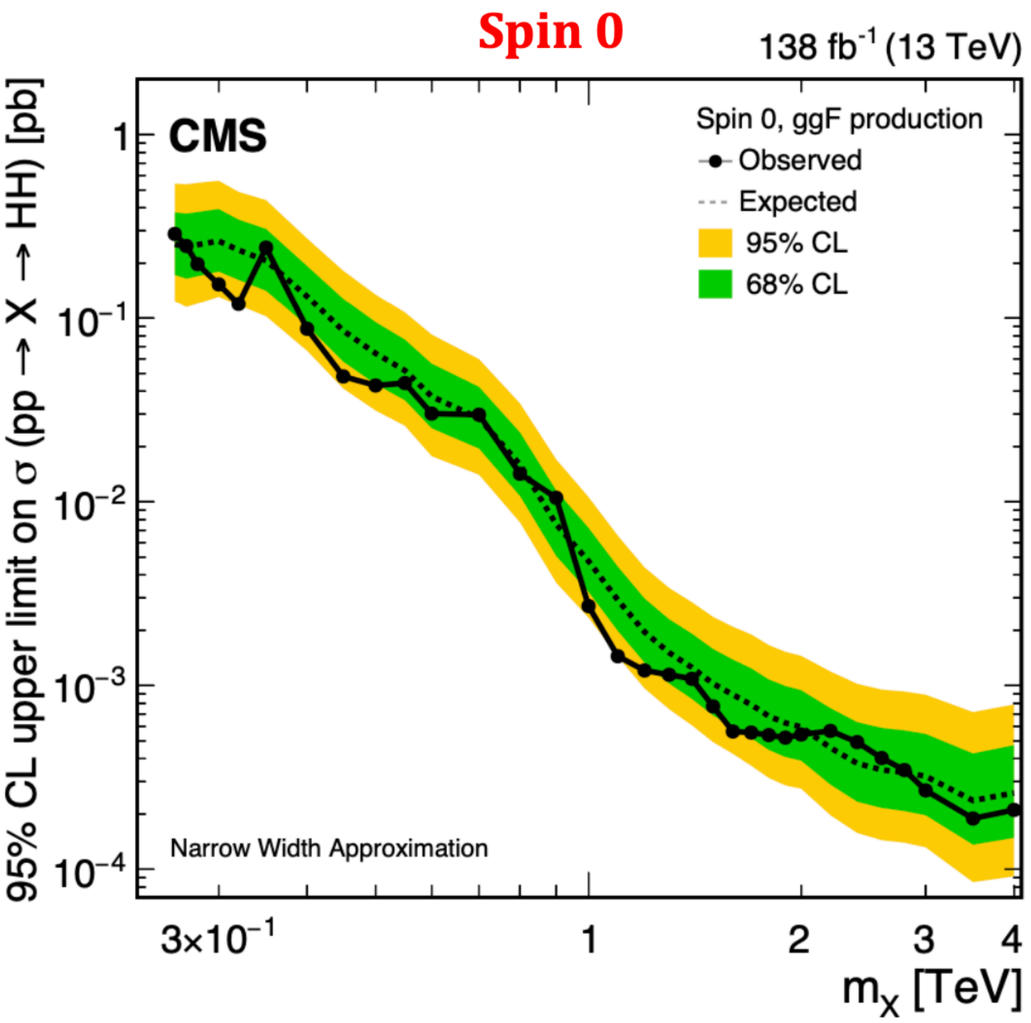
HH combination and per channel results

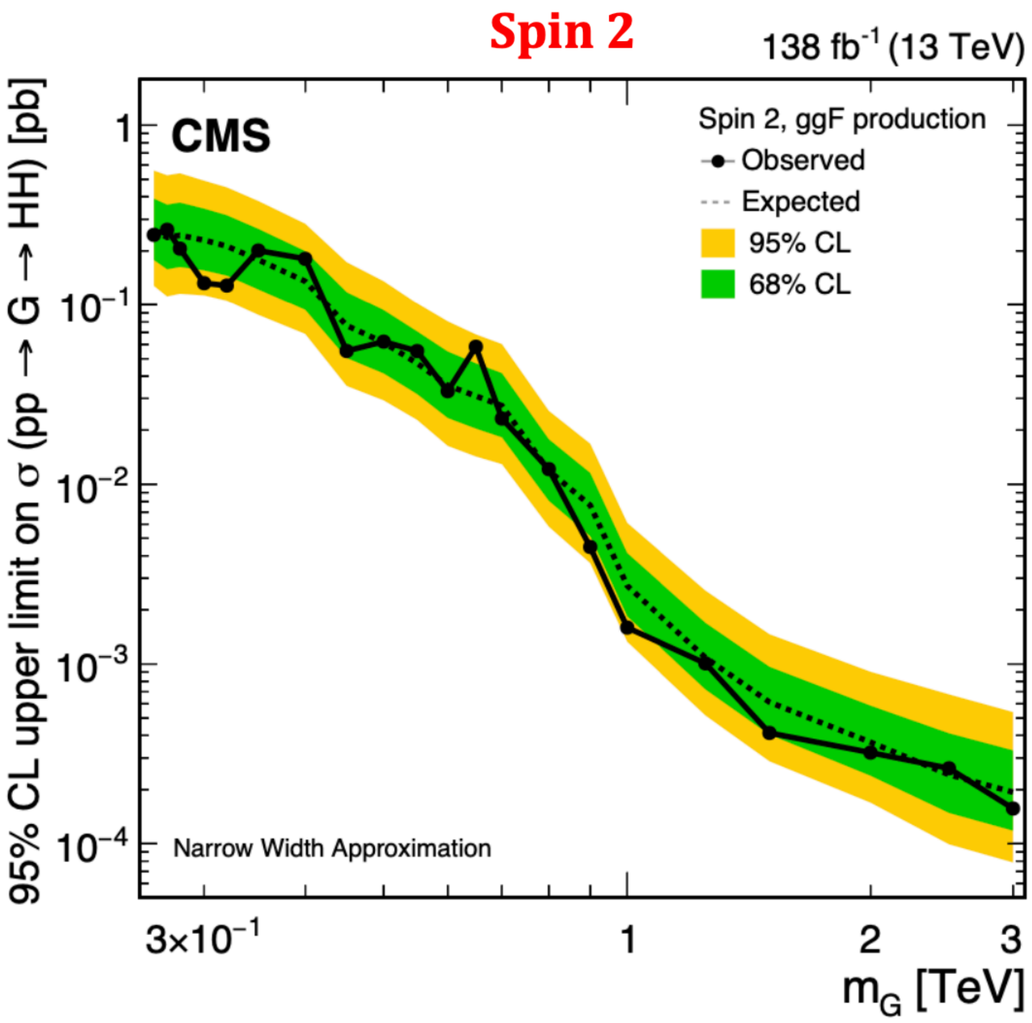
- In the high mass range, the combination result is **dominated by the bbbb channel**.
- A gain in sensitivity is observed in the intermediate mass range $(400\text{-}700\text{GeV})$.





HH combination results

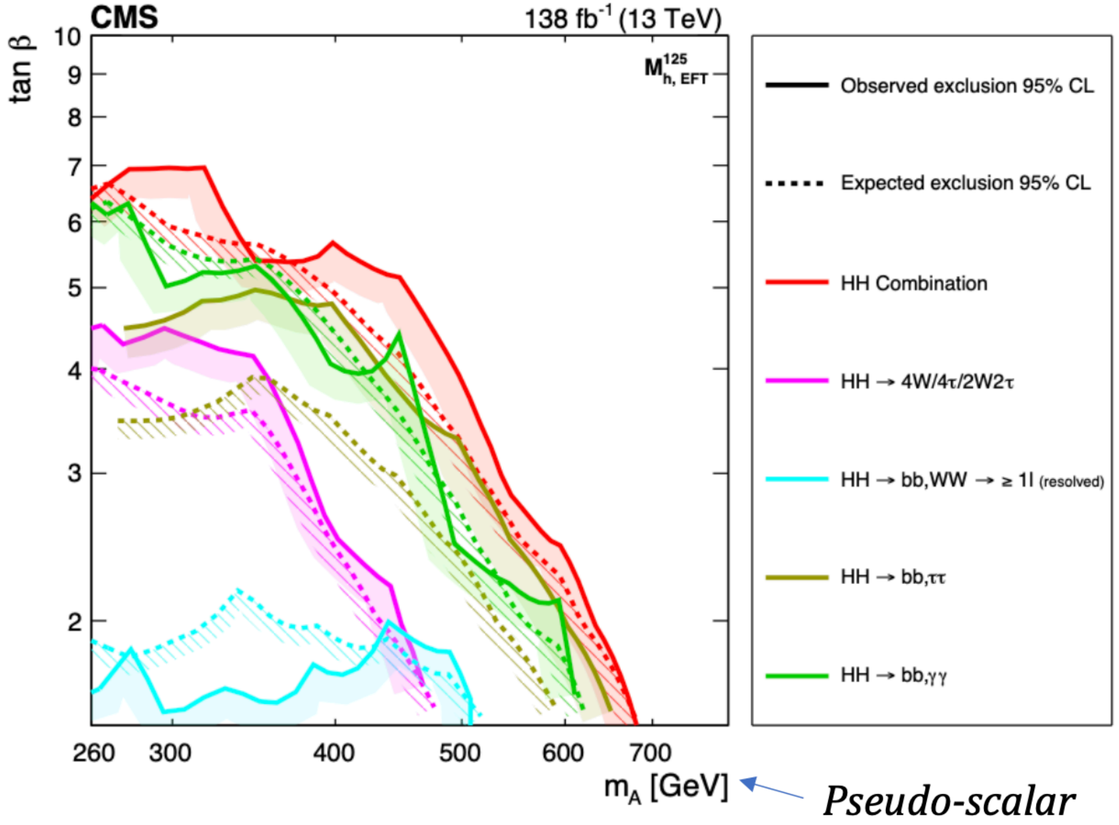


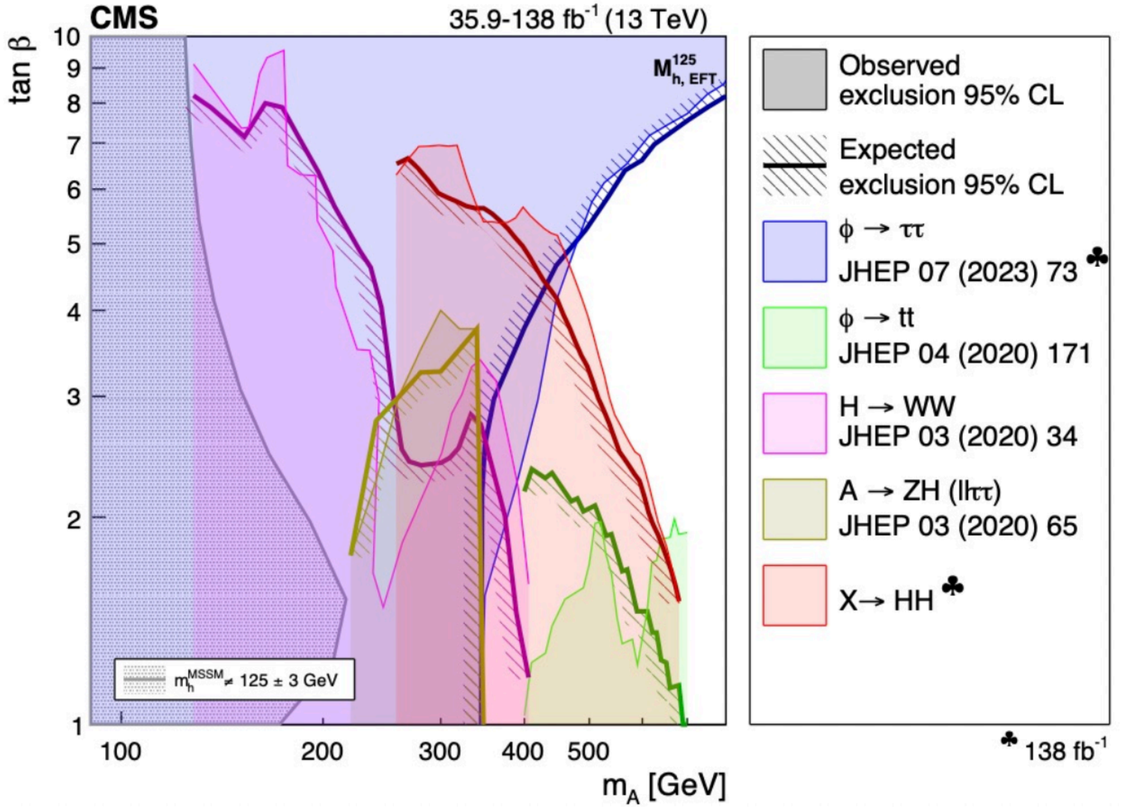


No excess was observed

MSSM

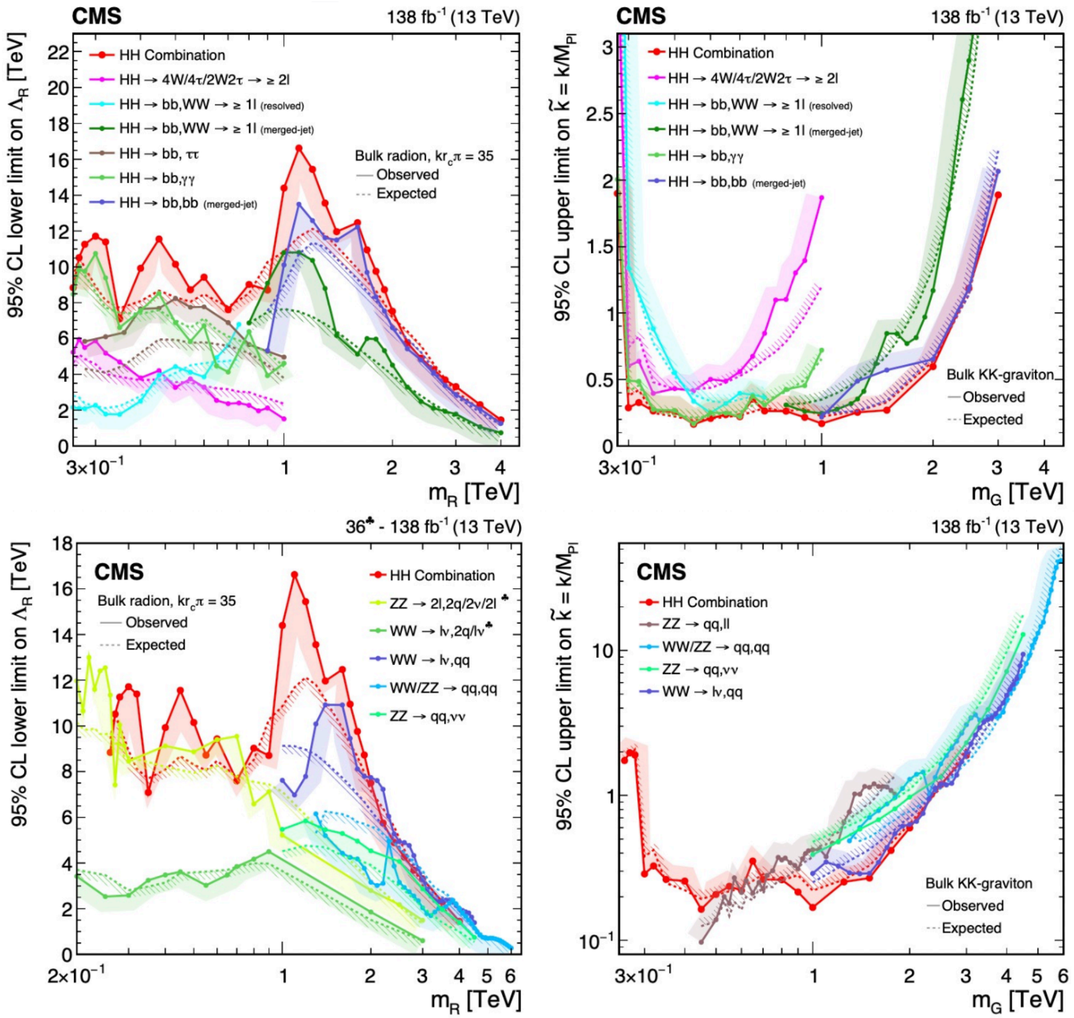
- The HH analysis is especially sensitive in the region mA <700 GeV, where the combined analysis yields enhanced exclusion power.
- The HH channel provides complementary sensitivity in the low-tanβ, mA <700GeV region, where traditional searches like φ→ττ are less effective.





HH Interpretation

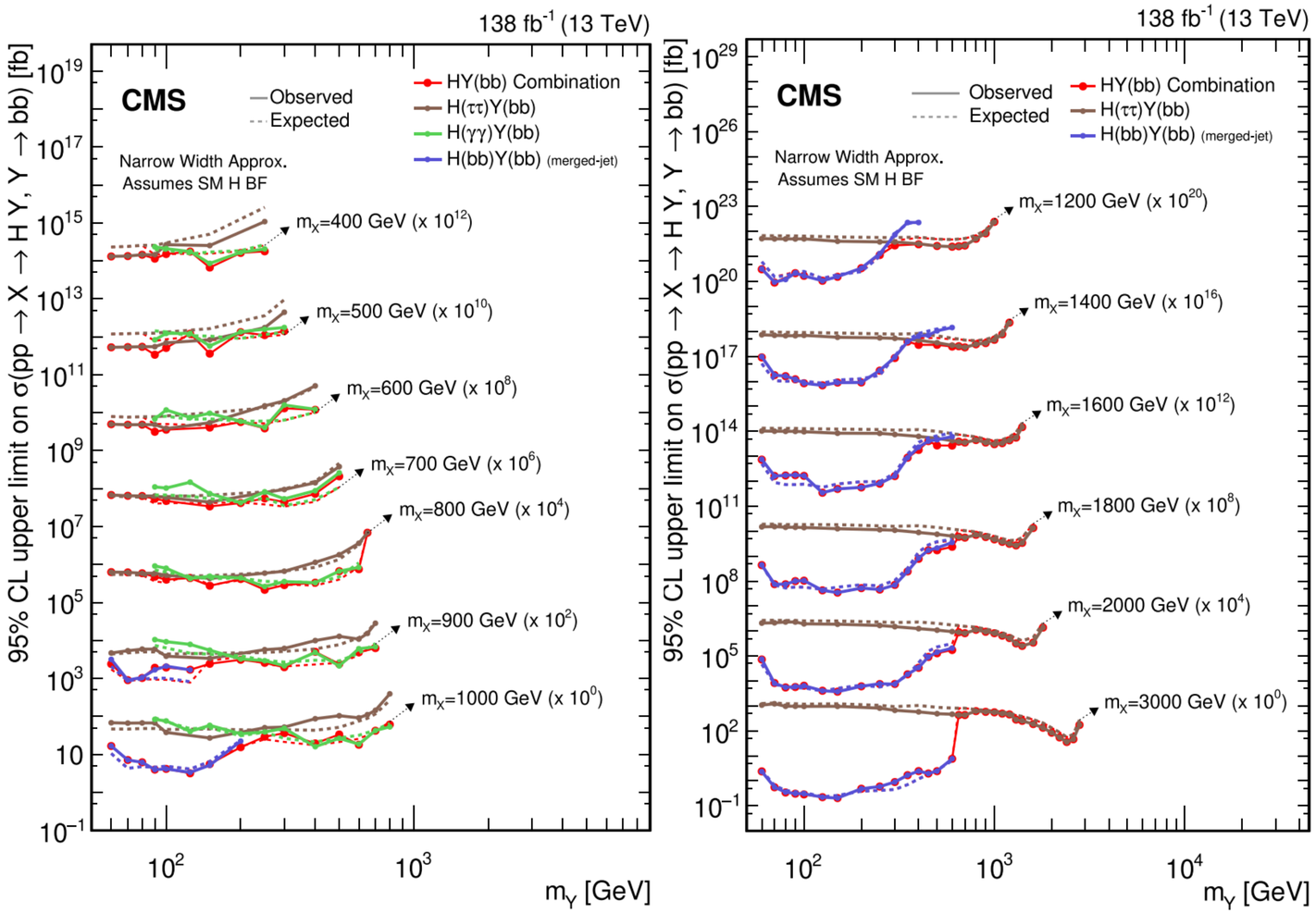
WED



- Top left shows 95% CL lower limits on the radion coupling scale ΛR as a function of the radion mass. The HH combination provides the strongest limit across a wide mass range, outperforming individual channels.
- Top-right plot shows the upper limits on the coupling k tilde for the graviton vs its mass. The HH combination gives leading sensitivity in the low mass region up to around 2.5 TeV.
- The bottom two plots compare HH with vector boson final states (ZZ and WW), showing limits for the radion (left) and graviton (right). These results highlight the complementarity of HH and VV channels, with the HH combination providing the strongest constraints in the low-mass region.

YH combination results

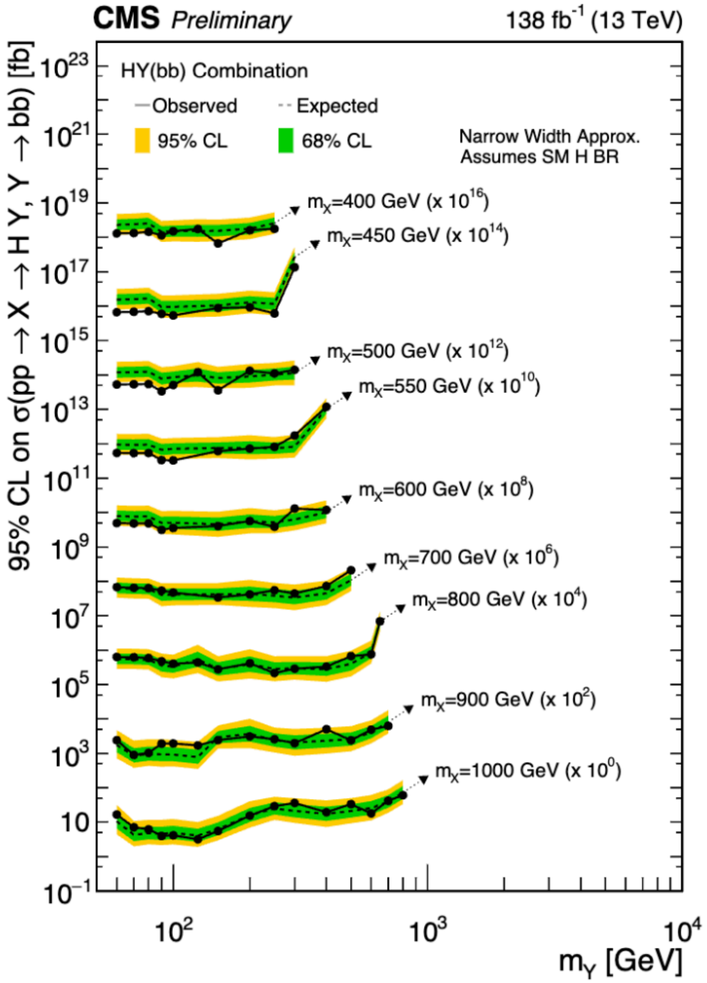
YH combination and per channel results

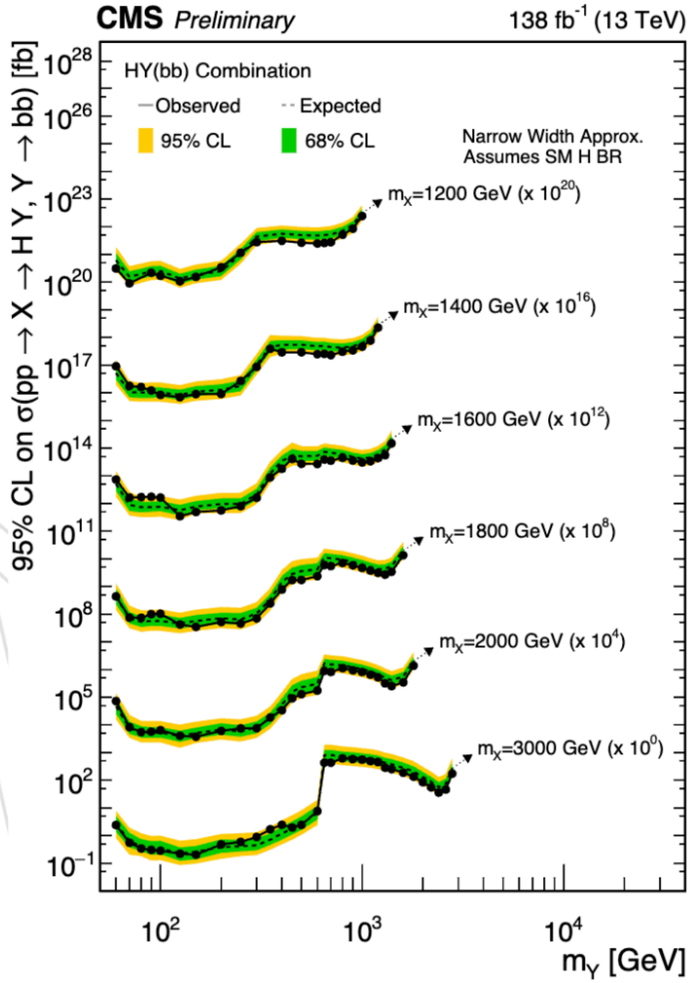


- In low mX region, the Y(bb)H (ττ) and Y(bb)H (γγ) analyses provide the best sensitivity.
- In high mX region (>1TeV), the Y(bb)H (bb) in the merged jet topology dominates for small and medium regions of mY
- In high mY region, the Y (bb)H (bb) sensitivity is reduced, because the boost of the Y is too small, the two b quarks can't merged into one single jets.

The results are obtained by scaling each channel according to the corresponding SM branching fraction of the Higgs boson decay.

YH combination results



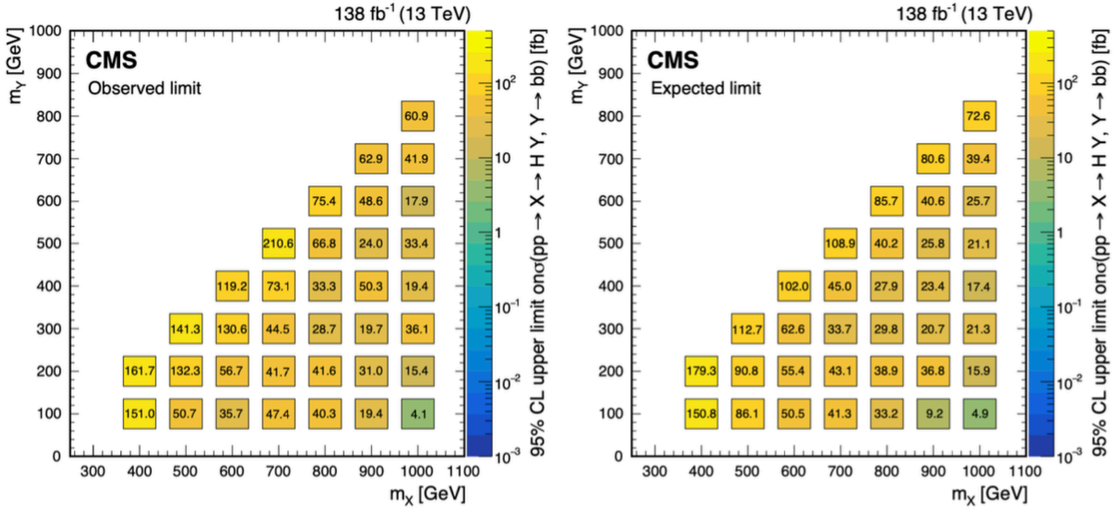


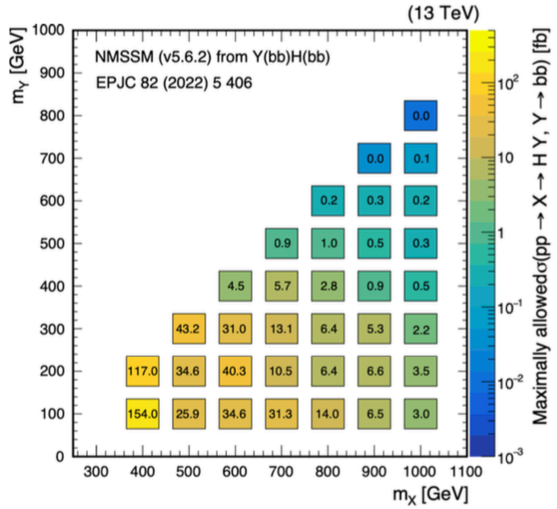
- The typical upper limits on σxB are approximately 50, 5, and 0.3 fb for mX =0.5, 1, and 3 TeV, respectively.
- No excess exceeding two standard deviations above the expected limit is observed at any of these mass points.

YH interpretation

NMSSM

- Expected (left) and observed (right) upper limit of the YH combination presented as a function of mX and mY
- NMSSM maximum allowed cross sections for comparison (bottom) from scans published in Eur. Phys. J. C 82 (2022), no. 5, 406:
  - based on NMSSMTools version 5.6.2
- No interesting contours of excluded area to show
  - only one experimental points mX = 400 GeV and mY = 150 GeV is excluded

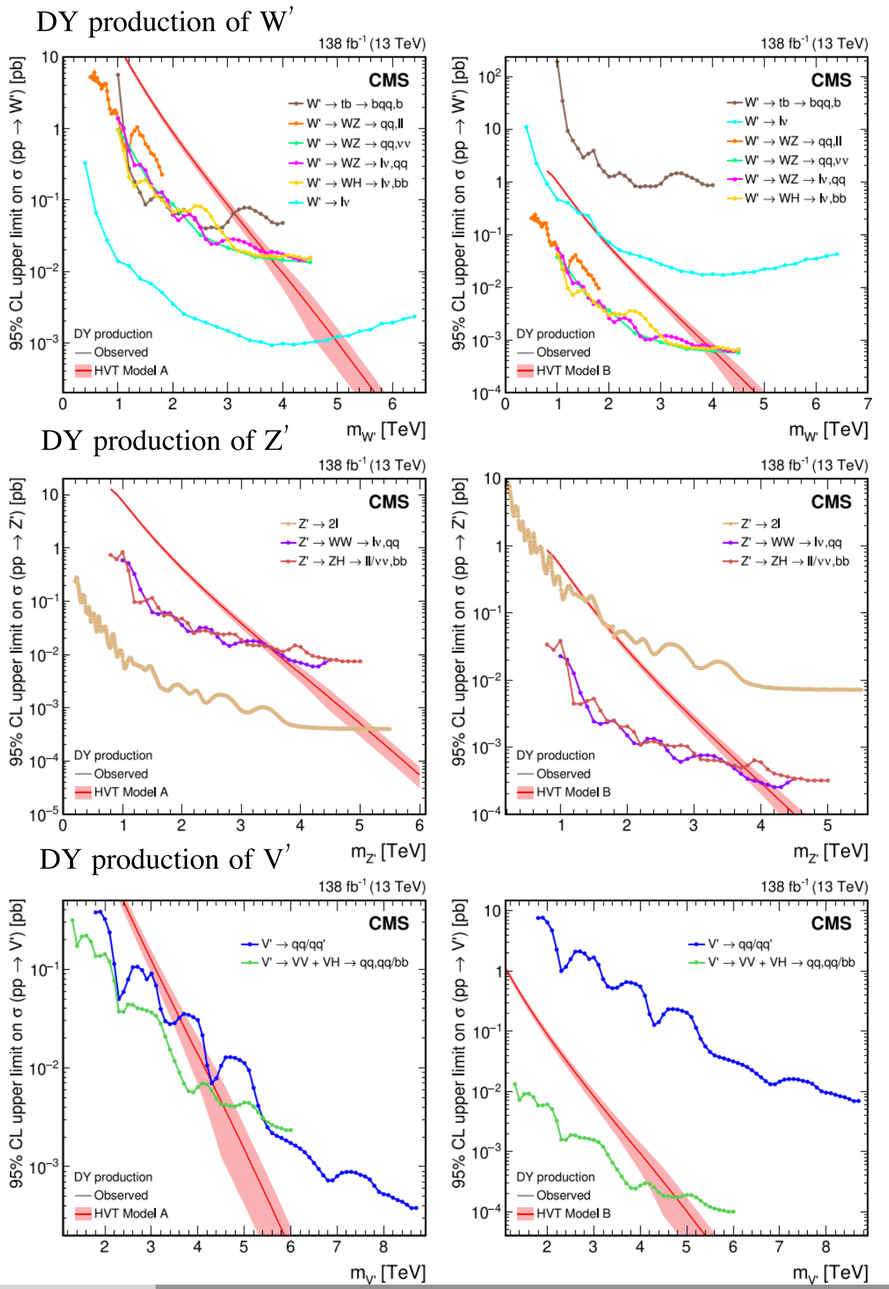




YH interpretation

Heavy vector triplet models

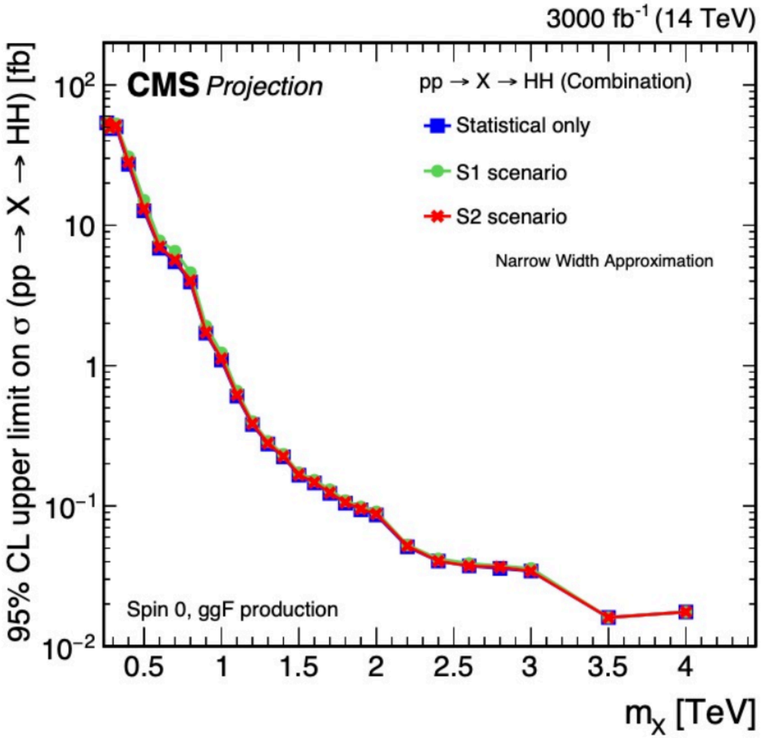
- Upper limits on the DY production cross section of W', Z' and combined V' spin-1 resonances assuming branching fractions of HVT model A (left) and model B (right)
- Theory predictions from HVT models A and B are also shown.
- The all-jets channels are sensitive to both W′ and Z′ production and are 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.

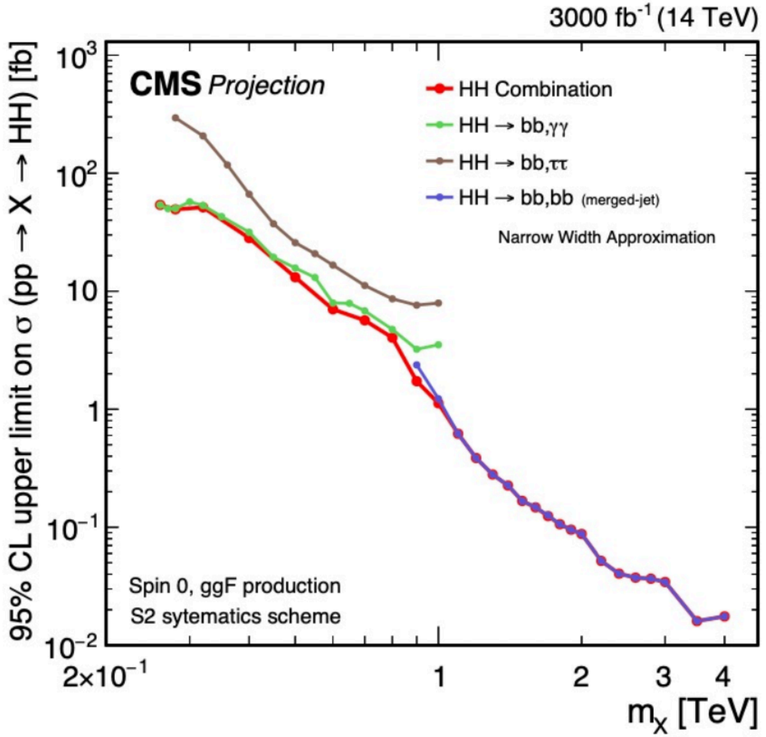


HH Projection for HL-LHC

scaling the Run 2 luminosity to 3000 fb^{-1}, which corresponds to the full HL-LHC dataset.

- To study how systematic uncertainties impact the final sensitivity, we consider three different scenarios:
  - S1: Directly use the same systematics as in the Run 2 analysis.
  - S2: Theoritical systematics are halved and experimental systematics are set to YR18/snowmass recommendations
  - S3: Only statistical uncertainties



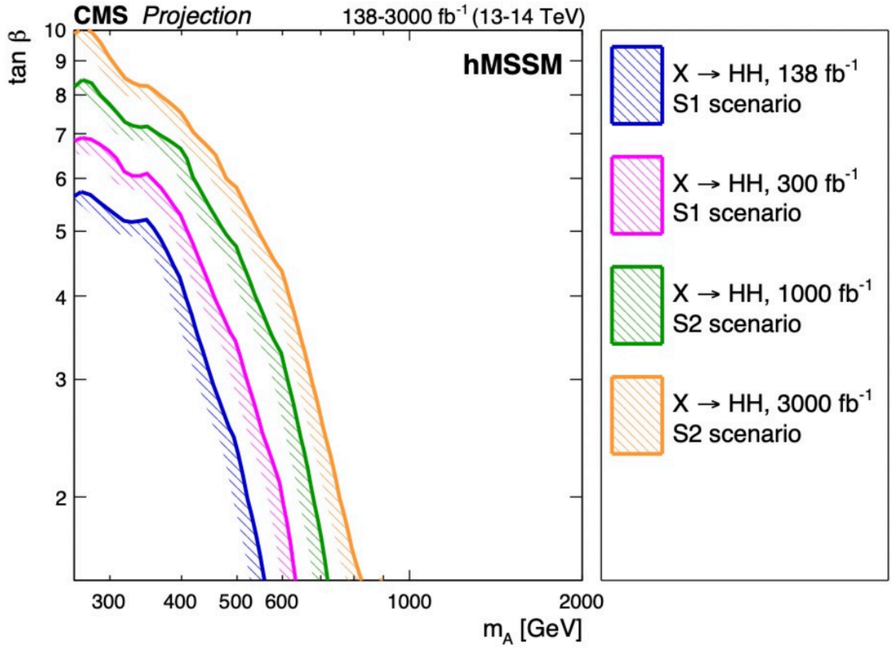


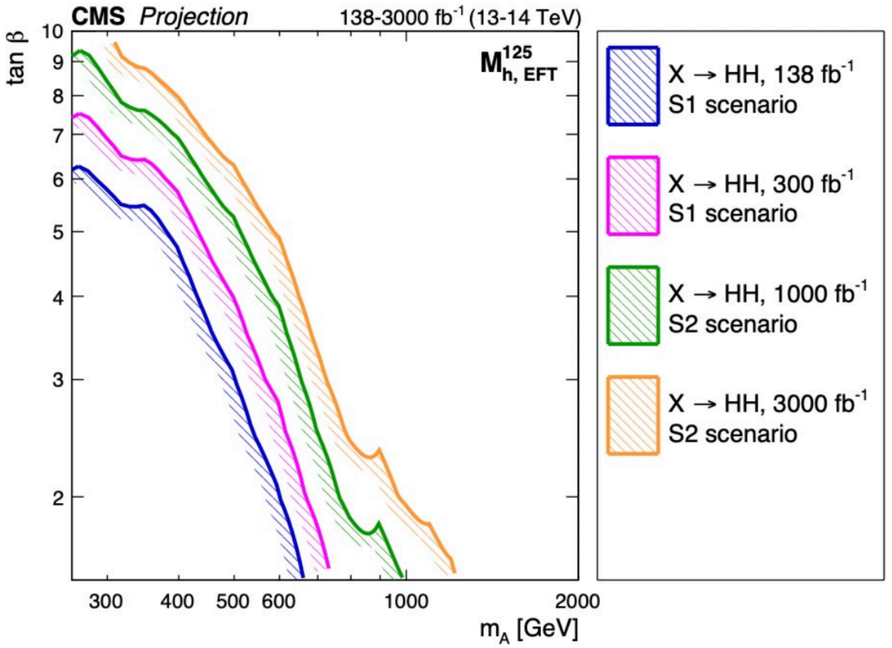
$bbbb$ and $bb\gamma\gamma$ dominates the combination

The combination will still be **statistics-dominated**

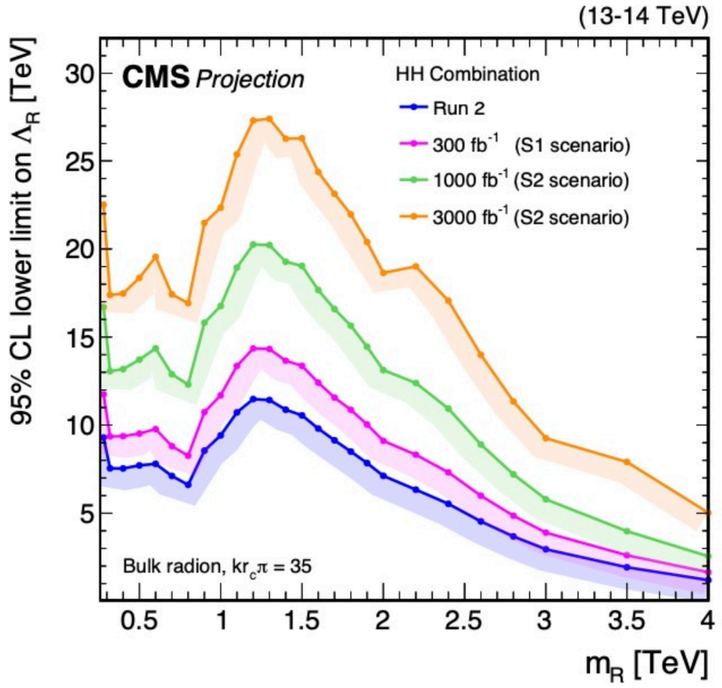
HH Projection

- MSSM: Exclusion in m_A increased of ≈ 250-300 GeV with HL-LHC
- WED: Exclusion limits are expected to at least double





MSSM

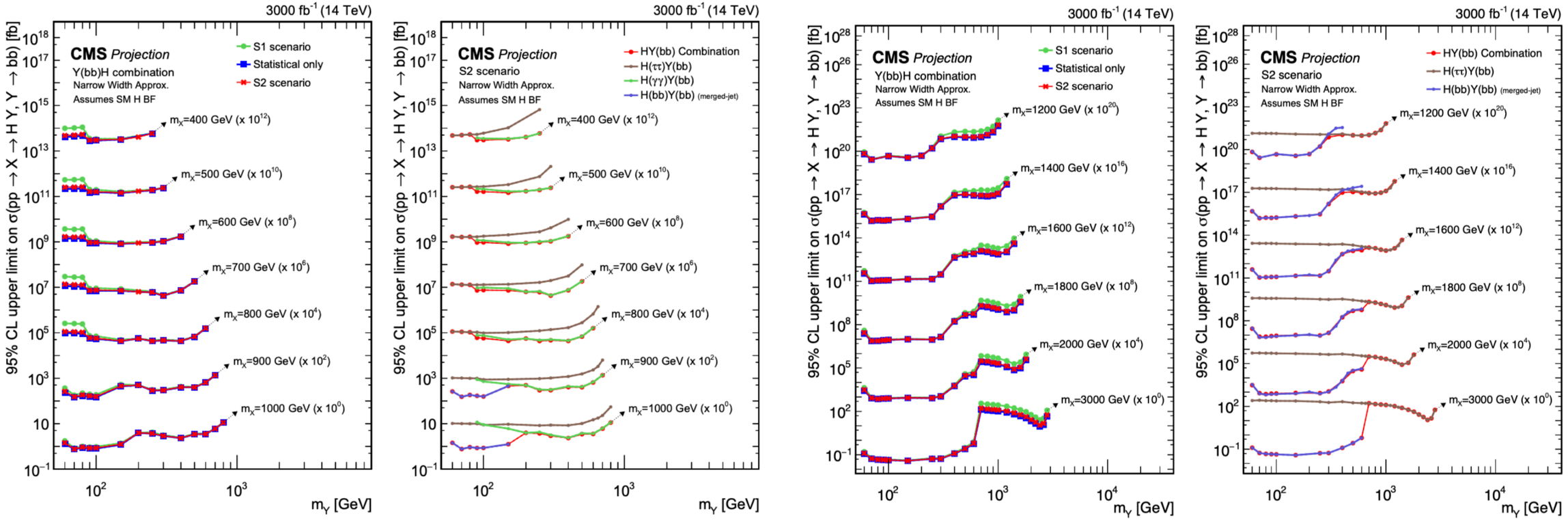


WED

YH Projection for HL-LHC

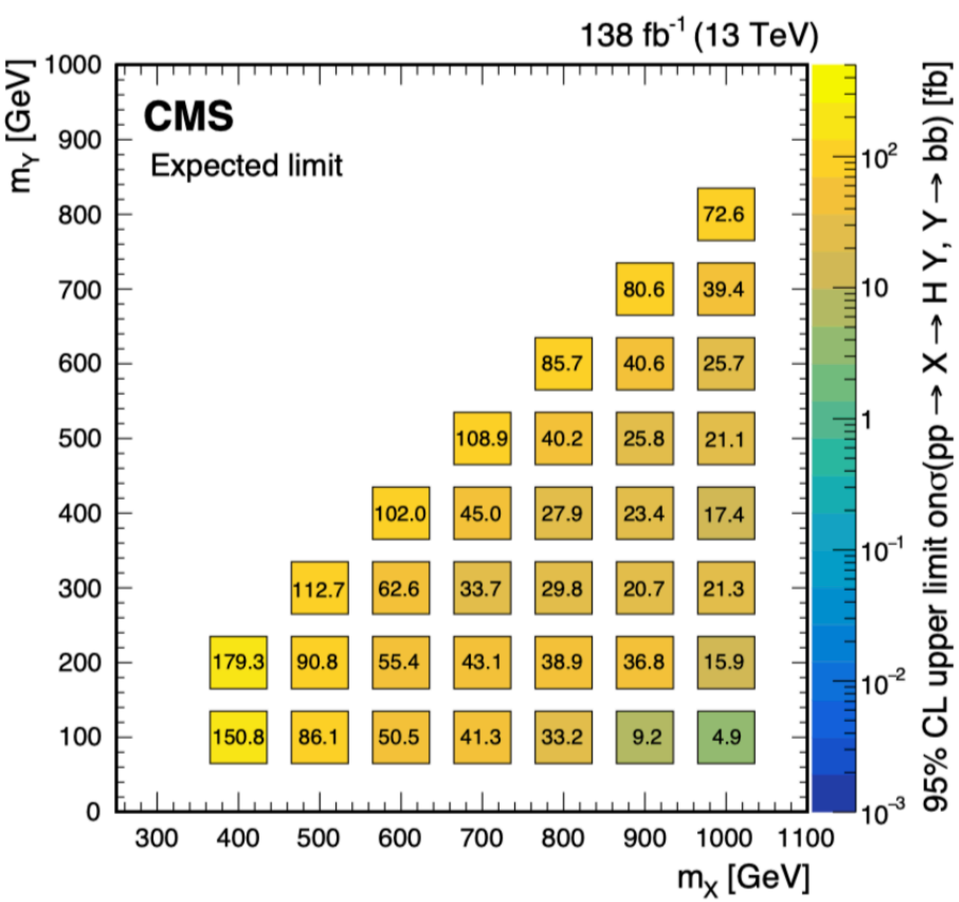
scaling the Run 2 luminosity to 3000 fb^{-1}, which corresponds to the full HL-LHC dataset.

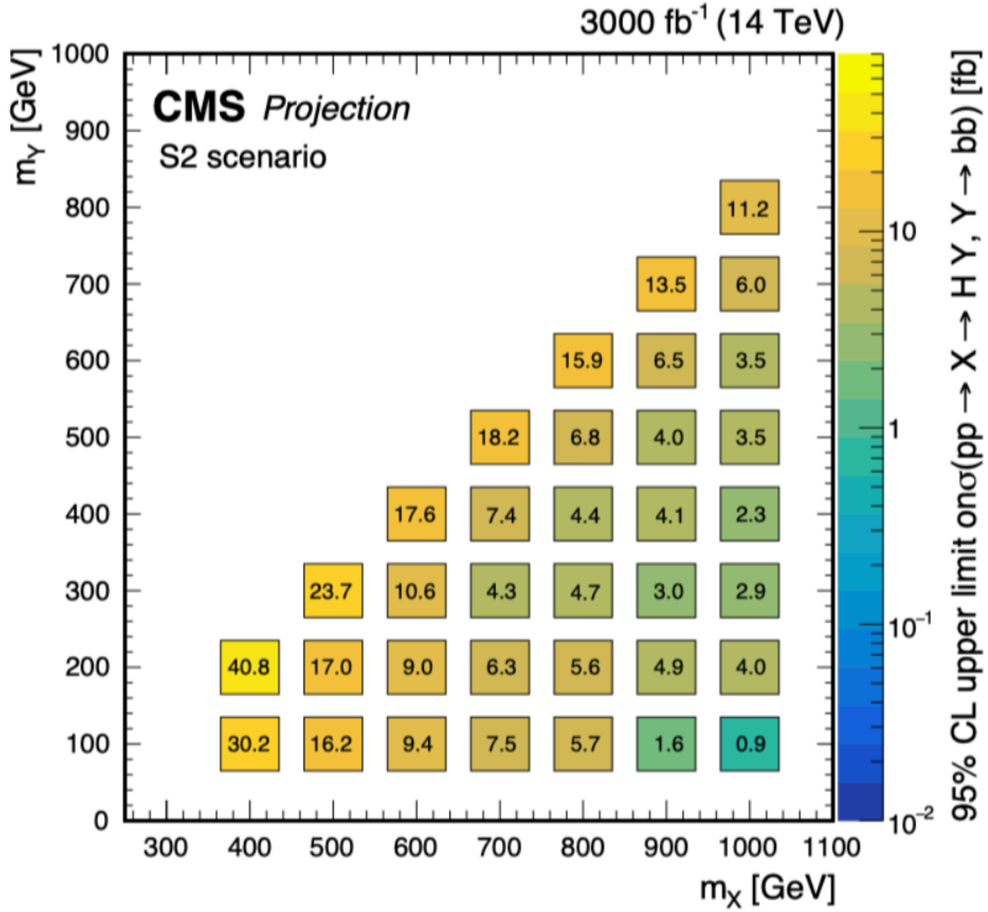
- To study how systematic uncertainties impact the final sensitivity, we consider three different scenarios:
  - S1: Directly use the same systematics as in the Run 2 analysis.
  - S2: Theoritical systematics are halved and experimental systematics are set to YR18/snowmass recommendations
  - S3: Only statistical uncertainties



YH Projection

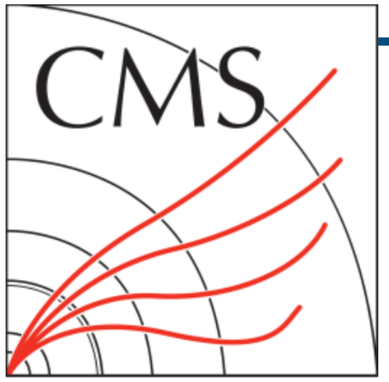
- Selected bins of expected upper limit projections of the YH combination presented as a function of mx and mY





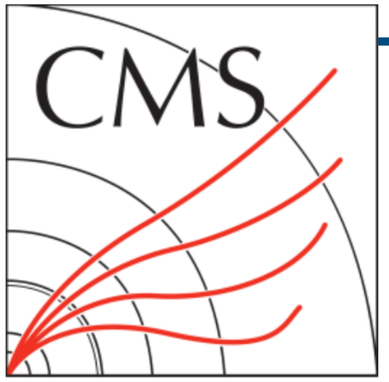
Summary

- A Combination of X->HH/YH searches was performed with LHC Run 2 data
  - Presented six X->HH results and their combination
  - Presented three X->YH results and their combination
  - Summarised X->VH results in CMS
- Interpretations
  - Interpret the results in different models(WED, MSSM, NMSSM…)
- HL-LHC Projected results
  - Reported the HH/YH projections with HL-LHC luminosity



Thank you!

中國科學院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences



Backup

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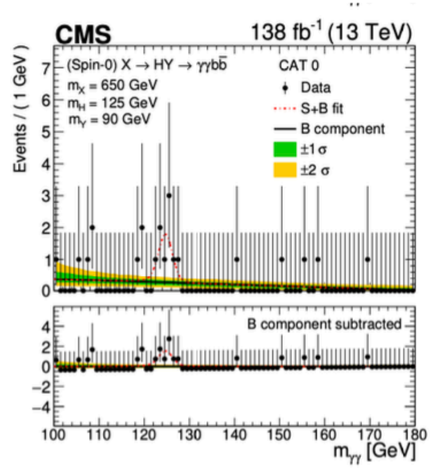
bbγγ (JHEP published)

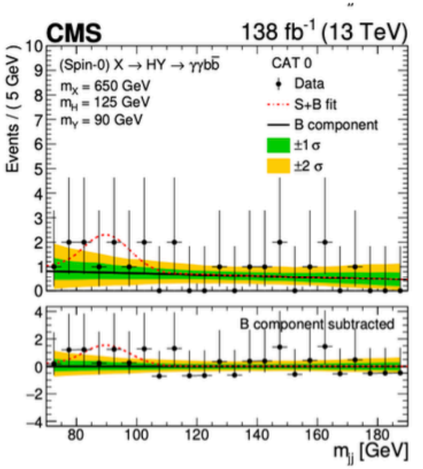
- Characteristics of bb channel :
  - Low branching ration, but clean final states.
  - HH and HY analysis
- For HY results, Higgs decays to , Y decays to bb
- Main backgrounds:
  - photon+Jets, diphoton+Jets, single Higgs
- Analysis strategy:
  - Standard Higgs to tagger.
  - Select two b-jets with highest b-score
  - Training BDT to reject non-resonant backgrounds
  - Training is performed for different mass ranges
  - 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 $(2.8)\sigma$ found at MX = 650 *GeV* and MY=90 *GeV*

	$m_Y < 300$ GeV	$m_Y = [300–500]$ GeV	$m_Y > 500$ GeV
$m_X < 500$ GeV	CAT 0 = 0.63–1.0 CAT 1 = 0.33–0.63 CAT 2 = 0.17–0.33		
$m_X = [500–700]$ GeV	CAT 0 = 0.55–1.0 CAT 1 = 0.40–0.55 CAT 2 = 0.21–0.40	CAT 0 = 0.60–1.0 CAT 1 = 0.35–0.60 CAT 2 = 0.18–0.35	
$m_X > 700$ GeV	CAT 0 = 0.50–1.0 CAT 1 = 0.30–0.50 CAT 2 = 0.21–0.30	CAT 0 = 0.35–1.0 CAT 1 = 0.24–0.35 CAT 2 = 0.18–0.24	CAT 0 = 0.40–1.0 CAT 1 = 0.29–0.40 CAT 2 = 0.13–0.29

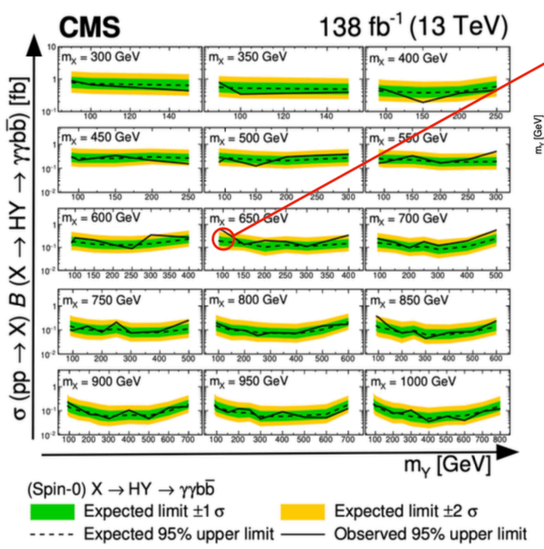
MVA categorisation



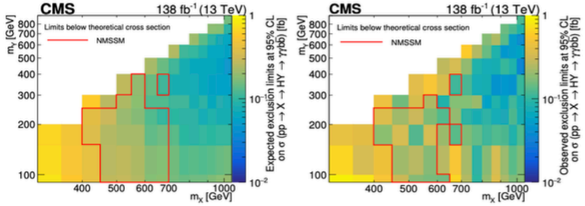
Diphoton-mass fits



Dijet mass fits



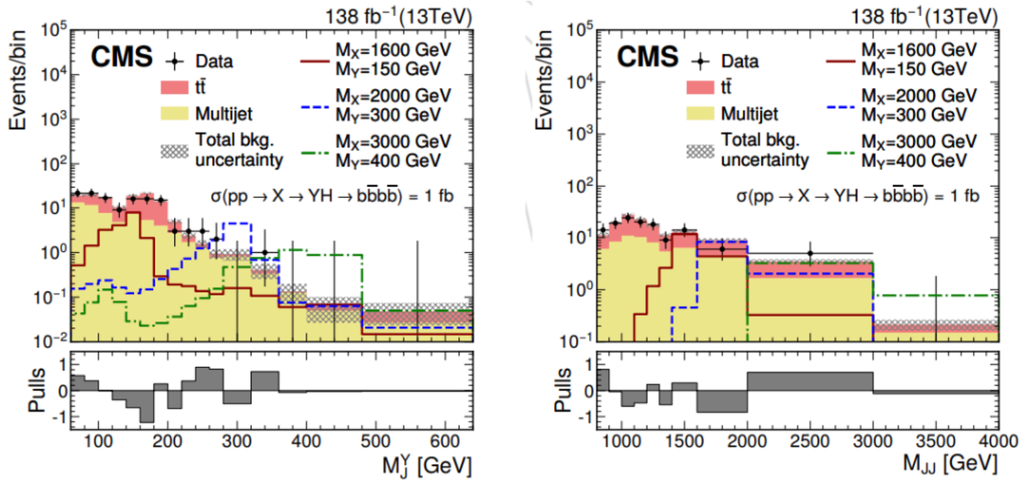
Excess of 3.8 (2.8)σ



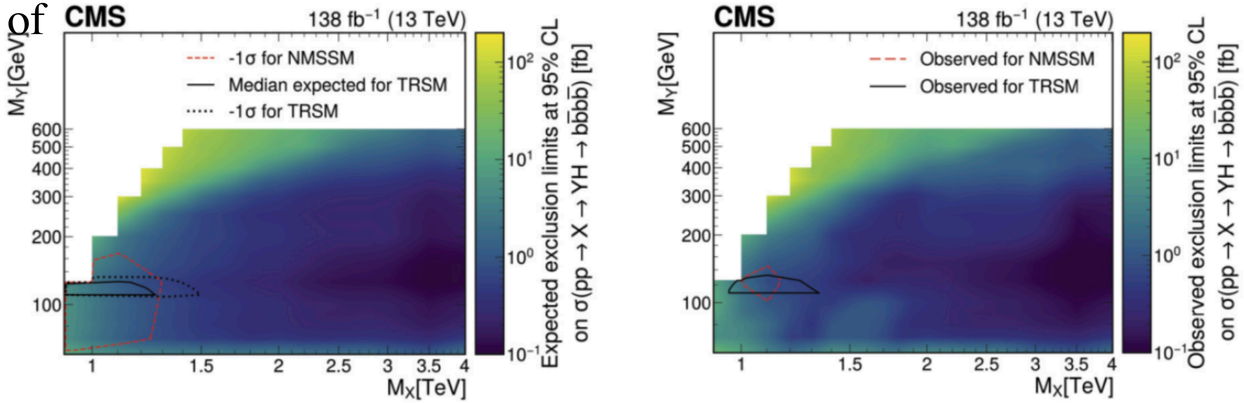
HY results

bbbb boosted(PLB published)

- Characteristics of bbbb boosted channel :
  - Largest branching ratio. Low backgrounds
  - At very high M , 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:
  - ttbar, 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 fits
- Results:
  - Both HH and HY were included

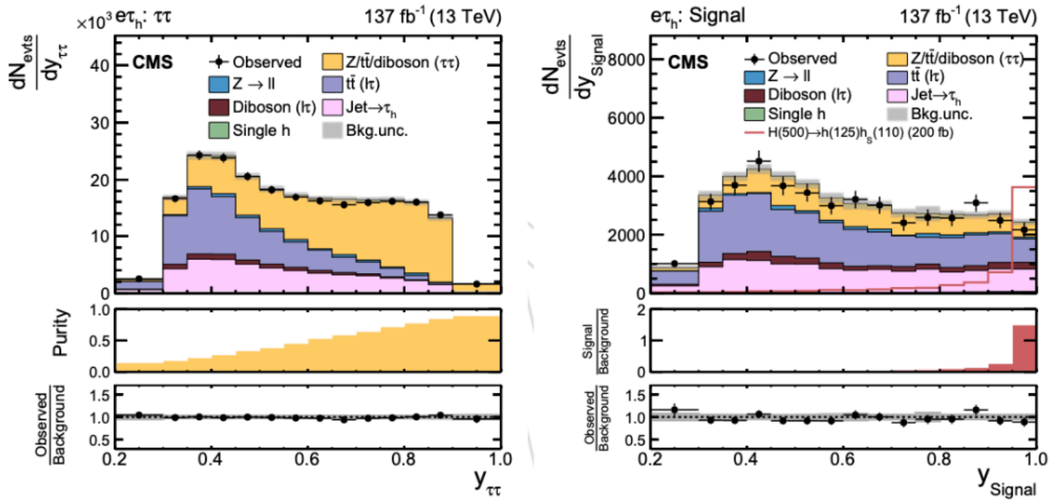


Distributions of M Y J (left) and MJJ (right) in the high-purity signal region of the Y(bb)H(bb) analysis in the merged jet topology

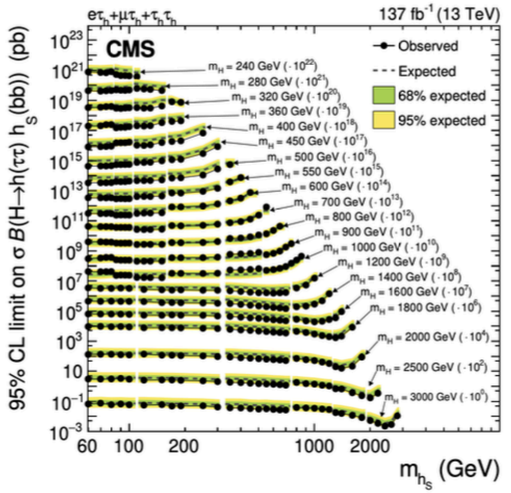


bbττ (JHEP published)

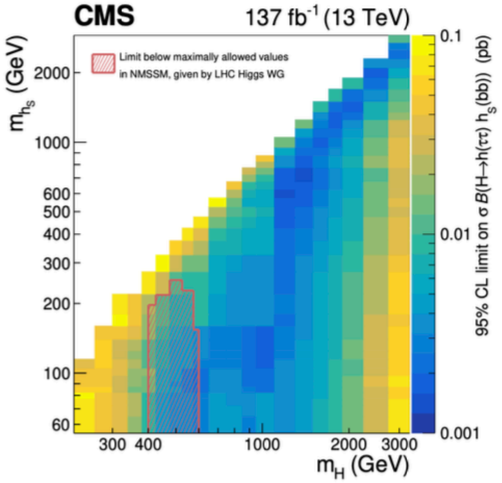
- Characteristics of bb channel :
  - Select events with a reconstructed tau lepton pair in the final states τhτh, eτh, μτh (Covered ~88% decays)
  - HY only analysis, Higgs decays to , Y decays to bb
- Main backgrounds:
  - Z, ttbar, diboson, WJets, fake , QCD, single Higgs
- Analysis strategy:
  - 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→ℓ ℓ , diboson, single top and single Higgs
- Signal extraction:
  - Maximum likelihood fits on neural-network outputs
- Results:
  - Only HY results, emulate HH results for combination



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



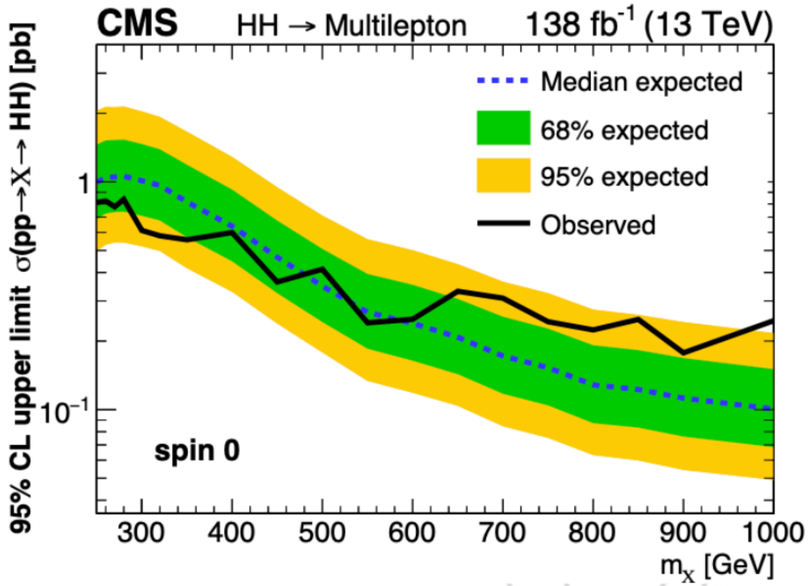
HY results

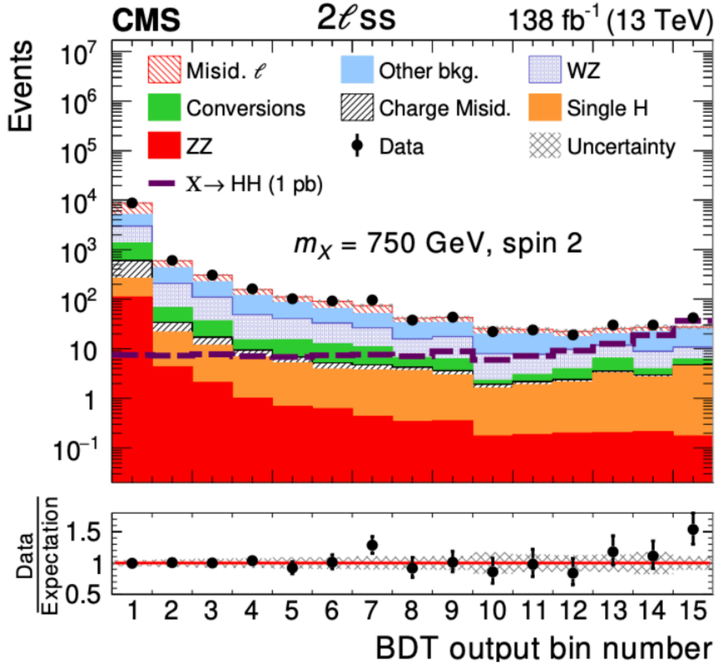


HY results

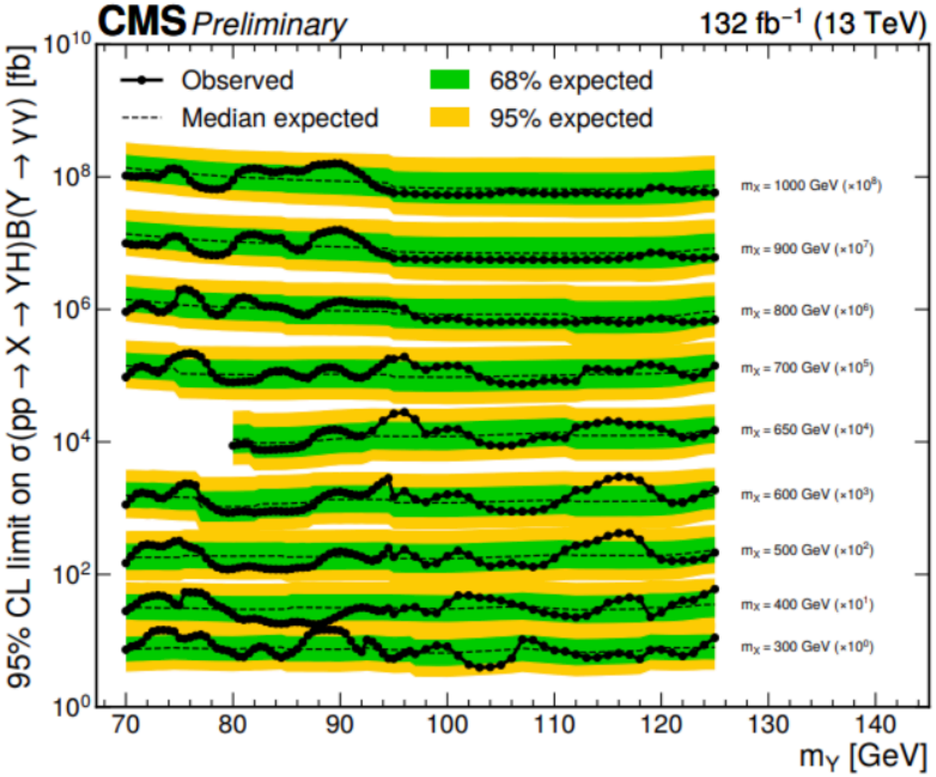
Mutilepton (JHEP published)

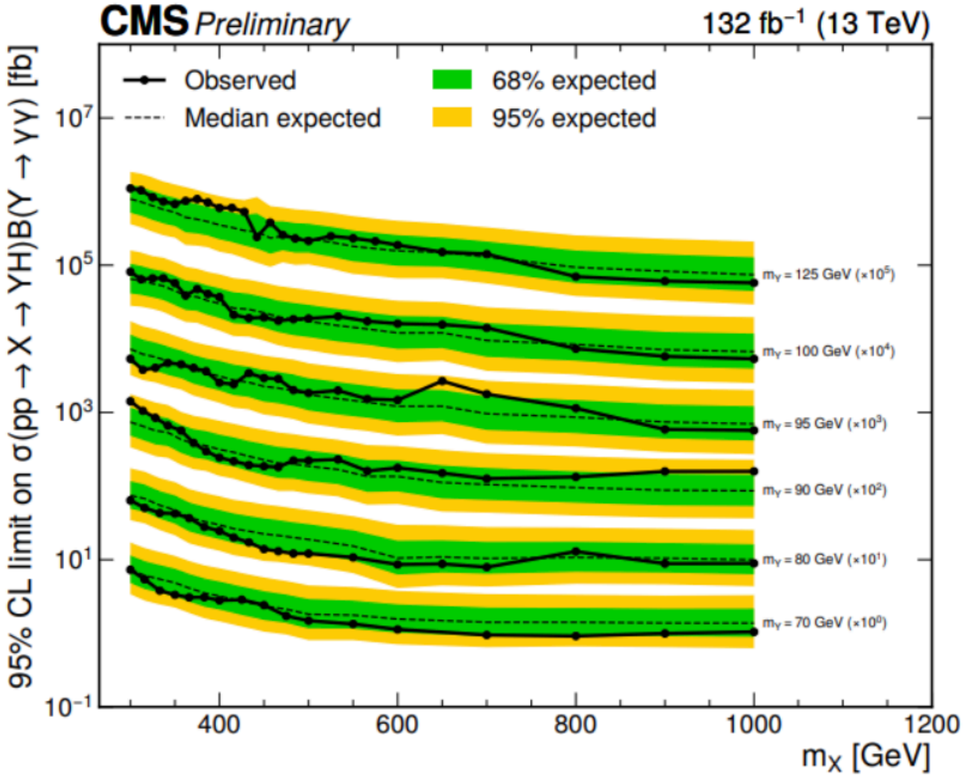
- ***WWWW***, ***WW*$\tau_h\tau_h$** and $\tau_h\tau_h\tau_h\tau_h$ decay modes
- For each event category, a set of **event level BDTs** is trained to separate resonant spin-0, resonant spin-2 and non- resonant HH signal from the corresponding backgrounds.
- To avoid overlap with other analyses, a **b-veto** is applied (DeepJet)
- Events are selected using a set of single-, double- and triple lepton triggers as well as di-tau and lepton-tau cross triggers.



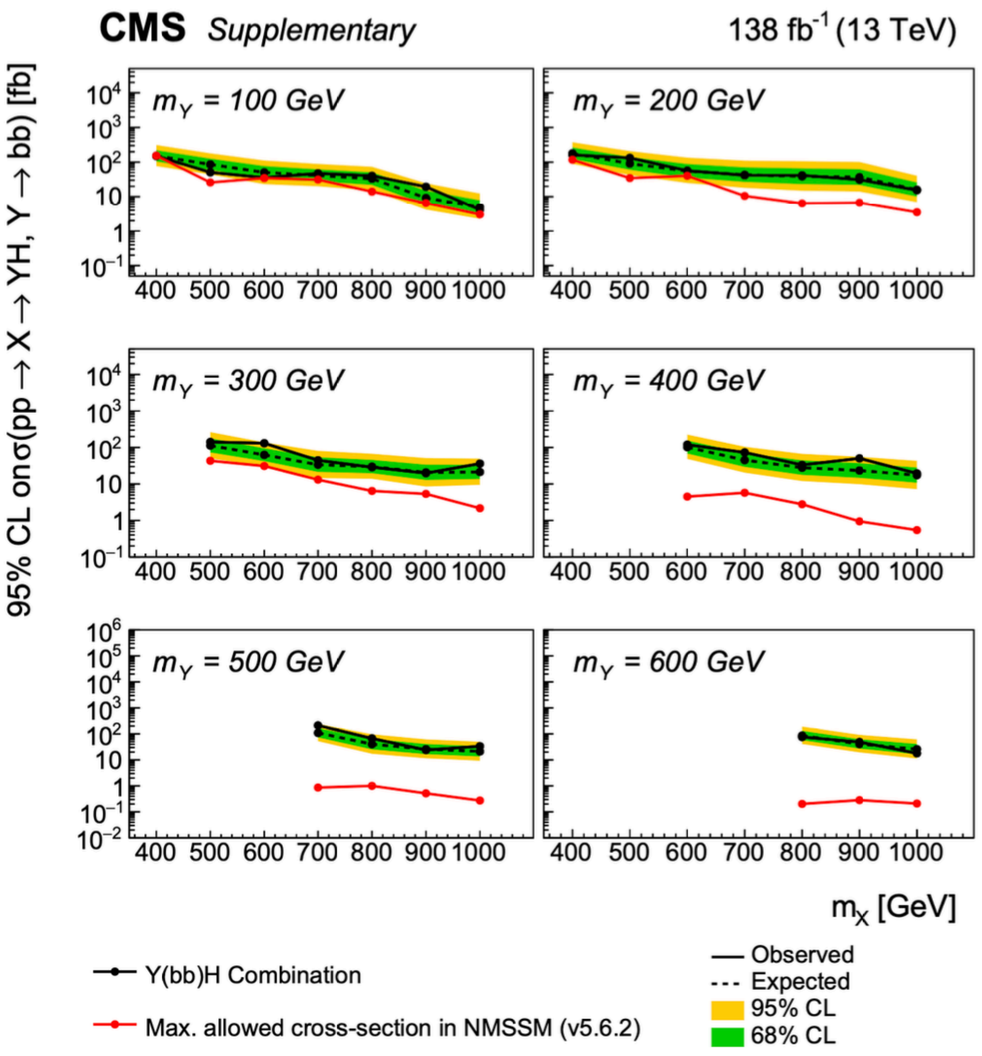


- No significant excess is seen in the X → Y(ττ)H(γγ) search at these masses. However, in the X → Y(γγ)H(ττ) search, local significances of 2.6 σ and 2.3 σ are found for mY = 95 GeV and mX = 600 GeV and mX =650 GeV respectively.

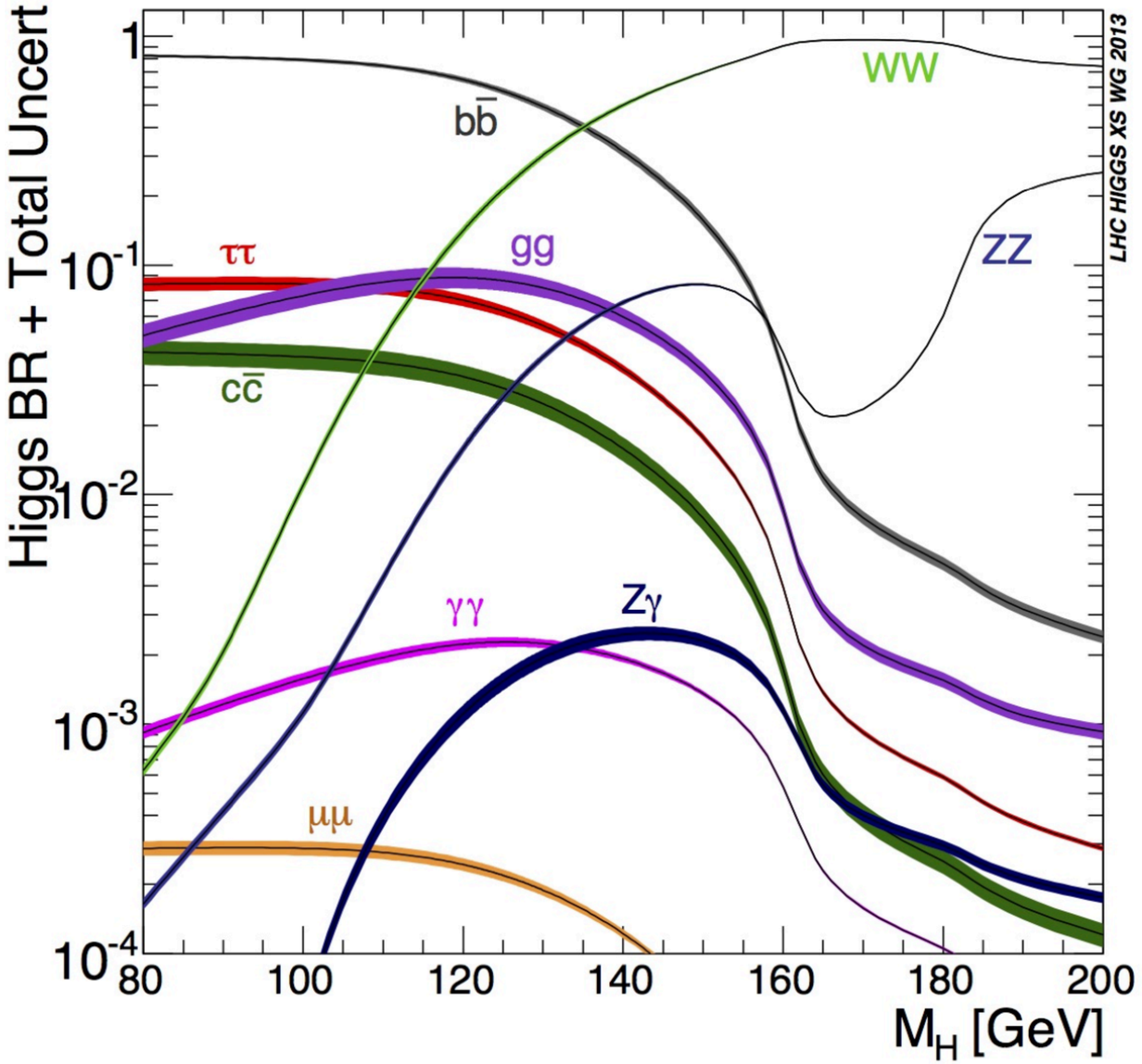




NMSSM comparison

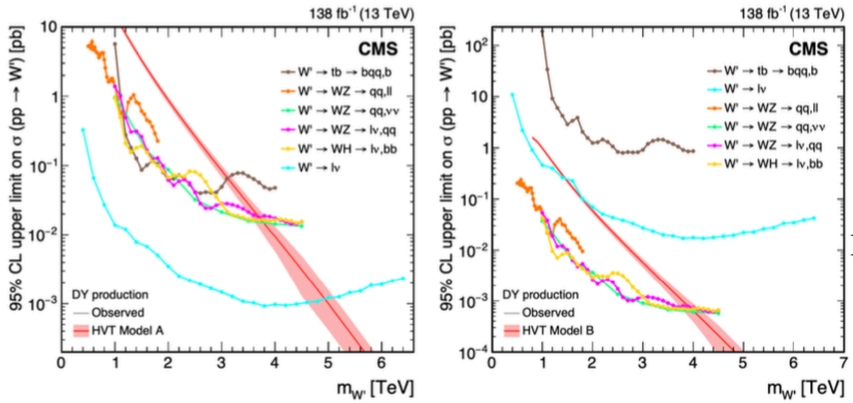


Higgs branching ratio

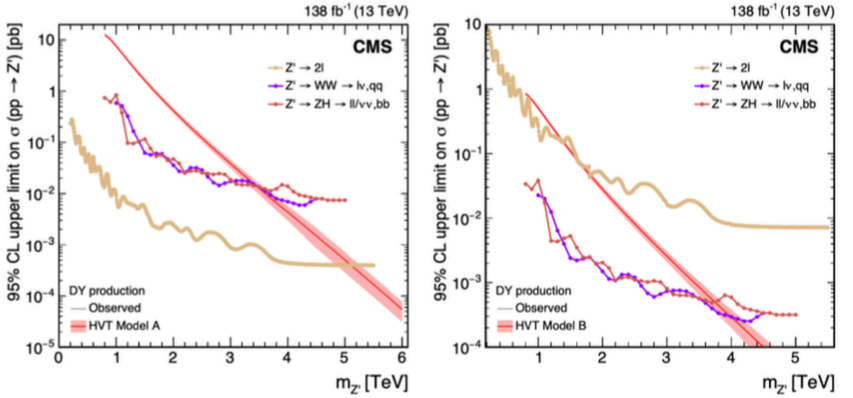


Heavy vector triplet models

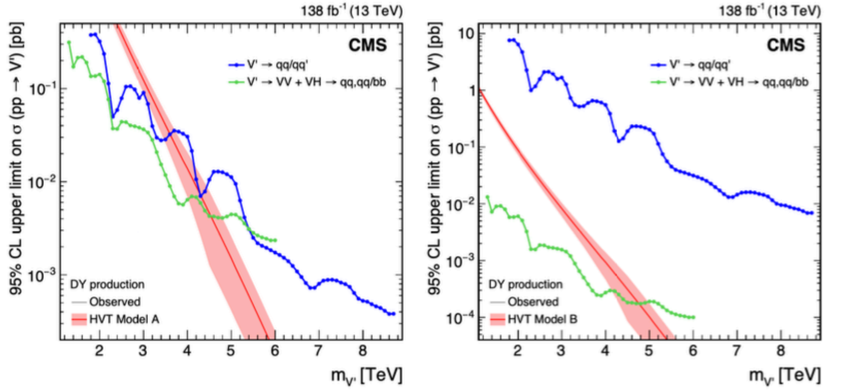
- Upper limits on the DY production cross section of W', Z' and combined V' spin-1 resonances assuming branching fractions of HVT model A (left) and model B (right)
- Theory predictions from HVT models A and B are also shown.
- The all-jets channels are sensitive to both W ′ and Z ′ production and are 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'

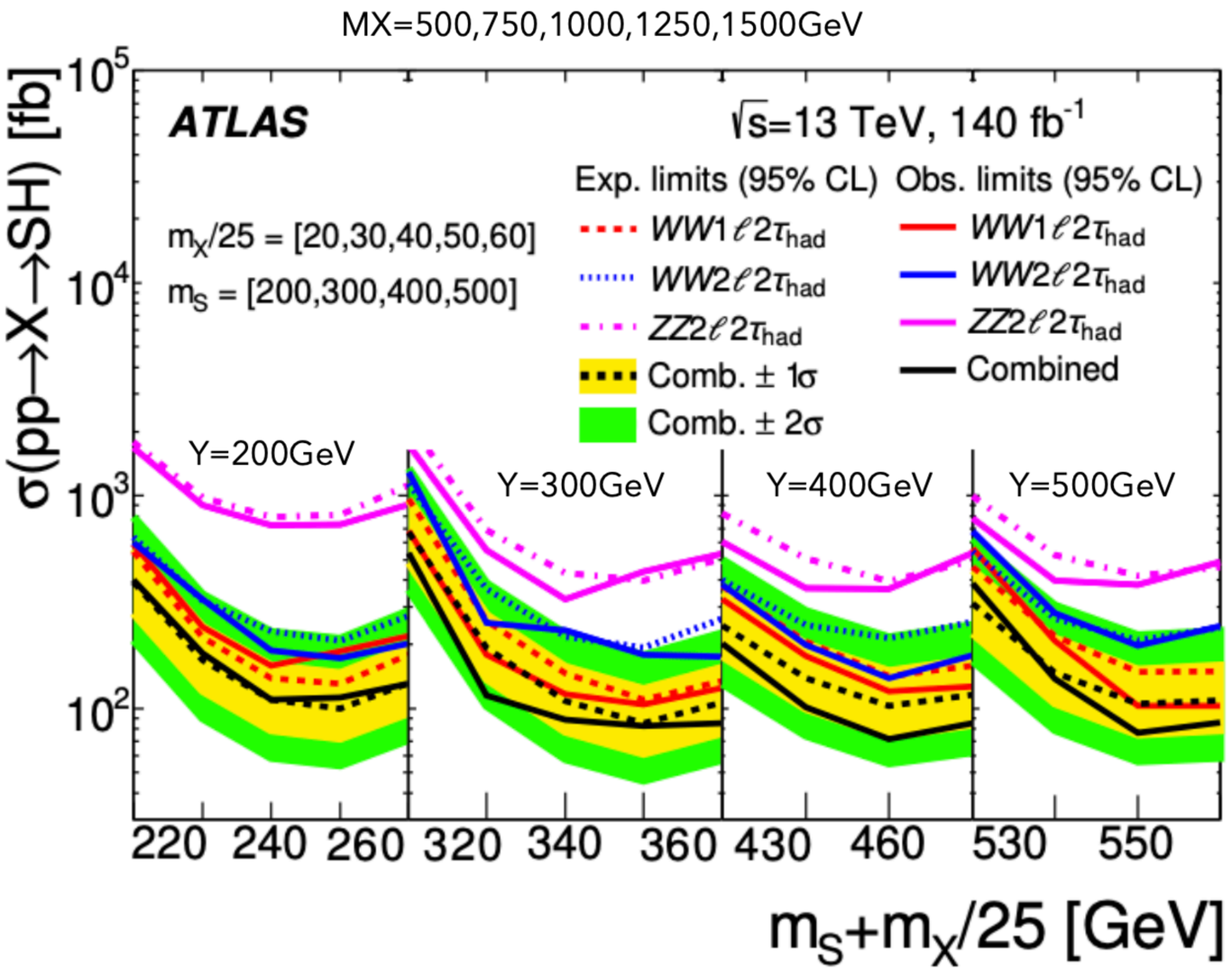


DY production of Z'



DY production of V'

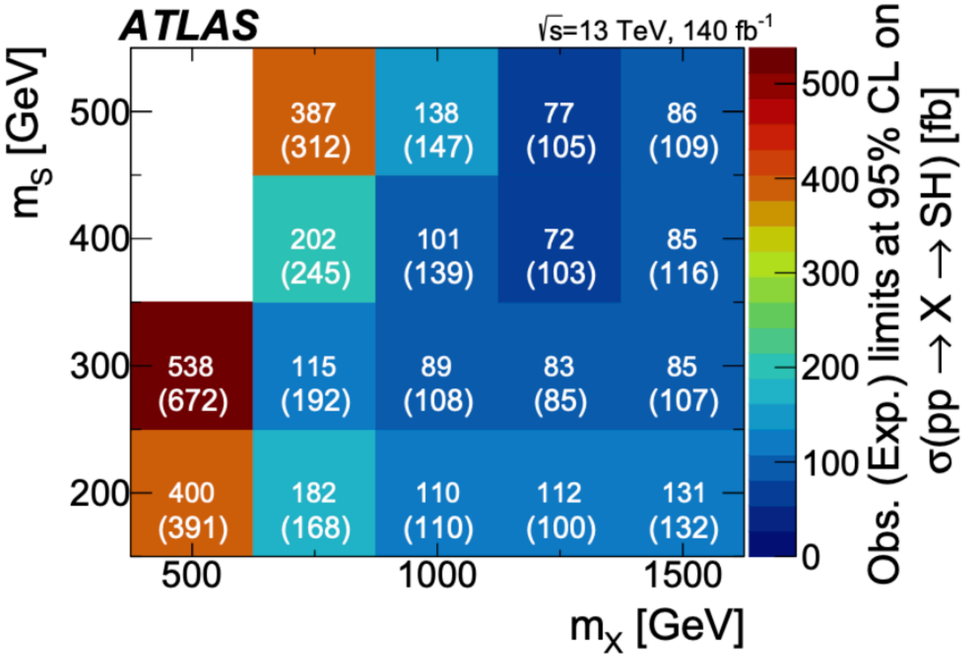
ATLAS combination results



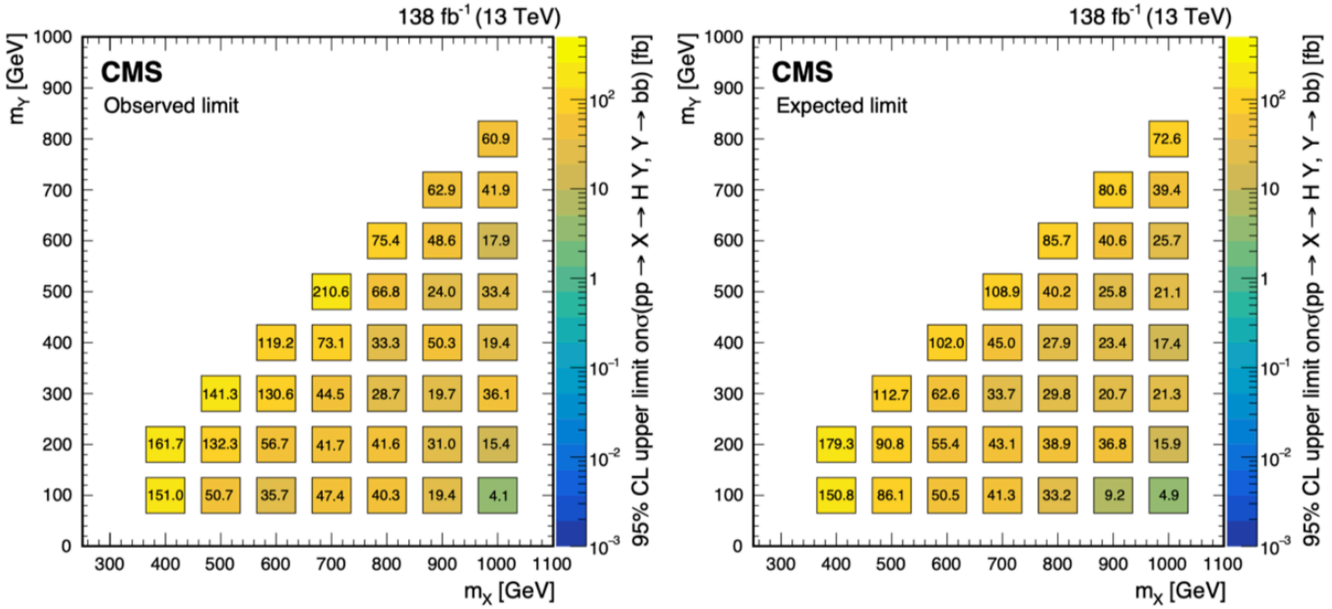
S branching fractions assuming the decays like a SM Higgs boson

https://arxiv.org/pdf/2307.11120

CMS ATLAS comparison



ATLAS results



CMS results