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

Searches for heavy resonances X decaying to a Higgs and another boson at CMS

Chu Wang on behalf of CMS HH/HY combination

The France-China collaboration

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.

Submitted to Physics Report

- **Over 20 institutes/universities contributed to this paper**
  - IP2L、PKU、IHEP have very important contributions
  - Good collaborations achieved in this work

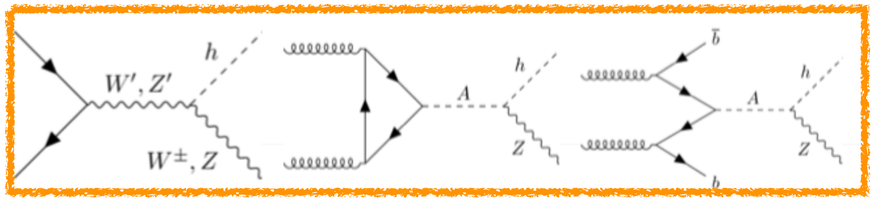
Outline

* Introduction
* YH/VH searches in CMS
* YH Projection
* Interpretation
* Summary

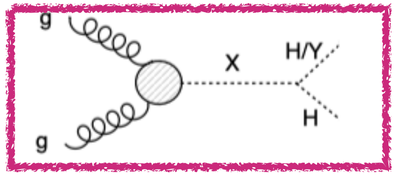
Introduction

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 H(125) boson and a vector boson
    - New heavy resonances could decay into H(125) boson and a new scalar Y
  - Higgs boson production through resonance decay → New physics



- Extended H sectors
- Heavy Vector Triplet



- NMSSM
- TRSM

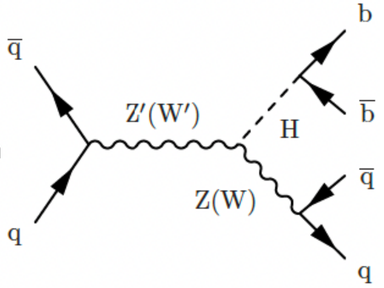
Extended Higgs sectors

- **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 or lepton-specific: Only quarks
    - Type Y or flipped: 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

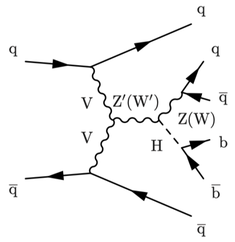
Supersymmetric and Heavy Vector Triplet models

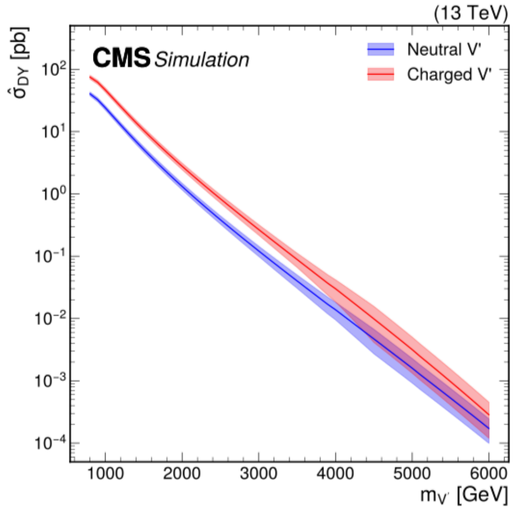
- **Supersymmetric models**
  - The Higgs sector of the minimal supersymmetric standard model (MSSM) has the structure of a Type II 2HDM
  - By adding an additional singlet field:
    - Defines next-to-minimal MSSM (NMSSM)
    - X → YH to be possible
- **Heavy Vector Triplet (W′ and Z′)**
  - Minimal extension of the SM gauge group
    - Additional force-carrying heavy vector bosons, W′ and Z′
    - W′ and Z′ could decays to VH
  - There are two production modes

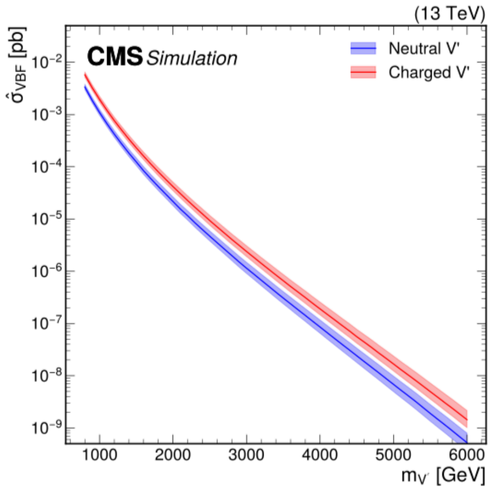
DY production



VBF production







Two main production modes cross sections, DY (Up), VBF (Down)

YH/VH searches in CMS

Status of YH/VH analyses in CMS

- **YH searches in the CMS:**
  - bbγγ (JHEP), in combination
  - bb$\tau\tau$ (JHEP), in combination
  - bbbb boosted (PLB), in combination
  - $\tau\tau$γγ (CMS-PAS-HIG-22-012)
  - bbbb,bbWW,WW$\gamma\gamma$,WW$\tau\tau$...
- Search ranges :
  - Heavy resonance X: 240GeV to 4.5TeV
  - New scalar Y: 60GeV to 2800 GeV

Y	H	m_X	m_Y	
b b	$\tau\,\tau$	240−3000	60−2800	resolved jets and τ leptons
b b	$\gamma\,\gamma$	300−1000	90− 800	resolved jets and photons
b b	b b	90−4000	60− 600	two merged bb jets

- **VH searches in the CMS:**
  - Z(ll)$\tau\tau$ (JHEP)
  - Z(ll+$\nu\nu$)bb (EPJC)
  - W(lν)bb (PRD)
  - Z(ll)bb (EPJC)
  - W(qq)bb (PLB)
- Search ranges :
  - Heavy resonance X: 220GeV to 6TeV

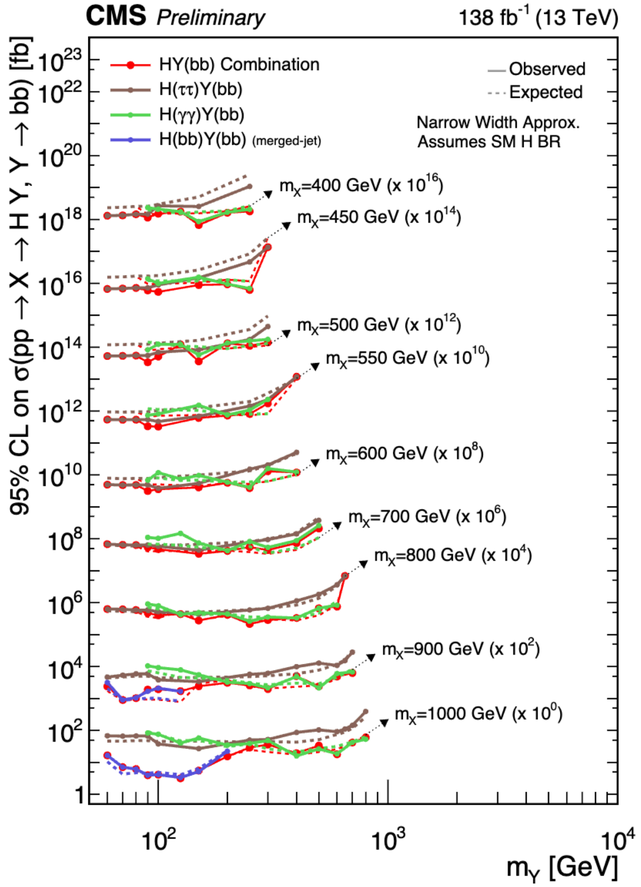
V	H	m_X	
Z($\ell\ell$)	$\tau\tau$	220 – 400	
Z($\ell\ell + \nu\nu$)	bb	225 – 1000	resolved jets
W($\ell\nu$)	bb	1000 – 4500	W $\to \ell\nu$ and merged bb jet
Z($\ell\ell$)	bb	800 – 4600	Z $\to \ell\ell/\nu\nu$ and merged bb jet
Z(qq)	bb	1300 – 6000	two merged jets

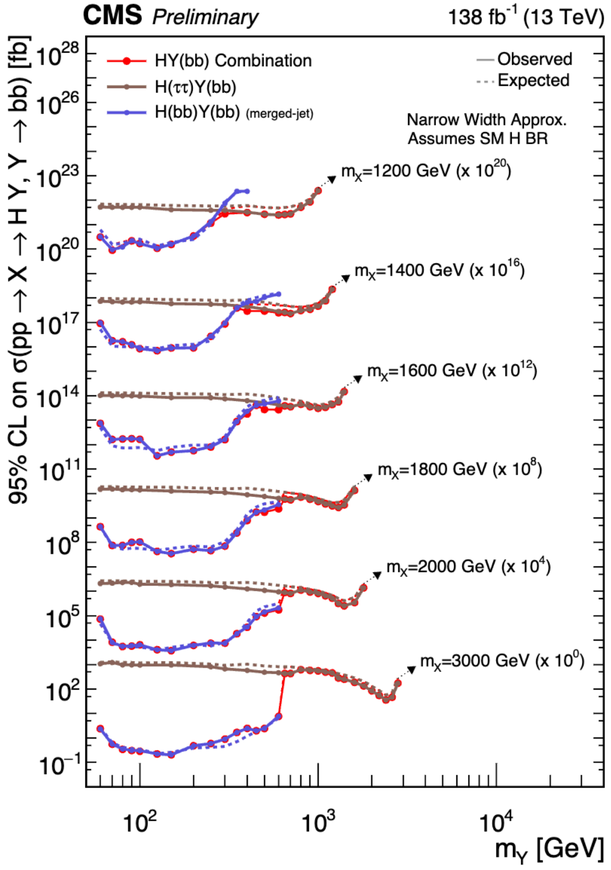
YH Combination

- **Systematics alignment is the same as HH combination**
- **For the 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 used grids in points of mX and (mX , mY) can differ across the various analyses.**
  - The combination is performed only for the points common to all analyses considered in the combination.

YH search Results

YH combination and per-channels results



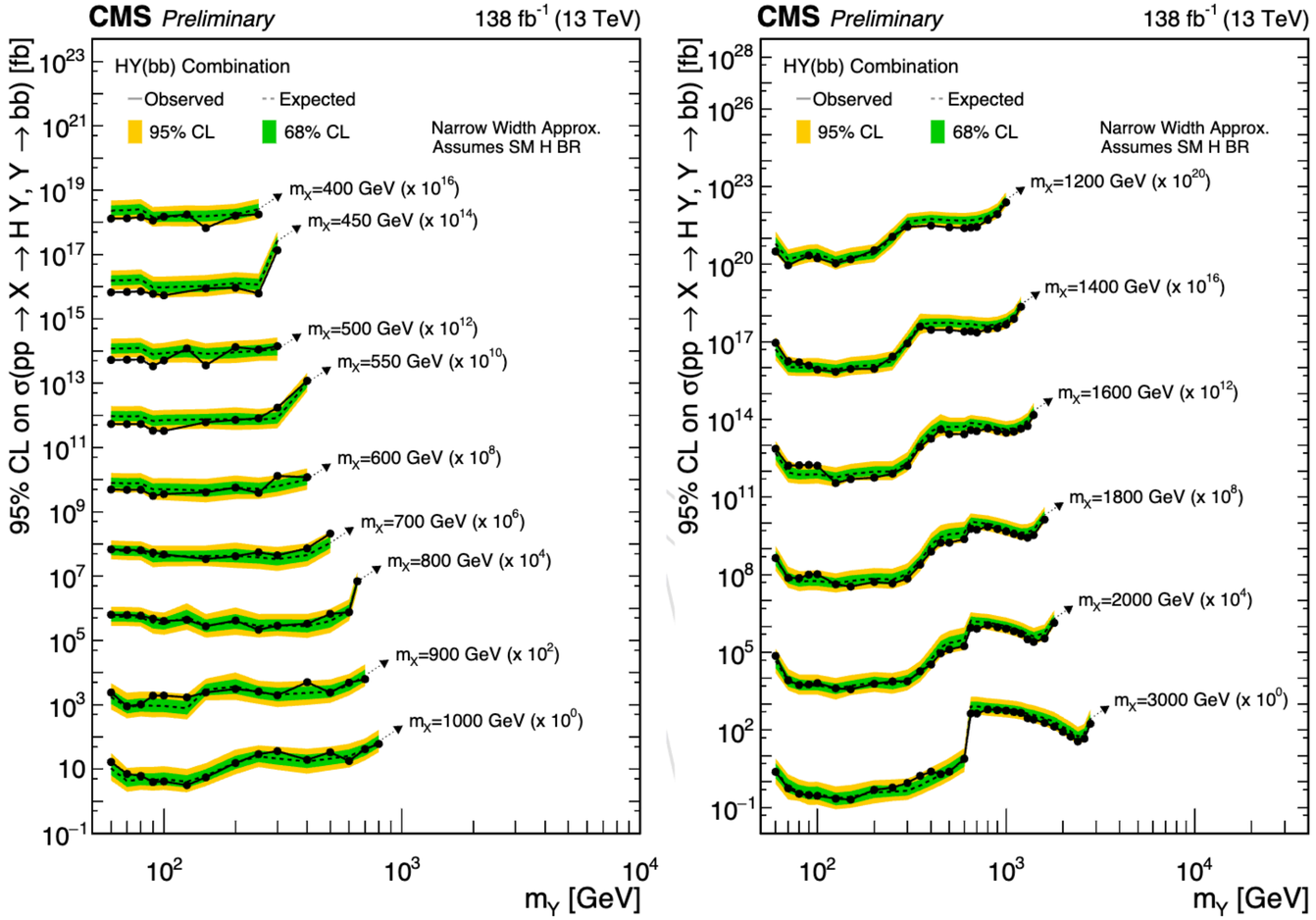


- **At low mX:**
  - The Y(bb)H (ττ) and Y(bb)H (γγ) analyses provide the best sensitivity
- **At mX=1000GeV and higher:**
  - The Y(bb)H (bb) in the merged jet topology dominates for small and medium values of mY
  - At the largest values of mY, the Y (bb)H (bb) sensitivity is reduced, because the boost of the Y is too small, the two b quarks can't merged into one single jets.

The 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.

Combination: Results

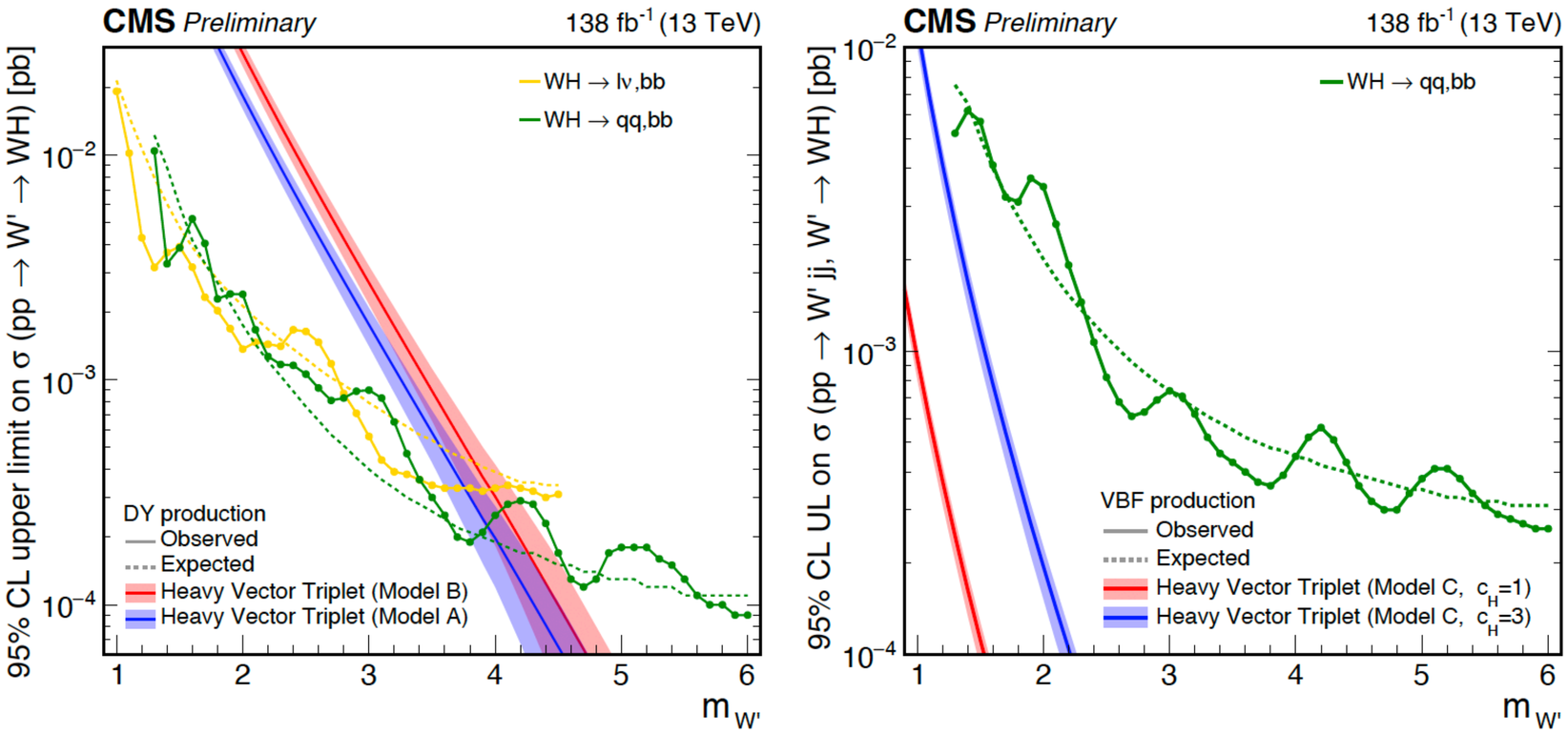
YH combination results with bands



- The typical exclusion upper limits on σ B are about 50, 5, and 0.3 fb for mX = 0.5, 1, and 3 TeV, respectively.
- No excess larger than two s.d. above the expected limit is observed at any of these mass points.

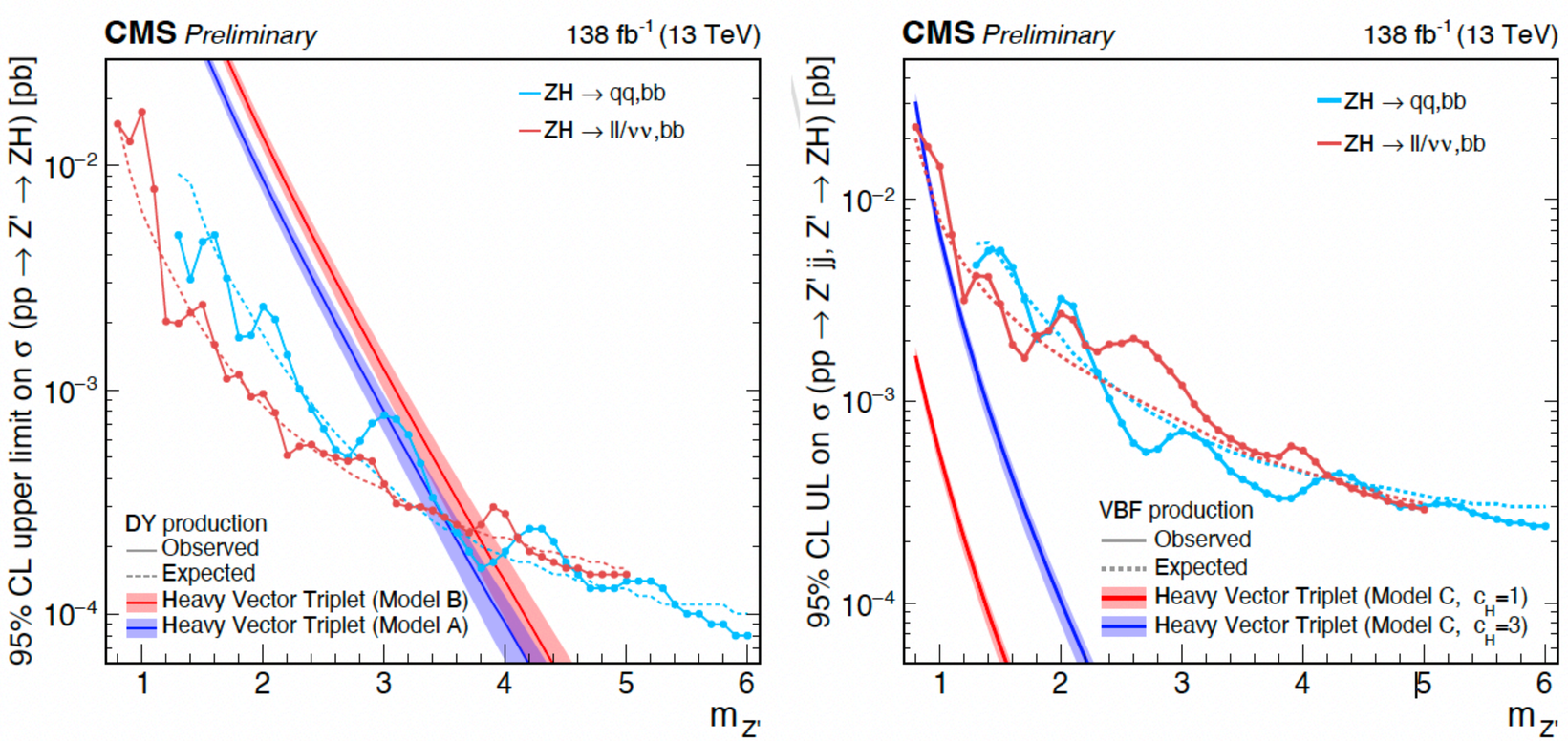
VH searches

- **Upper limit result:**
  - Upper limits on the production cross section times branching fraction of W' spin-1 resonance for the DY (left) and VBF (right) production modes, compared to theory predictions from HVT models.



VH searches

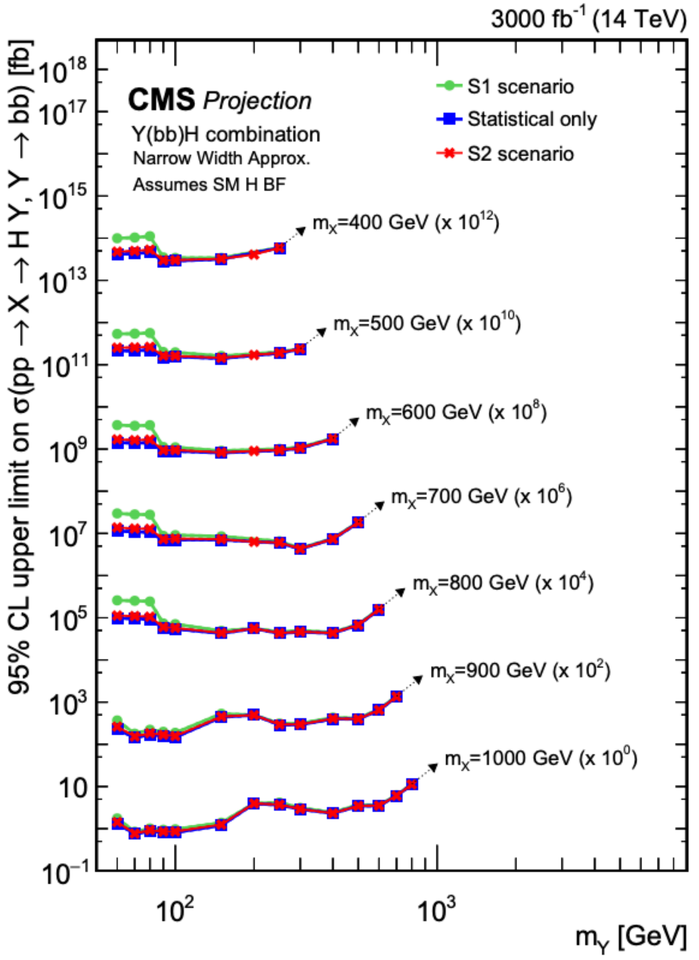
- **Upper limit result:**
  - Upper limits on the production cross section times branching fraction of Z' spin-1 resonance for the DY (left) and VBF (right) production modes, compared to theory predictions from HVT models.

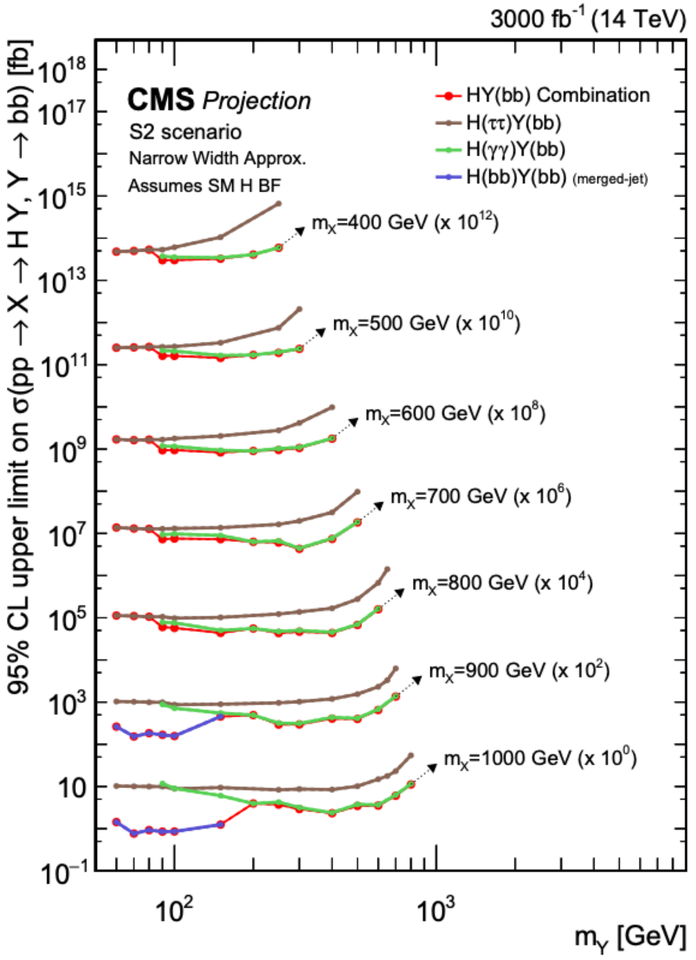


YH Projection

YH Projection

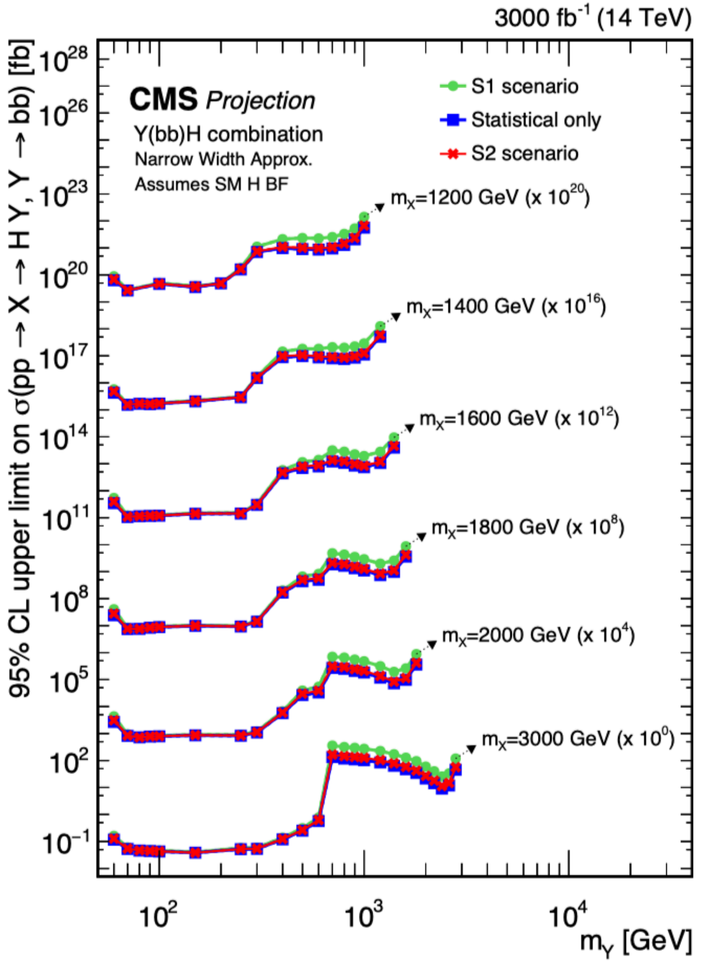
- **Signal cross sections have been scaled to the centre-of-mass energy of 14 TeV**
- **Lumi projected to 3000 fb-1**
- **Systematics scenarios:**
  - S1: All the systematic uncertainties are assumed to remain the same as in Run 2.
  - S2: The theory uncertainties are halved, while the experimental uncertainties are set according to the recommendations
  - Statistic only

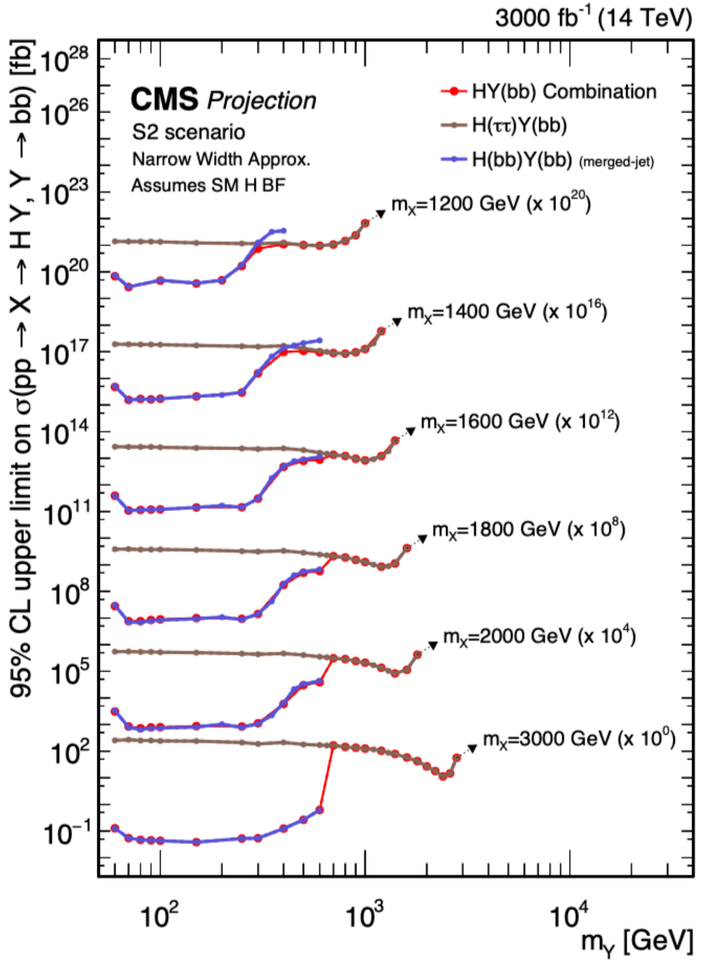




YH Projection

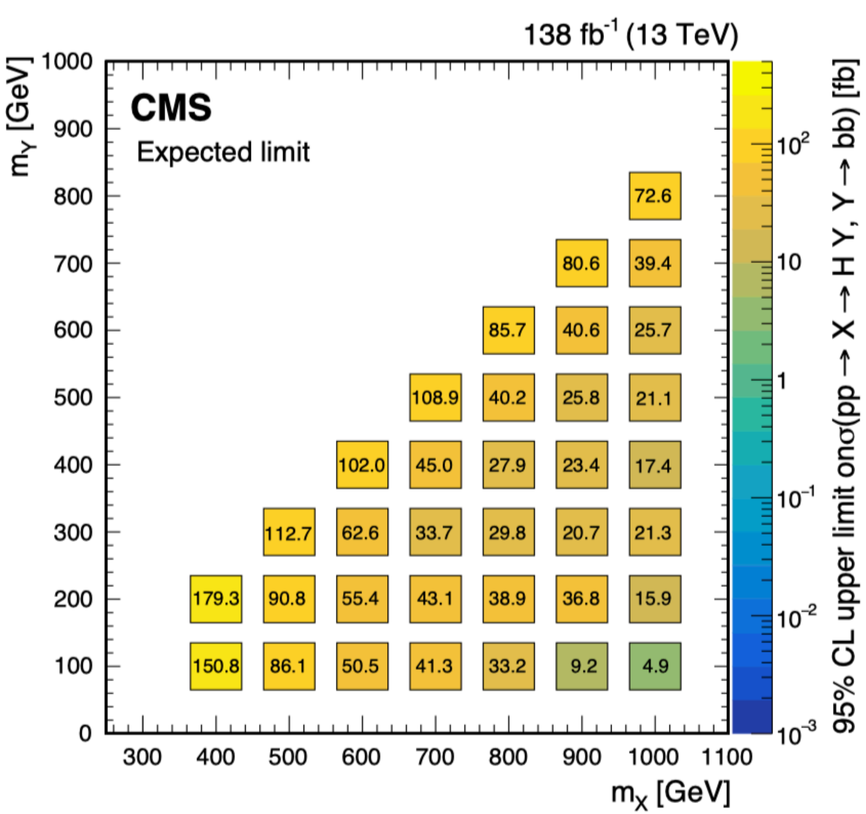
- **Signal cross sections have been scaled to the centre-of-mass energy of 14 TeV**
- **Lumi projected to 3000 fb-1**
- **Systematics scenarios:**
  - S1: All the systematic uncertainties are assumed to remain the same as in Run 2.
  - S2: The theory uncertainties are halved, while the experimental uncertainties are set according to the recommendations
  - Statistic only

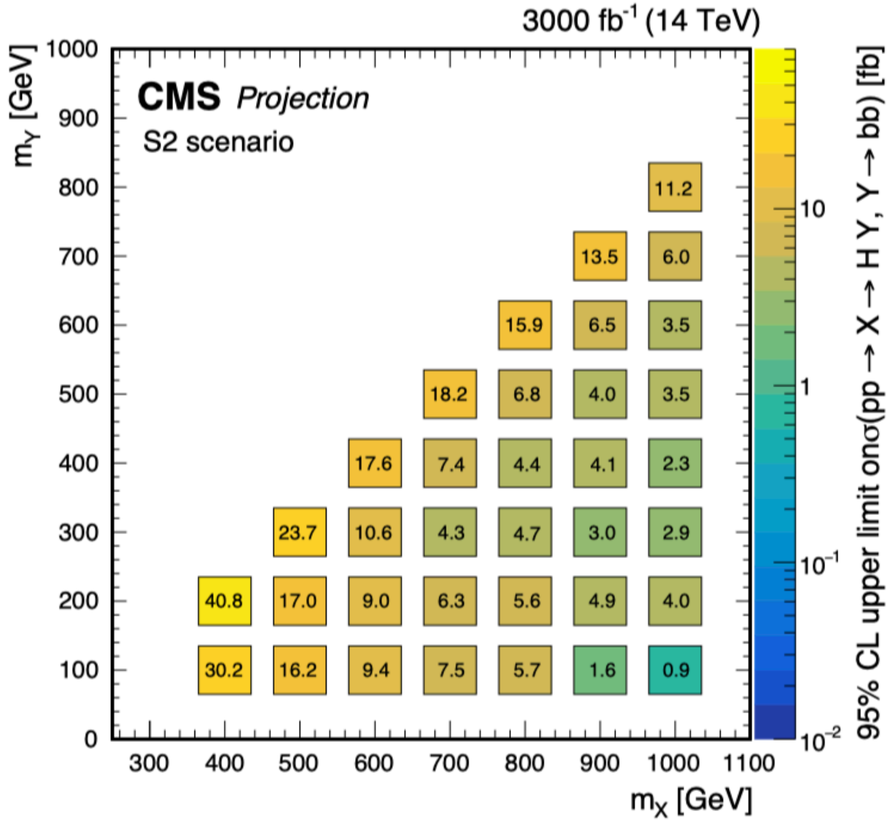




YH Projection

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

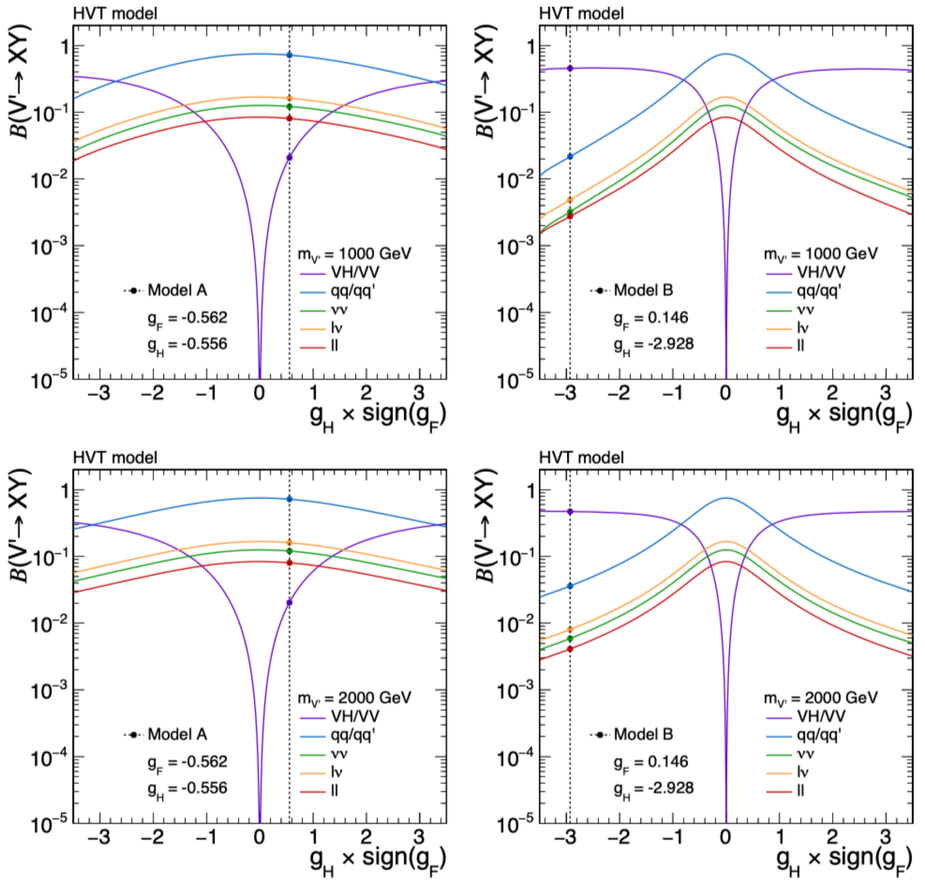




Interpretation

Heavy Vector Triplet benchmarks

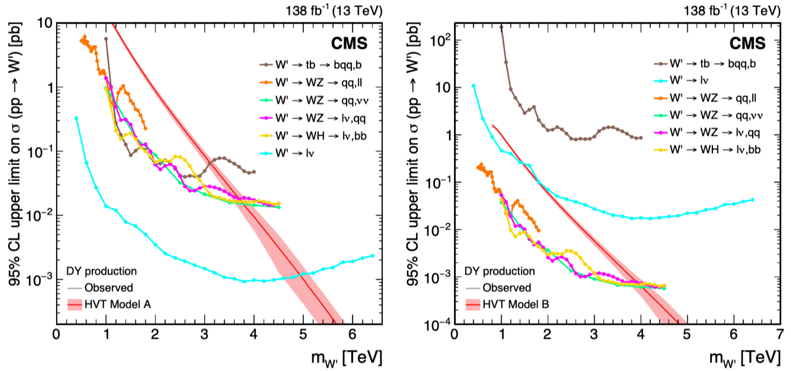
- **Heavy Vector Triplet (W′ and Z′)**
  - Minimal extension of the SM gauge group
    - Additional force-carrying heavy vector bosons, W′ and Z′
  - The W' and Z' coupling is proportional to:
    - gF = $g^2 c_F / g_V$, to fermions, g is the SU(2) Lgauge coupling, cF scales the W′ and Z′ couplings to 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.



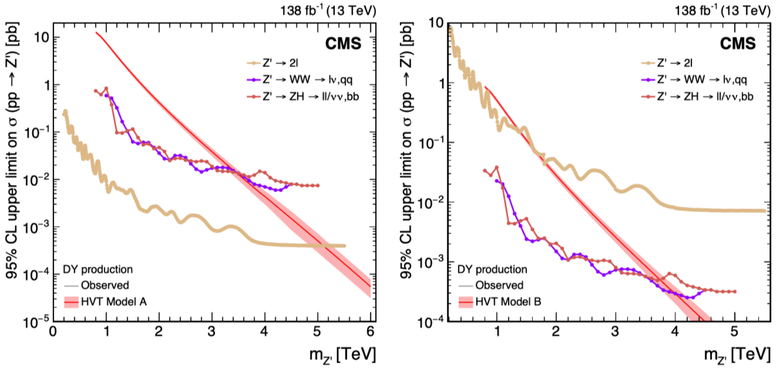
Branching fractions in model A and B in mV'=1000 and 2000GeV

Heavy vector triplet models

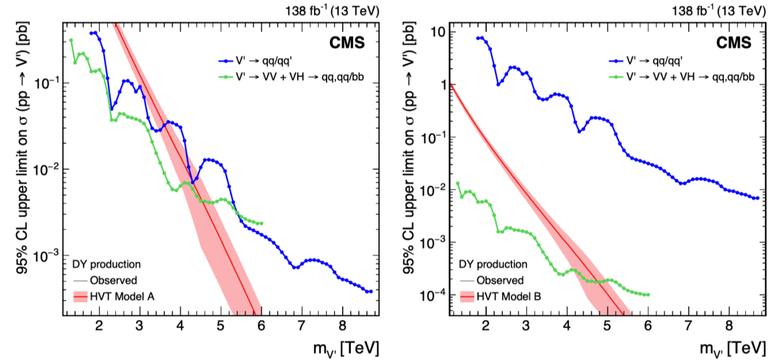
- Upper limits on the DY production cross section of W', Z' and combined V' spin-1 resonances assuming branching fractions of HVT model A (left) and model B (right)
- Theory predictions from HVT models A and B are also shown.
- The all-jets channels are sensitive to both W ′ and Z ′ production and are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



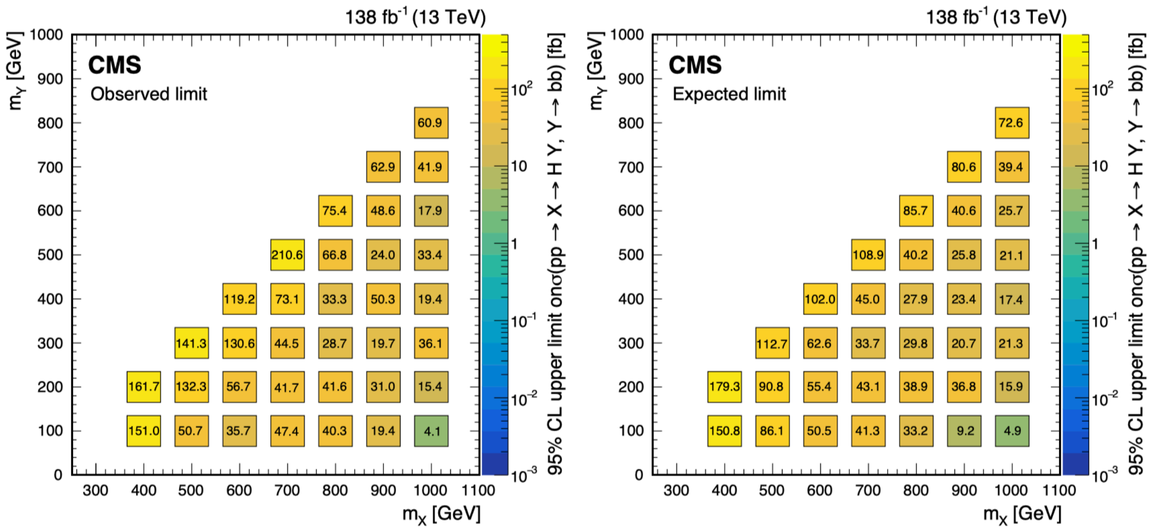
DY production of Z'

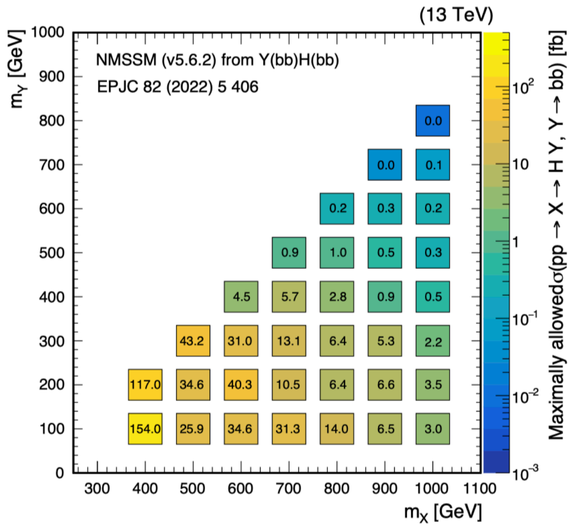


DY production of V'

Extended H sectors - NMSSM

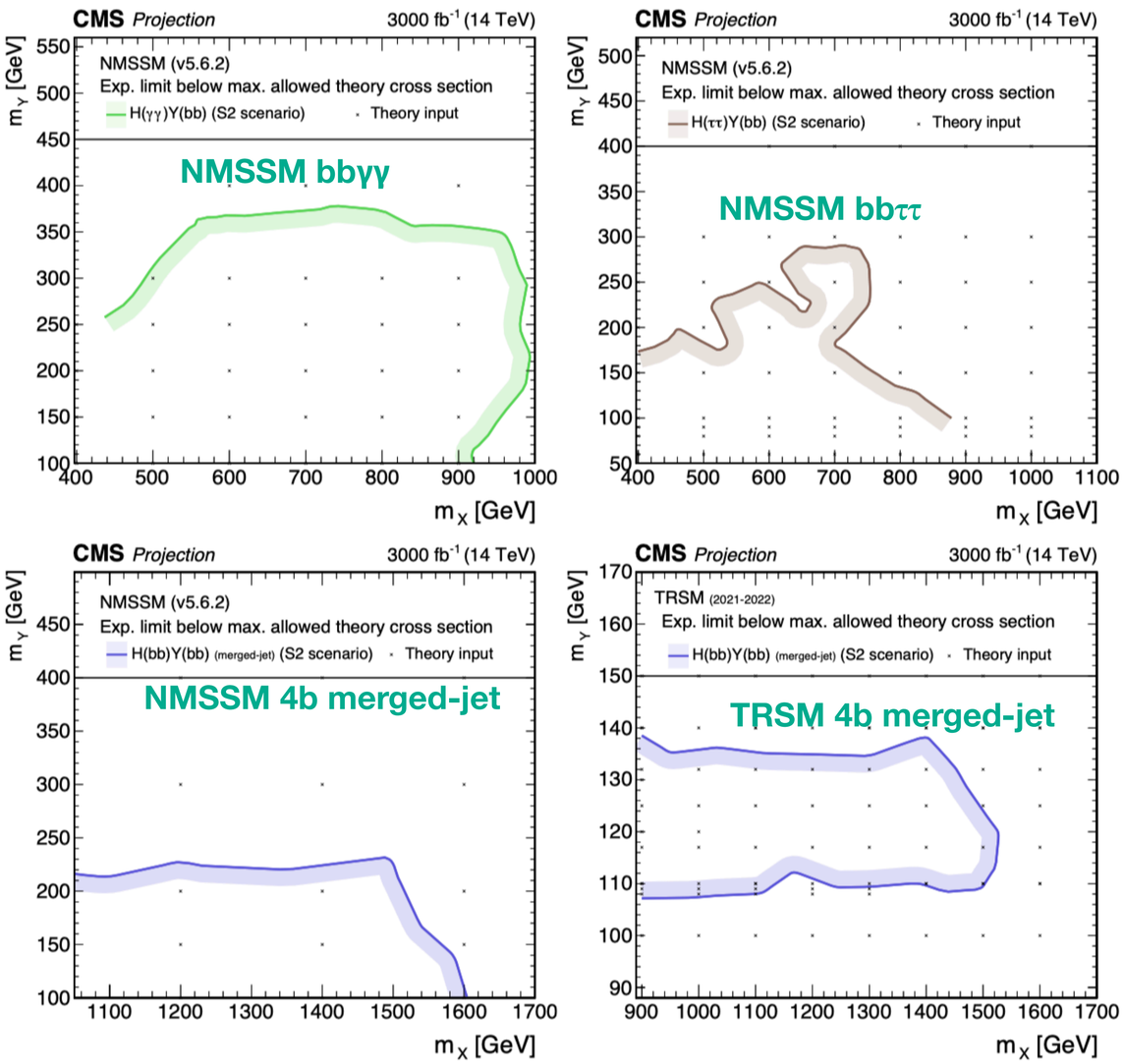
- **Expected (left) and observed (right) upper limit of the YH combination presented as a function of mX and mY**
- **NMSSM maximum allowed cross sections for comparison (bottom) from scans published in Eur. Phys. J. C 82 (2022), no. 5, 406:**
  - based on NMSSMTools version 5.6.2
- **No interesting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





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.



Summary

Summary

- **The X→YH/VH searches in CMS**
  - Presented three X→YH results and their combination
  - Summarised X→VH results in CMS
- **HL-LHC Projected results**
  - Reported the YH projections with HL-LHC luminosity
- **Interpretations**
  - Interpret the results in different models

Thanks!

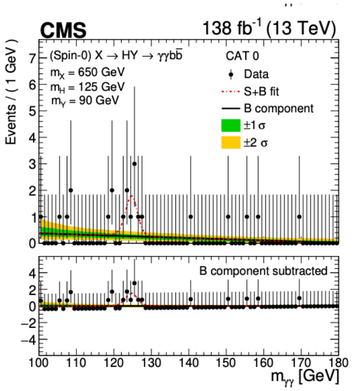
Backup

bb$\gamma\gamma$ (JHEP published)

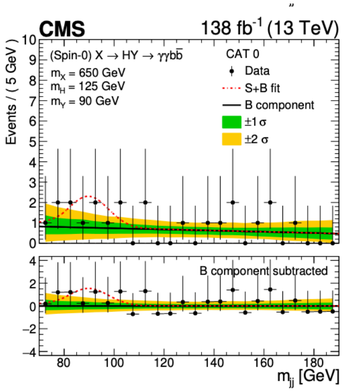
- **Characteristics of bb$\gamma\gamma$ channel :**
  - Low branching ration, but clean final states.
  - HH and HY analysis
    - For HY results, Higgs decays to $\gamma\gamma$, Y decays to bb
- **Main backgrounds:**
  - photon+Jets, diphoton+Jets, single Higgs
- **Analysis strategy:**
  - Standard Higgs to $\gamma\gamma$ tagger.
  - Select two b-jets with highest b-score
  - Training BDT to reject non-resonant backgrounds
  - 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)σ found at M_X= 650 GeV and M_Y = 90 GeV

	$m_Y < 300\,\text{GeV}$	$m_Y = [300\text{–}500]\,\text{GeV}$	$m_Y > 500\,\text{GeV}$
$m_X < 500\,\text{GeV}$	CAT 0 = 0.63–1.0 CAT 1 = 0.33–0.63 CAT 2 = 0.17–0.33		
$m_X = [500\text{–}700]\,\text{GeV}$	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	
$m_X > 700\,\text{GeV}$	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

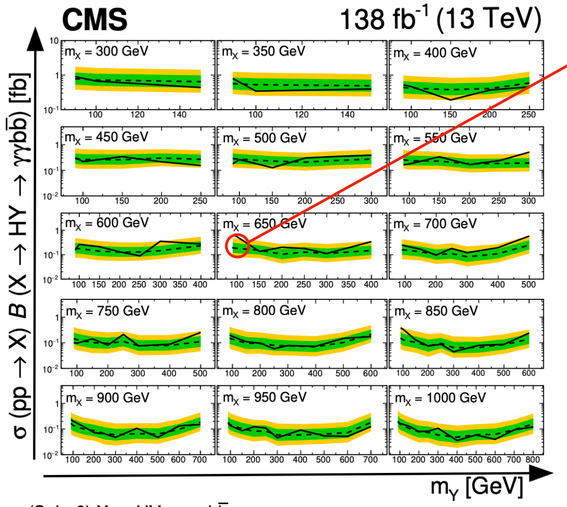
MVA categorisation



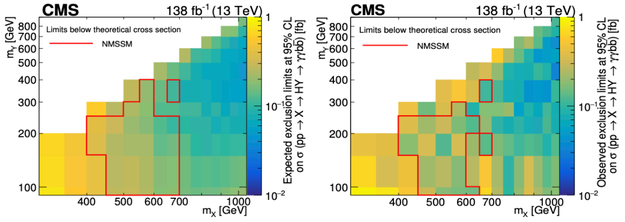
Diphoton-mass fits



Dijet mass fits



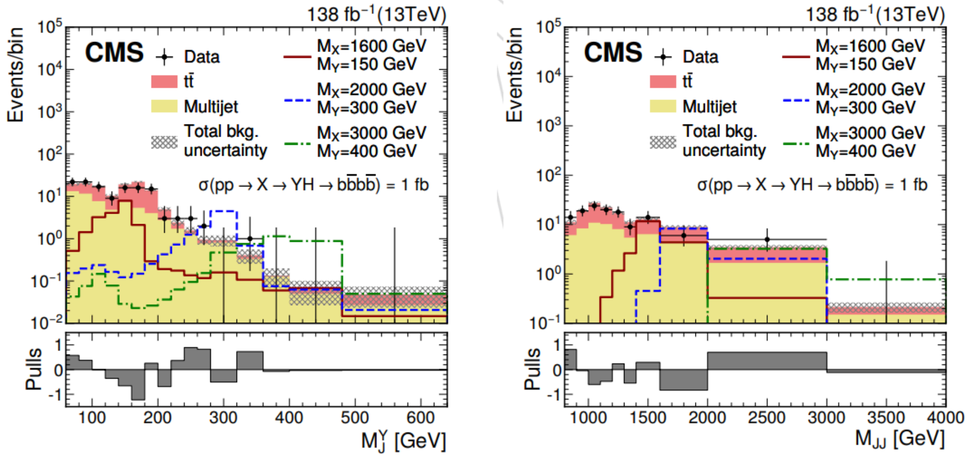
Excess of 3.8 (2.8)σ



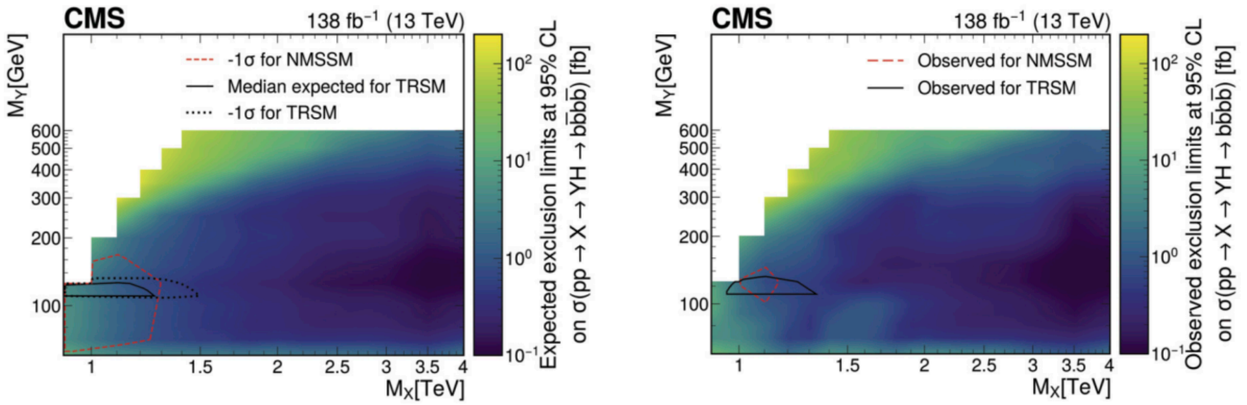
HY results

bbbb boosted (PLB published)

- **Characteristics of bbbb boosted channel :**
  - Largest branching ratio. Low backgrounds
  - At very high M_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

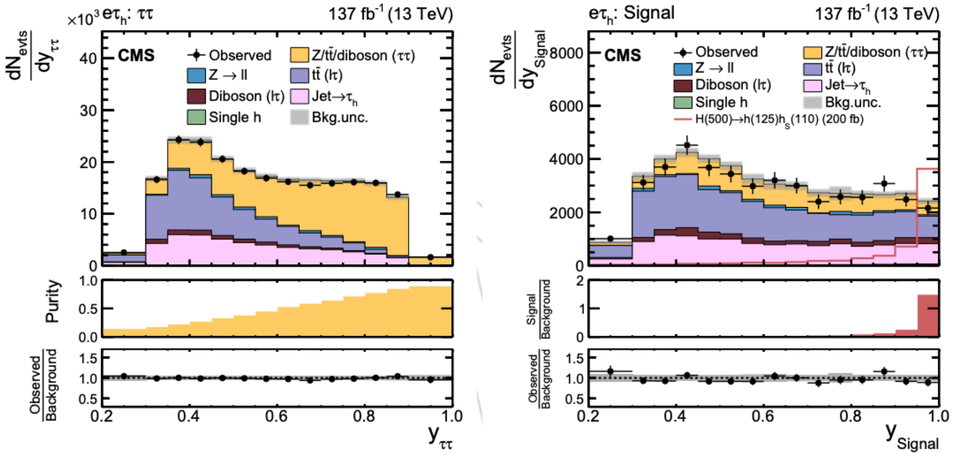


Distributions of M Y J (left) and MJJ (right) in the high-purity signal region of the Y(bb)H(bb) analysis in the merged jet topology

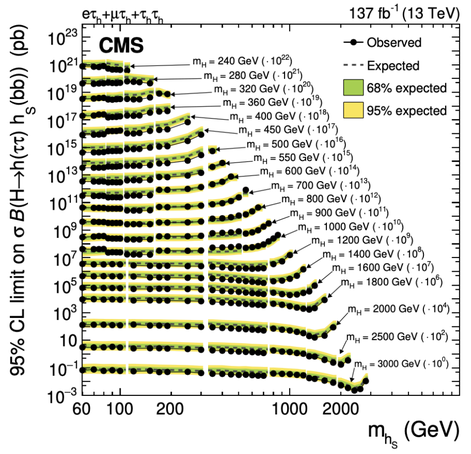


bb$\tau\tau$ (JHEP published)

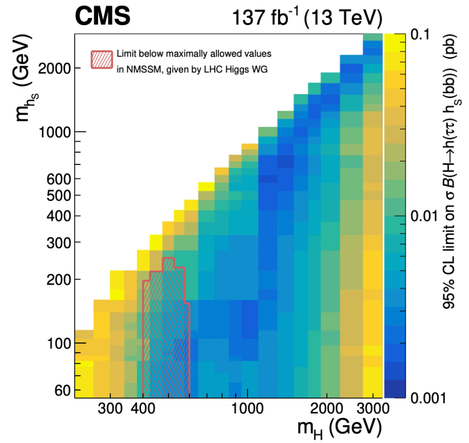
- **Characteristics of bb$\tau\tau$ channel :**
  - Select events with a reconstructed tau lepton pair in the final states $\tau_h\tau_h$, eτ_h, $\mu\tau_h$ (Covered ~88% $\tau\tau$ decays)
  - HY only analysis, Higgs decays to $\tau\tau$, Y decays to bb
- **Main backgrounds:**
  - Z,$t\bar{t}$, diboson, 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



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



HY results

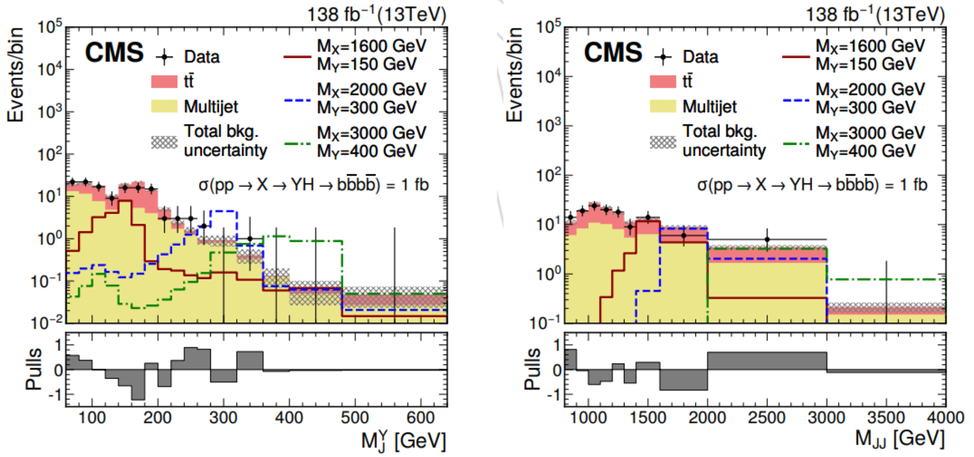


HY results

Backup: bbbb boosted (B2G-21-003)

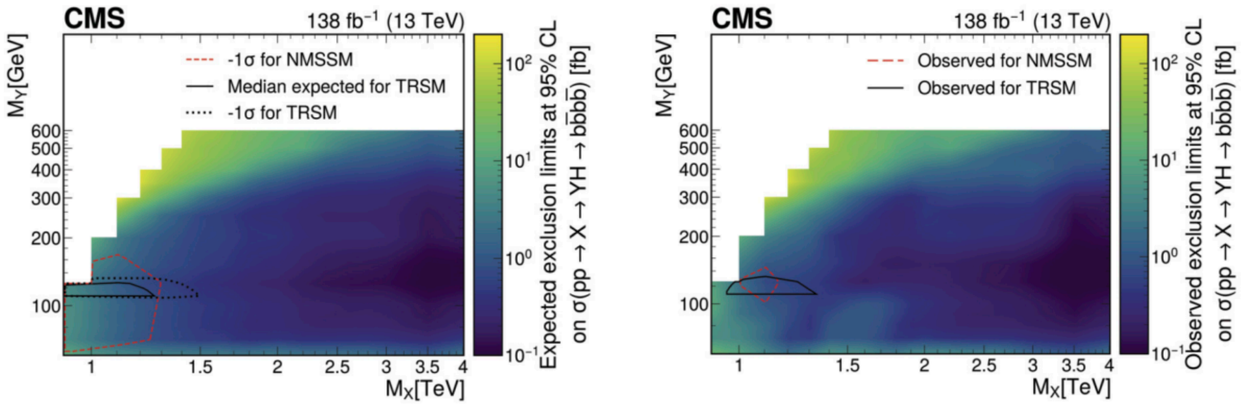
- **Characteristics of bbbb boosted channel :**
  - Largest branching ratio. Low backgrounds
  - At very high M_X, because of the boost, the two b-jets might merged to a fat-jet
  - Explored both HH and HY scenarios, Y decays to bb, H decays to bb
- **Main backgrounds:**
  - $t\bar{t}$, QCD multijets, 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

In paper ~~already published plot~~



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

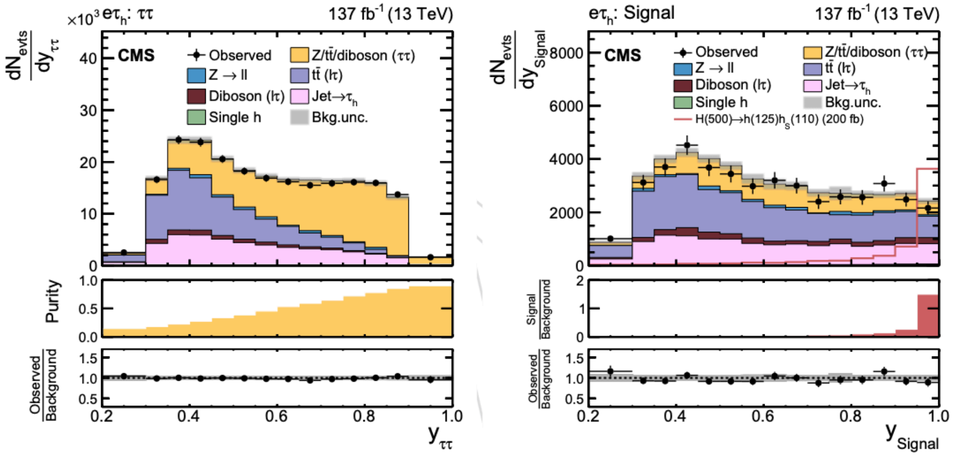
Plot source



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

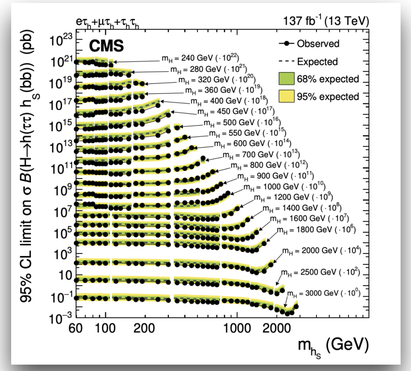
- **Characteristics of bb$\tau\tau$ channel :**
  - Select events with a reconstructed tau lepton pair in the final states $\tau_h\tau_h$, eτ_h, $\mu\tau_h$ (Covered ~88% $\tau\tau$ decays)
  - HY only analysis, Higgs decays to $\tau\tau$, Y decays to bb
- **Main backgrounds:**
  - Z,$t\bar{t}$, diboson, 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

In paper already published plot

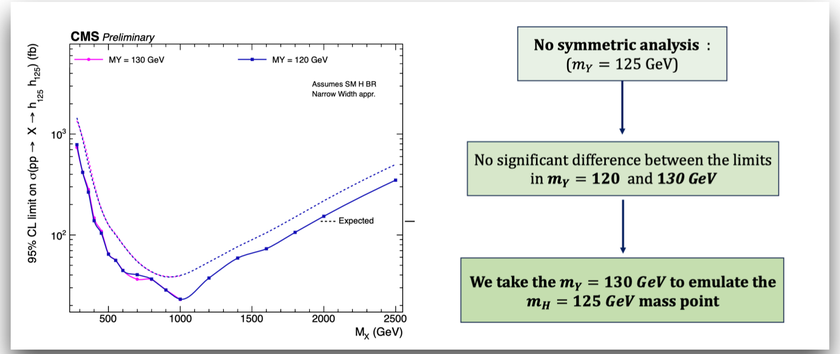


Distributions of the NN output scores , in different event categories after NN classification

Plot source

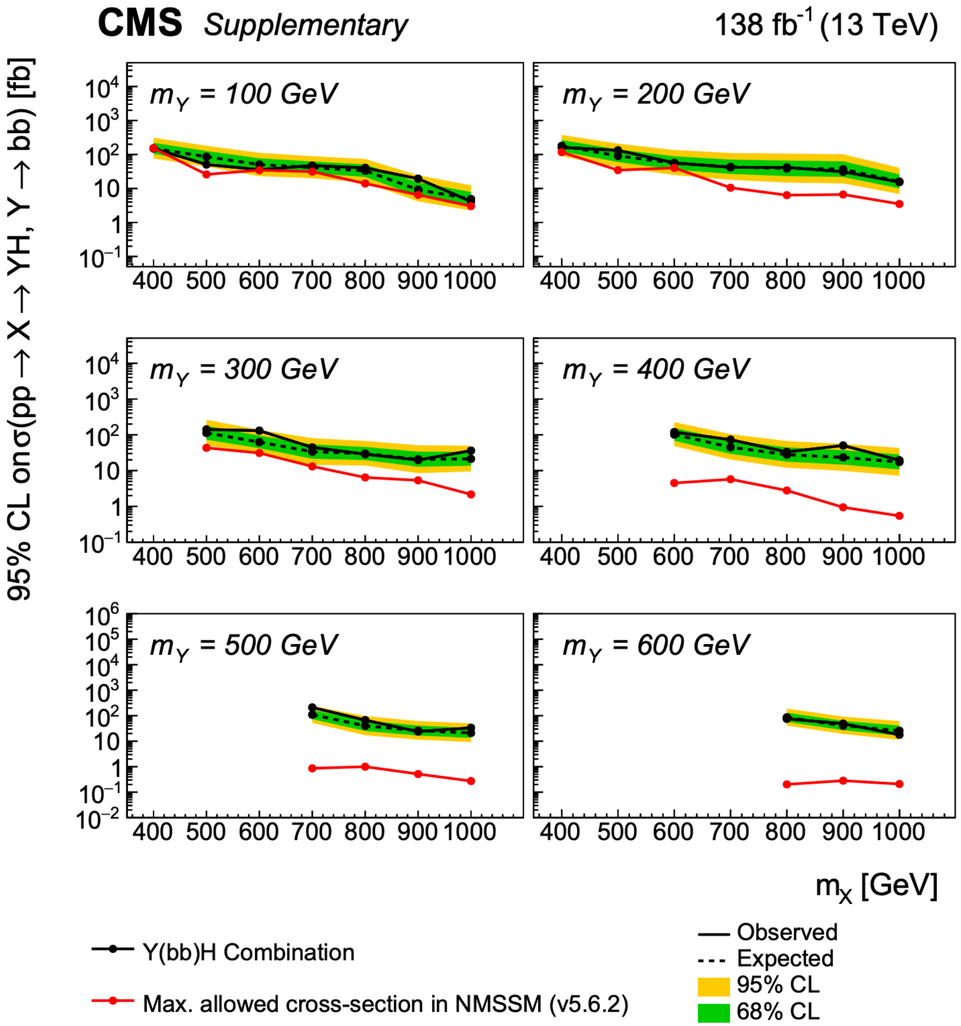


Original HY results

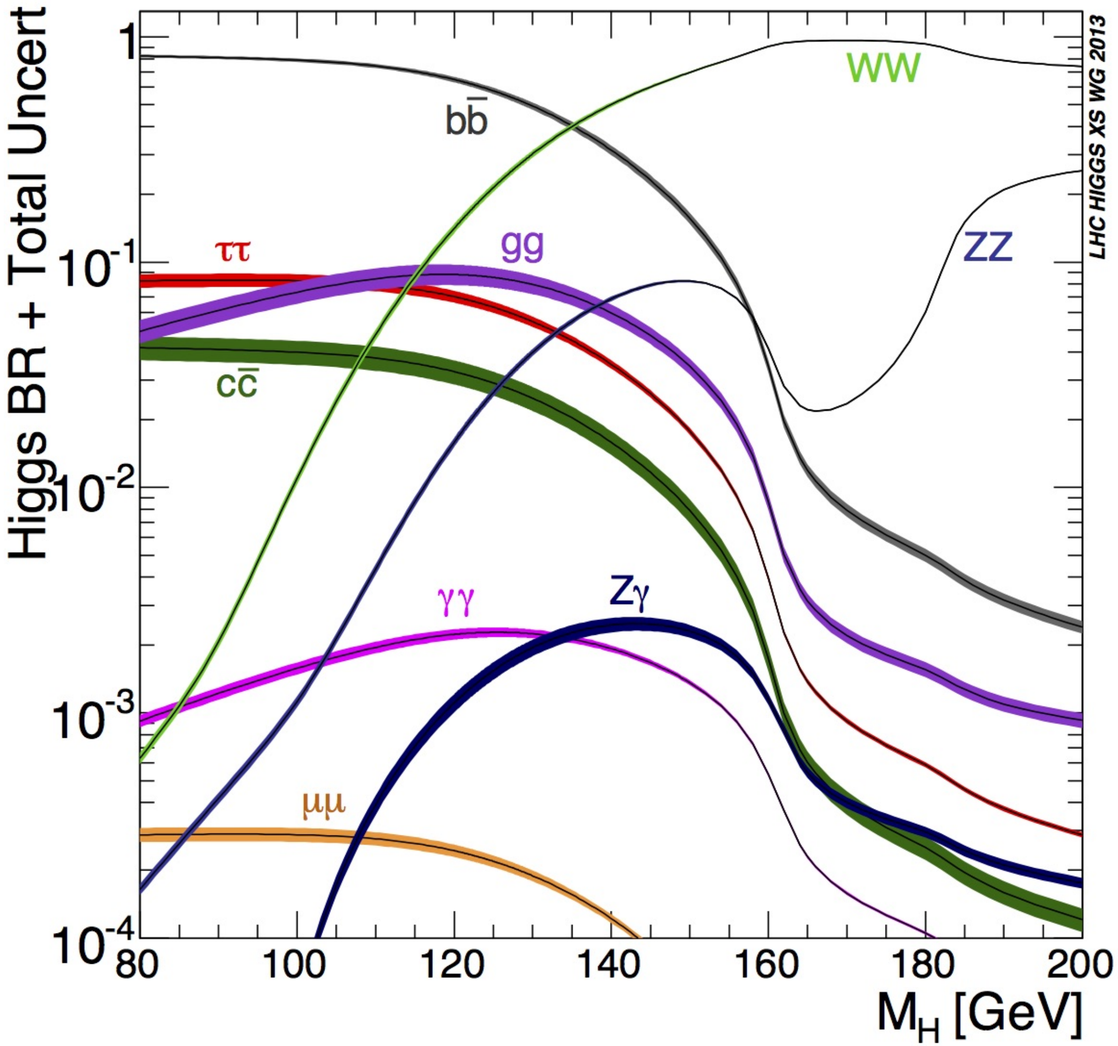


Emulation of HH results

NMSSM comparison

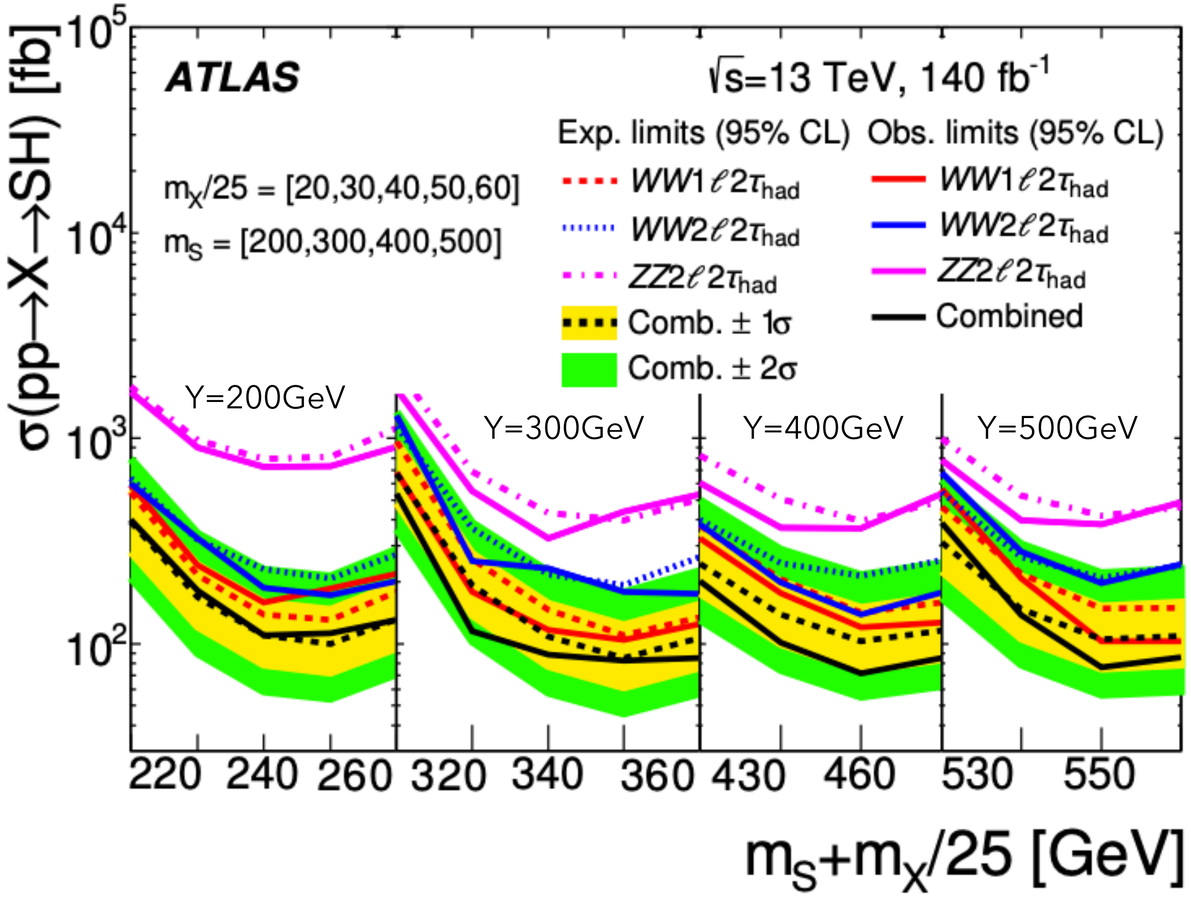


Higgs branching ratio



ATLAS combination results

MX=500,750,1000,1250,1500GeV

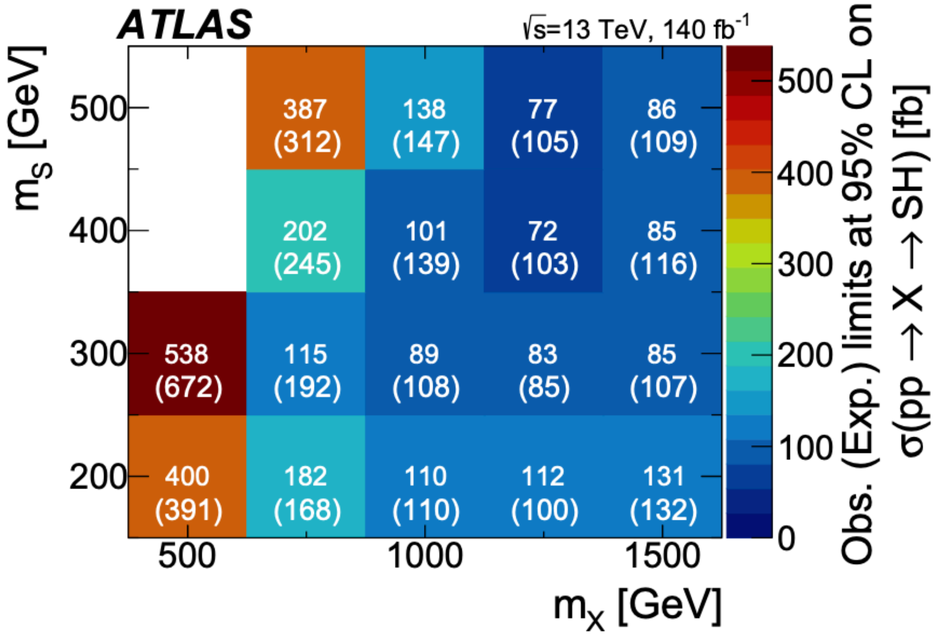


S branching fractions assuming the decays like a SM Higgs boson

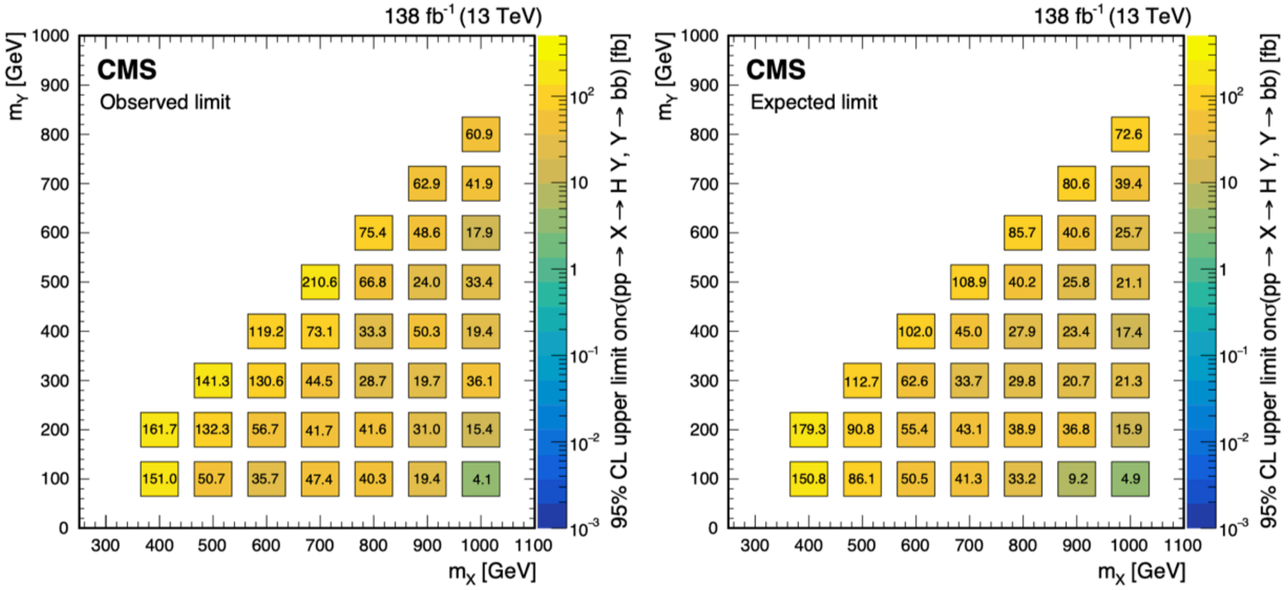
plot link

ATLAS combination results

- **ATLAS vs CMS**



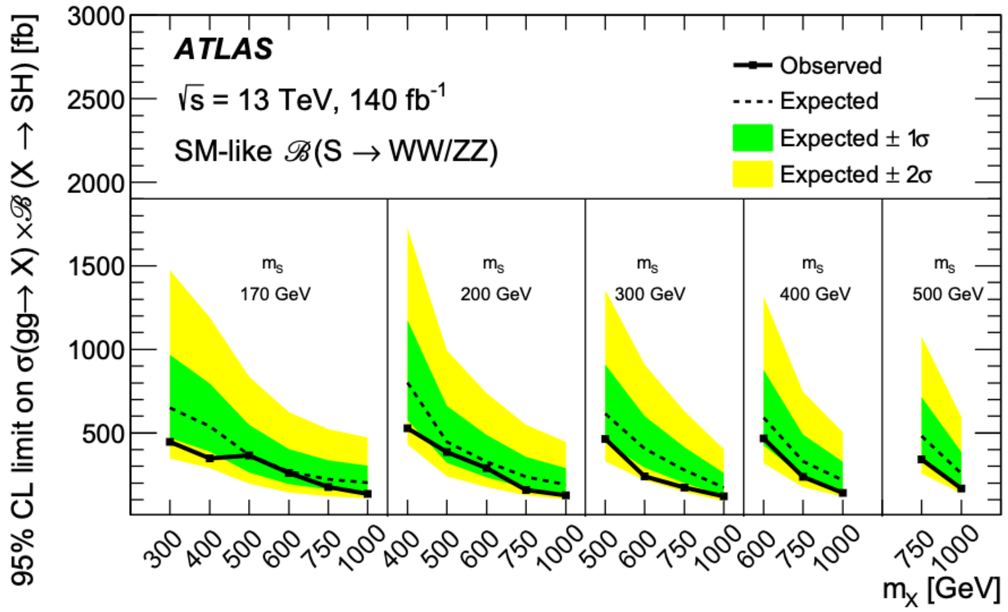
ATLAS results



CMS results

ATLAS VV$\gamma\gamma$ results

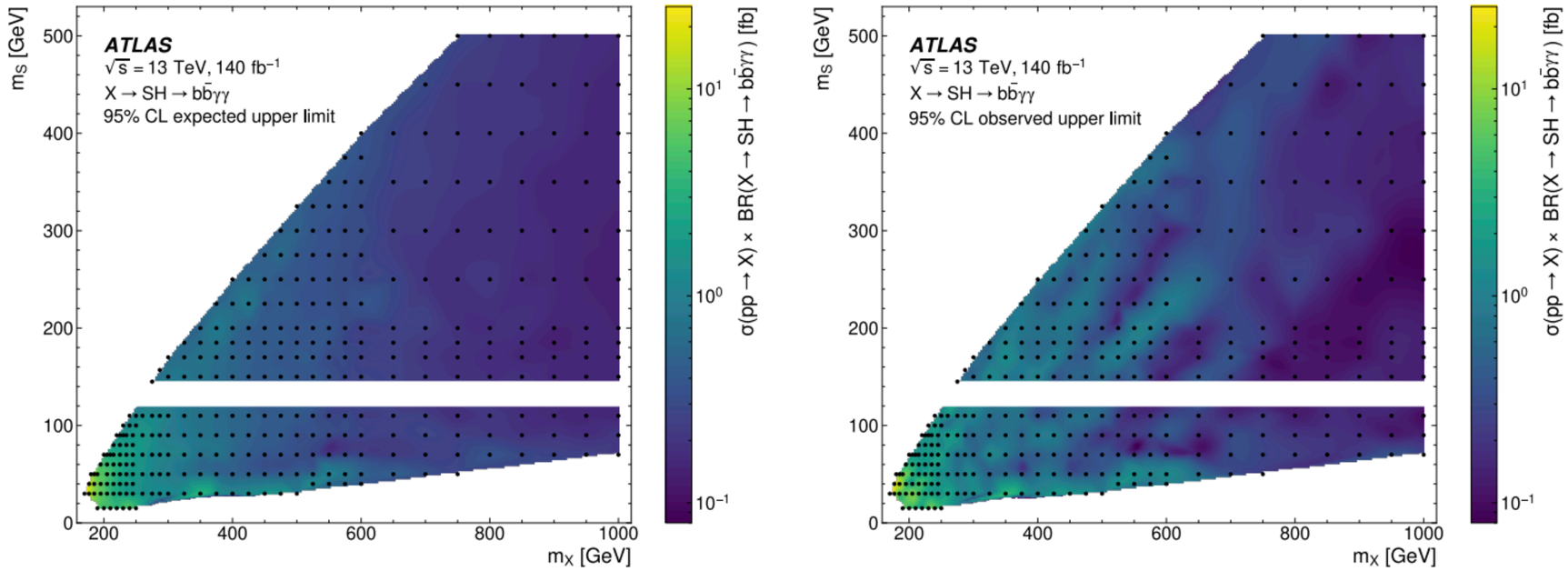
- **The observed (expected) upper limits lie in the range of 530 – 120 fb (800 – 170 fb) under the assumption that $\mathcal{B}$(S→ WW/ZZ) corresponding to those the SM Higgs boson would have at the mass of the particle.**



link

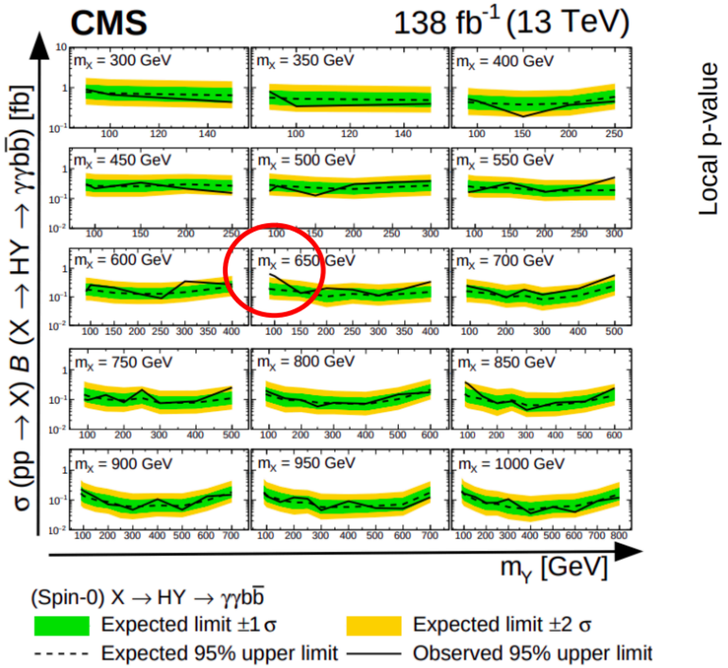
ATLAS bbγγ

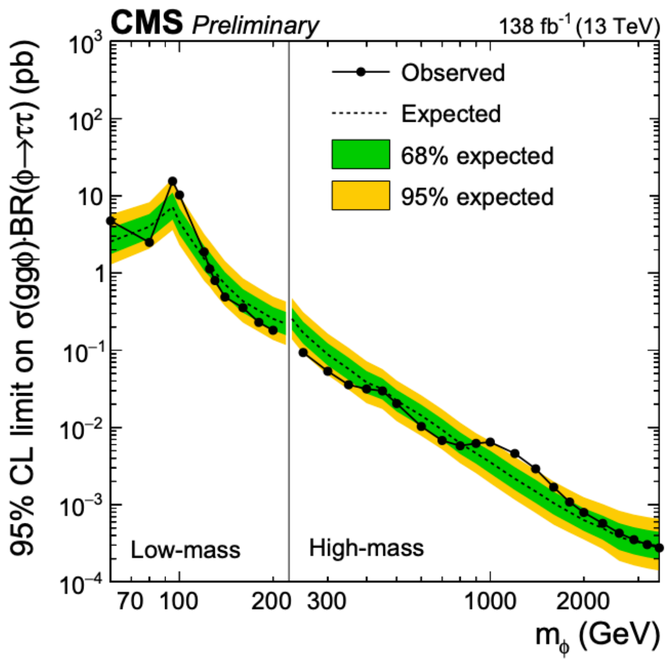
- **The largest deviation from the background-only expectation occurs for (mX, ms) = (575, 200) GeV with a local (global) significance of 3.5 (2.0) standard deviations.**

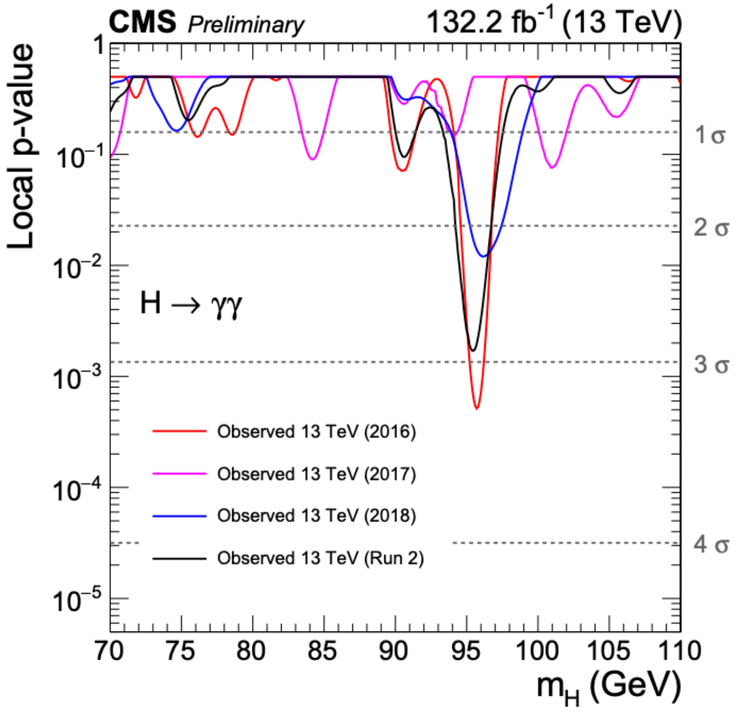


plot source

CMS excess







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

[Additional Higgs search]

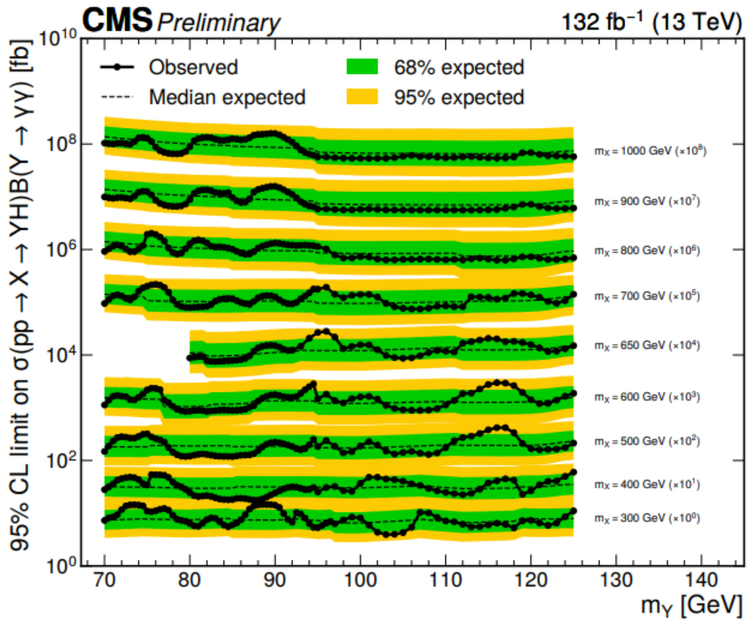
The largest deviation from the expectation is observed for ggϕ production at mϕ = 100 GeV with a local (global) p-value of 3.1 (2.7) standard deviations (s.d.)

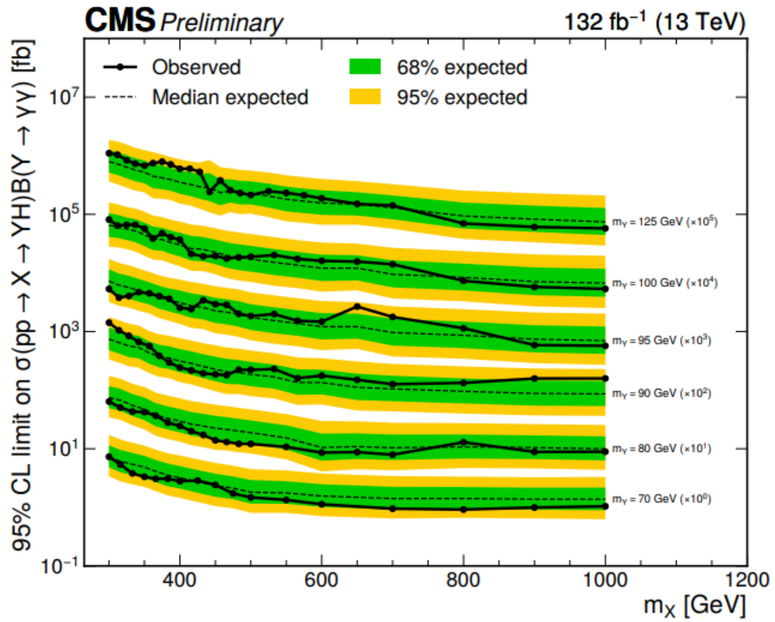
[Low mass Higgs search]

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

CMS $\tau\tau\gamma\gamma$

- **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.**



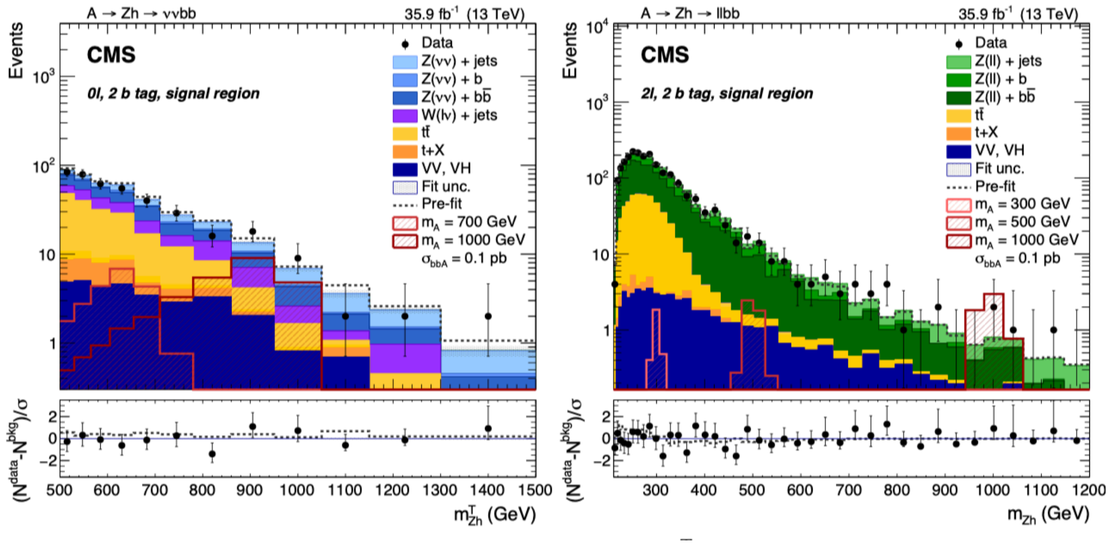


plot source

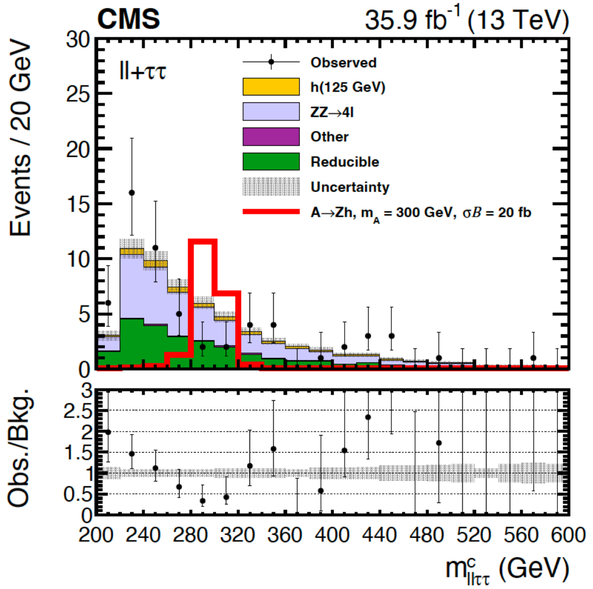
VH searches: sub-TeV mass region

- **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

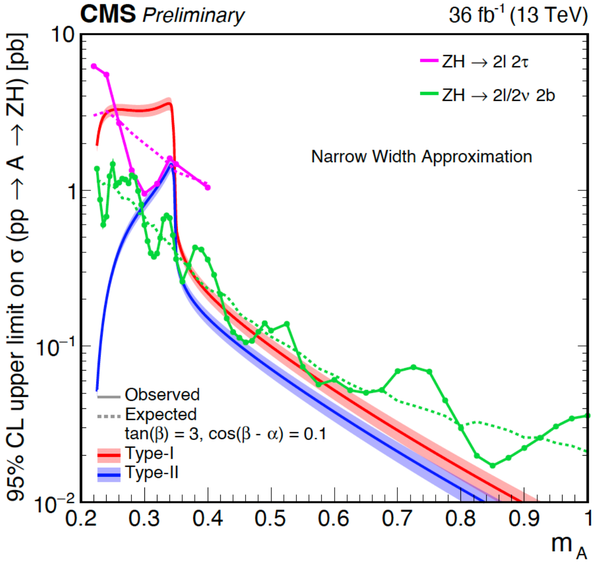
$$m_{\mathrm{ZH}}^{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}^{\mathrm{H}} \left[1 - \cos\Delta\phi(\mathrm{H}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})\right]}$$



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

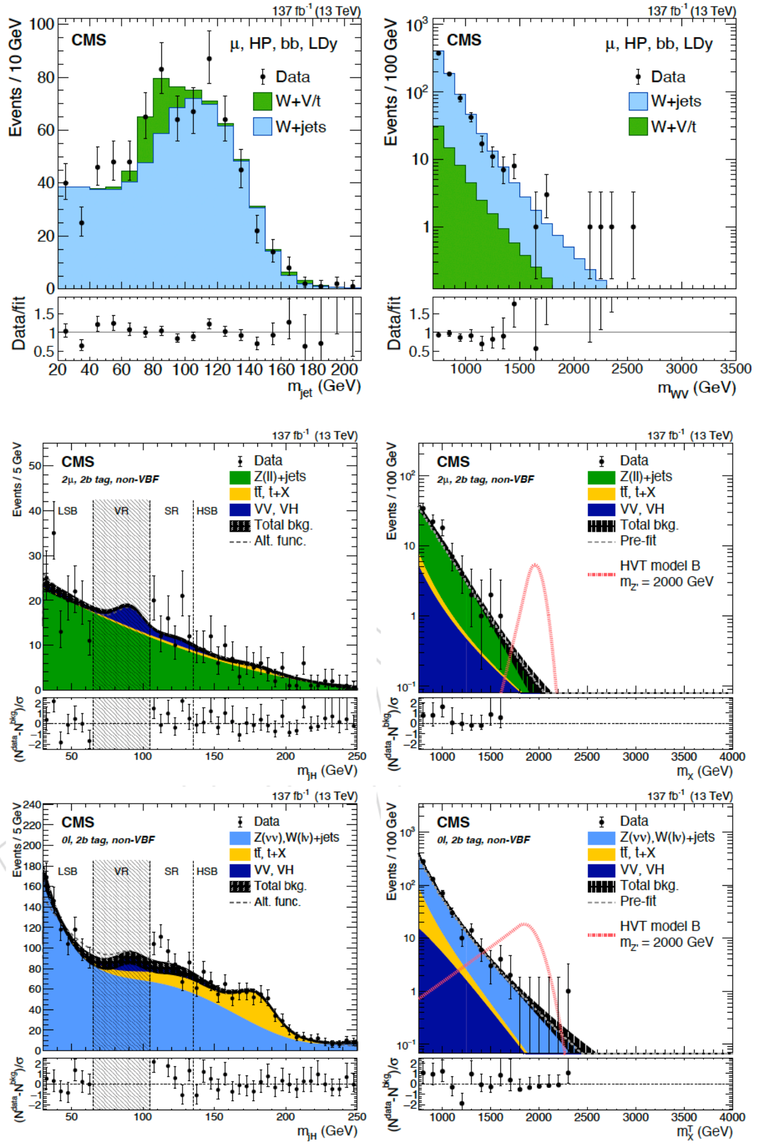
VH searches: high mass region

- **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

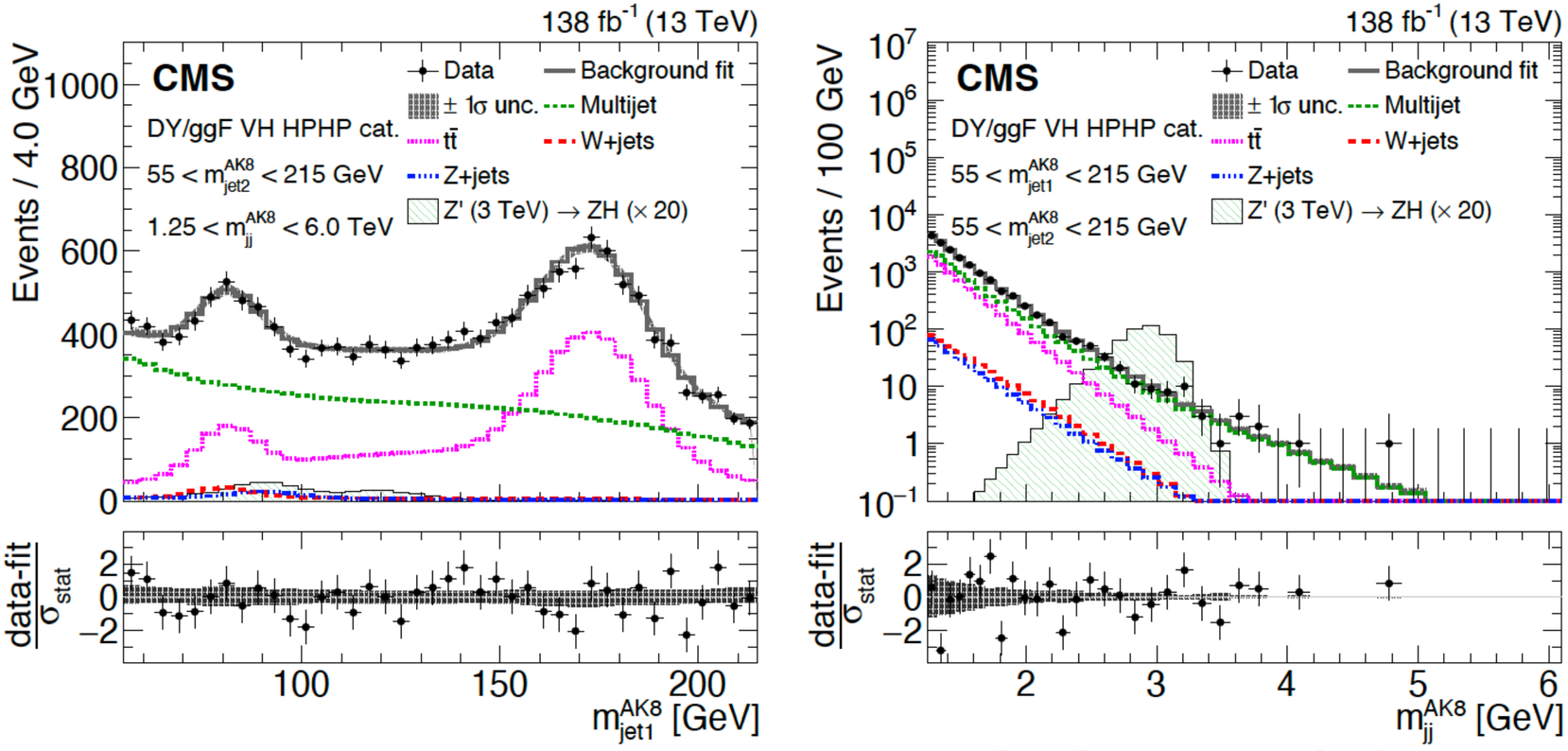
Z(ll)H(bb) channel

Z(vv)H(bb) channel



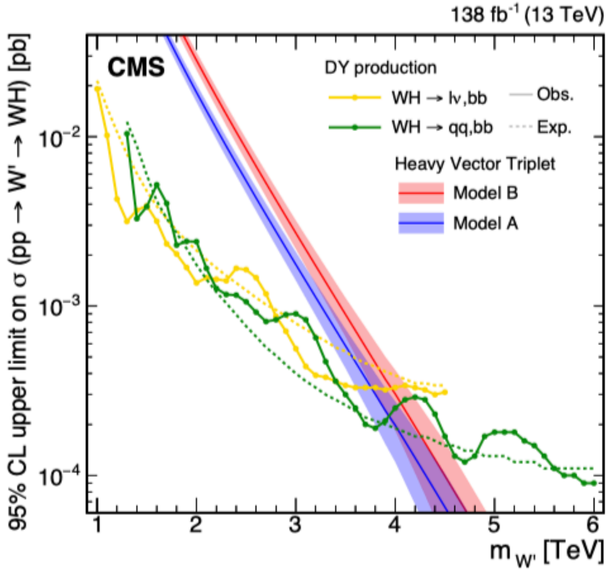
VH searches: high mass region

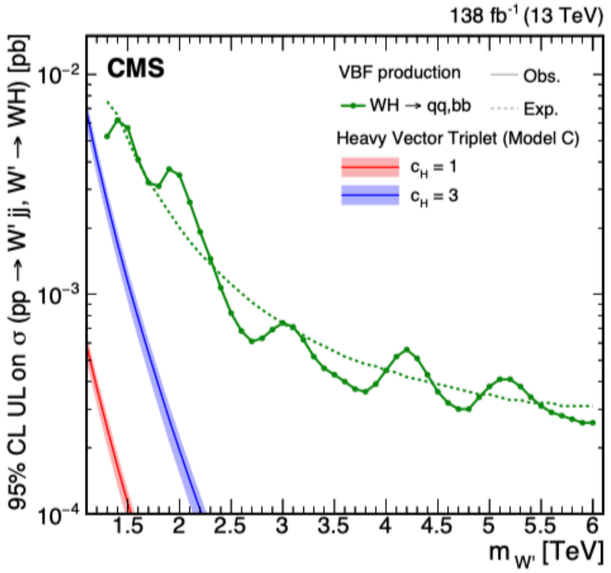
- **Hadronic V boson decays:**
  - Presence of two AK8 jets with pT > 200 GeV
  - invariant mass of the selected AK8 jets > 1250 GeV

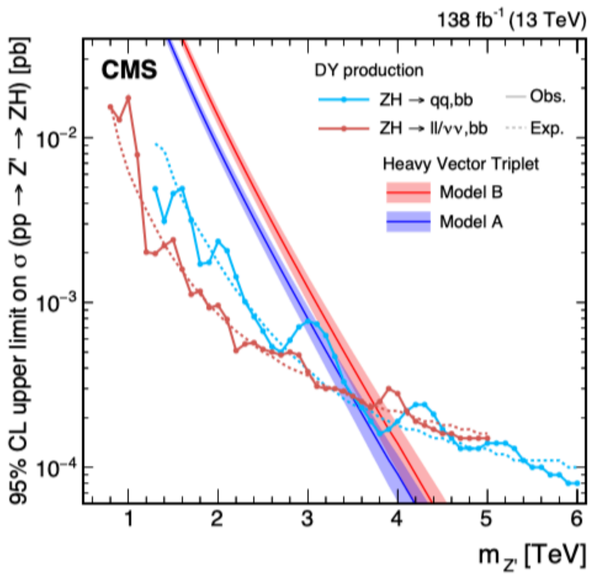


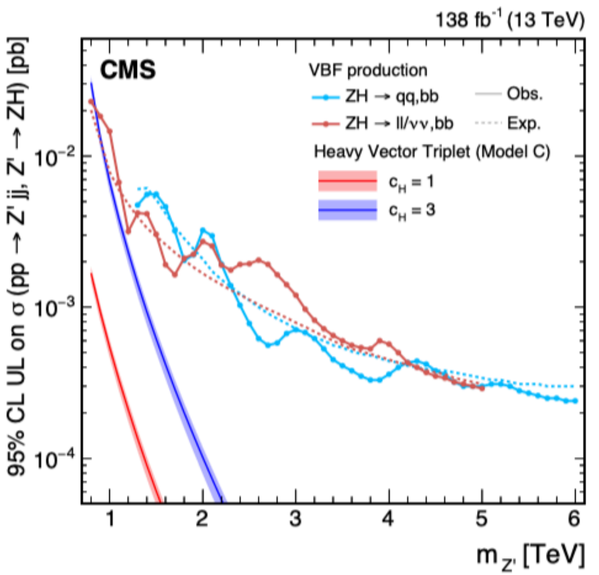
VH searches

- **Search for X → WH:**
  - The exclusion limits reach values of σ B below 0.1 and 0.3 fb for the DY and VBF topologies, respectively.
  - In DY production the results from searches with leptons in the final state yield a stronger exclusion for mW ′ masses below 1.7 TeV and mZ ′ below 3.2 TeV. For higher masses, the fully hadronic final state shows higher sensitivity.



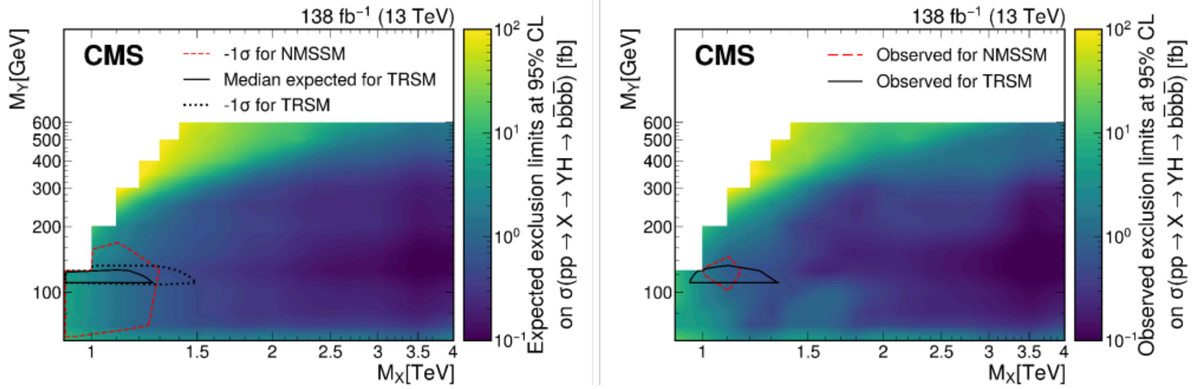






Extended H sectors - TRSM

- bbbb excludes part of the allowed TRSM parameter space in a wedge-shaped region between mX ≈ 1000–1300 GeV and around mY≈ 125 GeV.

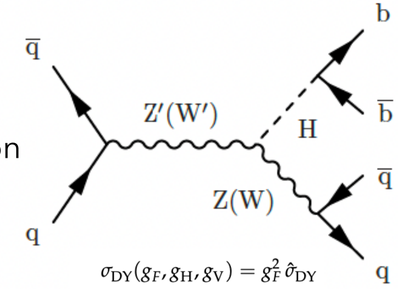


https://www.arxiv.org/pdf/2310.18045

Supersymmetric and HVT

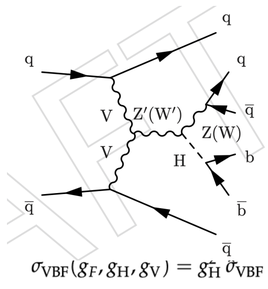
- **Supersymmetric models**
  - The Higgs sector of the minimal supersymmetric standard model (MSSM) has the structure of a Type II 2HDM
  - By adding an additional singlet field:
    - Defines next-to-minimal MSSM (NMSSM)
    - X → YH to be possible
- **Heavy Vector Triplet (W ′ and Z ′)**
  - Minimal 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 g F=−0.562 and g H = −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.

DY production



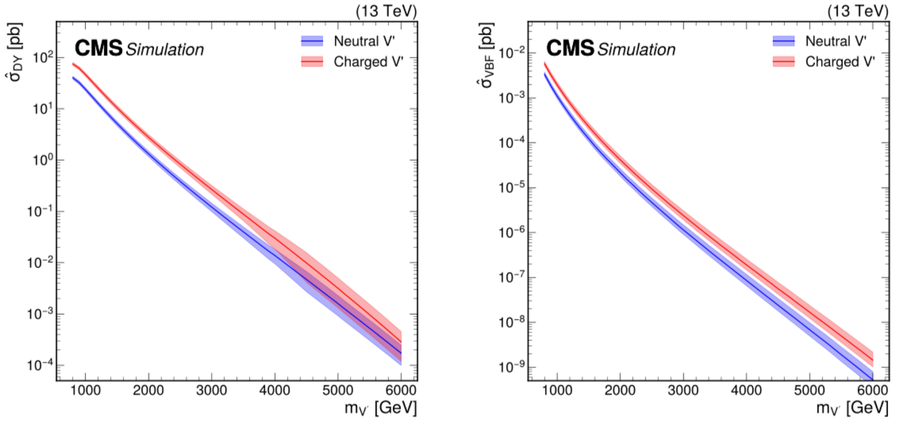
$\sigma_{DY}(g_F, g_H, g_V) = g_F^2 \hat{\sigma}_{DY}$

VBF production

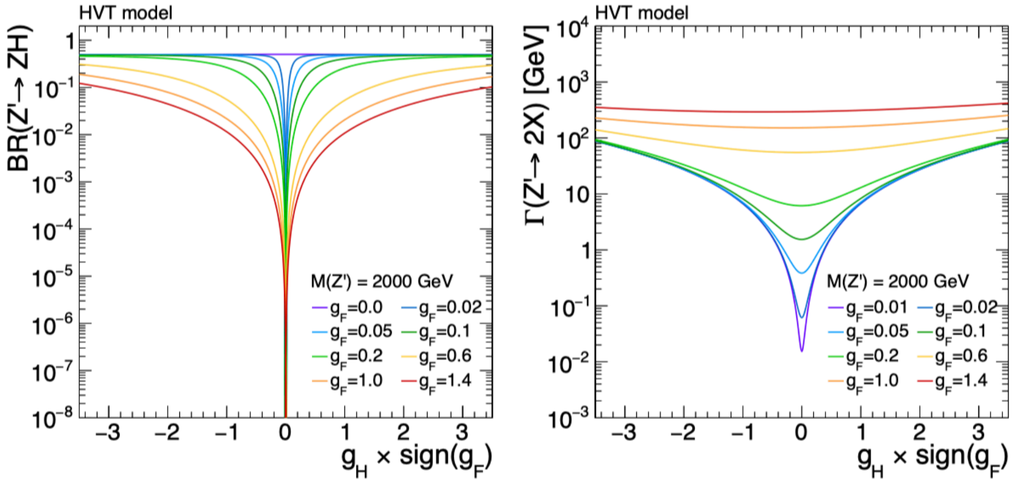


$\sigma_{VBF}(g_F, g_H, g_V) = g_H^2 \hat{\sigma}_{VBF}$

- The BR of V' to VH start to dominate at high |gH|



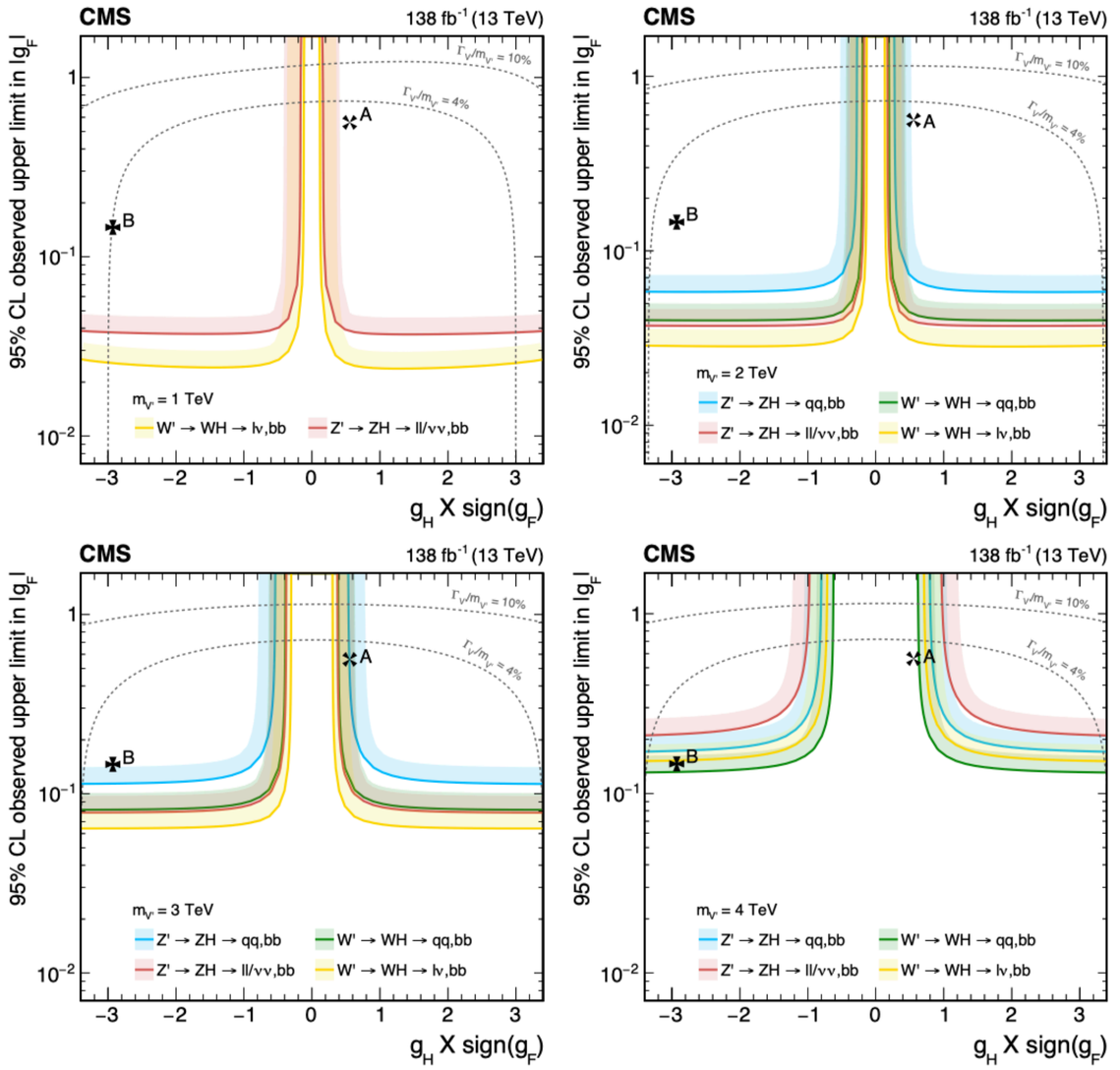
Two main production modes cross sections, DY (left), VBF (right)



Branching fraction for the Z ′ → ZH decay mode (left) and total decay width

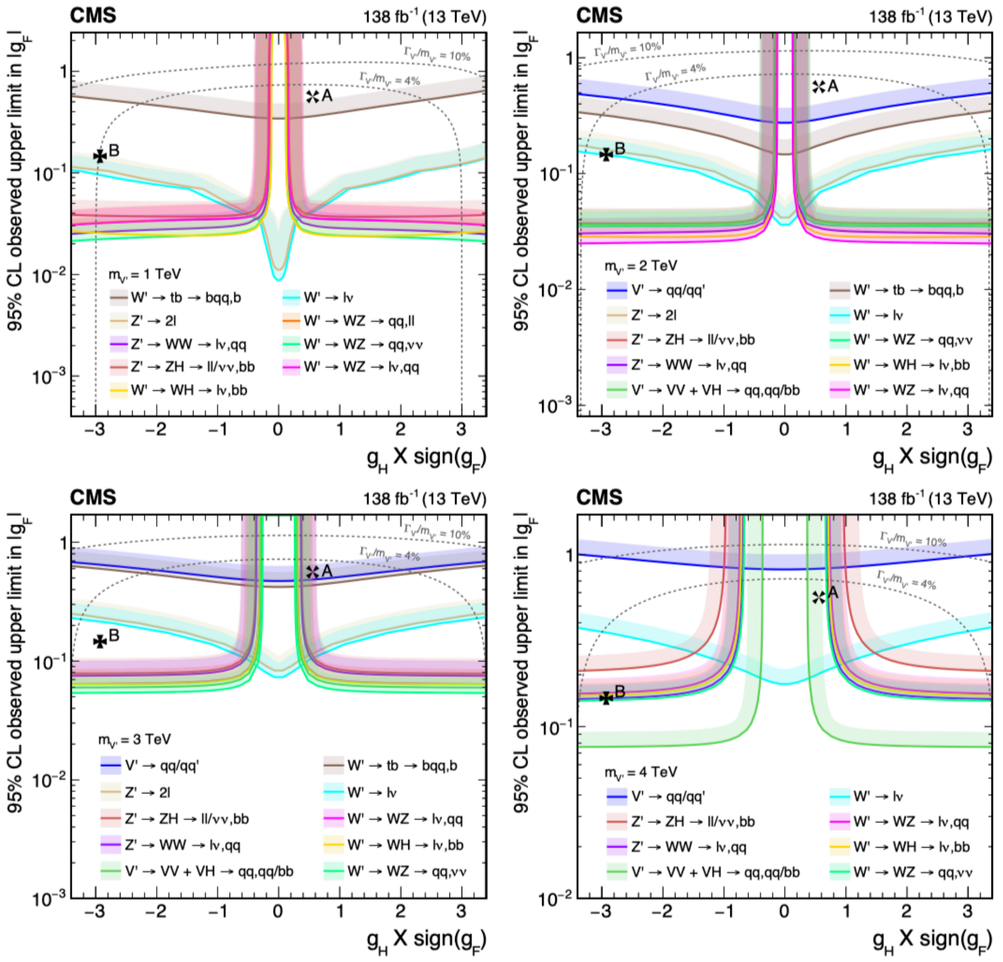
Heavy vector triplet models

- mV’ = 1,2,3 and 4 TeV hypotheses, cross section exclusion limits from DY production (previous slides) translated into 2D upper limits on the coupling parameters for fermions and bosons of the HVT model
- Excluded areas are indicated by the direction of the shading along the exclusion contours.
- The dotted lines denote coupling values above which the relative width of the resonance, ΓV′/mV′ , exceeds 4 and 10%, respectively, implying that the narrow width approximation no longer applies.
- The couplings corresponding to the heavy vector triplet models A and B are indicated by cross markers.
- Only VH results are included



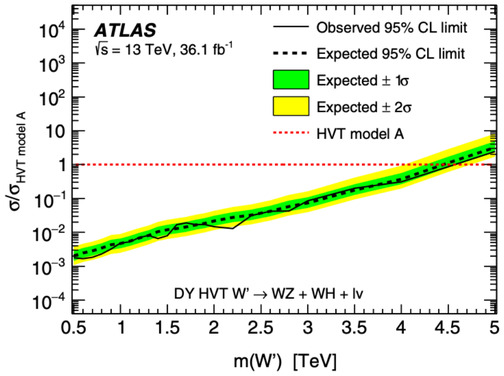
Heavy vector triplet models

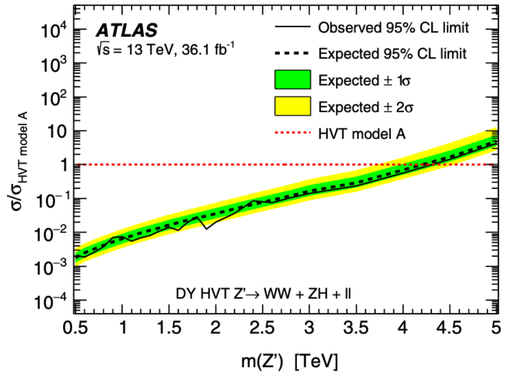
- mV’ = 1,2,3 and 4 TeV hypotheses, cross section exclusion limits from DY production (previous slides) translated into 2D upper limits on the coupling parameters for fermions and bosons of the HVT model
- Constraints from VH production, VV and fermion pair production for comparison
- Constraints from VH searches are most stringent
  - apart from the region with small boson coupling, where complementary searches with fermion final states provide stronger constraints
- Excluded areas are indicated by the direction of the shading along the exclusion contours.
- The dotted lines denote coupling values above which the relative width of the resonance, Γ V ′ /m V ′ , exceeds 4 and 10%, respectively, implying that the narrow width approximation no longer applies.
- The couplings corresponding to the heavy vector triplet models A and B are indicated by cross markers.

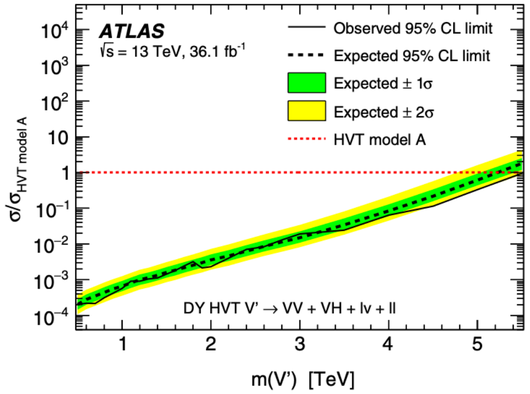


ATLAS results

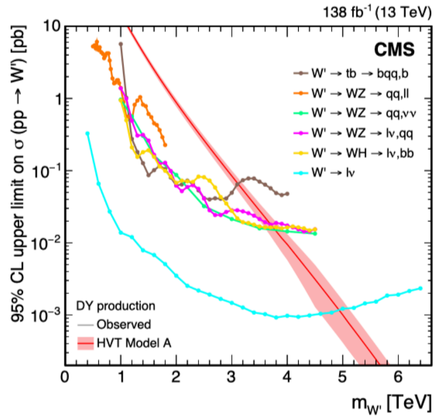
- The W ′ and Z ′ masses V' are excluded up to ~4.5, ~4.3 and 5.5 TeV respectively, in model A in ATLAS results
- The W ′ and Z ′ masses V' are excluded up to ~5.0, ~5.2 and 4.5 TeV respectively, in model A in CMS results

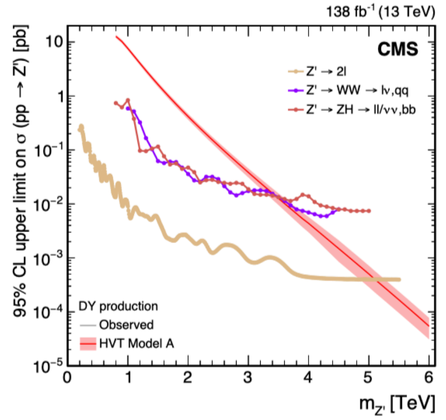


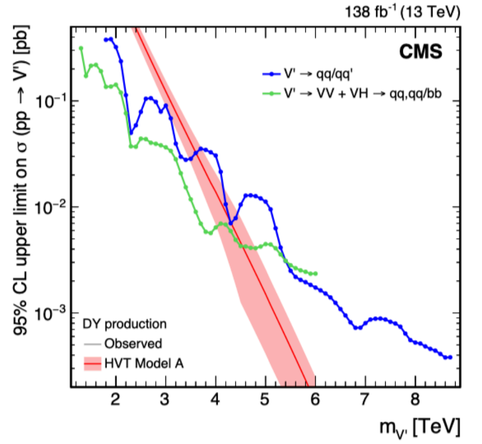




ATLAS results from PRD







Heavy vector triplet models