Search for Higgs boson production through resonance decays

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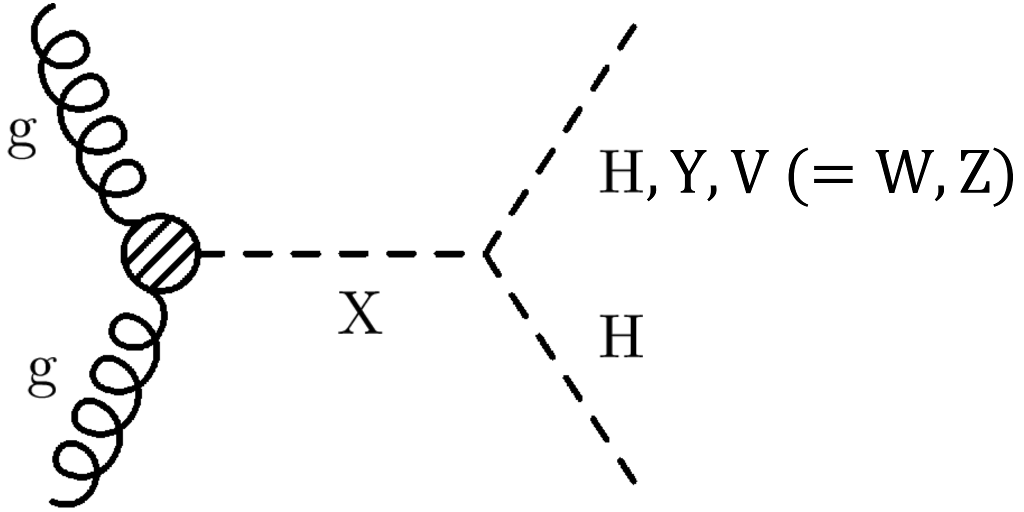


HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Introduction

- Dominant production mechanisms and accessible main decay modes of the H boson* have been experimentally established
  - search narrowing down on nonresonant HH production → report by Simona Palluotto later in this session
- Can the H boson be produced through decay of a heavy resonance?
  - another potential source e.g. of HH pairs?
  - ➔ not in SM… any observation of resonant Higgs boson production would imply New Physics
  - ➔ H boson is an important probe for extensions of the SM
- Presentation is largely based on a recent comprehensive review article:

CMS Collaboration, *Searches for Higgs boson production through decays of heavy resonances*, arxiv:2403.16926, March 2024 (submitted to Physics Reports)

*Nomenclature: in this presentation, H always denotes the SM-like Higgs boson found at 125 GeV

Physics models for resonant H production

Only a small selection

- Extended Higgs sectors
  - **MSSM:** two Higgs doublets
    - two CP-even, one CP-odd, two charged Higgs bosons
  - **NMSSM:** two Higgs doublets and one singlet
    - three CP-even, two CP-odd and two charged Higgs bosons
  - **Real-singlet extension:** one additional singlet
    - two CP-even Higgs bosons
  - **TRSM:** Two real-singlet model
    - three CP-even Higgs bosons

Signatures:

X→HH, X→ZH

X→YH (, X→HH, X→ZH)

X→HH

X→YH (, X→HH)

Physics models for resonant H production (cont'd)

- **WED:** Warped extra dimensions
  - heavy resonances:
    - spin 0: Radion (R)
    - spin 2: Kaluza-Klein graviton (G)

Signatures:

R→HH
G→HH

- **HVT:** Heavy vector triplet
  - heavy spin 1 vector bosons:
    - $W'^{\pm}$
    - Z'

Signatures:

W'→WH
Z' → ZH

Overview of individual searches

	Process	Reference	Interpretation
VH	$X \rightarrow Z(\ell\ell)H(\tau\tau)$	CMS PAS HIG-22-004 **NEW!**	Extended Higgs sector
	$X \rightarrow Z(\ell\ell + \nu\nu)H(bb)^{boosted}$	EPJ C 79 (2019) 564	HVT
	$X \rightarrow W(\ell\nu)H(bb)^{boosted}$	PRD 105 (2022) 032008	
	$X \rightarrow Z(\ell\ell)H(bb)^{boosted}$	EPJ C 81 (2021) 688	
	$X \rightarrow Z(qq)H(bb)^{boosted}$	PLB 844 (2023) 137813	
HH	$X \rightarrow H(bb)H(WW)$	JHEP 07 (2024) 293	Extended Higgs sector, WED
	$X \rightarrow H(bb)H(WW)^{boosted}$	JHEP 05 (2022) 005	
	$X \rightarrow H(WW + \tau\tau)H(WW + \tau\tau)$	JHEP 07 (2023) 095	
HH +YH	$X \rightarrow Y(bb)H(\tau\tau)$	JHEP 11 (2021) 057	
	$X \rightarrow Y(bb)H(\gamma\gamma)$	JHEP 05 (2024) 316	
	$X \rightarrow Y(bb)H(bb)^{boosted}$	PLB 842 (2023) 137392	
	$X \rightarrow Y(\gamma\gamma)H(\tau\tau) + Y(\tau\tau)H(\gamma\gamma)$	CMS PAS HIG-22-012 **NEW!**	(Backup)

arxiv:2403.16926

HH combination

YH combination

$X \to VH$ decays

$A \to Z(\ell\ell)H(\tau\tau)$

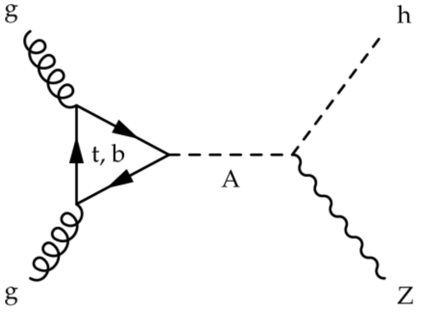
Low mass region (m < 1 TeV)

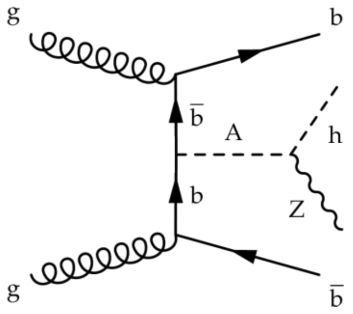
CMS PAS HIG-22-004

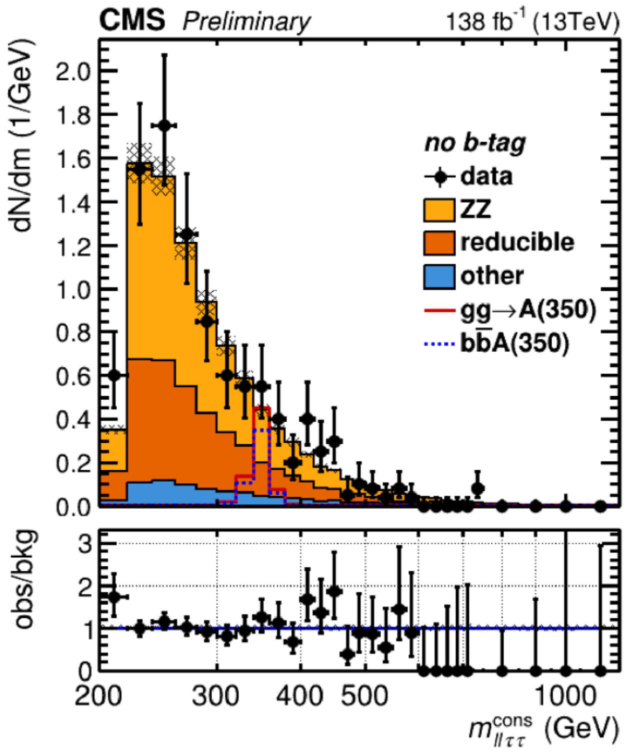
NEW!

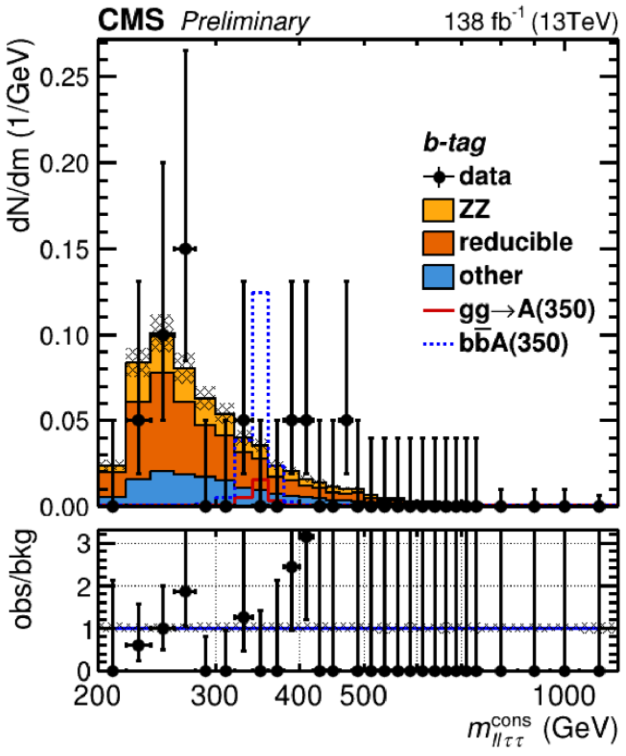
- Studying inclusive and b-associated production
  - mass range of 200–800 GeV probed
- H reconstructed in $\tau\tau$ decay modes $e\tau_{had}$, $\mu\tau_{had}$ and $\tau_{had}\tau_{had}$
- Invariant mass of A candidate inferred by likelihood fit
  - 125 GeV mass constraint fit on H candidate improves mass resolution

➔ No excess observed







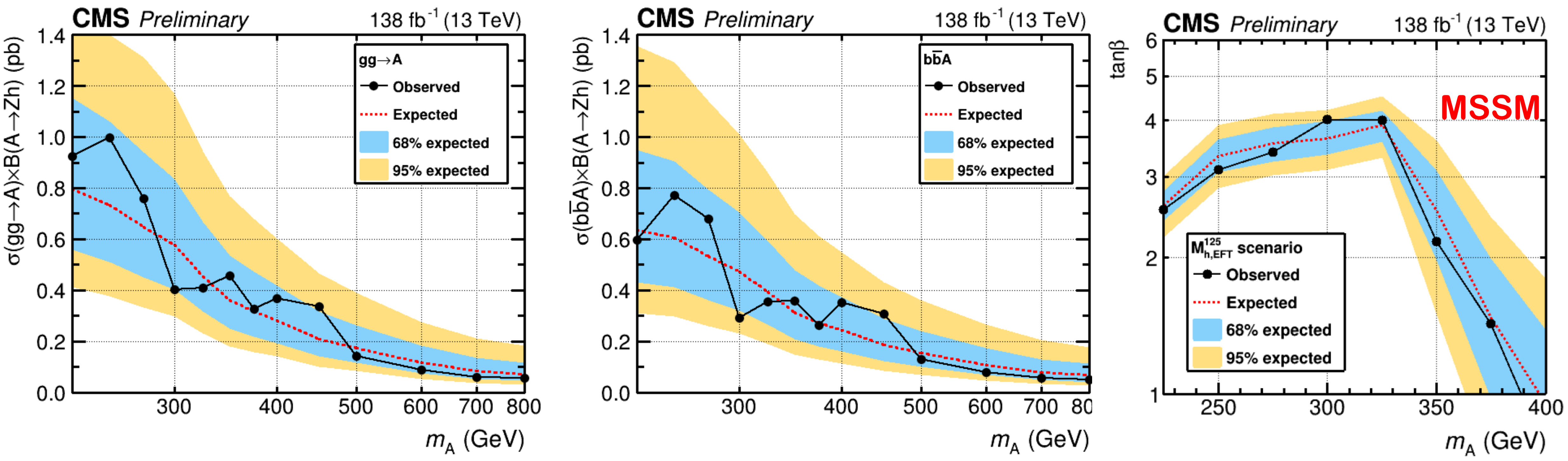


$A \rightarrow Z(\ell\ell)H(\tau\tau)$ (cont'd)

CMS PAS HIG-22-004

Interpretation

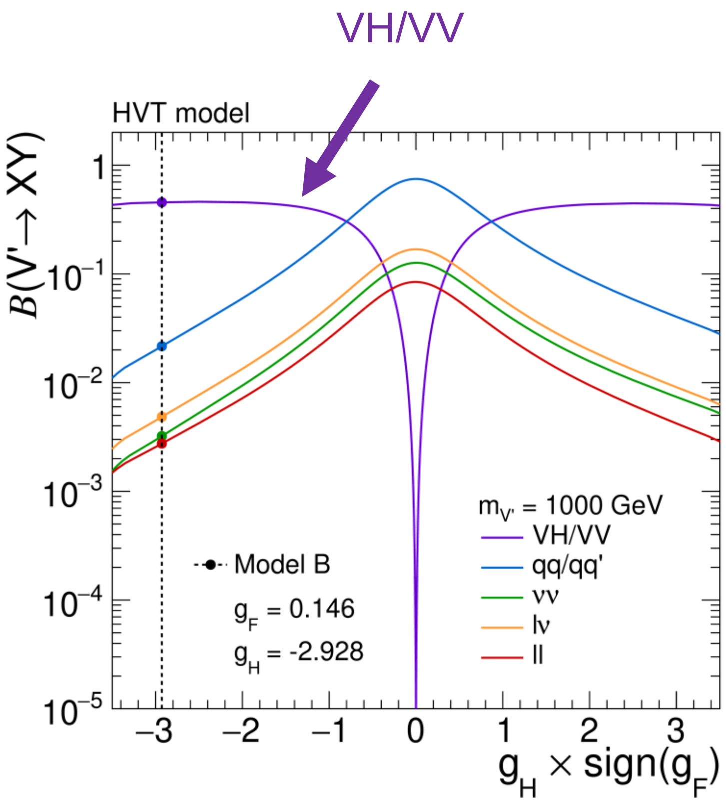
- Cross section upper limits significantly improved compared to 2016-only analysis
- MSSM interpretation: excluding values of $\tan\beta < 2.2$ for $225 \leq m_A \leq 350$ GeV in $M_{h,EFT}^{125}$ scenario [1]



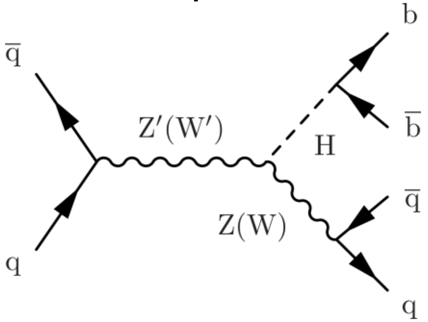
[1] H. Bahl, S. Liebler, and T. Stefaniak, "MSSM Higgs benchmark scenarios for Run 2 and beyond: The low tan β region", Eur. Phys. J. C 79 (2019) 279

Heavy vector triplet (HVT) models → W' and Z'

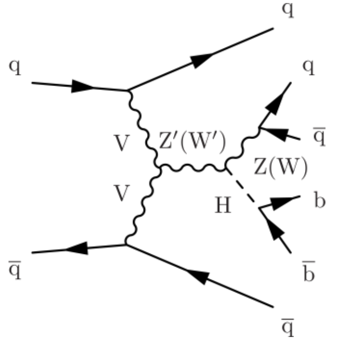
- Extensions of SM gauge groups with new force-carrying vector bosons W' and Z'. Examples:
  - weakly coupled W' and Z' models
  - little Higgs models
  - composite Higgs scenarios
- Decays to VH final states possible: $W' \to WH,\ Z' \to ZH$
- Phenomenology studied with simplified Lagrangian
  - **Model A:** weakly coupled extended gauge theory
  - **Model B:** mimics strongly coupled composite Higgs model
  - **Model C:** suppressed couplings to fermions
    - only VBF production possible
- In particular in models B and C, couplings to bosons are larger than to fermions → large branching fractions to VH and VV



Drell-Yan production



Vector boson fusion

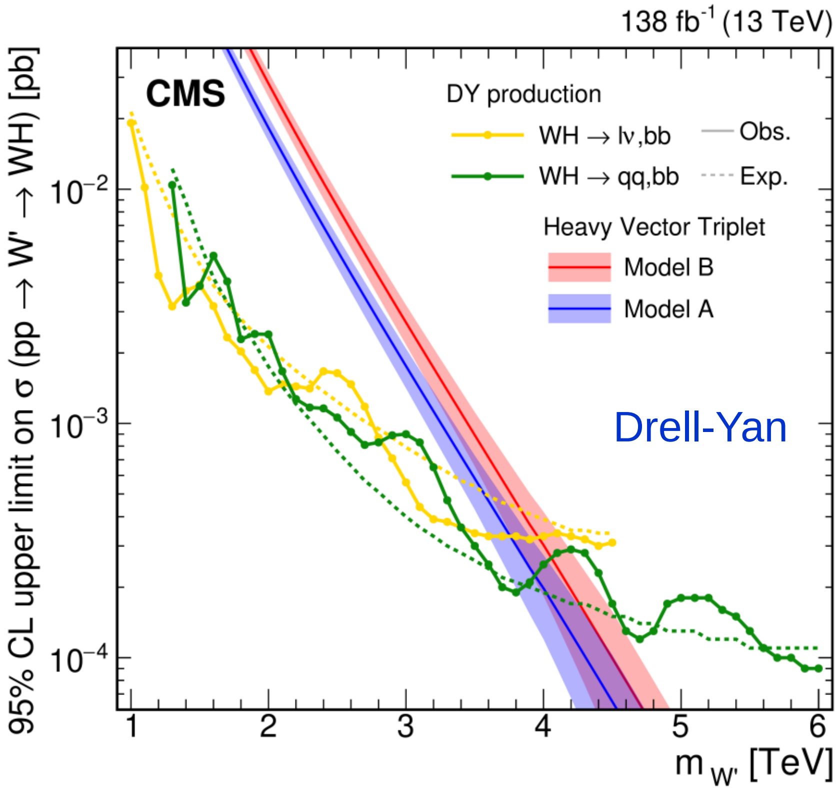


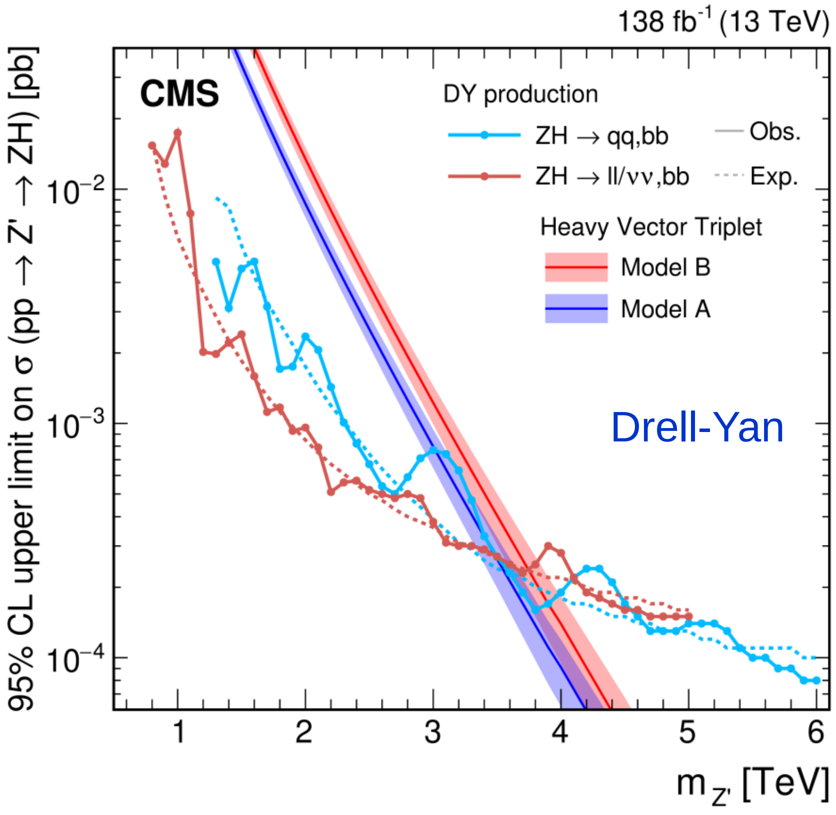
$V' \rightarrow VH$

High mass region (m > 1 TeV)

arxiv:2403.16926

- Final states with leptons dominate for masses up to 1.7 GeV (W') and 3.2 GeV (Z')
  - for higher masses, fully hadronic channels show higher sensitivity (boosted signatures)
- Drell-Yan production: sensitive to models **A** + **B** up to masses of ~4 TeV

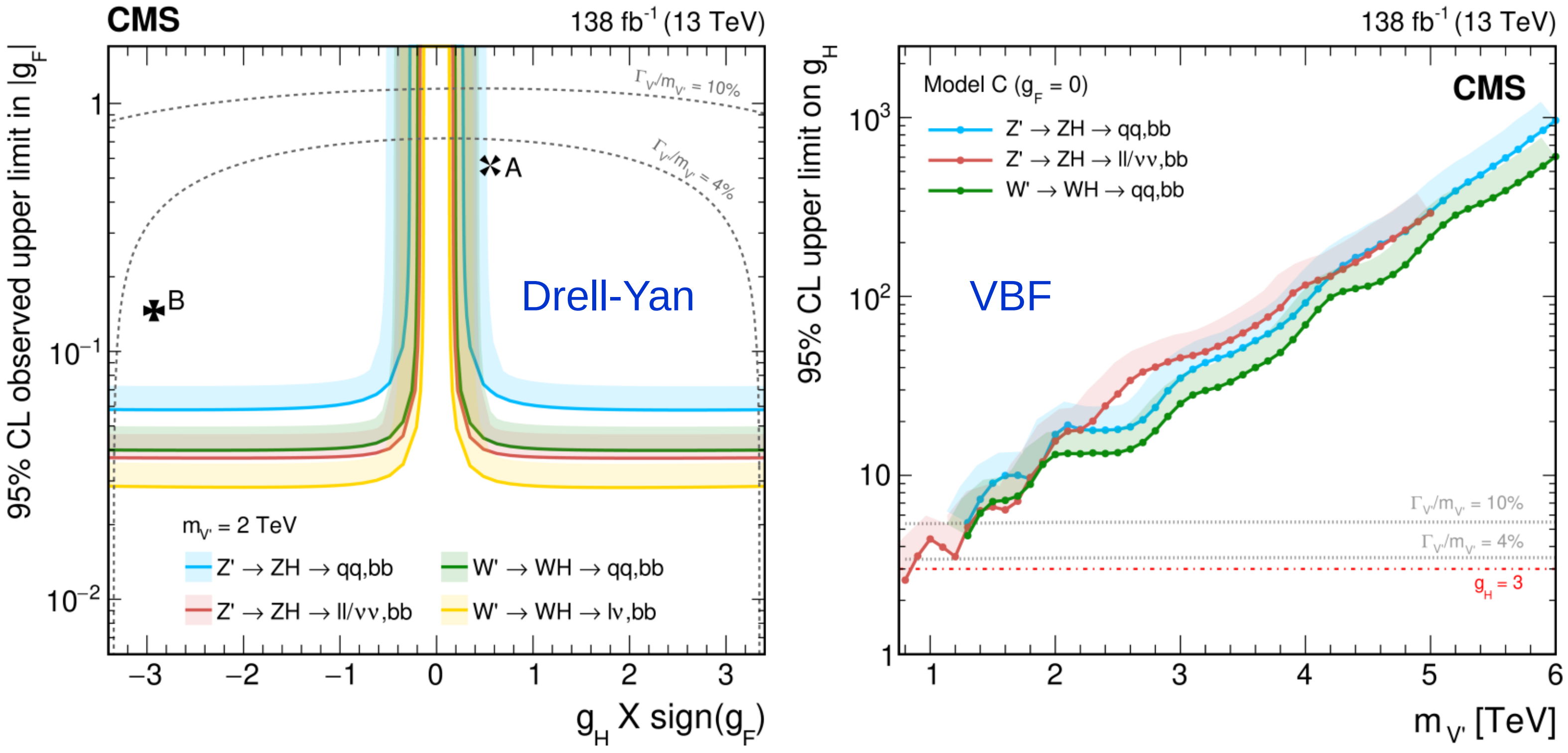




HVT couplings from $V' \rightarrow VH$

arxiv:2403.16926

- For Drell-Yan production, strong exclusions in g_F, g_H parameter space
  - except in the very low g_H region, which is however accessible by fermionic modes (like $W' \rightarrow \ell\nu$) (→Backup)
  - ➔ models **A** and **B** excluded for $m_{V'} = 2\,TeV$
- For model **C** (exclusively VBF production), data set not yet sufficient to exclude couplings below $g_H = 3$



$X \rightarrow HH$ decays

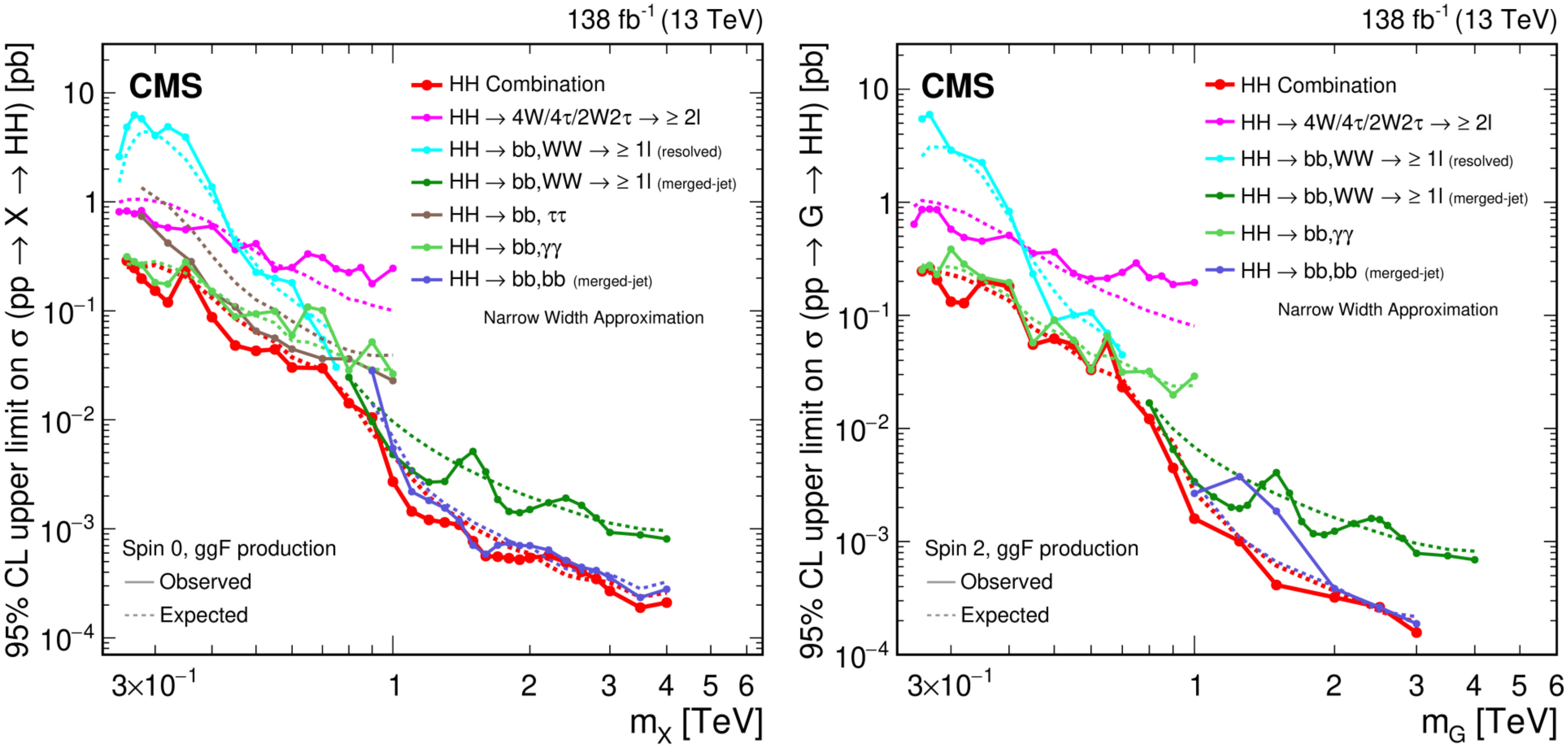
X→HH searches

arxiv:2403.16926

- Six analyses in five different final states
  - use $B_{SM}(H)$ to bring all channels on same footing

➔ All observed limits compatible with SM expectations

➔ Combination improves sensitivity in particular in range 0.5–1 TeV



➔ Best limits to date for masses below 320 GeV and above 800 GeV

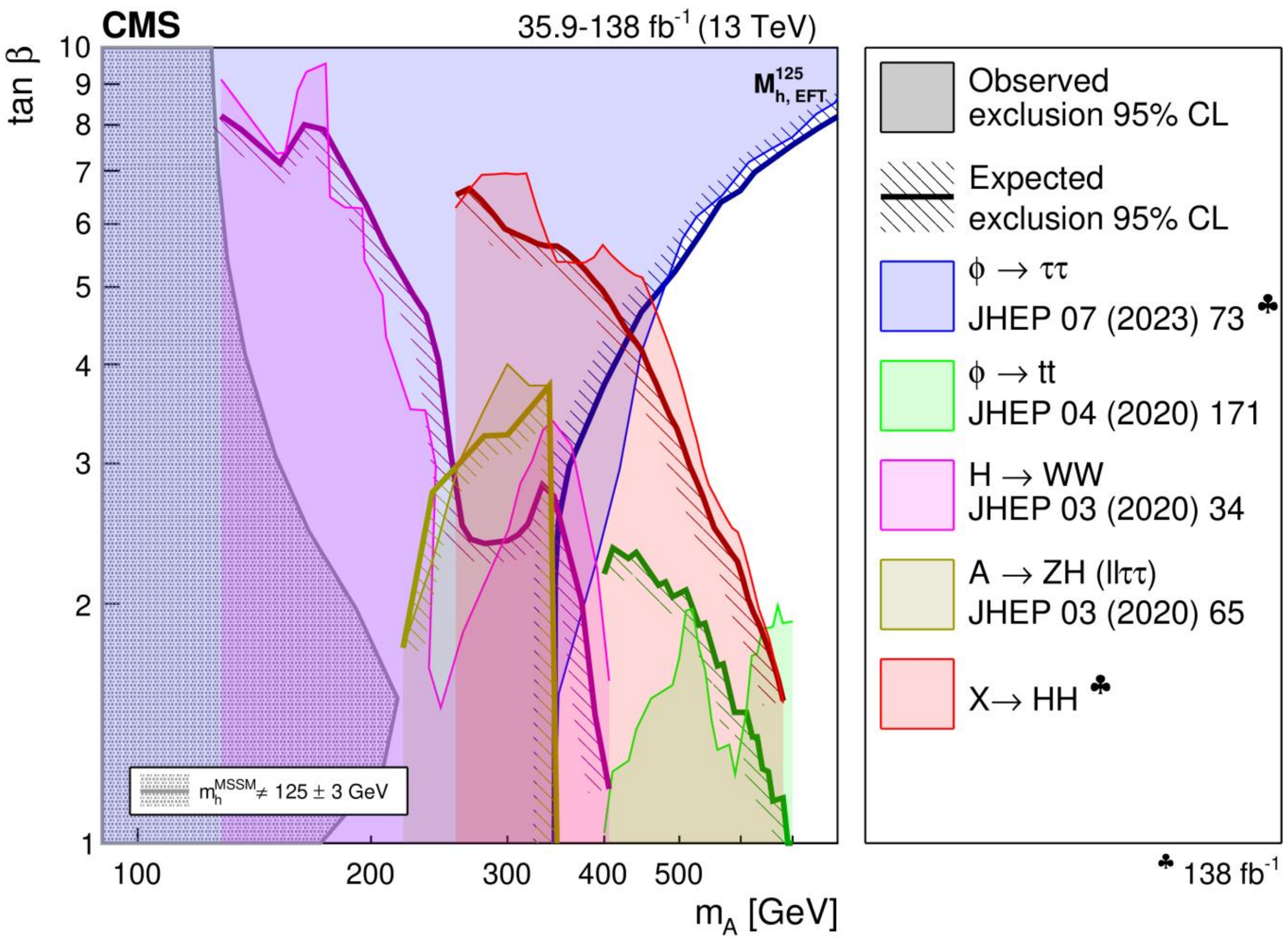
X→HH searches: interpretations in the MSSM

arxiv:2403.16926

- MSSM benchmark scenarios: X→HH channel gives strongest observed lower limits on tan β
  - M_h^{125} scenario not very suitable for HH measurements since inconsistent with H(125) mass at low $\tan\beta$
  - here using $M_{h,EFT}^{125}$ scenario

➔ For m_A>400 GeV, HH combination provides unique exclusions

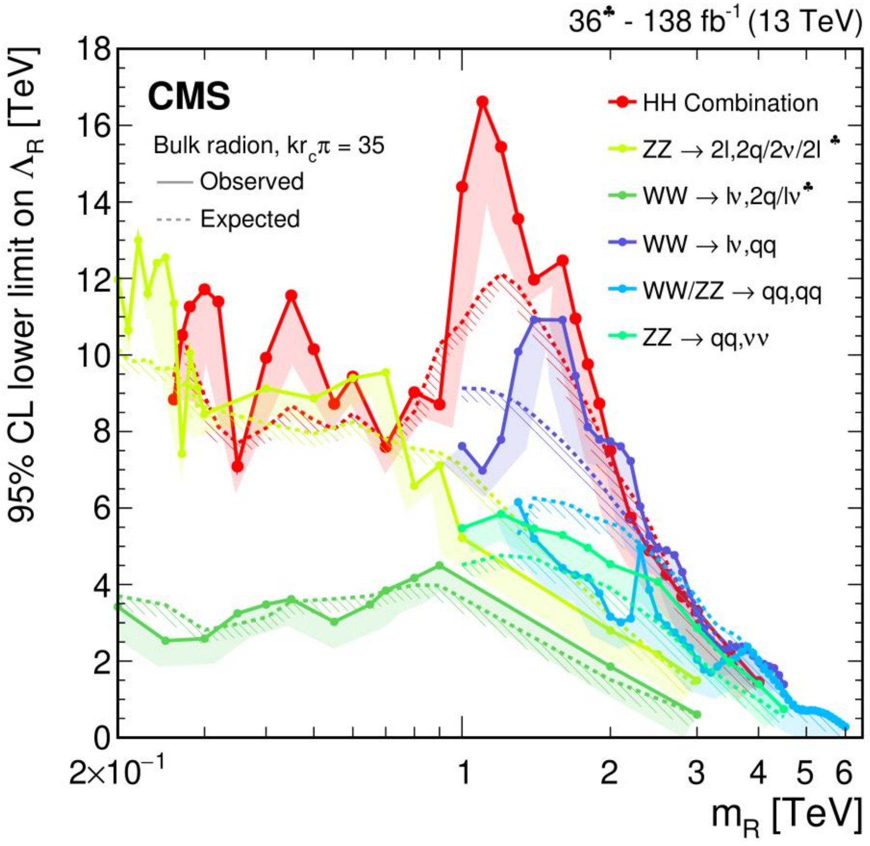
➔ Together with other channels, exclude $m_A \leq 450\ GeV$

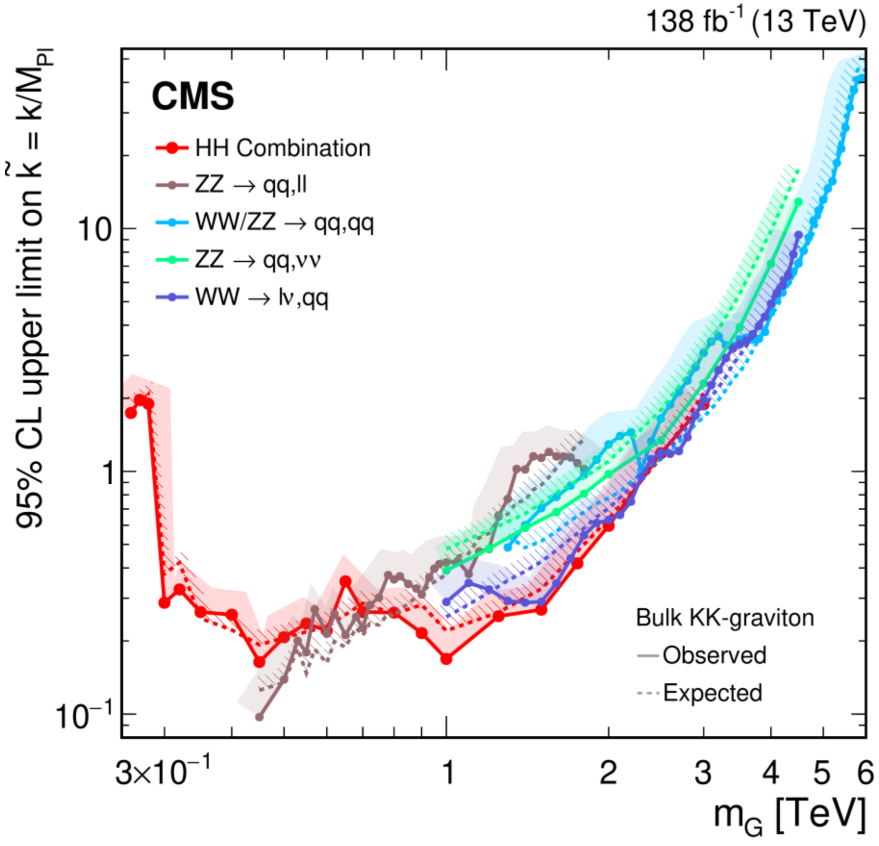


X→HH searches: interpretations in WED

arxiv:2403.16926

- Lower limits on radion model parameter Λ_R (from spin 0)
  - ➔ best sensitivity for m_R=1–2 TeV
- Upper limits on graviton parameter $\tilde{k}$ (from spin 2)
  - ➔ best sensitivity for m_G=250-450 GeV and 700-2000 GeV



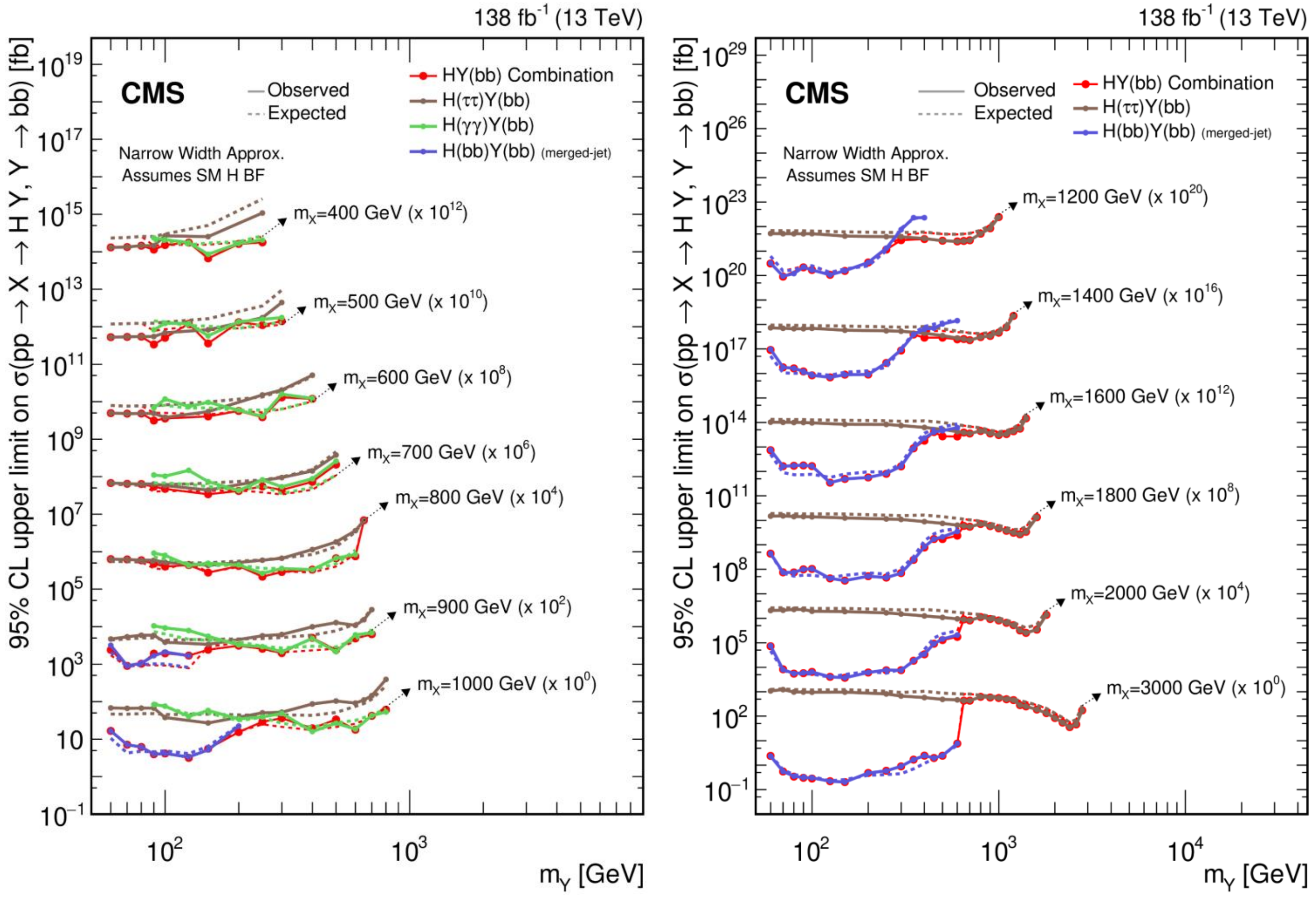


$X \to YH$ decays

X→YH searches: first combination!

arxiv:2403.16926

- Combination of analyses in $Y(bb)H(\tau\tau)$, $Y(bb)H(\gamma\gamma)$ and $Y(bb)H(bb)$ boosted channels
  - possible because all share the $Y \to bb$ decay mode
  - assume SM branching fractions for H boson
- The boosted topology dominates
  - at large m_X, except near the kinematic limit
  - at medium m_X and low m_Y
- Otherwise, the resolved $Y(bb)H(\tau\tau)$, $Y(bb)H(\gamma\gamma)$ channels dominate the combination

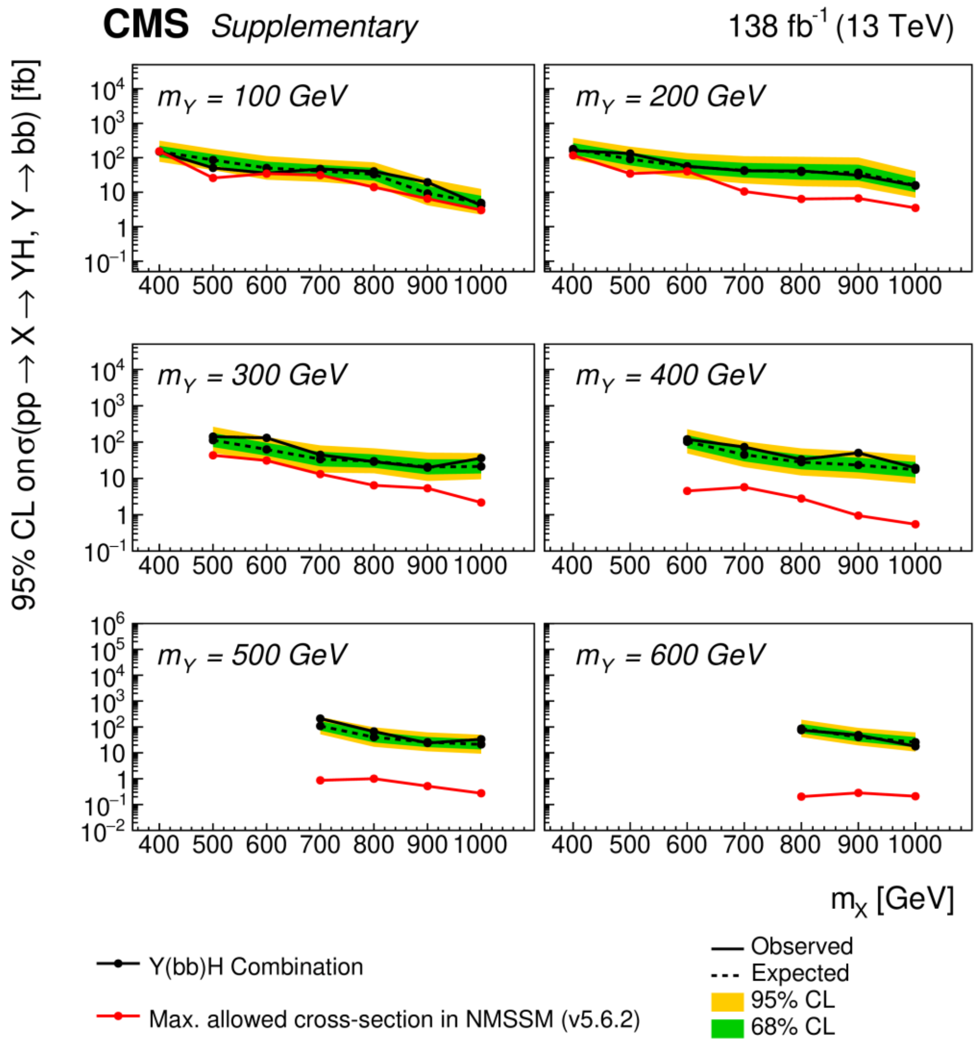


X→YH: interpretation within NMSSM theory

arxiv:2403.16926

- Comparing with the "maximally allowed" cross sections taking existing measurements into account
  - this is a moving target (here NMSSMTools v5.6.2 [1])
  - measurements by us and others are already taken into account in the maximization → no "additional" exclusion due to our data as expected

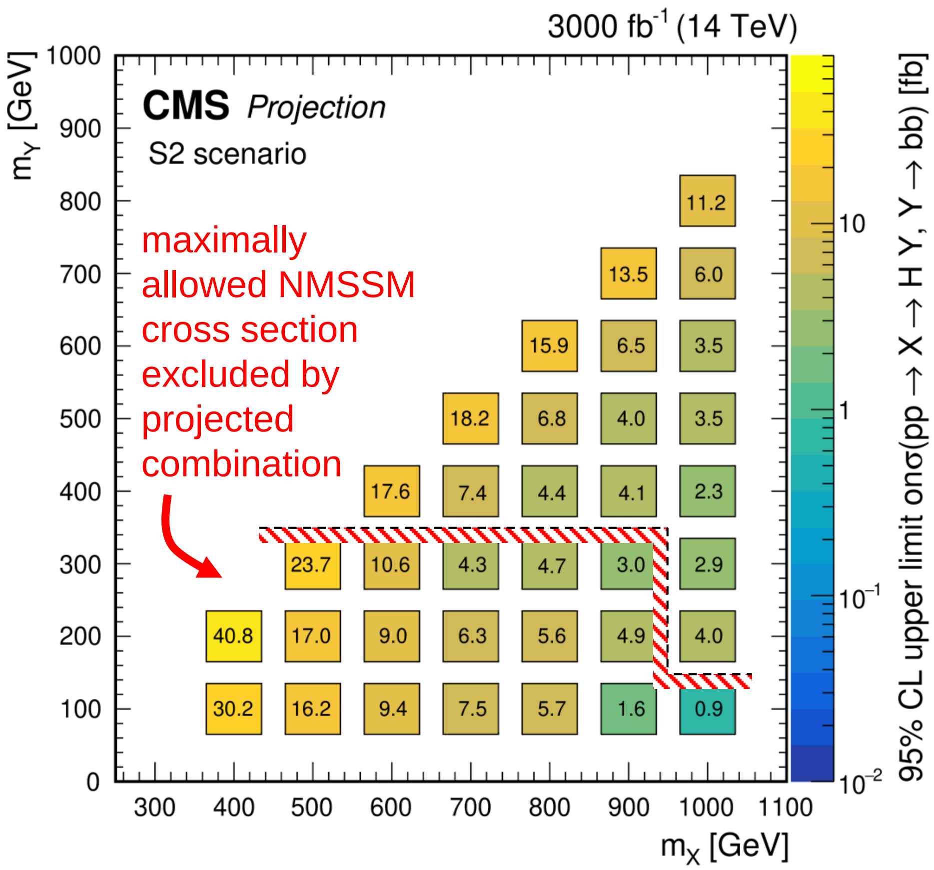
→ While our data are touching the maximally allowed cross sections at low m_Y, the constraints at large m_Y are mostly indirect (through the NMSSM parameter space)

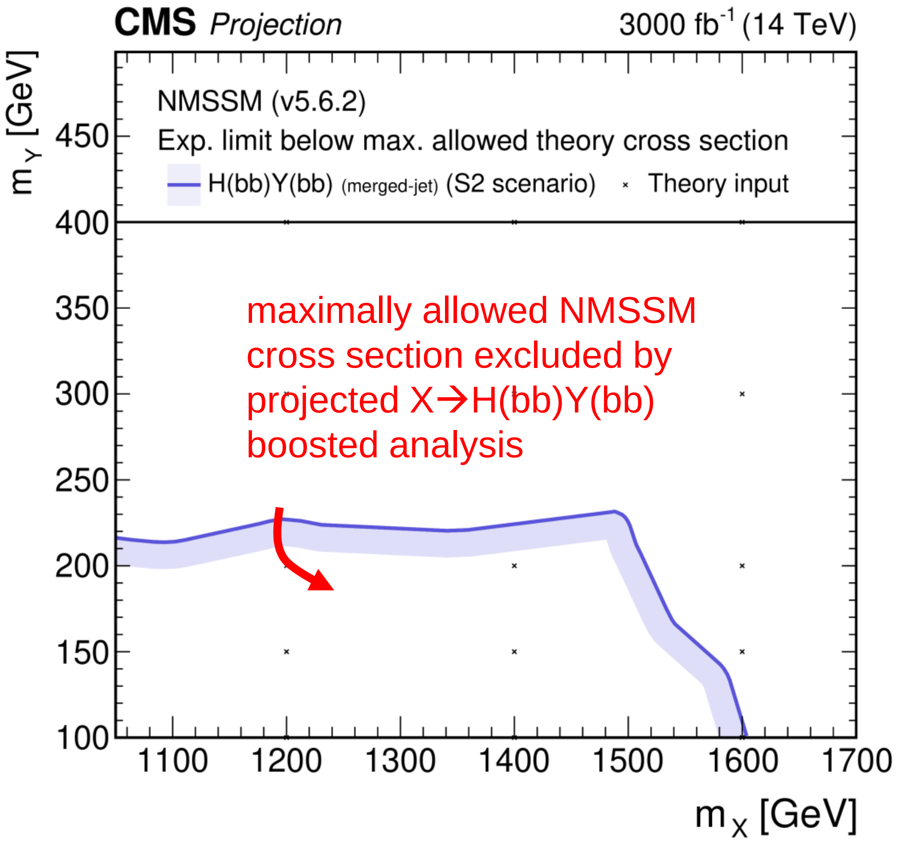


[1] U. Ellwanger and C. Hugonie, "Benchmark planes for Higgs-to-Higgs decays in the NMSSM", Eur. Phys. J. C 82 (2022) 406.

X→YH: outlook towards HL-LHC

arxiv:2403.16926





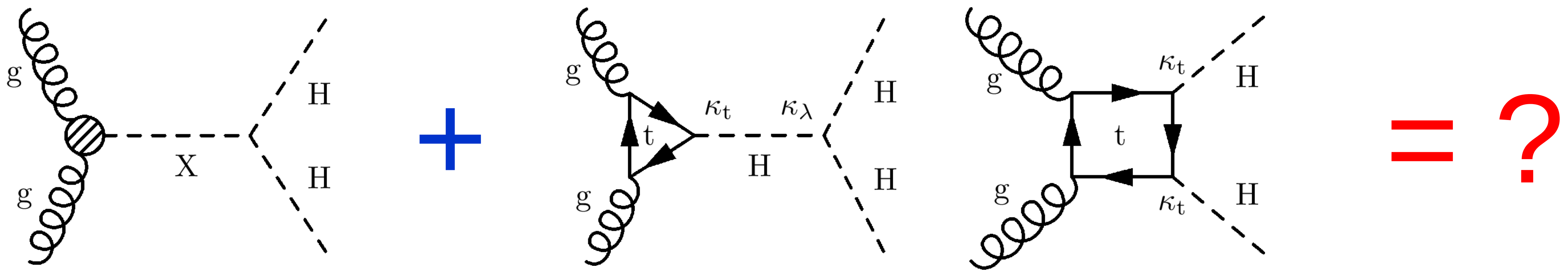
➔ CMS measurements at the HL-LHC are projected to exclude most of the currently allowed cross sections for m_Y < 200–300 GeV

Finite width and interference

Finite width and interference

- Most of the shown measurements are based on the narrow width approximation (NWA)
  - natural width negligible compared to experimental resolution
  - no interference
- In general, however, interference between non-resonant and resonant HH production is possible
  - at which level of sensitivity does finite width become relevant?
  - how strong are effects of interference?

resonant | nonresonant



Finite width and interference (cont'd)

- Here: use the "real singlet extension" of the SM Higgs sector [1]
  - besides H there is only one additional (heavy) Higgs boson X; both states mix with an angle α
  - X has SM-like couplings to fermions and vector bosons multiplied by sin α; X→HH governed by trilinear coupling parameter λ_{HHX}

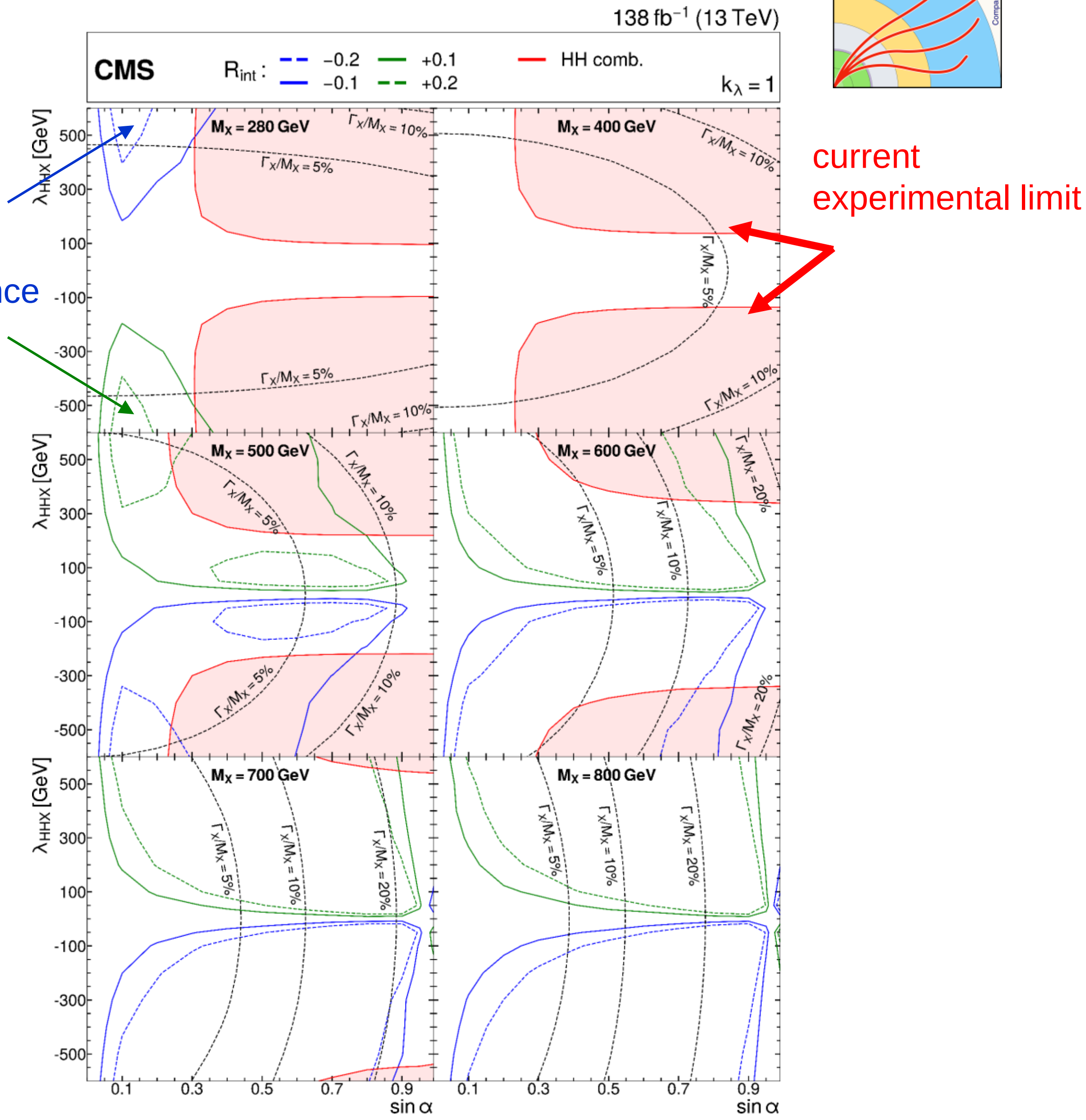
- Quantities to study:
  - relative width: $\frac{\Gamma_X}{m_X}$
  - relative effect of interference: $R_{int} = \frac{\sigma^{full} - (\sigma^{resonant-only} + \sigma^{nonresonant})}{\sigma^{resonant-only} + \sigma^{nonresonant}}$

[1] Following approach in: A. Papaefstathiou and G.White, JHEP 05 (2021) and JHEP 02 (2022) 185

Finite width and interference (cont'd)

arxiv:2403.16926

- Studied as function of $\sin\alpha$ and λ_{HHX} parameters
- Our measurement constrains $\sigma(pp \to X) \times B(X \to HH)$
  - $\sin\alpha$ drives $\sigma(pp \to X)$, λ_{HHX} drives $B(X \to HH)$
  - ➔ explains shape of experimental exclusion
- Blue (–) and green (+) isolines indicate regions of strong interference effects
  - ➔ sizable values of R_{int} mostly in regions which are currently beyond our experimental sensitivity
  - ➔ some exceptions at large values of $\sin\alpha$, which are however in conflict with measured H couplings



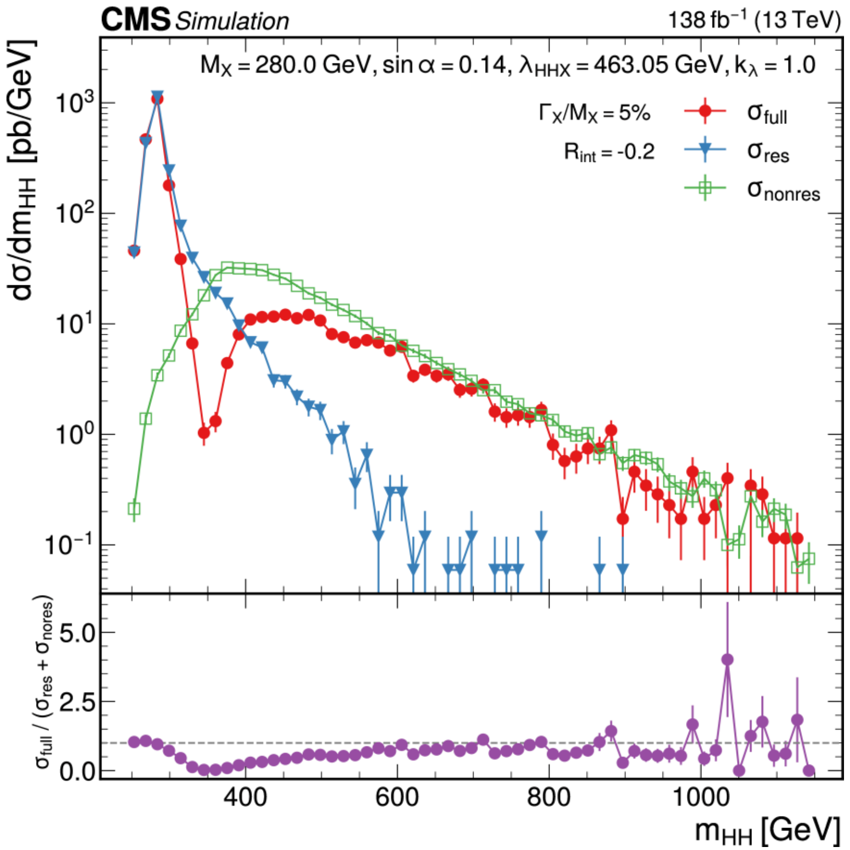
Finite width and interference (cont'd)

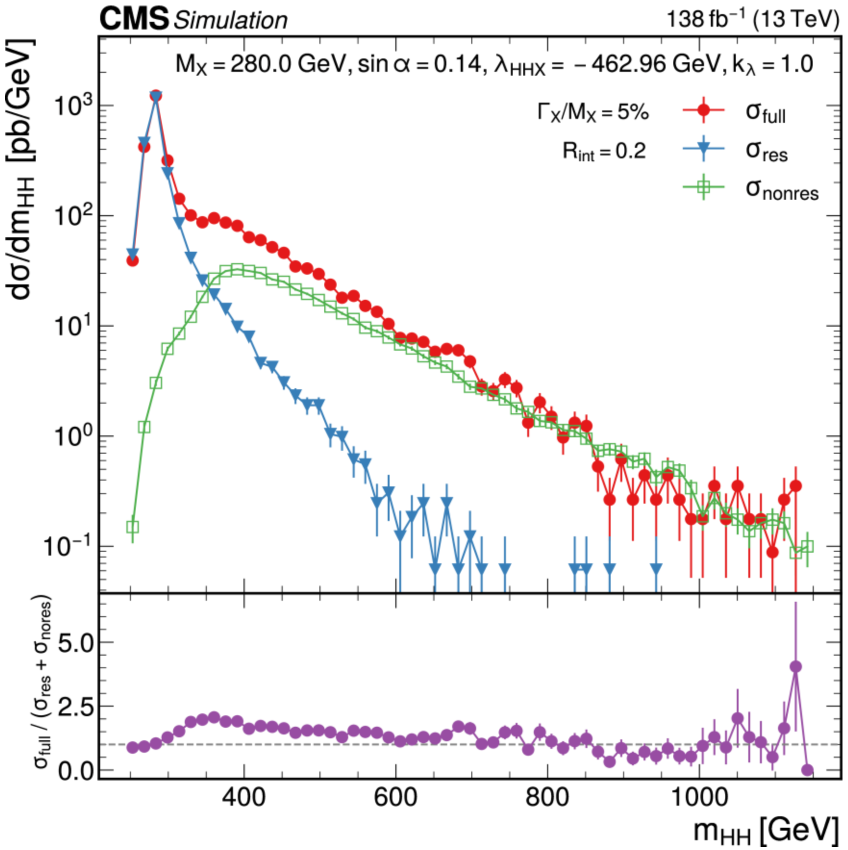
arxiv:2403.16926

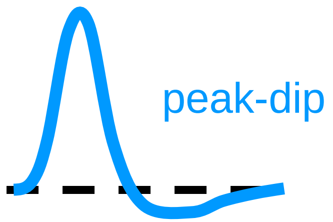
- Also the "line shape" of the signal ($= \sigma_{full} - \sigma_{nonres}$) is affected by the interference
  - examples for $R_{int} = \pm 0.2$
- Destructive interference → peak-dip effect (or reversed)
- Constructive interference → peak-tail effect

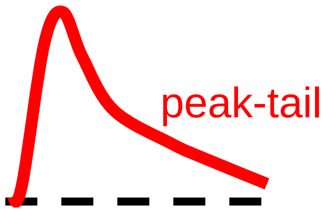
➔ Strong shape modifications occur in parameter regions which are yet beyond our sensitivity

➔ Could become relevant for HL-LHC









Summary

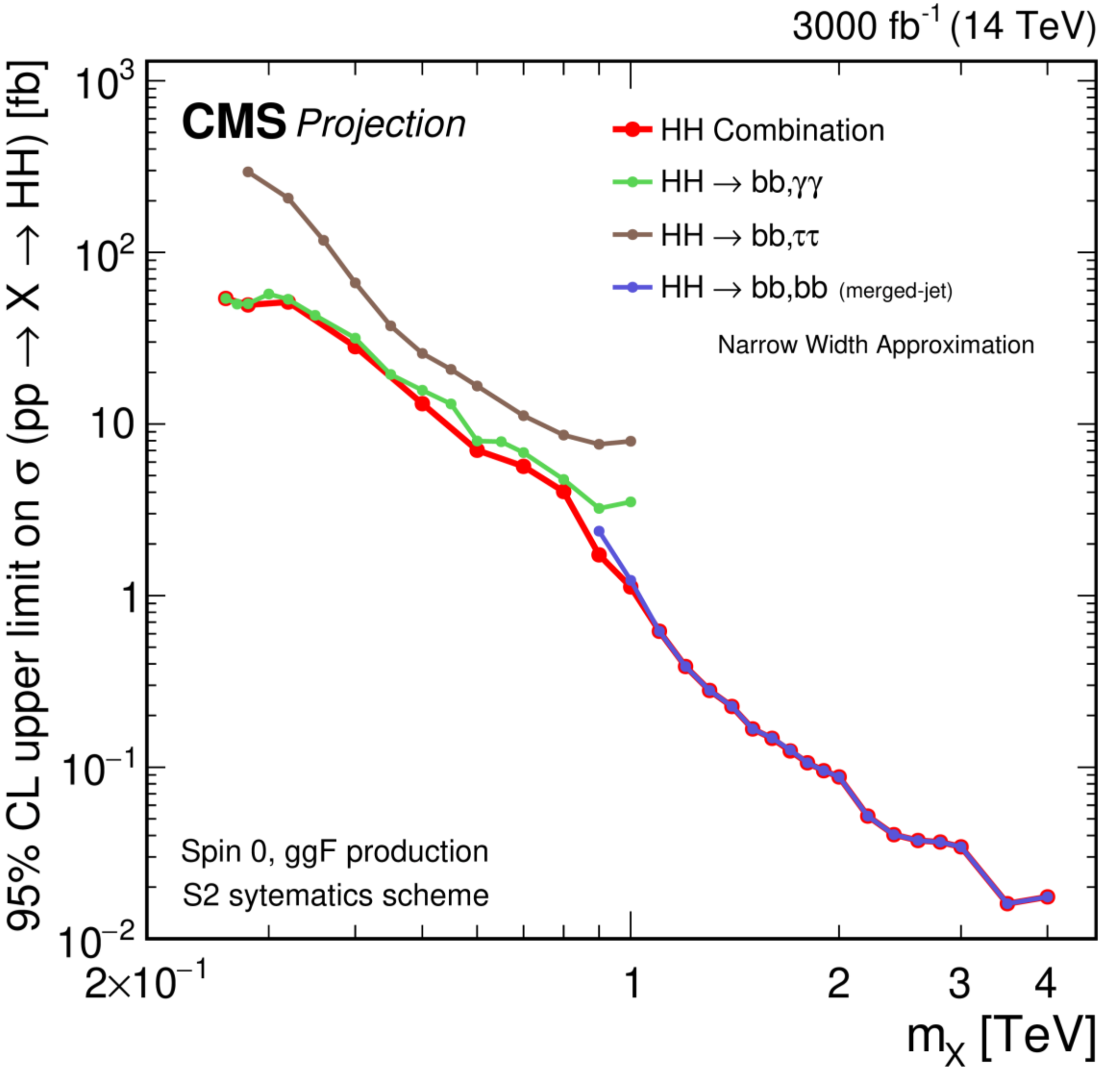
- Comprehensive set of measurements searching for resonant H production in VH, HH and YH decay modes
  - strong experimental constraints, in particular through recent combinations
  - interpretations in extended Higgs sector, warped extra dimension and heavy vector triplet models
  - projections towards HL-LHC
  - novel study of finite width and interference effects
  - many more results can be found in the comprehensive review article arxiv:2403.16926

- Further results from full Run 2 are still emerging (two were shown)
- Run 3 is progressing, HL-LHC on the horizon → next levels of precision

➔ Exciting research program ahead!

Outlook

Projection of X→HH combination towards HL-LHC



Backup

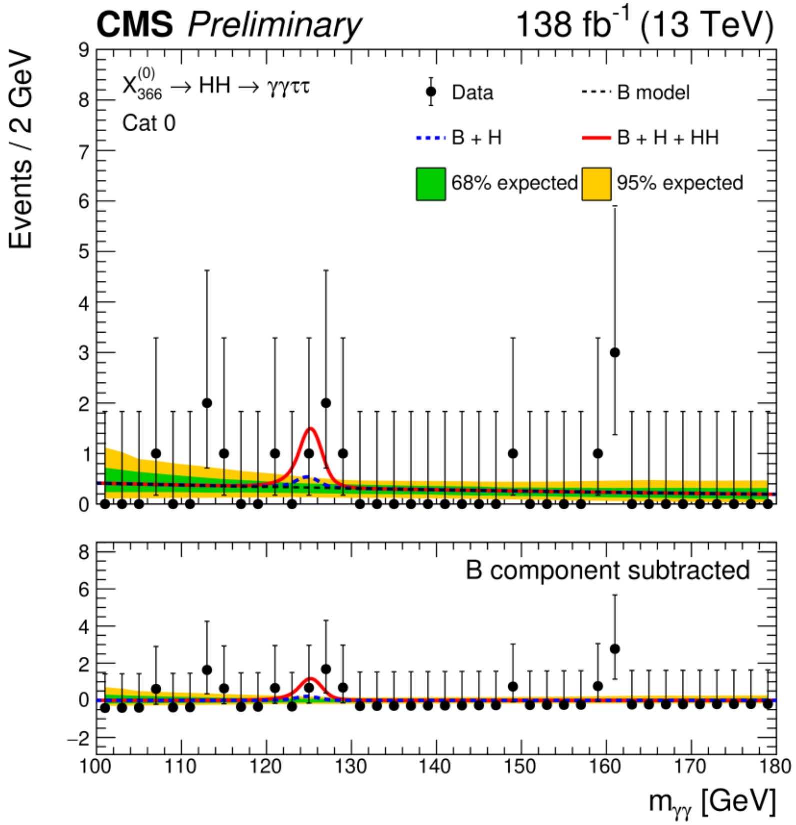
$X \to H/Y(\gamma\gamma)H(\tau\tau)$ and $H/Y(\tau\tau)H(\gamma\gamma)$

NEW!

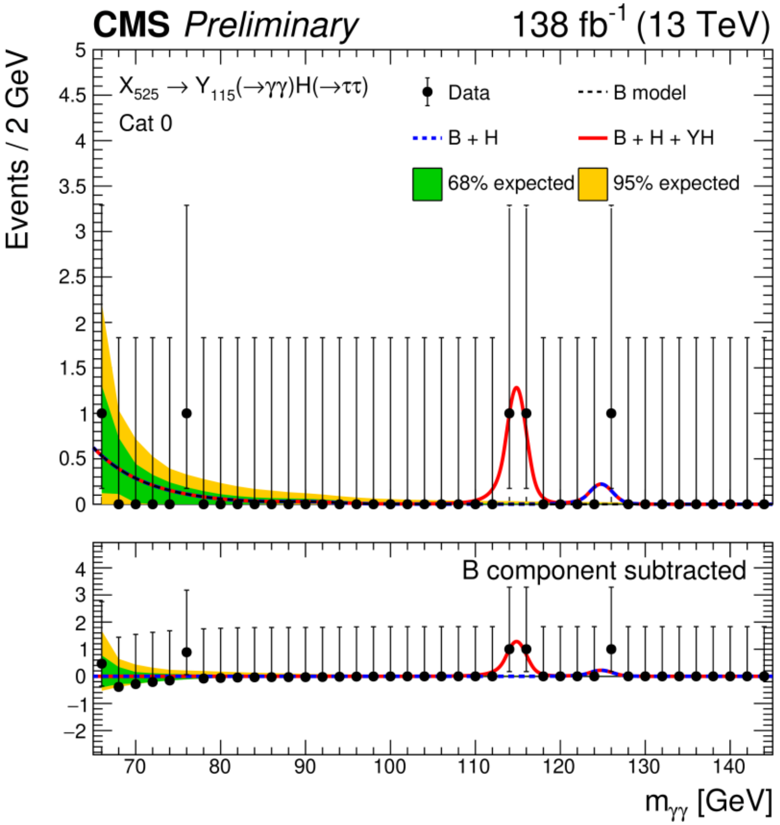
CMS PAS HIG-22-012

- Next level: non-bb Y decays
- $\gamma\gamma\tau\tau$: small branching fraction but clean signature and background situation
- Parametric neural network in (M_X, M_Y) for event classification
- Signal extraction in $m_{\gamma\gamma}$ distributions
- Resonant backgrounds from
  - single H production
  - Drell-Yan with $Z \to ee$ mis-identified as photons

$X \to H(\gamma\gamma)H(\tau\tau)$, spin 0
$M_X = 366\ GeV$



$X \to Y(\gamma\gamma)H(\tau\tau)$
$M_X = 525\ GeV$, $M_Y = 115\ GeV$

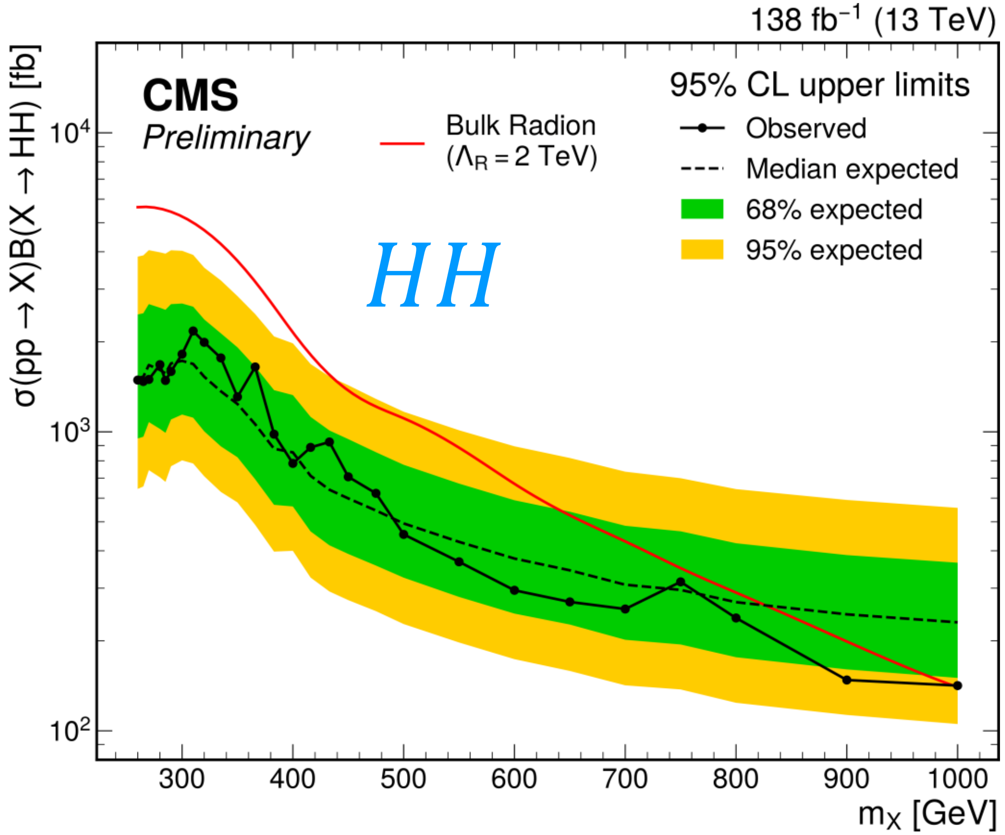


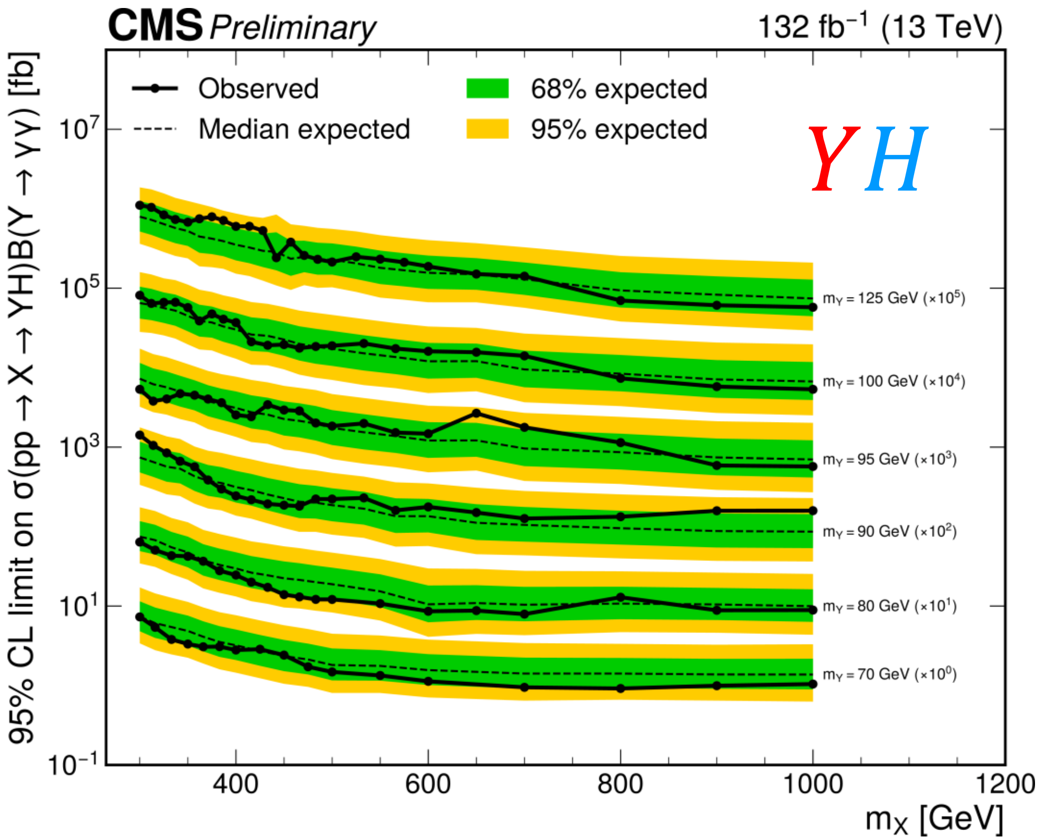
$X \rightarrow H/Y(\gamma\gamma)H(\tau\tau)$ and $H/Y(\tau\tau)H(\gamma\gamma)$ (cont'd)

NEW!

CMS PAS HIG-22-012

- ➔ HH results: exclude bulk radion of $\Lambda_R = 2\,TeV$ in full mass range (less stringent than combination)
- ➔ YH results: particular sensitivity for low m_Y due to dedicated low-mass $\gamma\gamma$ trigger



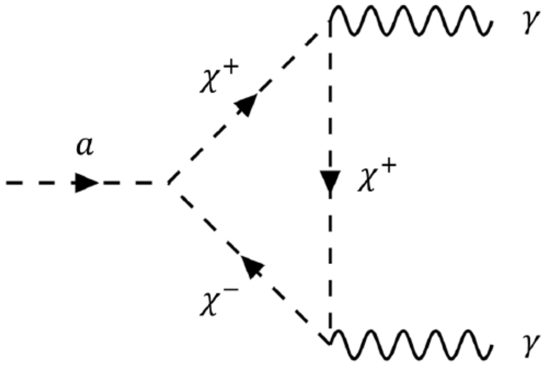


$X \to H/Y(\gamma\gamma)H(\tau\tau)$ and $H/Y(\tau\tau)H(\gamma\gamma)$ (cont'd)

NEW!

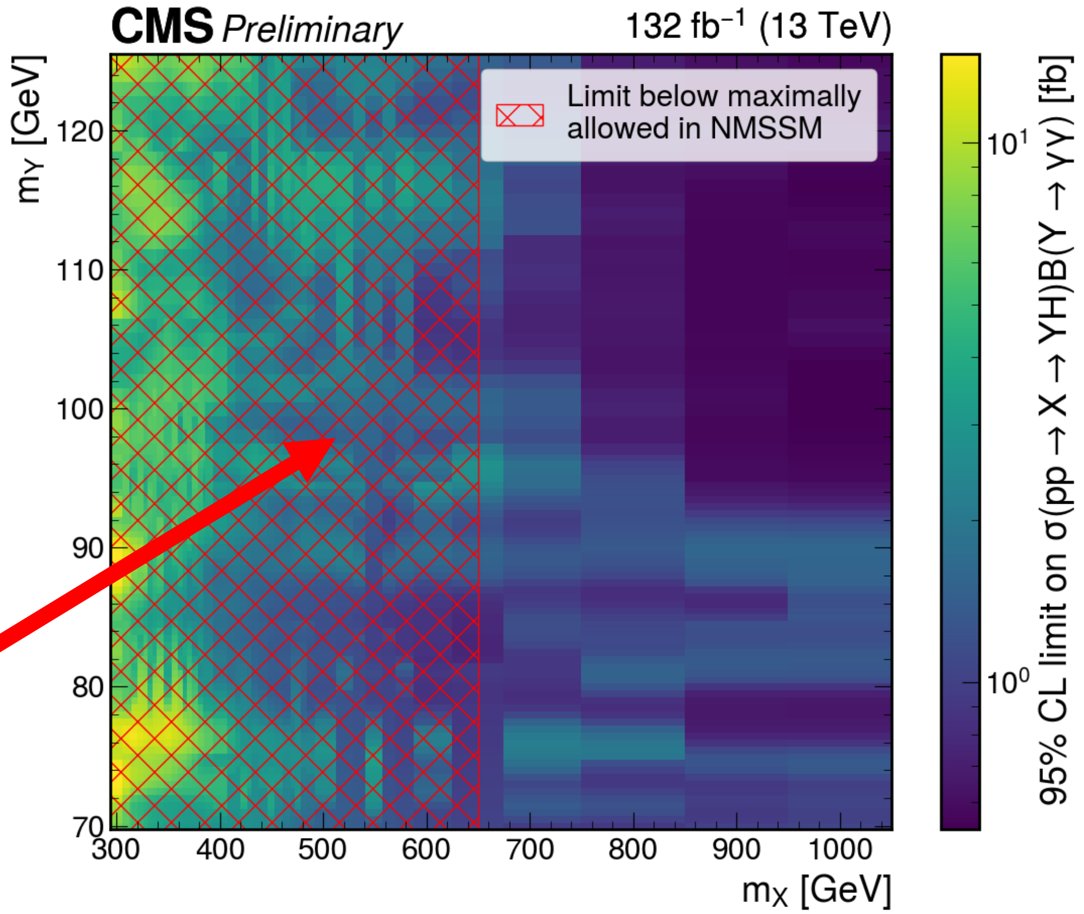
NMSSM interpretation

CMS PAS HIG-22-012



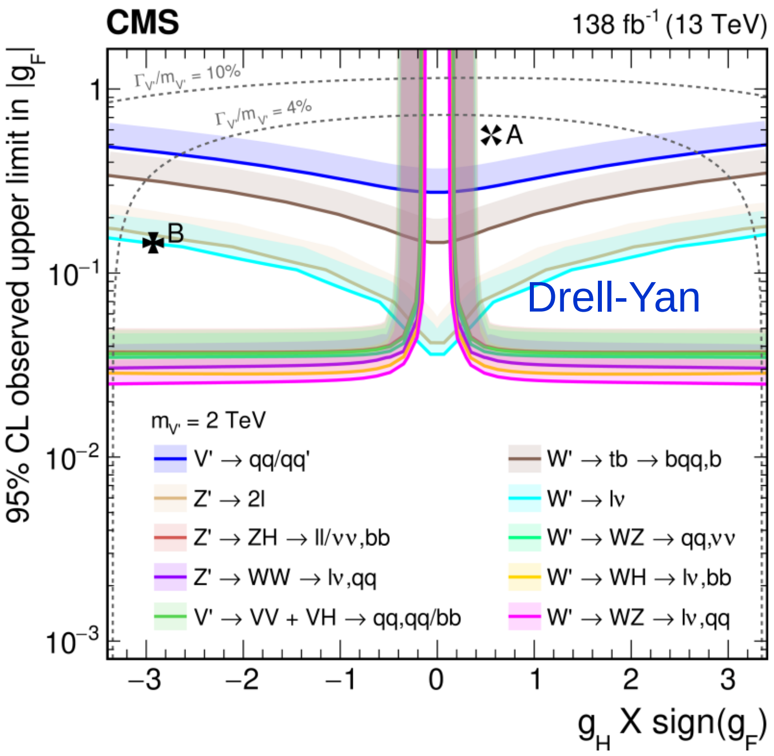
- In the NMSSM interpretation, Y might be largely a singlet Higgs boson with strongly suppressed couplings to SM particles
  - $Y \to \gamma\gamma$ still possible via chargino loop
  - ➔ dominant decay mode

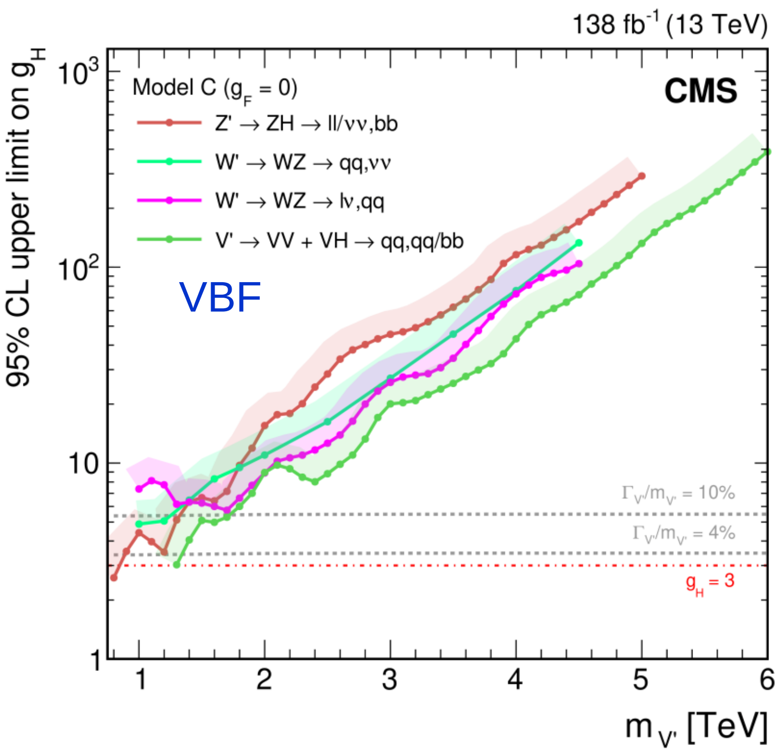
➔ Excluding a wide range of hitherto allowed cross sections for $M_X \leq\ 600\ GeV$



HVT couplings from $V' \to VH$ and other channels

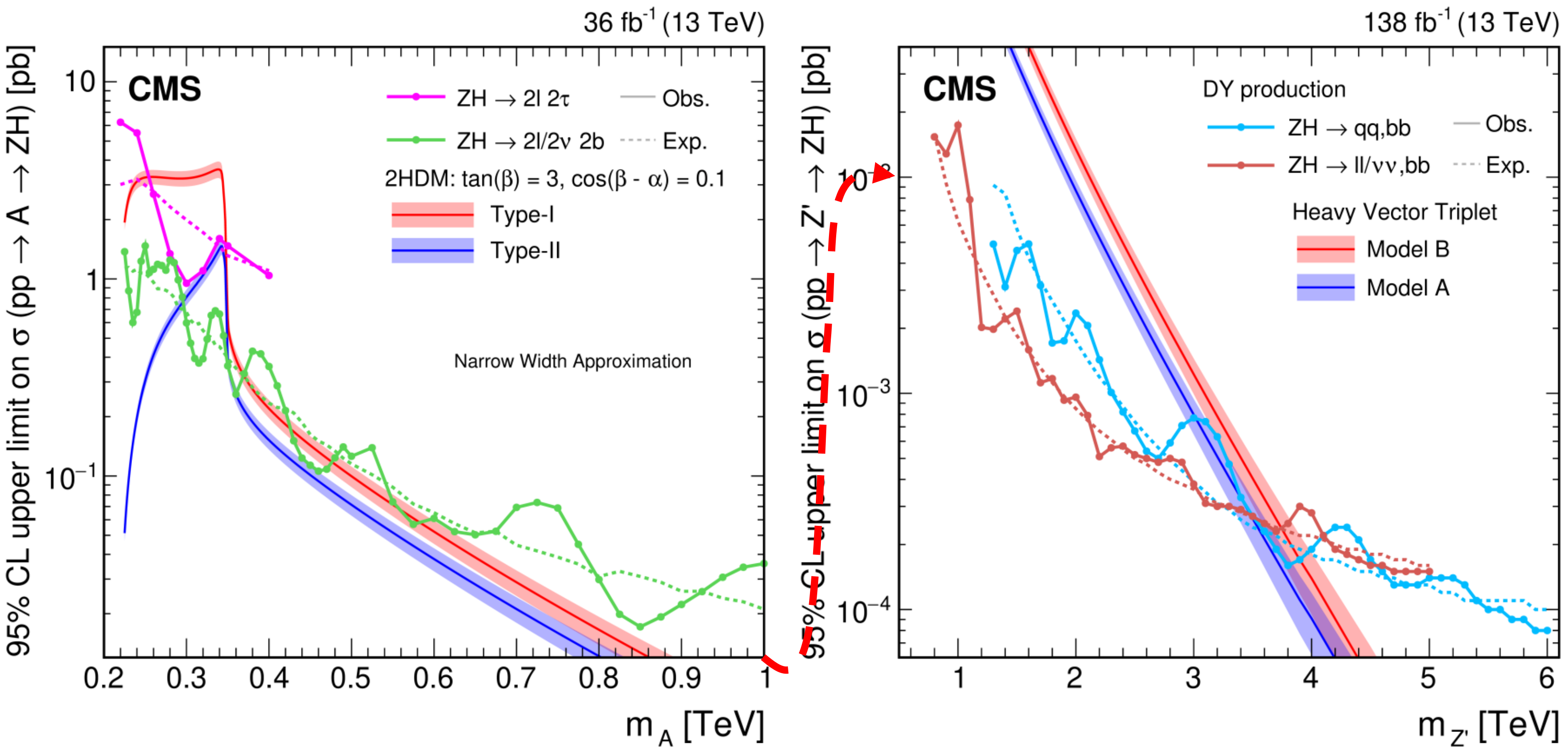
- For Drell-Yan production, strong exclusions in g_F, g_H parameter space
  - except in the very low g_H region, which is however accessible by fermionic modes (like $W' \to \ell\nu$)
  - models A and B excluded for $m_{V'} = 2\,TeV$
- For model C (exclusively VBF production), data set not sufficient to exclude couplings below $g_H = 3$



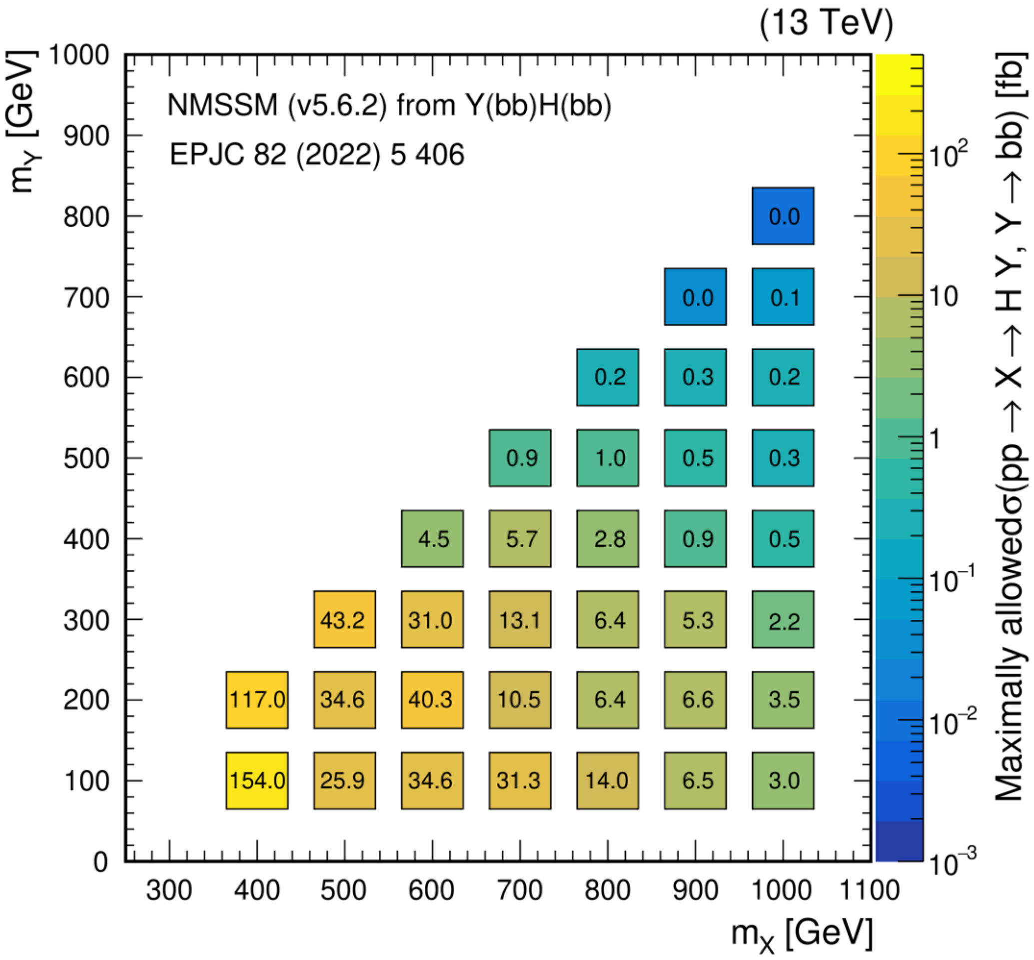


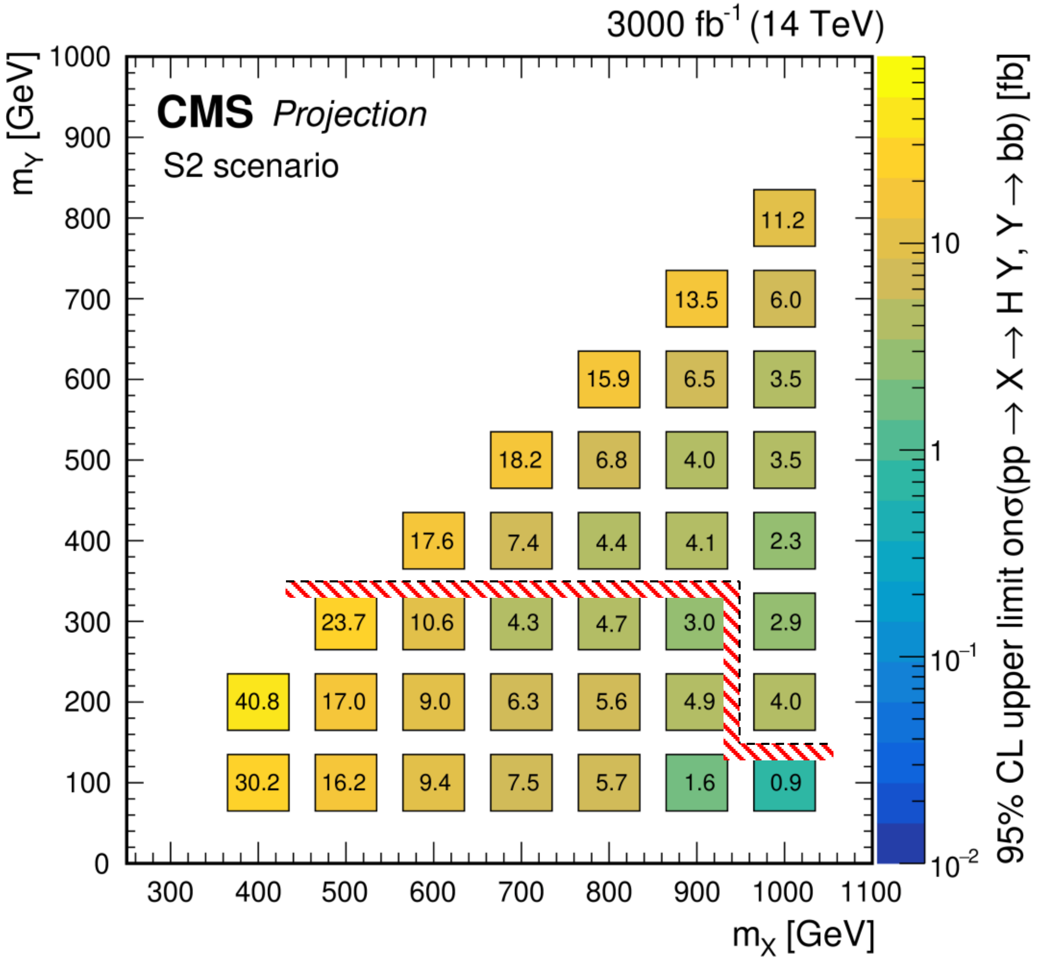
X→VH: low-mass vs high mass regions

- m < 1 TeV: extended Higgs sector searches (e.g. A)
- m > 1 TeV: searches for heavy vector bosons



X→YH: NMSSM theory vs HL-LHC projection

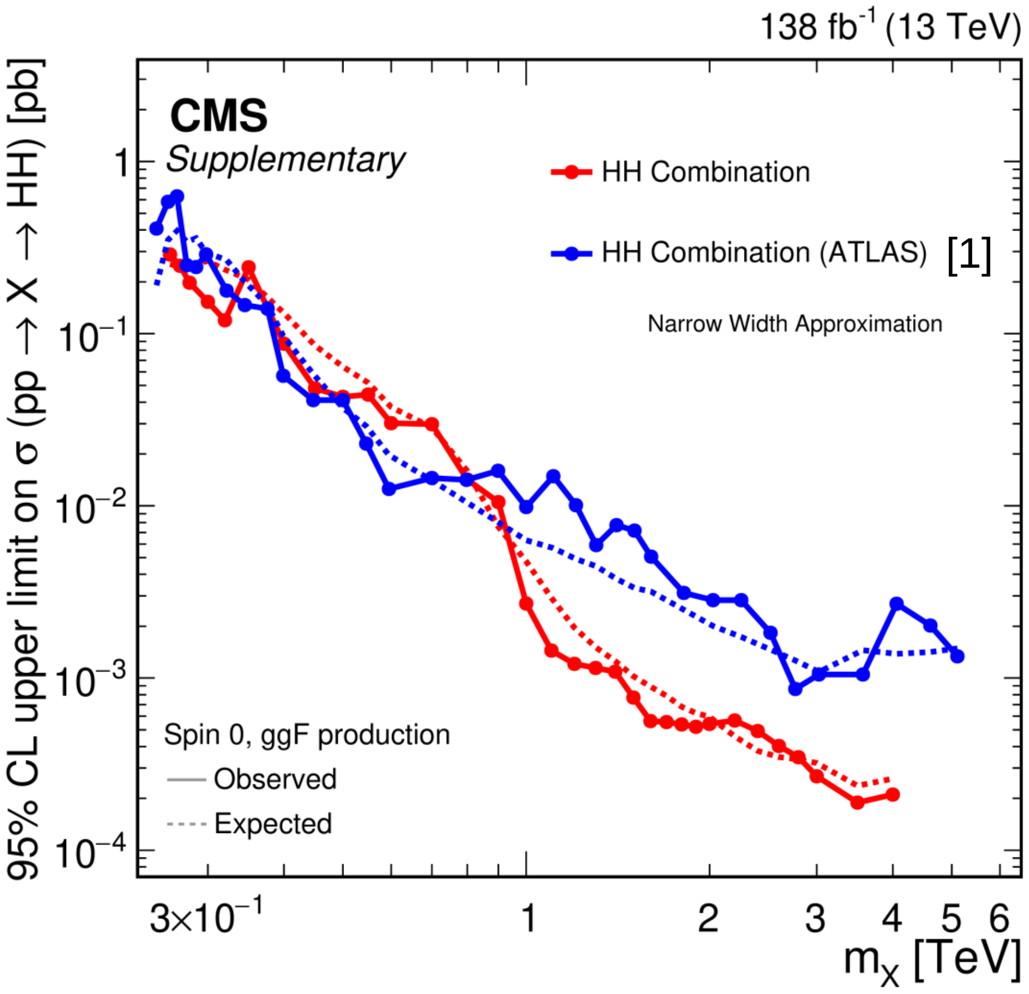




Tables of analyses in review article

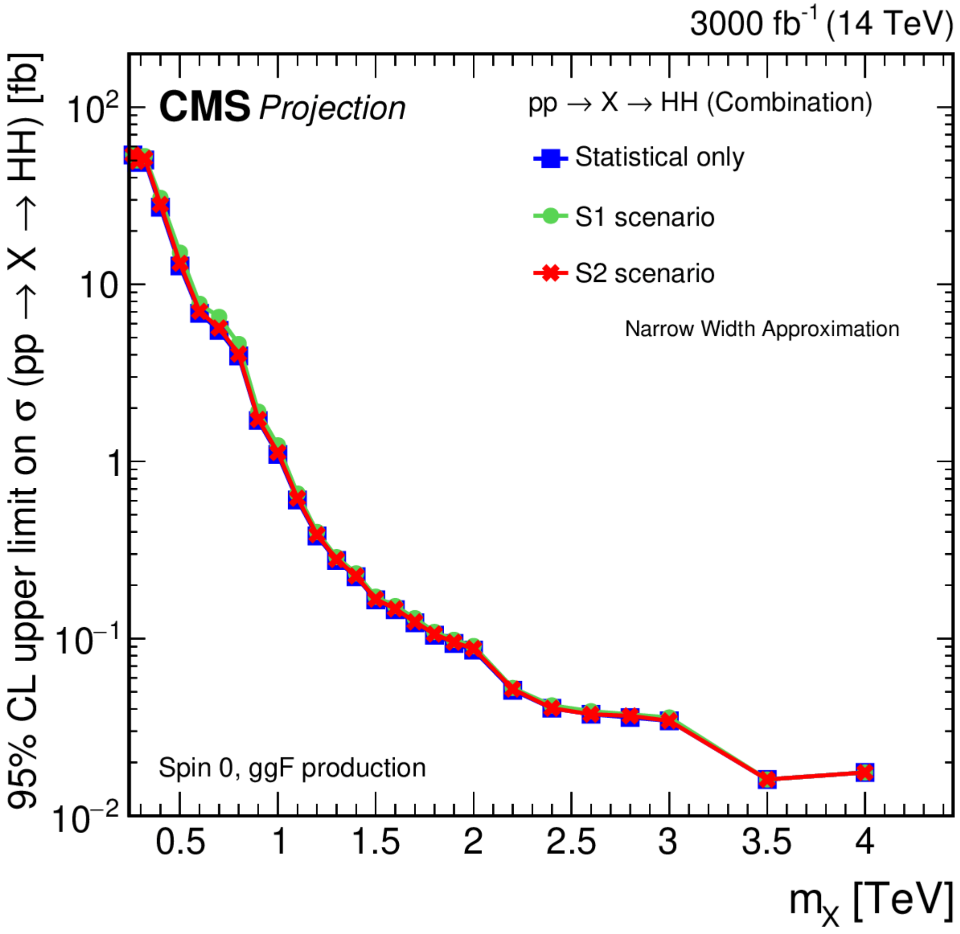
Target final state		Ref.	Mass coverage (GeV)		Comment
V	H		m_X		
$Z(\ell\ell)$	$\tau\tau$	[107]	220 – 400		
$Z(\ell\ell+\nu\nu)$	bb	[108]	225 – 1000		resolved jets
$W(\ell\nu)$	bb	[109]	1000 – 4500		$W \to \ell\nu$ and merged bb jet
$Z(\ell\ell)$	bb	[110]	800 – 4600		$Z \to \ell\ell/\nu\nu$ and merged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

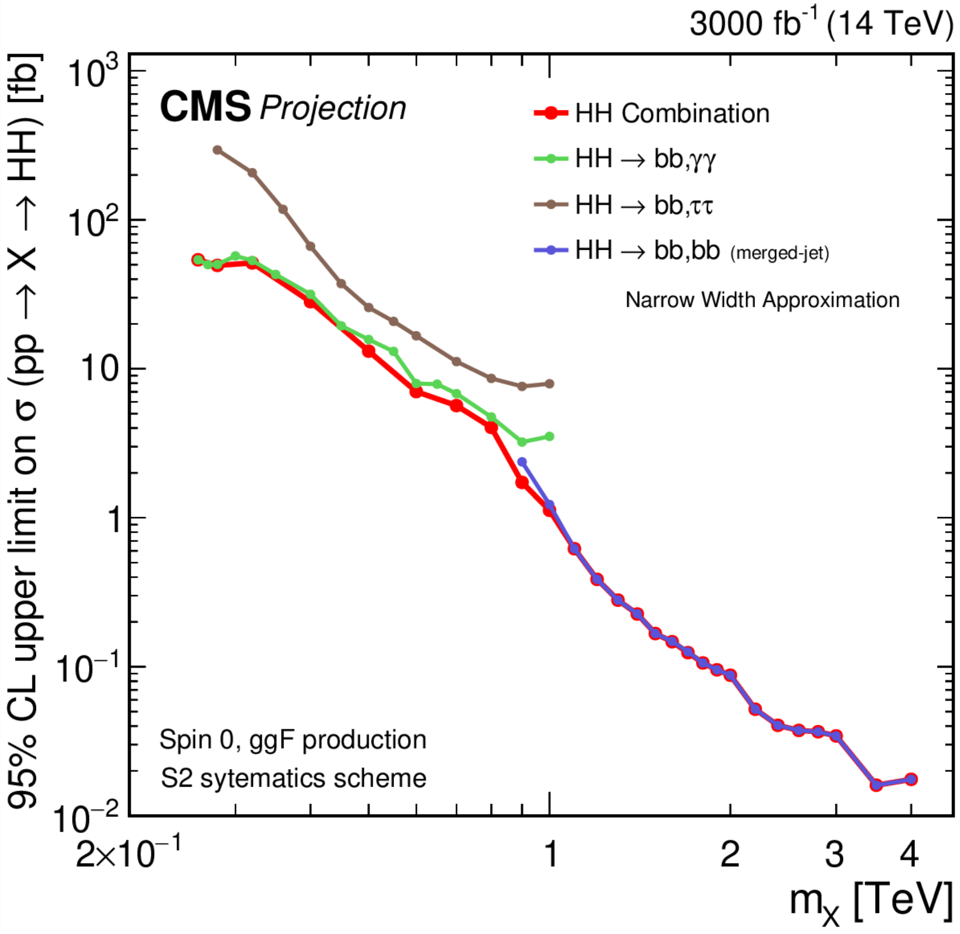
X→HH: ATLAS vs CMS



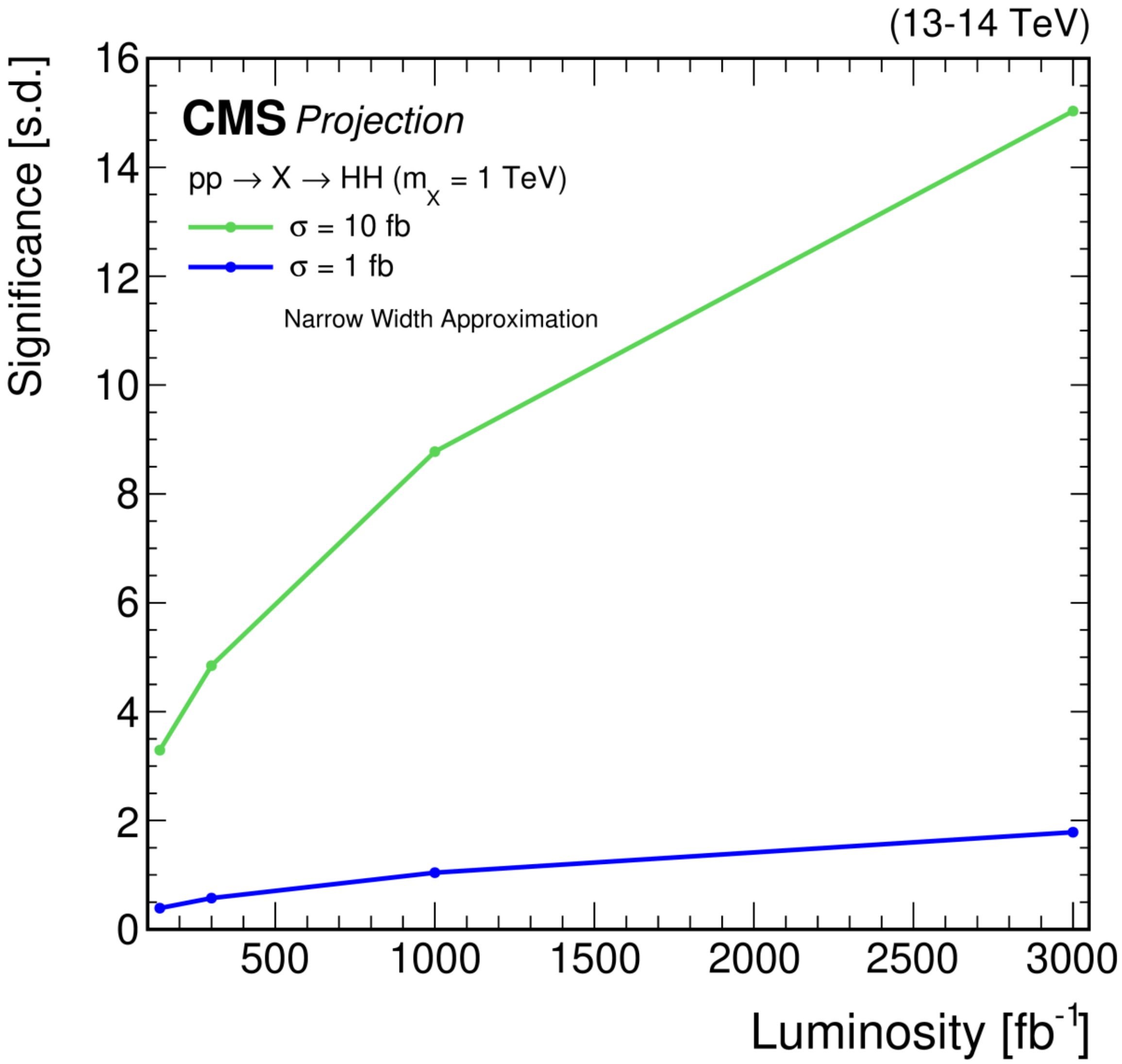
[1] ATLAS Collaboration, "Combination of searches for resonant Higgs boson pair production using pp collisions at $\sqrt{s} = 13\,TeV$ with the ATLAS detector", arXiv:2311.15956,
Phys. Rev. Lett. 132 (2024) 231801

X→HH projections

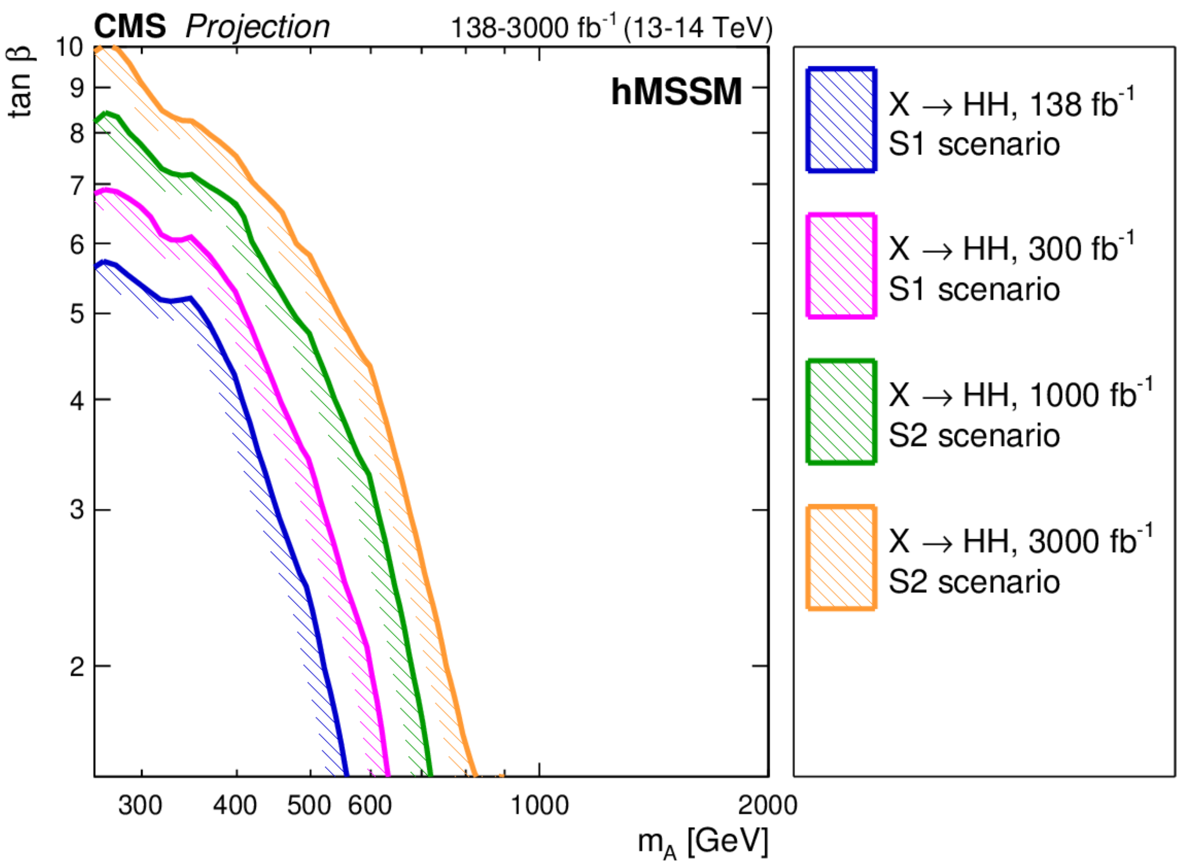


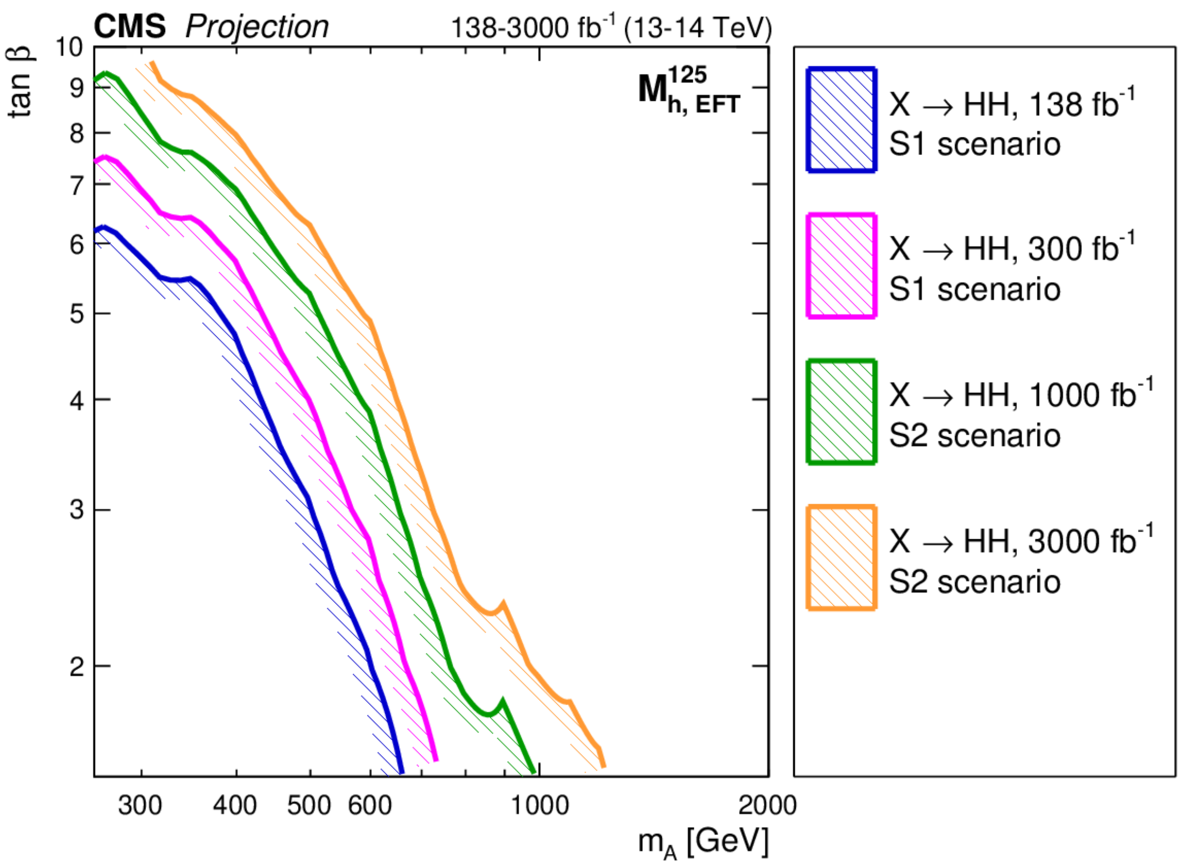


Expected discovery significance for a spin-0 resonance

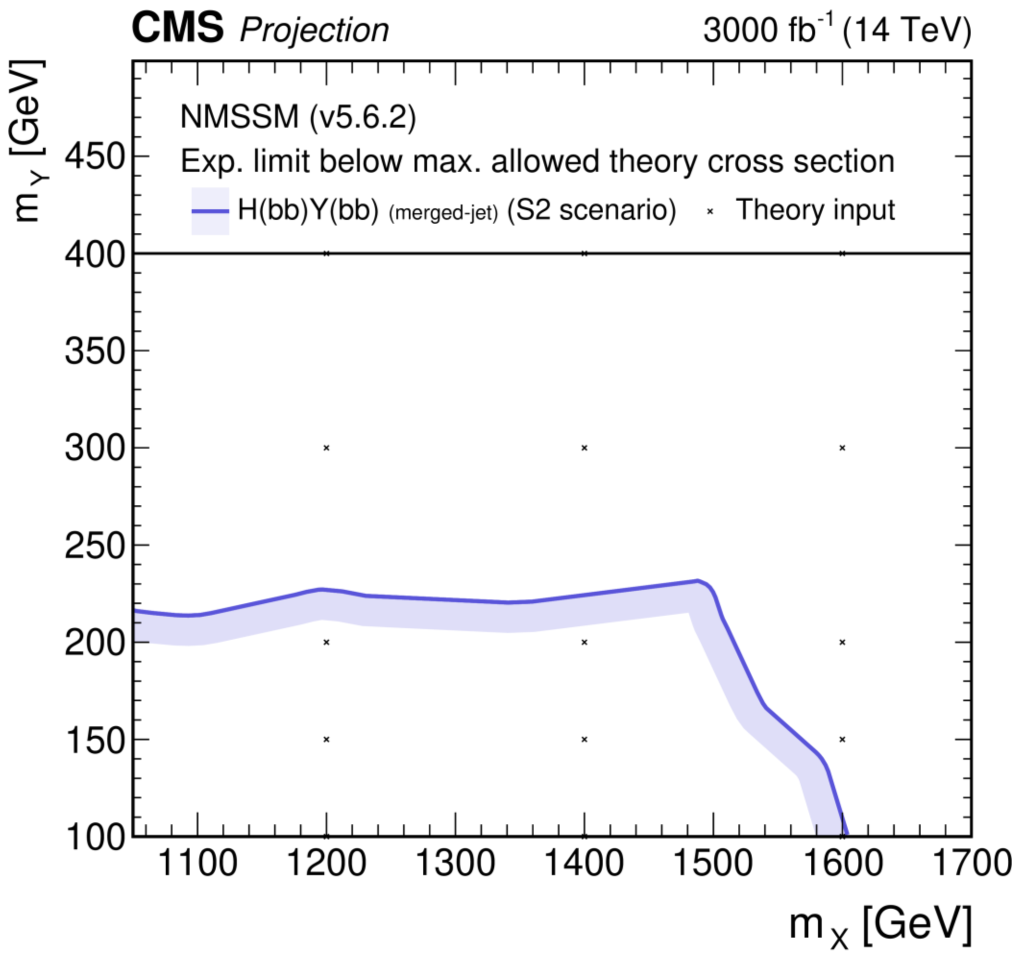


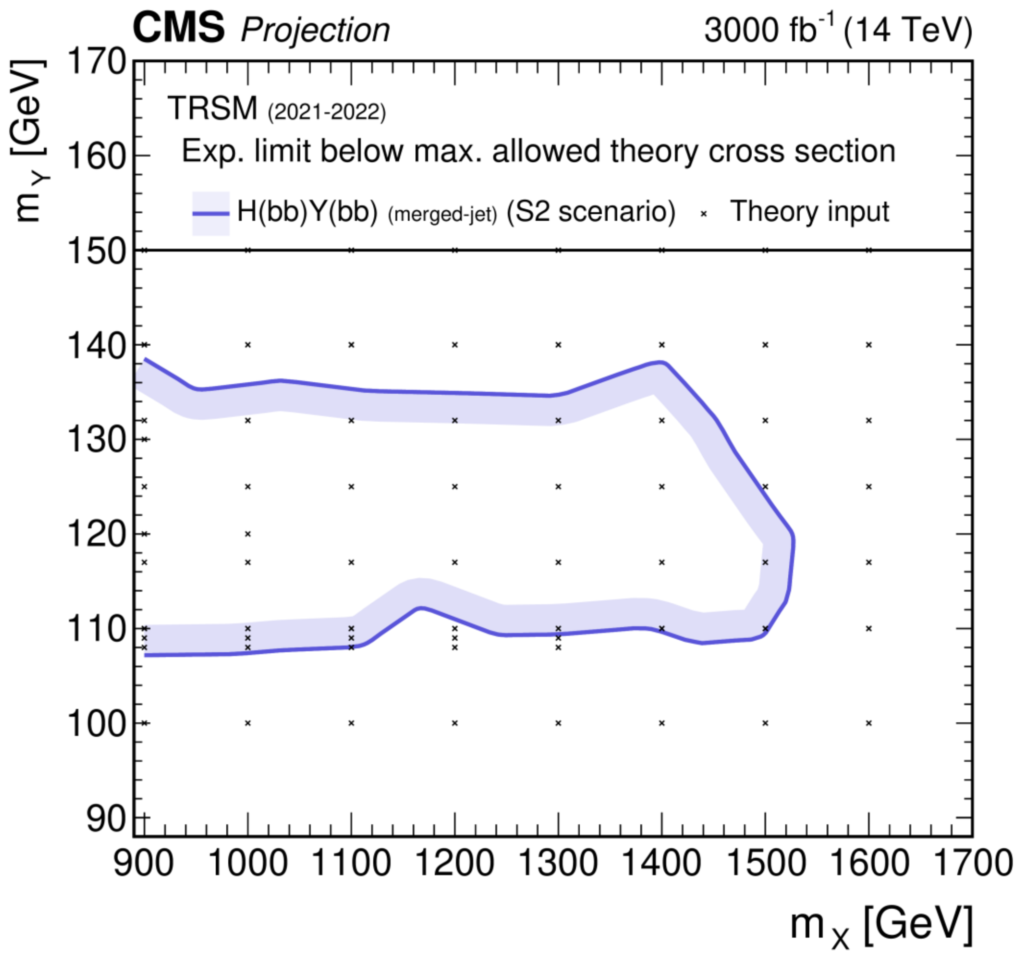
X→HH: projected MSSM interpretations





NMSSM vs TRSM projection





$X \rightarrow HH/YH \rightarrow (bb)(\gamma\gamma)$

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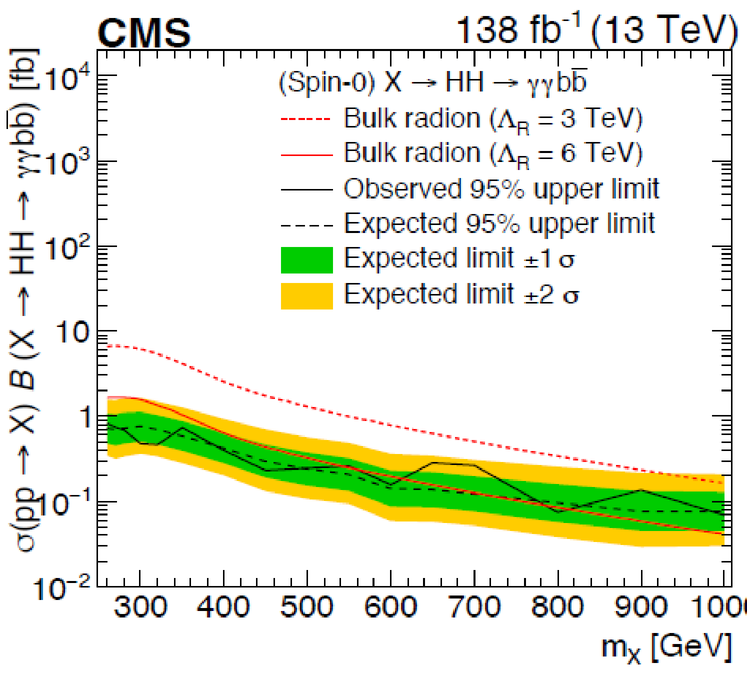
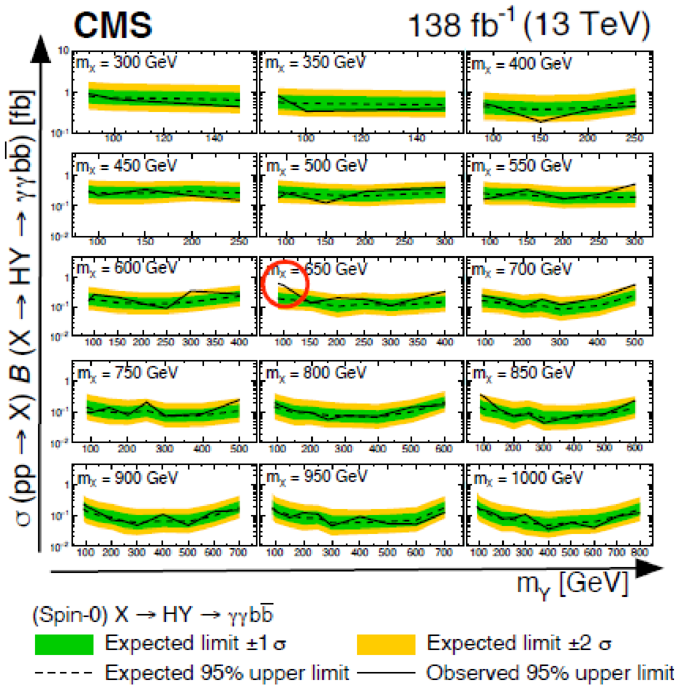
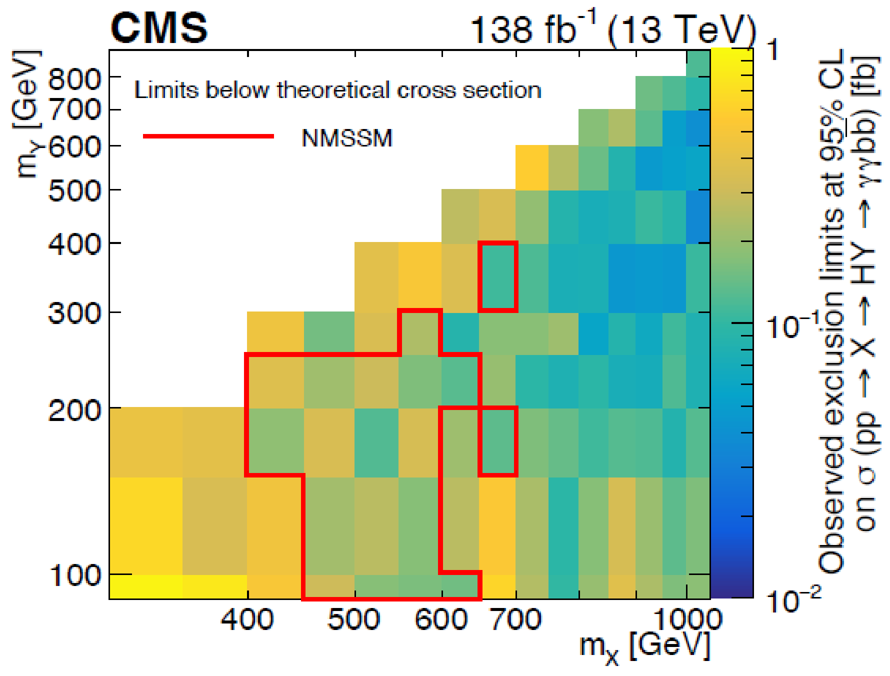
- Simultaneous two-dimensional (2D) fit to $(m_{\gamma\gamma}, m_{jj})$ distribution in all categories
- The largest deviation from background-only hypothesis with local (global) significance of 3.8σ ($\leq 2.8\sigma$) is observed for $m_X = 650\ GeV$ and $m_Y = 90\ GeV$

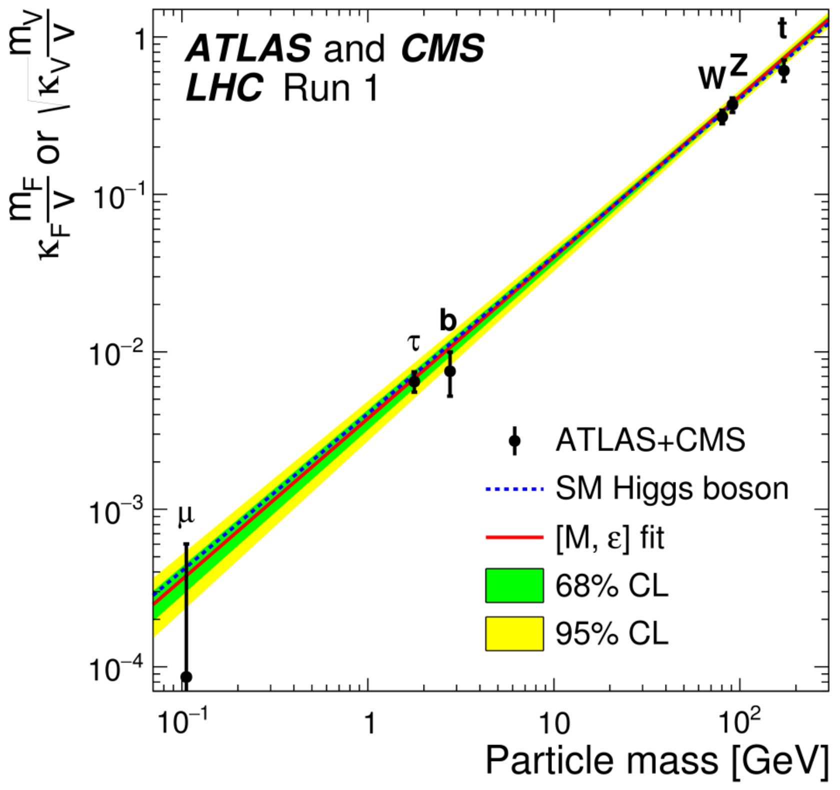




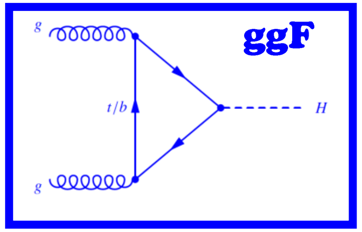


Higgs boson: discovery and exploration

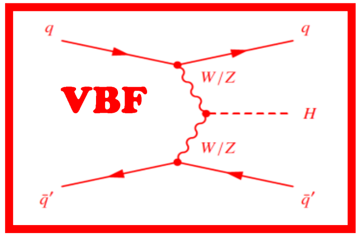
- 2012: Observation of the Higgs boson by ATLAS and CMS
  - initially in di-boson decay modes
- 2016: Run 1 couplings combination (ATLAS+CMS)
  - properties found to be SM-like within current precision
- 2017-18: Discovery of 3rd generation Yukawa couplings
  - via $H \to \tau\bar{\tau}$ and $H \to b\bar{b}$ decays, ttH production
- Now: precision measurements with full Run 2 data



Higgs boson production and decay



~87%



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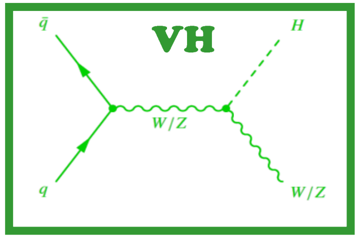

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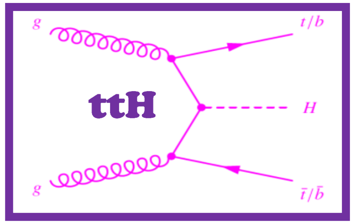

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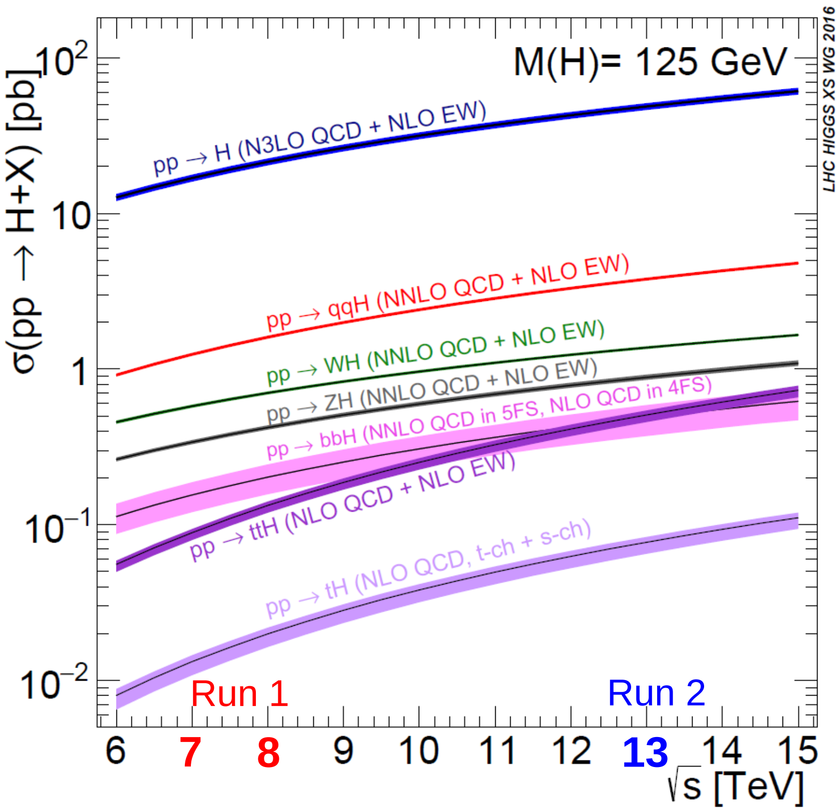

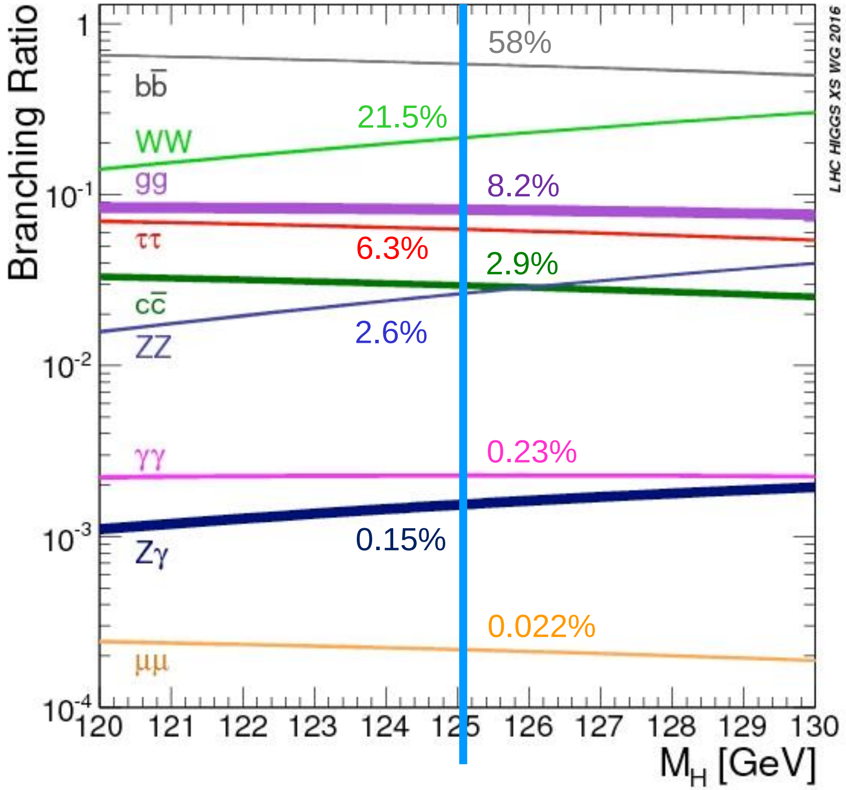

$125.09 \pm 0.24\ GeV$ **(Run 1)**