

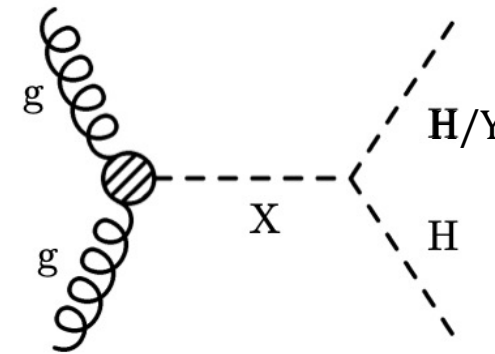
# Searches for heavy resonances decaying into a Higgs boson pair or one Higgs boson and a new scalar ( $X \rightarrow HH/HY$ ) at CMS

Higgs Hunting 2024

**Elise Jourd'huy** , on behalf of CMS

# Higgs to probe new physics

Higgs sector as a tool to probe physics  
**beyond the SM**



Some **BSM theories** predict additional particles  
Like a **resonance X** **decaying into** :

- A **Higgs(125) pair**
- A **Higgs(125)** and a new scalar **Y**

# Extended Higgs Sectors

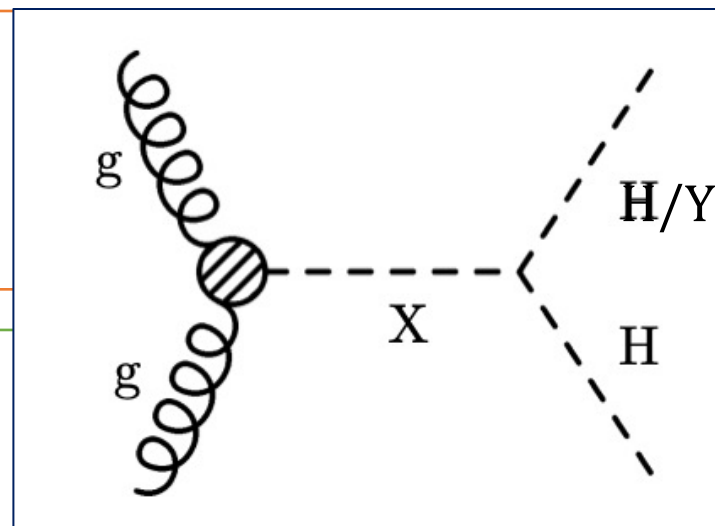
*The Higgs sector does not need to be minimal (SM) → Can be extended with additional singlet, doublet, ...*

➤ **Additional real singlet :**

- Introduce a new real singlet S, leading to a new scalar X :  $X \rightarrow HH$
- Adding one more real singlet (TRSM) :  $X \rightarrow HY/HH$

➤ **Additional doublet : 2HDM**

- 3 neutral and 2 charged Higgs bosons
- $X \rightarrow HH$  and  $A \rightarrow ZH$
- Possible couplings of second doublet with fermions :
  - 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+lepton
- Additional singlet (N2HDM, NMSSM) :  $X \rightarrow HY$  possible



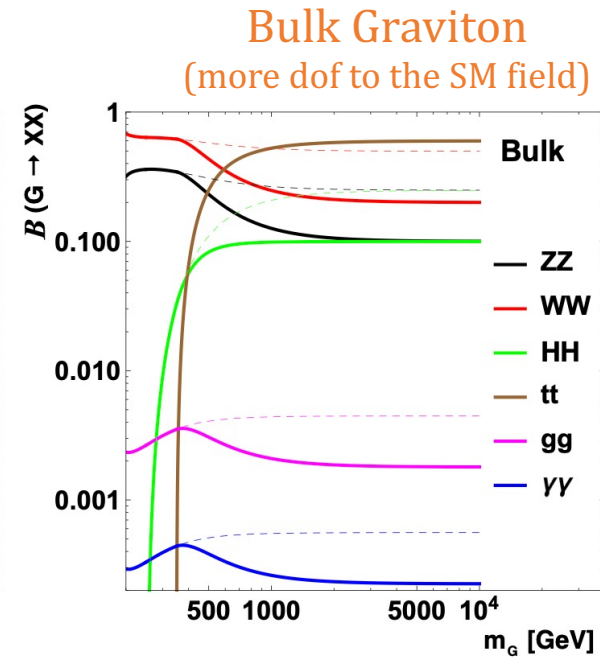
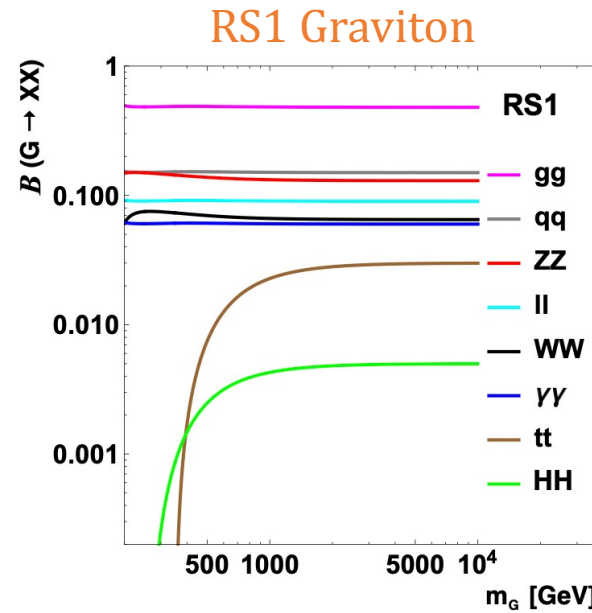
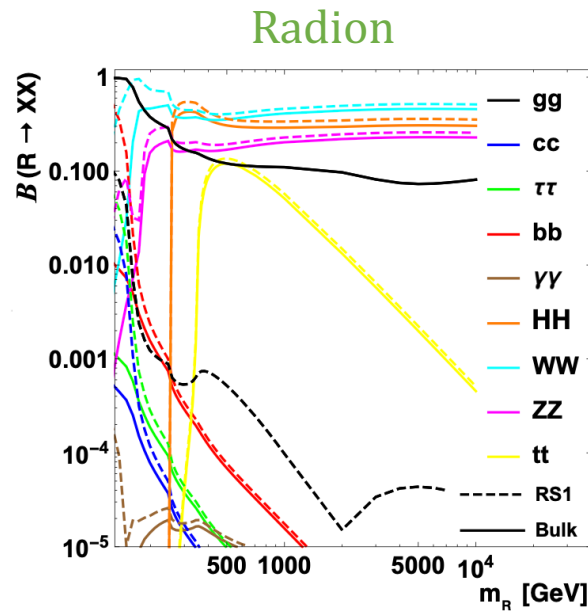
**Minimal supersymmetric standard model (MSSM)**

# Warped Extra Dimension (WED)

*Phys.Rev.Lett.* 83:3370–3373, 1999

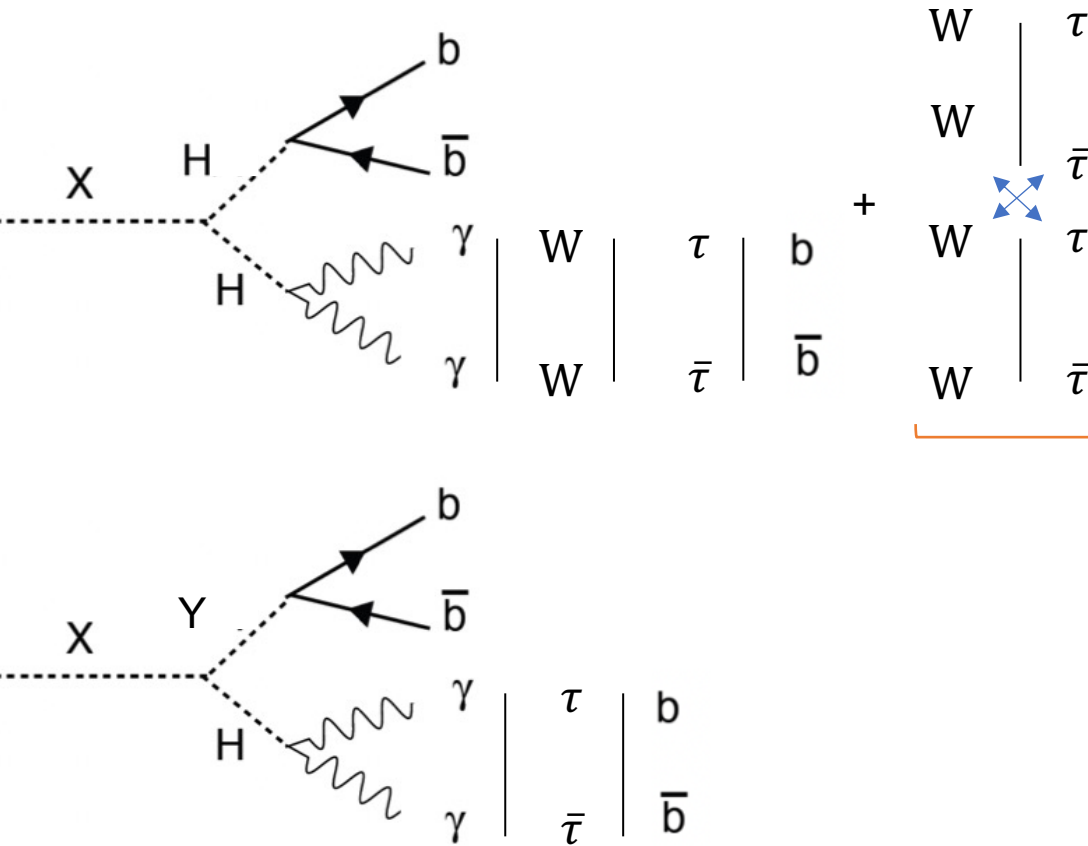
Warped Extra Dimension by Randall and Sundrum (RS) → Existence of an **extra spatial dimension**

- Existence of a **spin 0 Radion** and a **spin 2 Kaluza-Klein (KK) Graviton**
- HH is among the **highest Branching Ratios** for the **Bulk scenario**



[arXiv:1404.0102v4](https://arxiv.org/abs/1404.0102v4)

# Analyses involved



	HH spin 2	HH spin 0	HY
<i>bbWW (resolved)</i>	<a href="#">JHEP 07 (2024) 293</a>		
<i>bbWW (boosted)</i>	<a href="#">JHEP 05 (2022) 005</a>		
<i>multilepton</i>	<a href="#">JHEP 07 (2023) 095</a>		
<i>bbbb (boosted)</i>	<a href="#">PLB 842 (2023) 137392</a>		
<i>bbγγ</i>	<a href="#">JHEP 05 (2024) 316</a>		
<i>bbττ</i>		<a href="#">JHEP 11 (2021) 057</a>	

# Involved analyses

Combination of these analyses was performed as part of a broader review ↓

						HH spin 2	HH spin 0	HY	
	$\gamma$	$W$	$\tau$	$h$	$W$	$\tau$			
	$bbWW$ (resolved)						<a href="#">JHEP 07 (2024) 293</a>		
	$\gamma$	$\tau$	$\tau$	$h$	$W$	$\tau$			
	Searches for Higgs boson production through decays of heavy resonances							<a href="#">005</a>	
	The CMS Collaboration*							<a href="#">095</a>	
	<a href="#">arXiv:2403.16926</a> , CMS-B2G-23-002							<a href="#">23) 137392</a>	
								<a href="#">024) 316</a>	
							<a href="#">11 (2021) 057</a>		

# Combination procedure

✓ **One event should not appear in two different analyses**

✓ **Systematics alignment**

The **systematics** that are supposed to behave the same way across analyses are considered **100% correlated**

✓ **Same normalization for all analysis**

HH : Each analysis is normalized to its SM BR

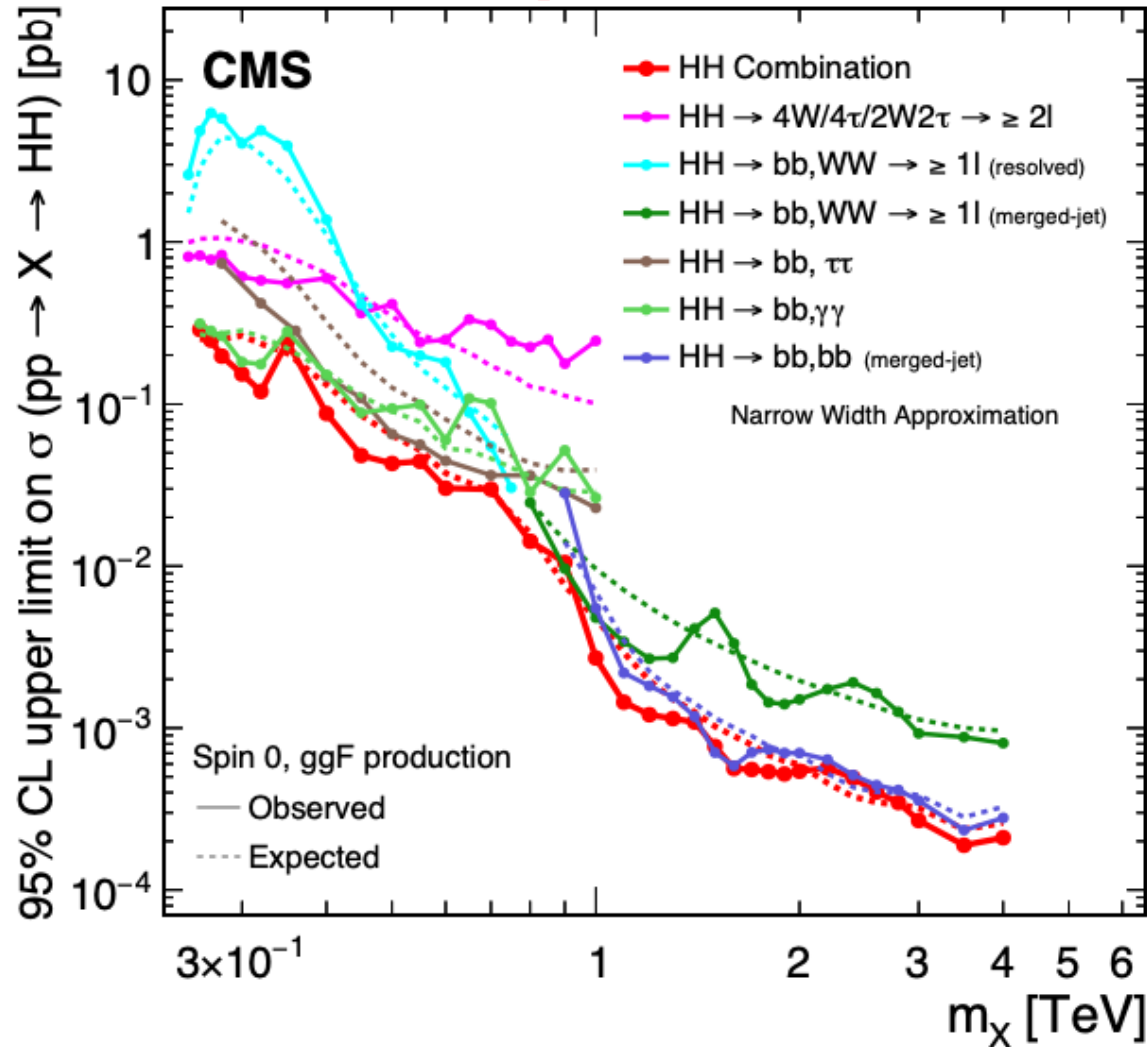
HY : Each analysis is normalized to the Higgs SM BR. No normalization for  $Y \rightarrow b\bar{b}$  to stay model independent

✓ **Statistical tests**

# Results for HH

Spin 0

138 fb<sup>-1</sup> (13 TeV)



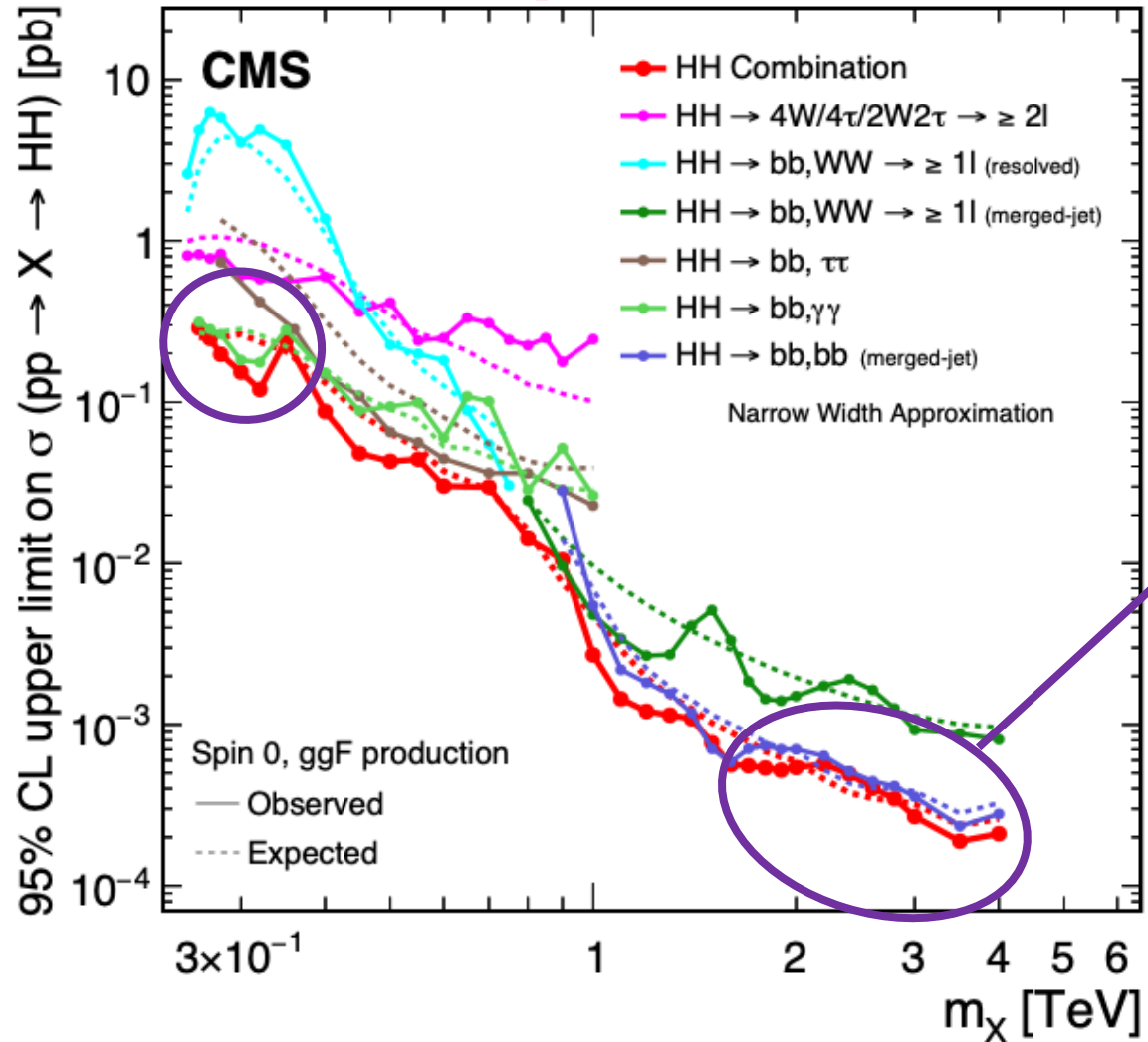
Wide mass range  $\rightarrow$  Wide range of sensitivity



# Results for HH

Spin 0

138 fb<sup>-1</sup> (13 TeV)



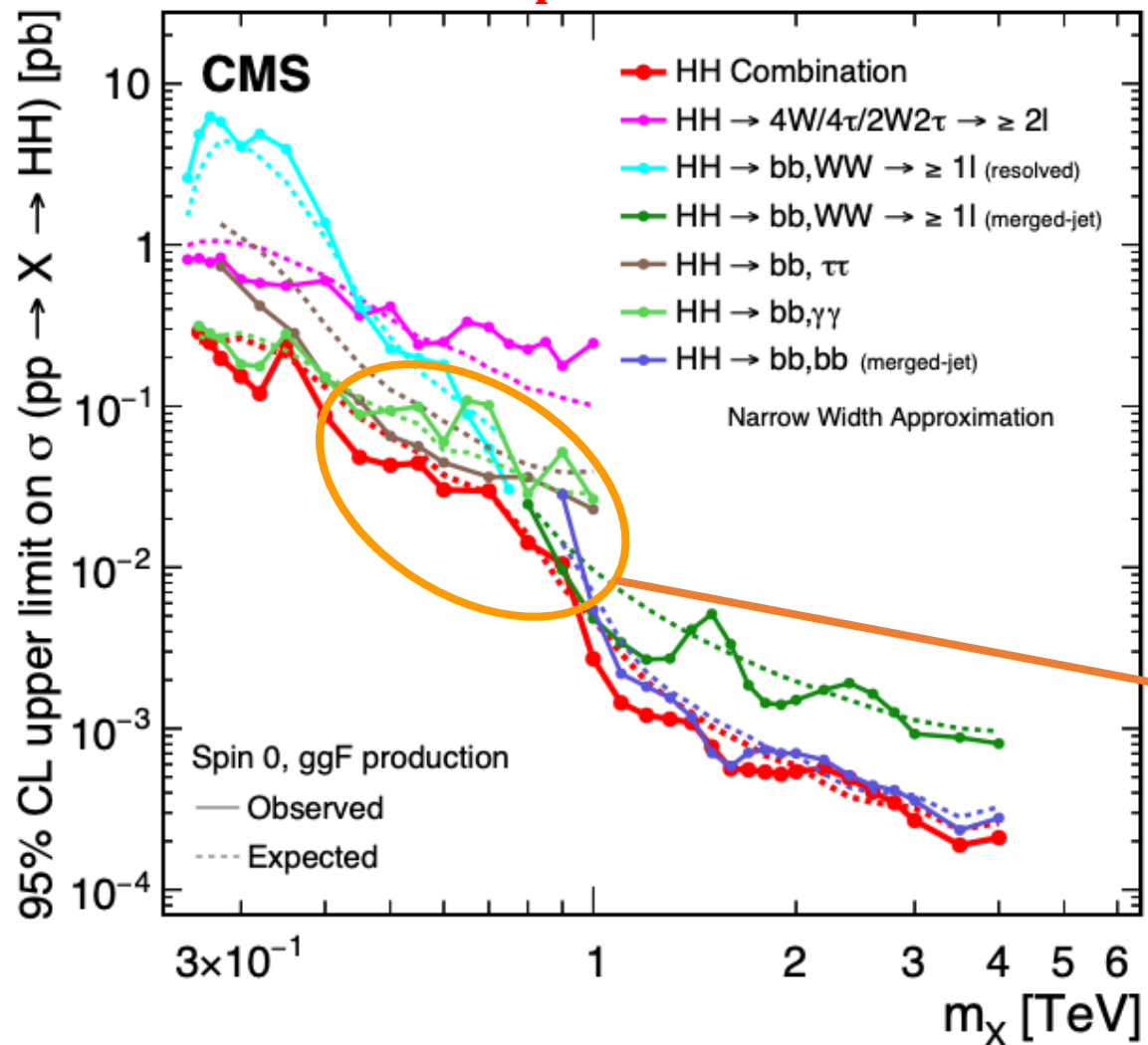
Wide mass range  $\rightarrow$  Wide range of sensitivity

Combination dominated by one channel

# Results for HH

Spin 0

138 fb<sup>-1</sup> (13 TeV)



Wide mass range  $\rightarrow$  Wide range of sensitivity

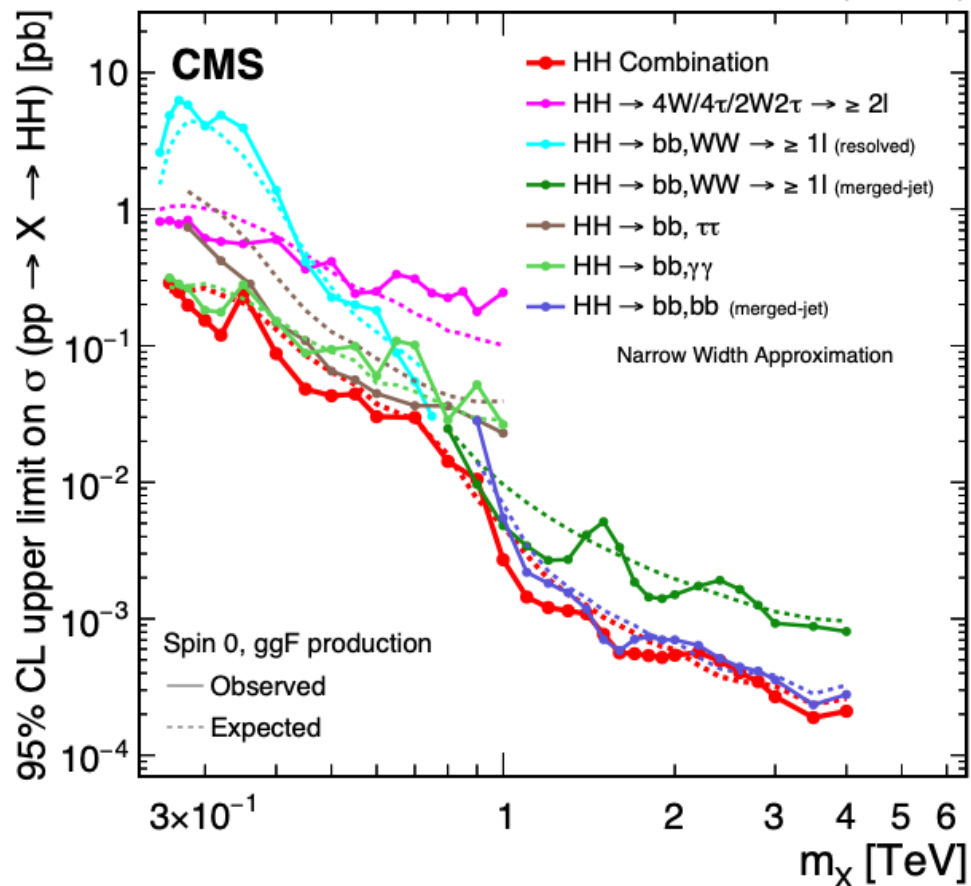
Combination dominated by one channel

Gain in sensitivity  
(400-700 GeV)

# Results for HH

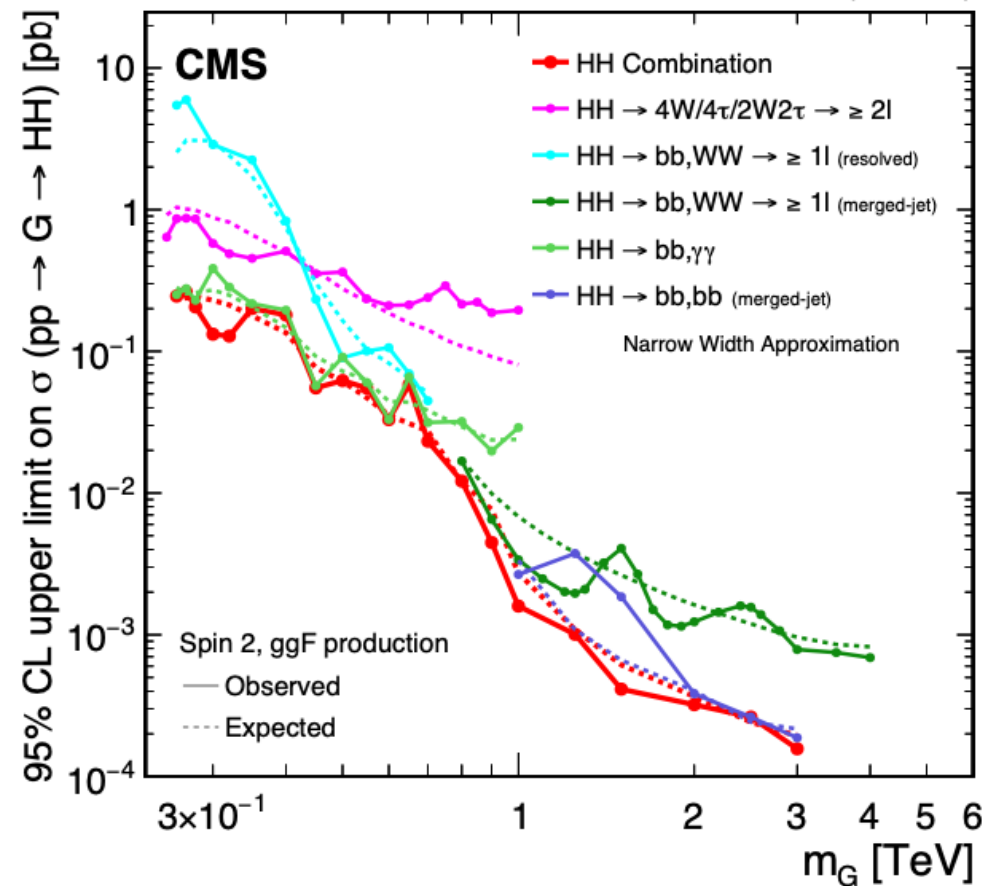
Spin 0

138 fb<sup>-1</sup> (13 TeV)



Spin 2

138 fb<sup>-1</sup> (13 TeV)

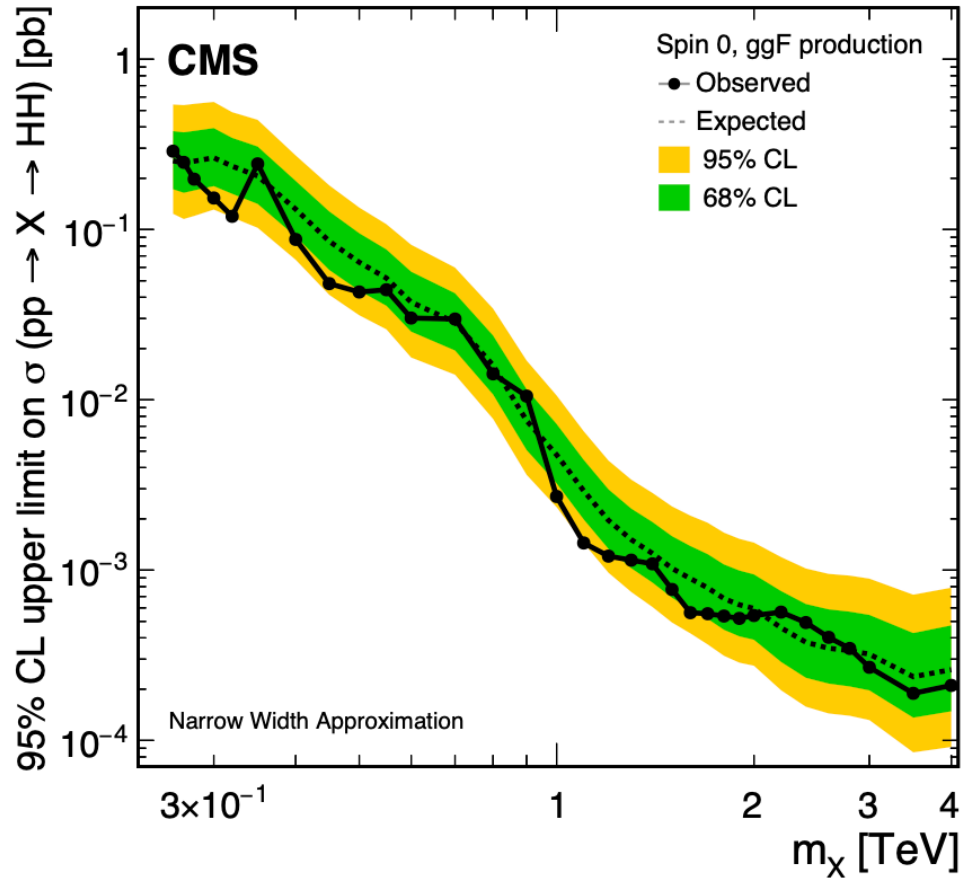


Different angular distributions  $\rightarrow$  different limits

# Results for HH

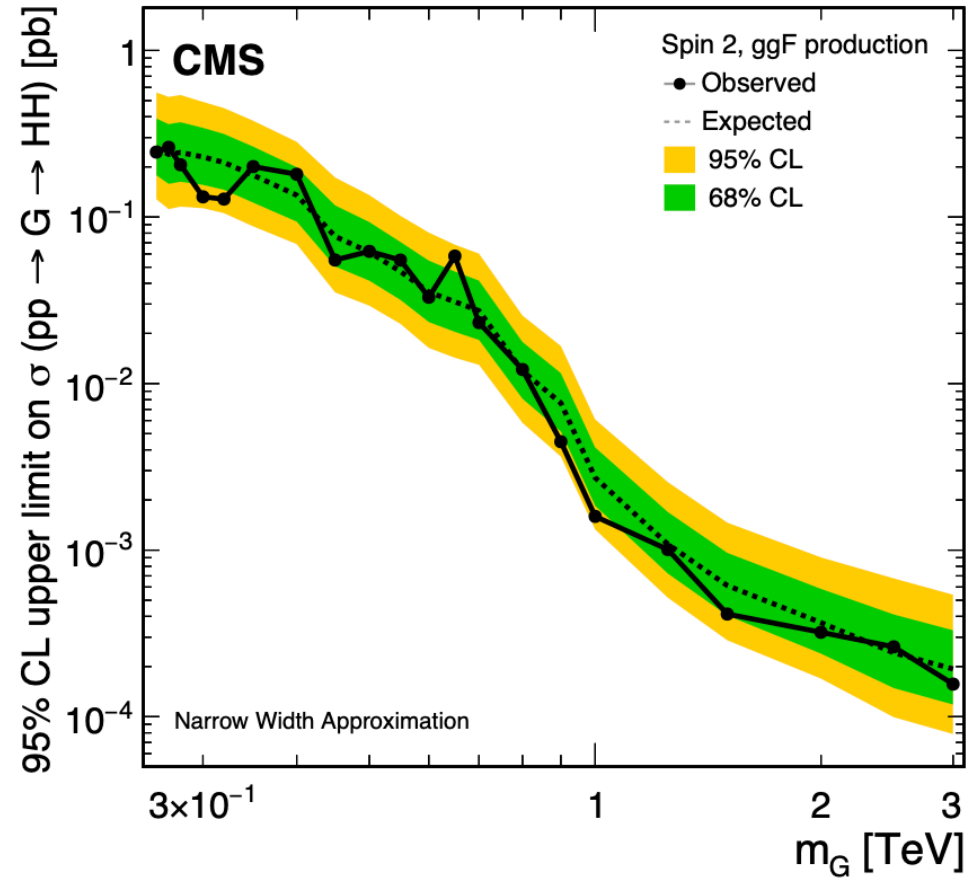
Spin 0

138 fb<sup>-1</sup> (13 TeV)



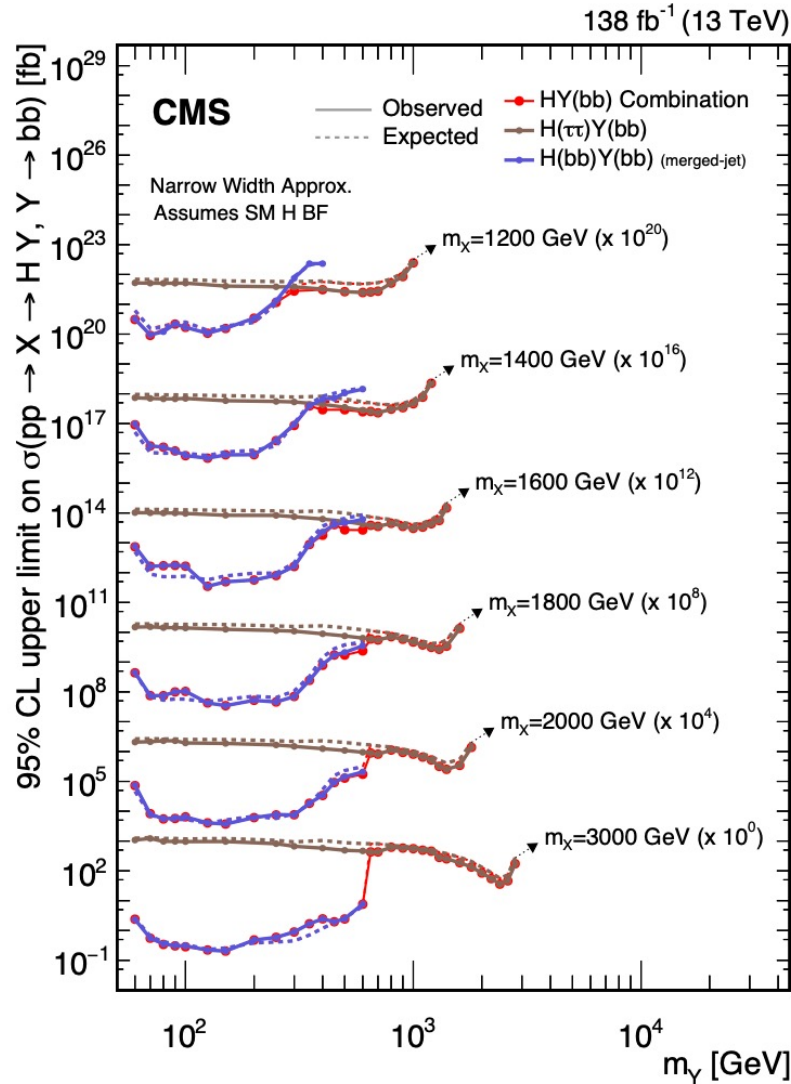
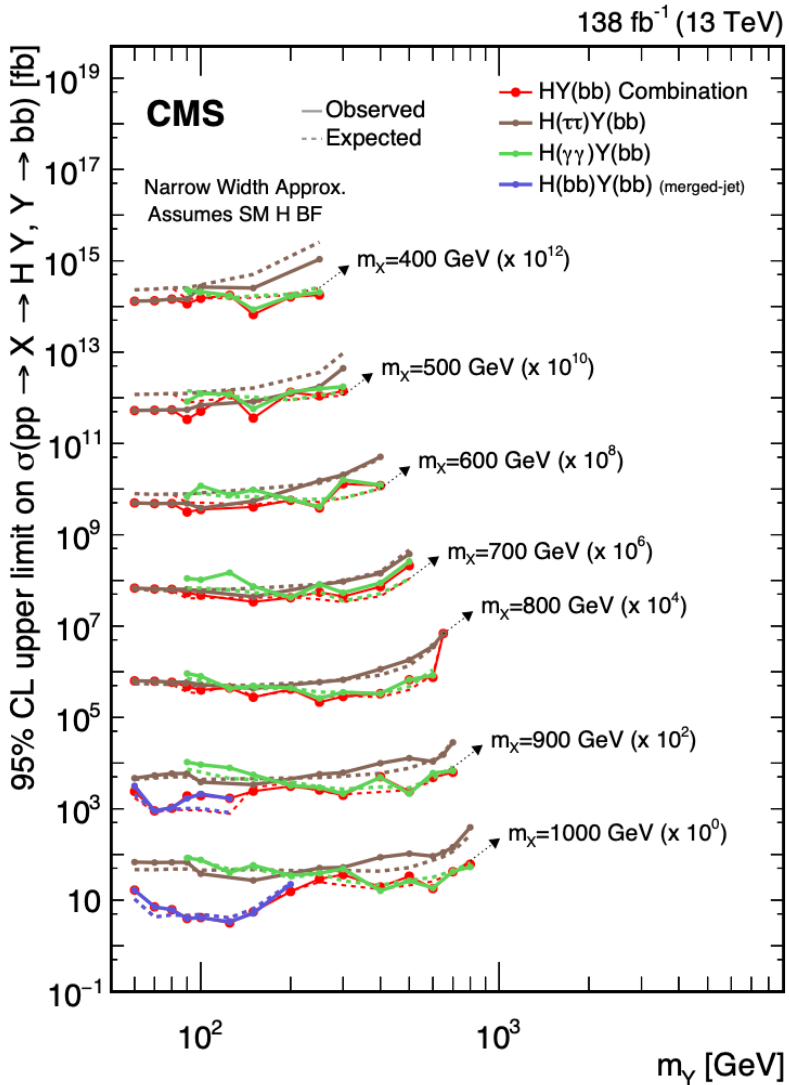
Spin 2

138 fb<sup>-1</sup> (13 TeV)



No excess observed

# Results for HY



Combination for the  $M_X$  in which we have several analyses.

The 4b boosted channel dominates the combination for  $M_X > 1 \text{ TeV}$  and small/medium values of  $M_Y$

No excess above 2 s.d. for the combined mass points

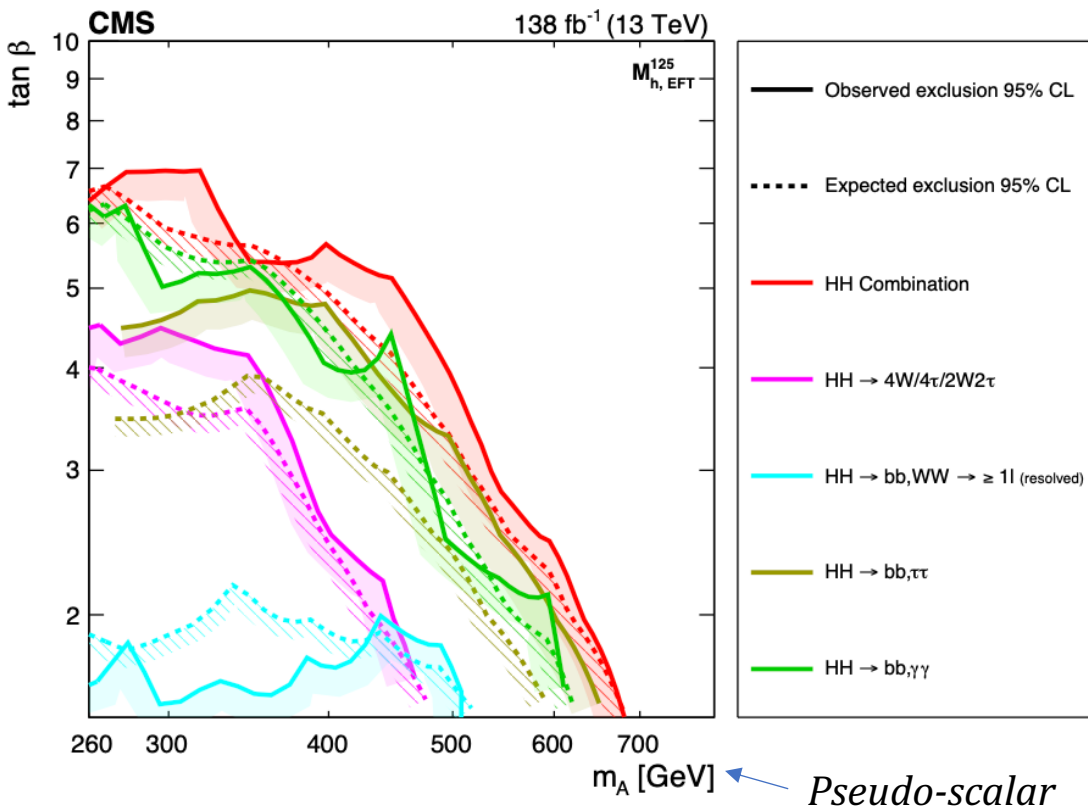
Considering a more complete combination

# Interpretation - MSSM $X \rightarrow HH$

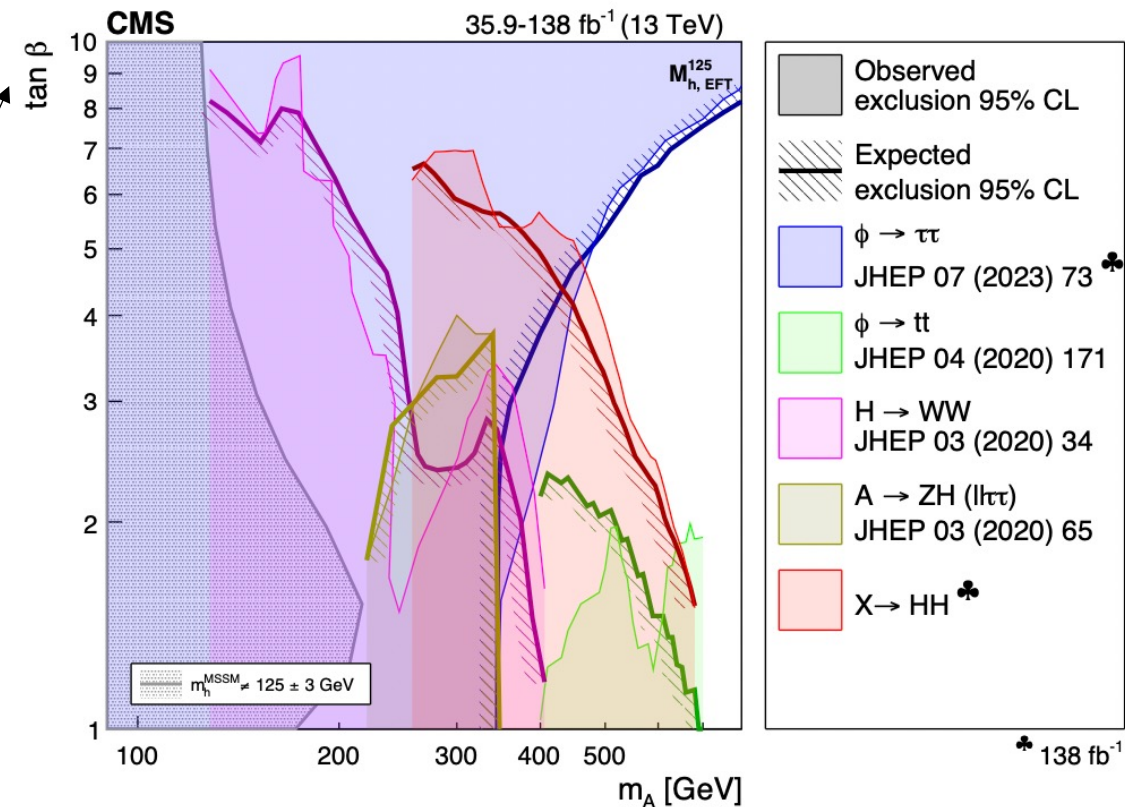
*hMSSM model in backup*

Particularly interesting when  $m_A < 700$  GeV

Unique exclusion limits for  $m_A > 400$  GeV !



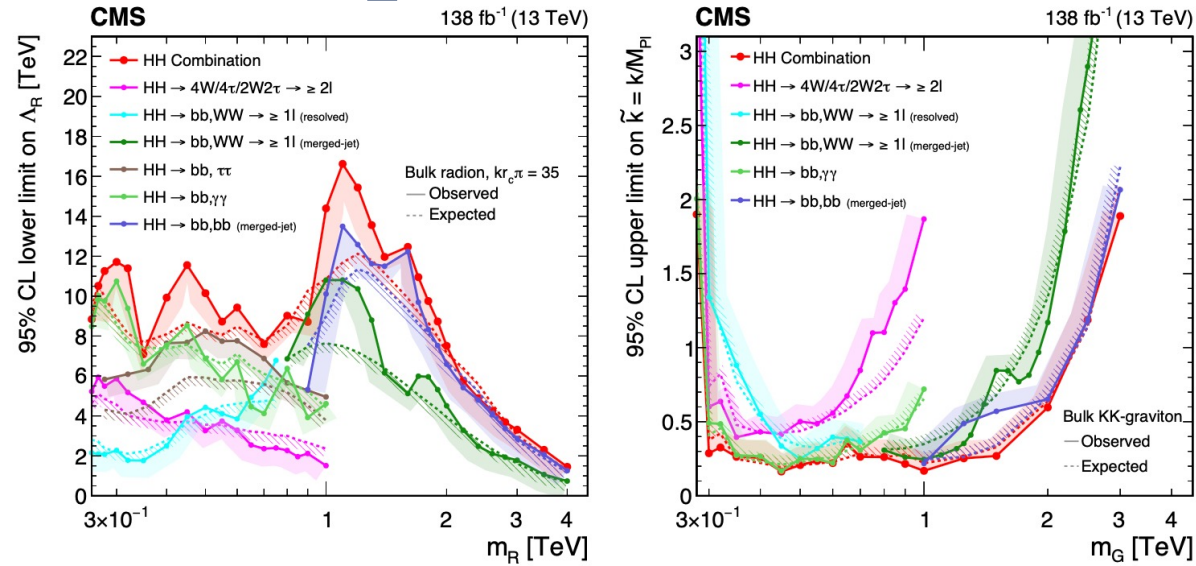
Ratio of  $v$ 's



# Interpretation - WED $X \rightarrow HH$

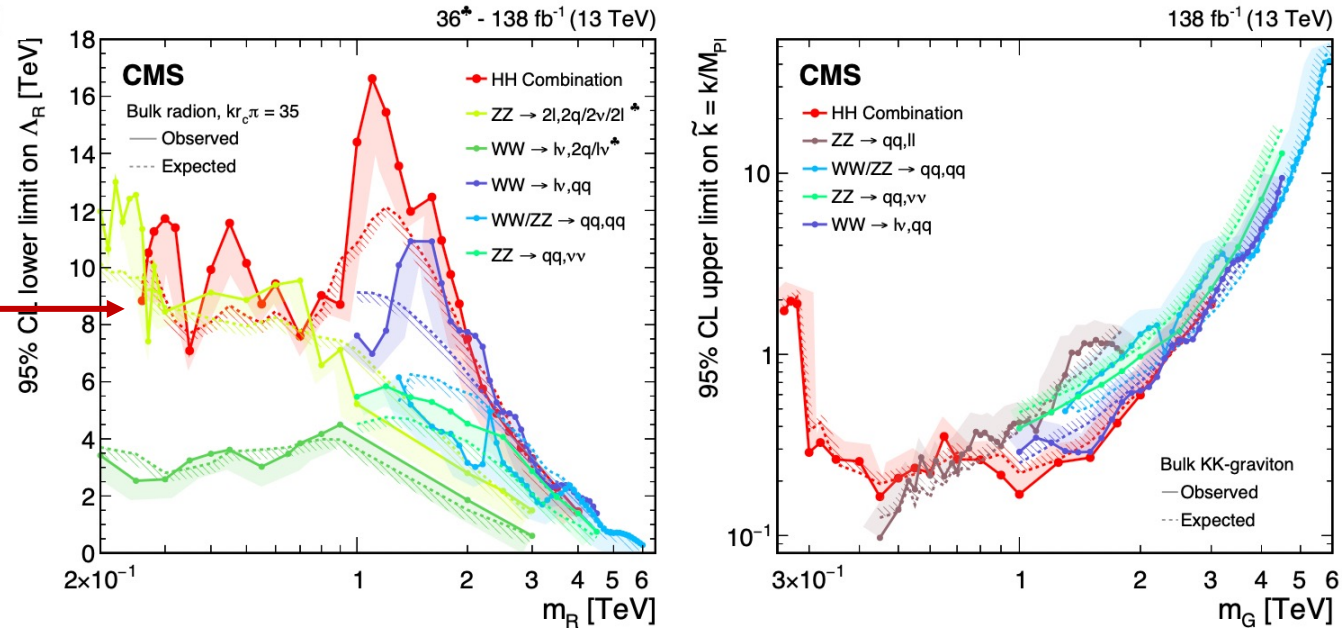
*HH decay channels vs combination*

$\Lambda_R$  : mass scale  
 $k$  : Warp factor,  $\overline{M}_{pl}$  : reduced Planck mass



Together with VV channel, **HH provides the strongest constraints on this model**

*HH combination vs Other Diboson searches*



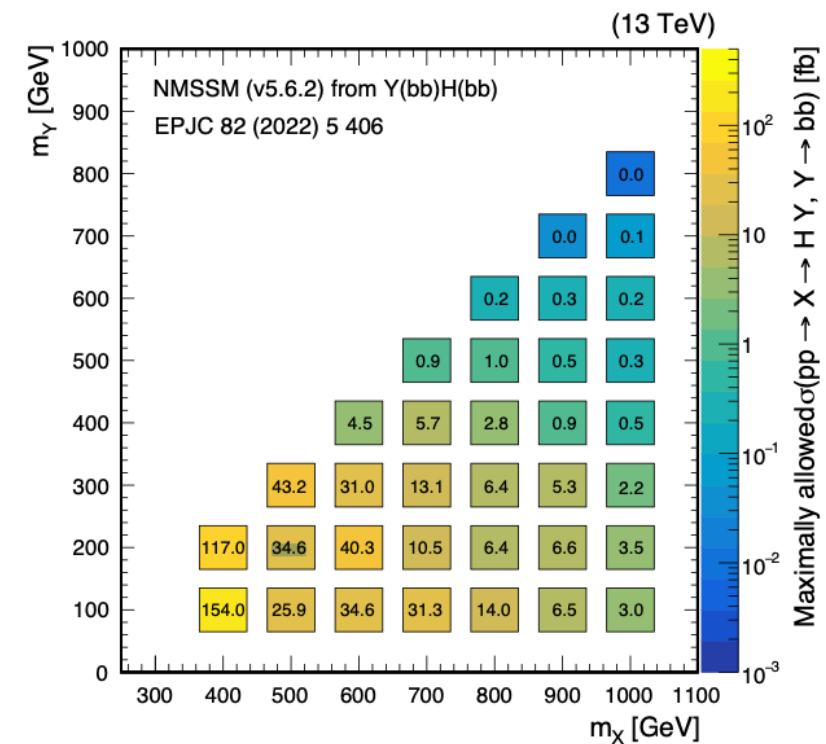
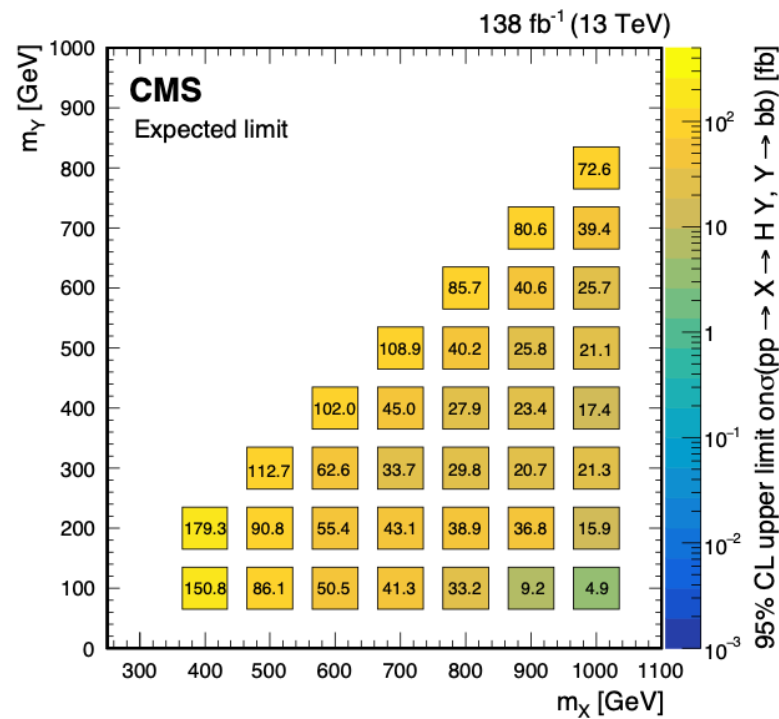
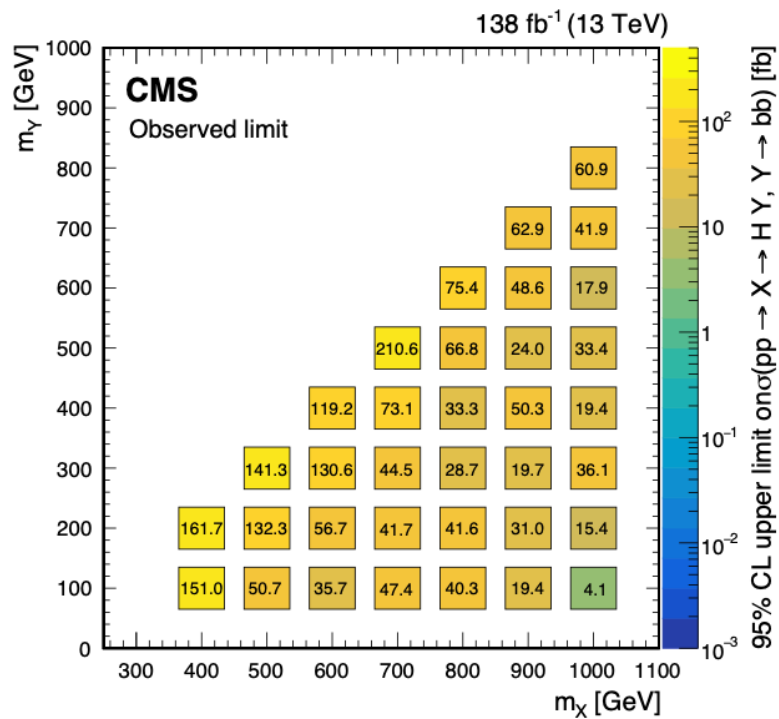
- **A Combination of  $X \rightarrow HH/HY$  searches was performed with LHC Run 2 data**
  - Combination offered a **great gain of sensitivity** for masses between 0.5 and 1 TeV for HH spin 0
  - No excess was observed
  - For HH spin0, below masses of 320 GeV and above 800 GeV, this combination gives the **strongest observed limits to date**
  - **New exclusion limits in MSSM and WED**



**Thank you !**

**Backup**

# NMSSM



# BR( $X \rightarrow HH$ ) in 2HDMs

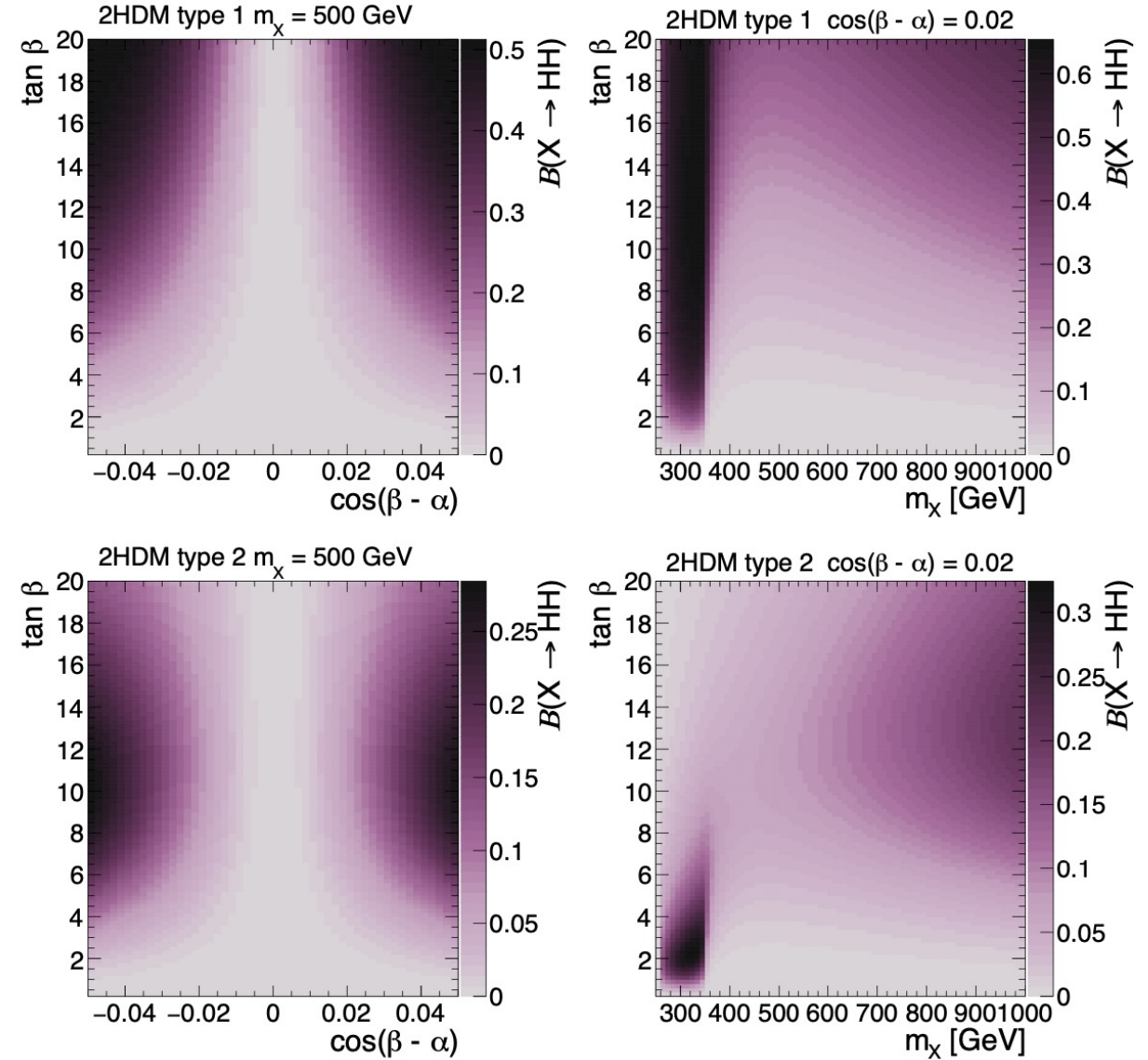


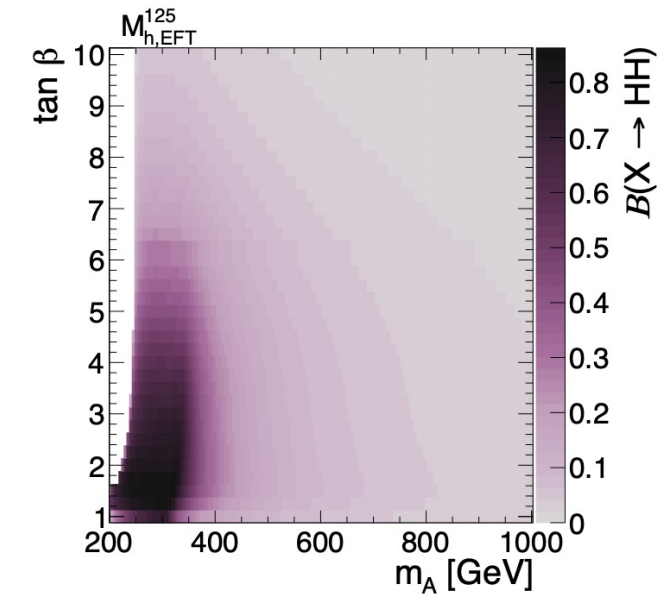
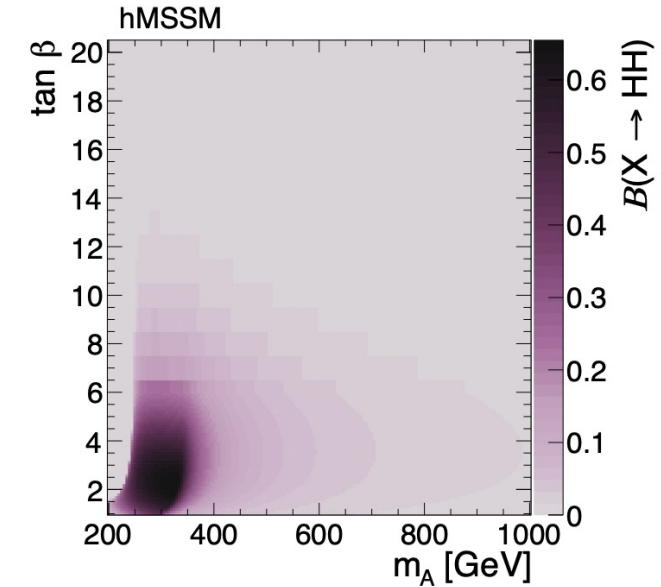
Figure 5: Branching fractions of  $X \rightarrow HH$  decays in 2HDMs of Type I (upper) and Type II (lower) in the  $\cos(\beta - \alpha)$ - $\tan \beta$  plane for  $m_X = 500$  GeV (left) and in the  $m_X$ - $\tan \beta$  plane for  $\cos(\beta - \alpha) = 0.02$  (right). The masses of all non-SM-like Higgs bosons are set to be the same,  $m_X = m_A$ , and  $m_{12}^2 = m_A^2 \tan \beta / (1 + \tan^2 \beta)$ . The branching fractions have been calculated with 2HDMC v1.8.0 [55, 56].

# Extended Higgs Sectors

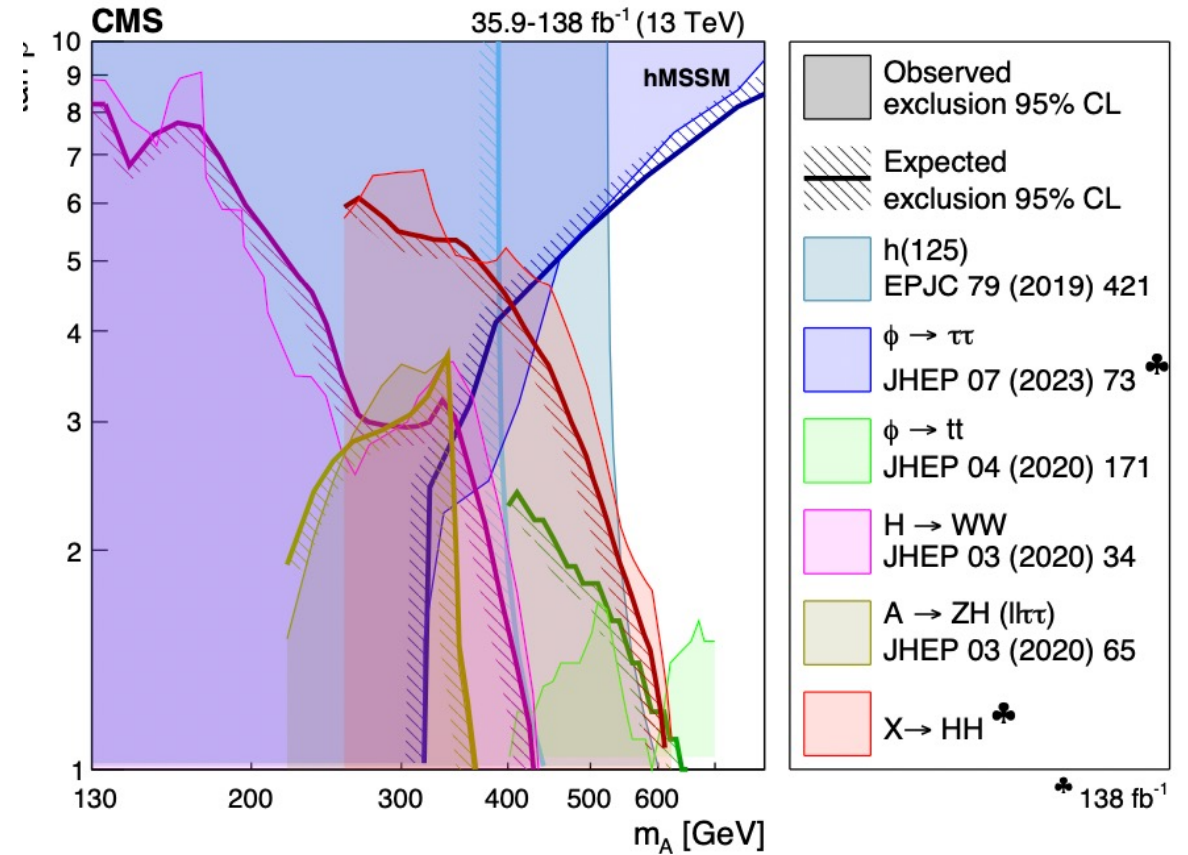
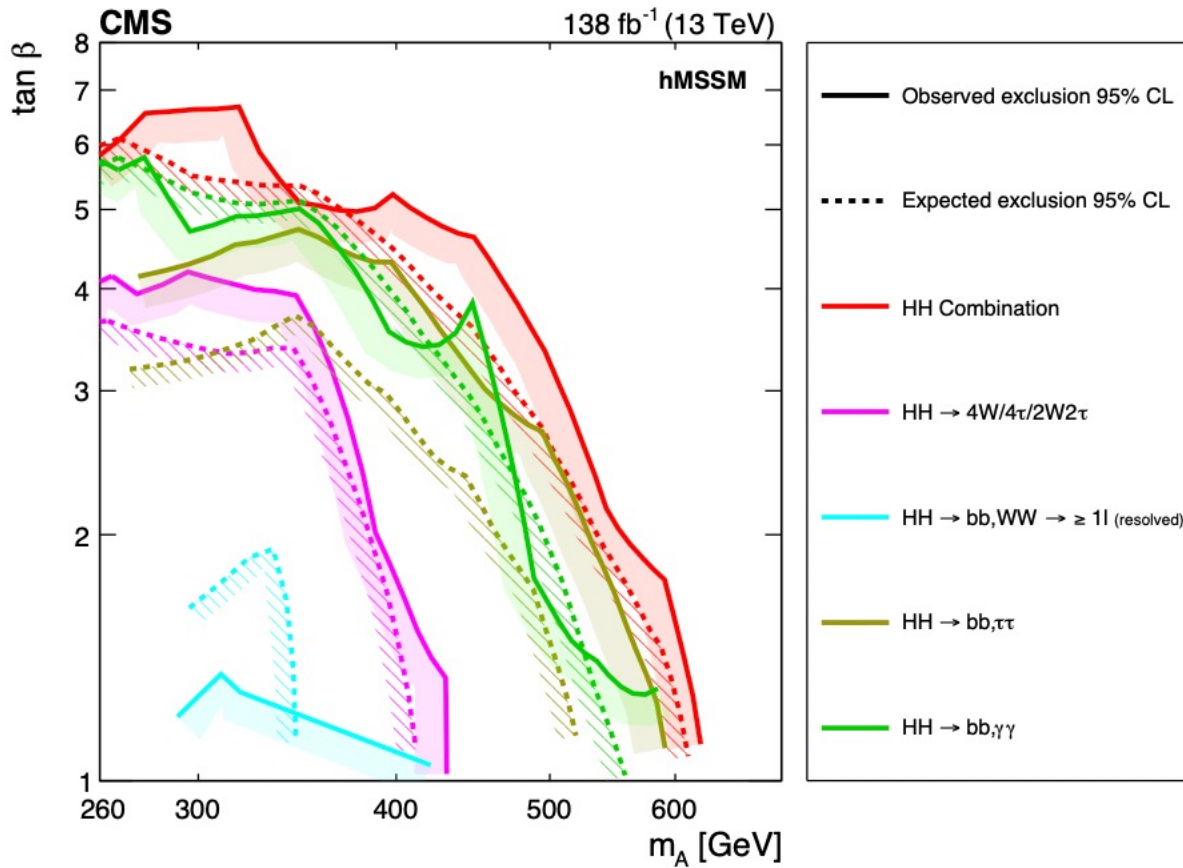
## Minimal supersymmetric standard model (MSSM)

### ➤ Additional doublet : 2HDM

- 3 neutral and 2 charged Higgs bosons
- $X \rightarrow HH$  and  $A \rightarrow ZH$
- Possible couplings of second doublet with fermions :
  - Type I : All charged fermions
  - Type II : Only up-type quarks
  - Type X or lepton-specific : Only quarks
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- Additional singlet :  $X \rightarrow HY$  possible

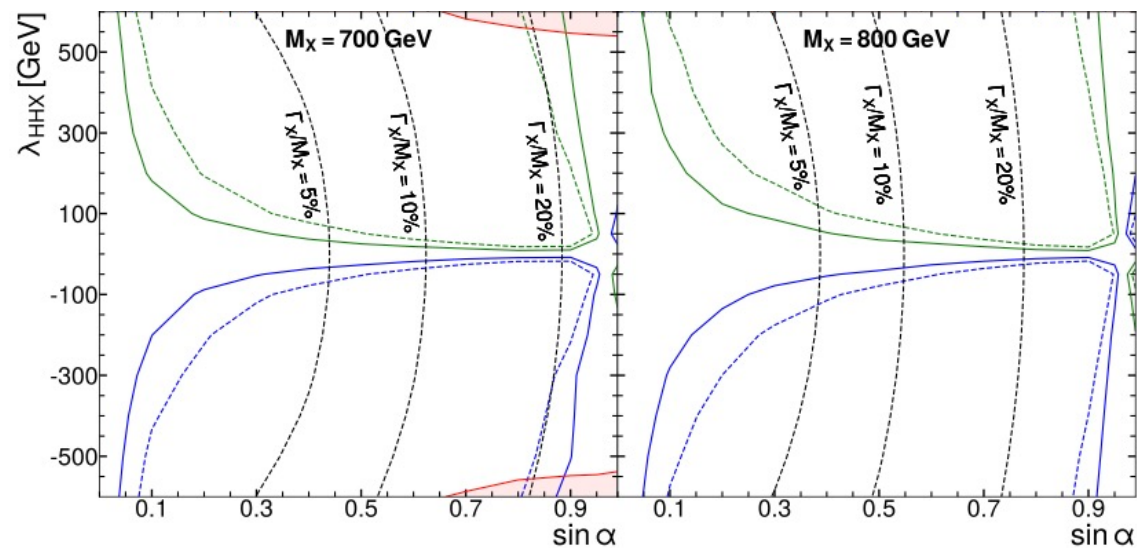
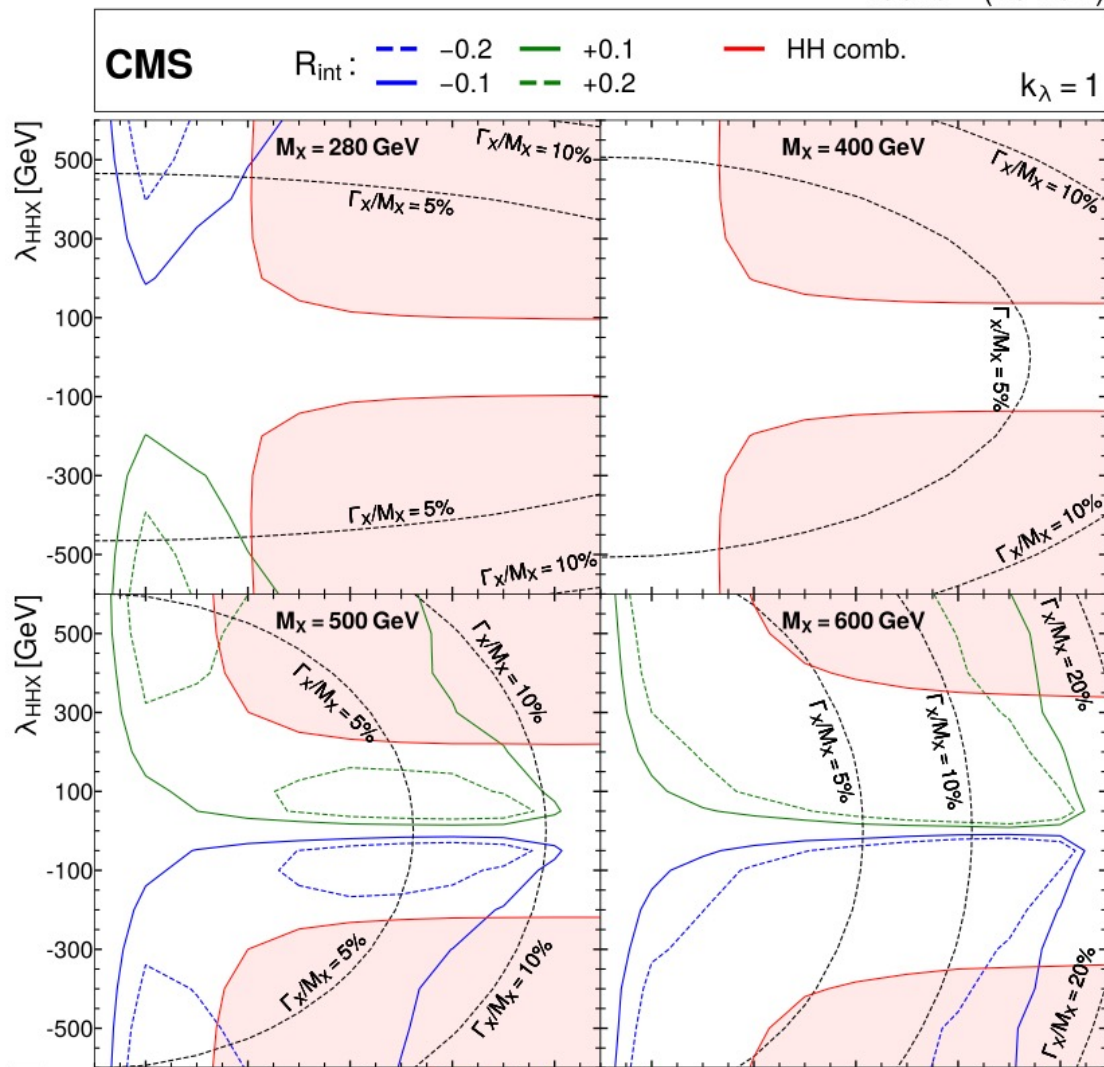


# Interpretation - hMSSM



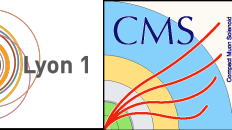
# Singlet model

138 fb<sup>-1</sup> (13 TeV)



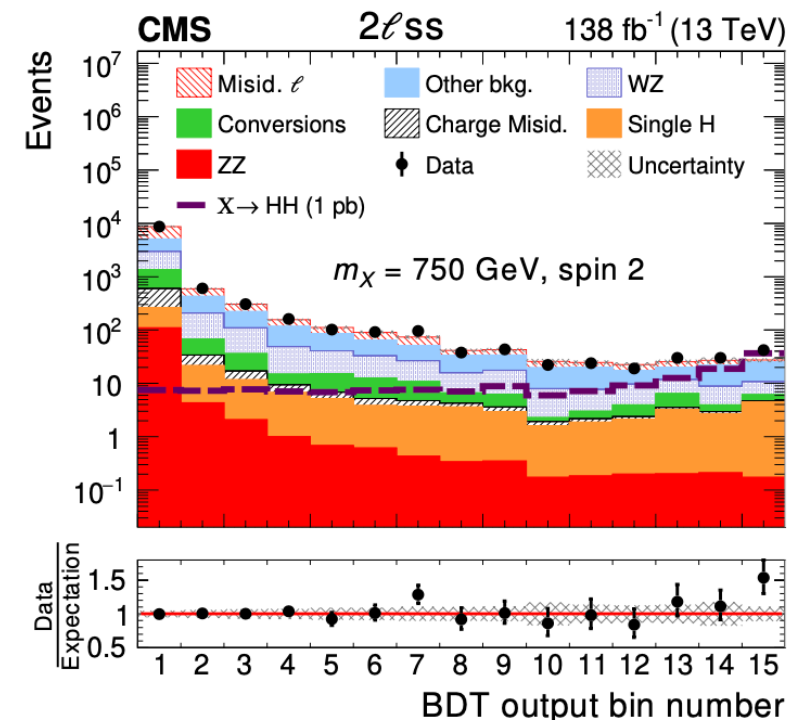
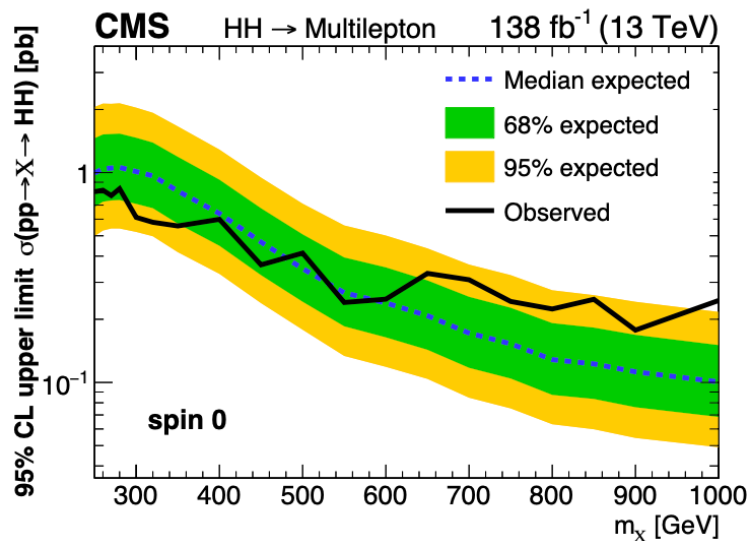
# Multilepton

$X \rightarrow HH$



[JHEP07\(2023\)095](#)

- $WWWW$ ,  $WW\tau_h\tau_h$  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)



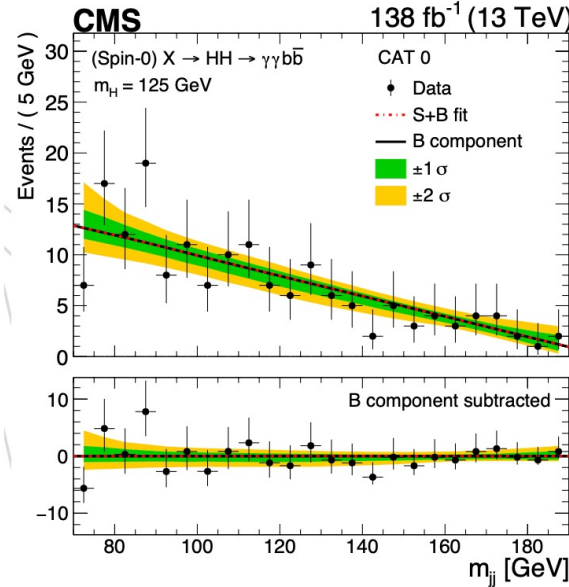
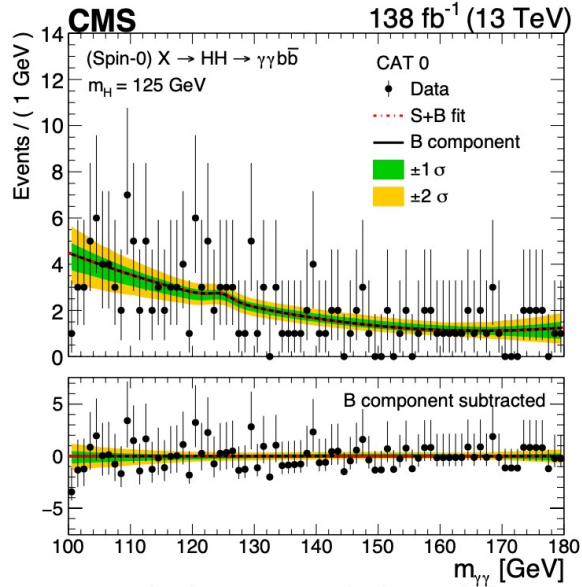
- Events are selected using a set of single-, double- and triple lepton triggers as well as di-tau and lepton-tau cross triggers.



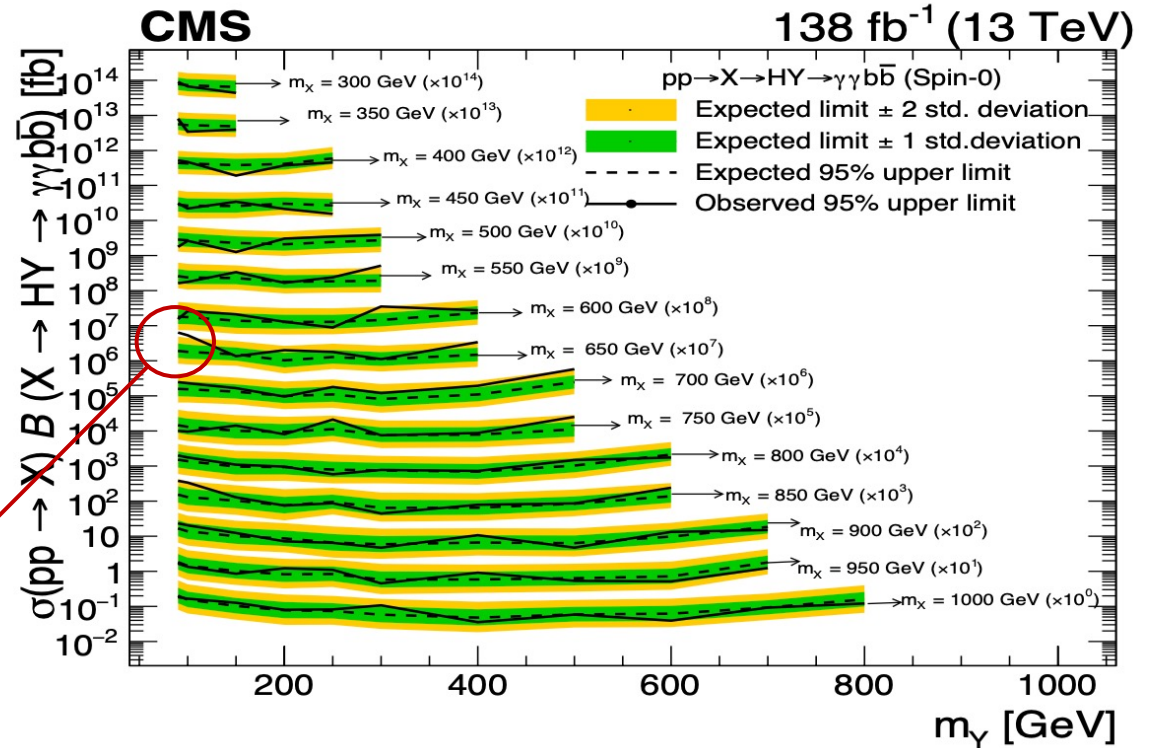
- Very low BR but **small background** contamination
- **2D fit** on the mass distributions of  $H \rightarrow \gamma\gamma$ ,  $H/Y \rightarrow b\bar{b}$

**Selection :**

- Two photons trigger
- b-jets : Jet pair with the highest DeepJet score sum

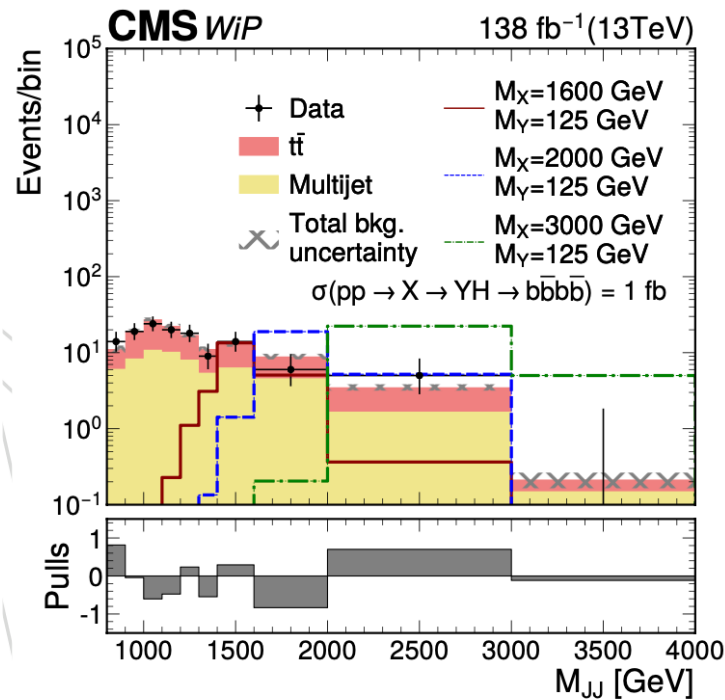
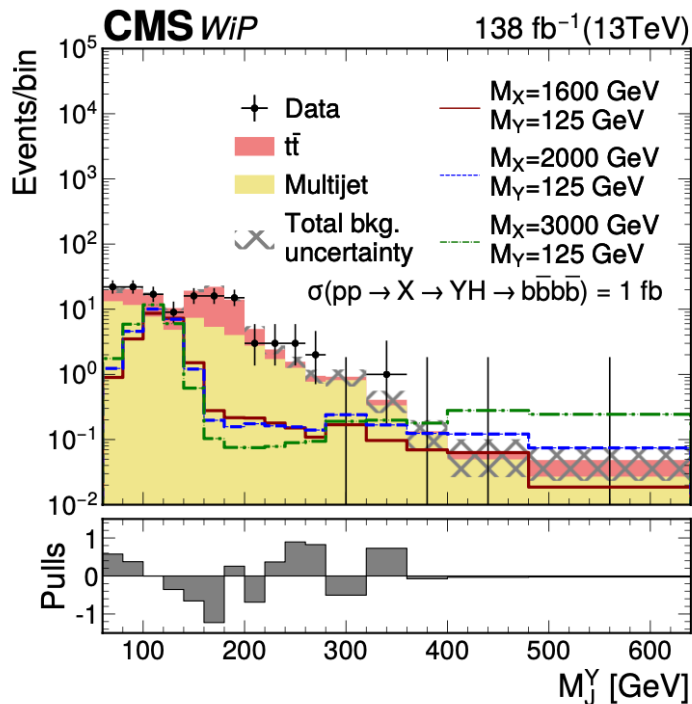


Excess of 3.8 (2.8) $\sigma$  found at  $m_X = 650 \text{ GeV}$  and  $m_Y = 90 \text{ GeV}$



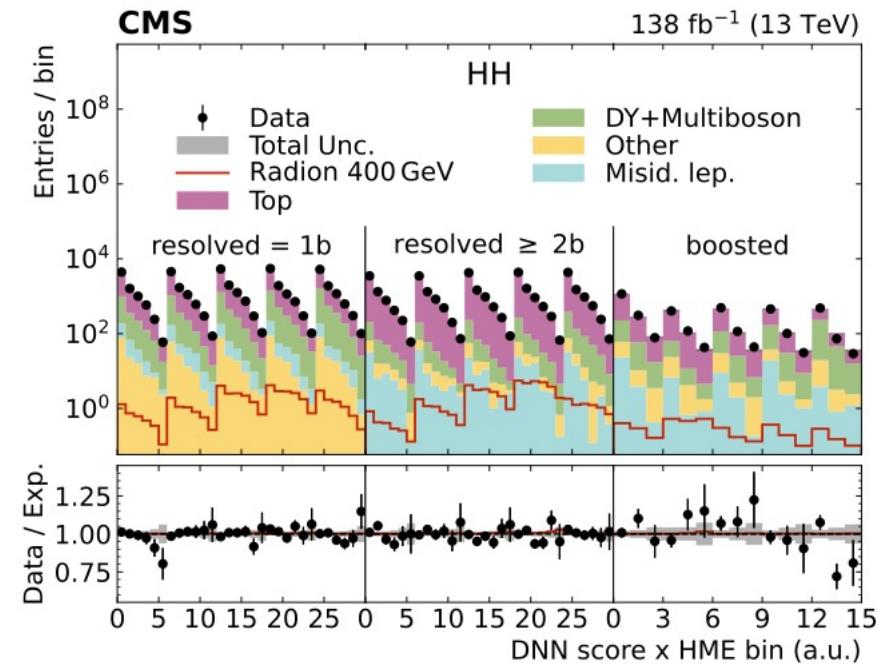
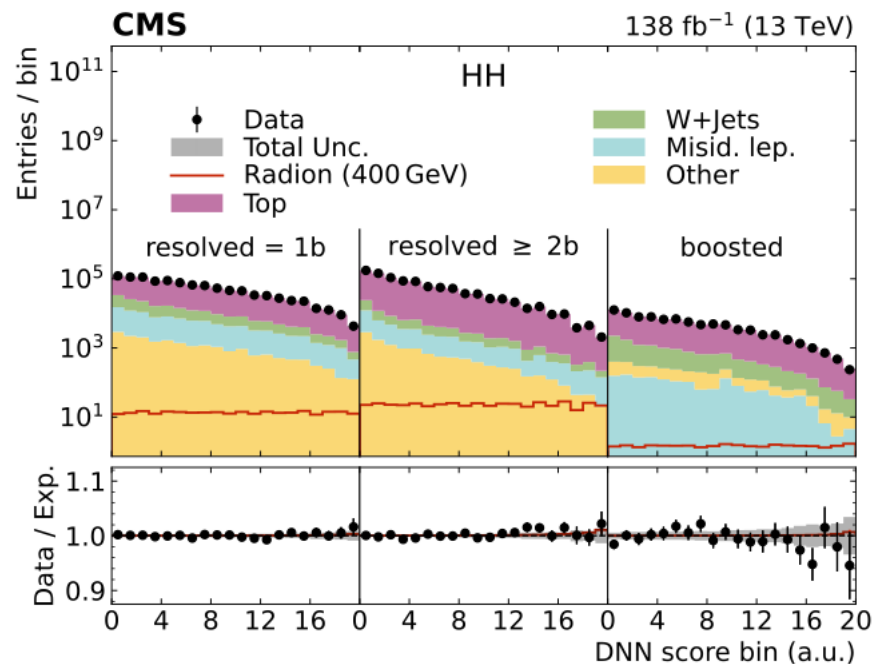
# 4b boosted

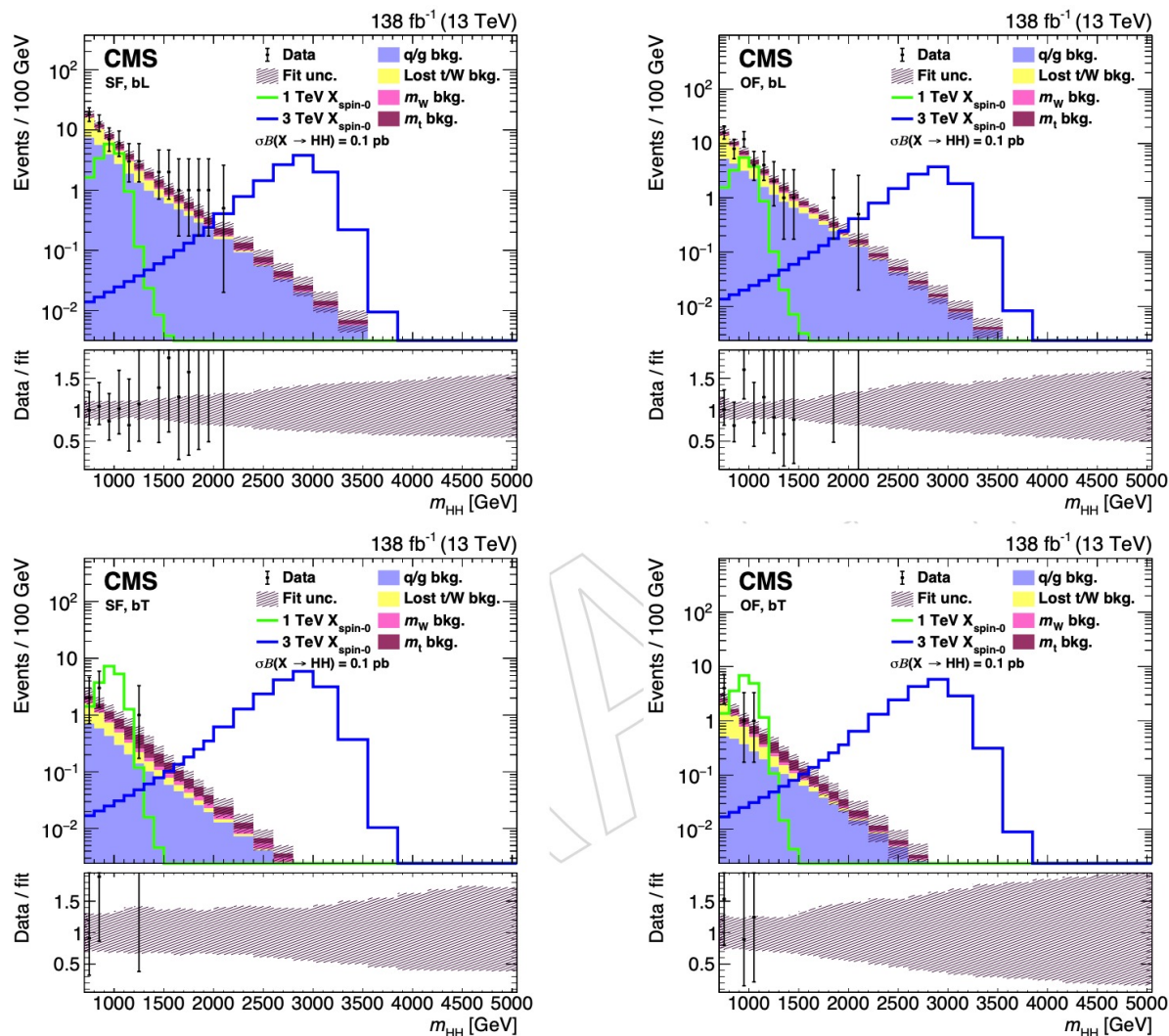
- 4b analysis at **high  $M_X$** . Very **high BR**. **Low background** search.
- **Jet substructure tagging**
- ParticleNet is employed to discriminate the decays of a boosted H boson to a pair of b quarks against a background of other jets



← Search for a narrow signal in 2D  $m_{jj}, m_j^Y$  plane

- $bbWW$  : 2<sup>nd</sup> largest BR
- Final states :  $bblq$  (SL)  $blll$  (DL)
- b-jets selection : DeepJet (AK4 jets) DeepCSV (AK8 subjects)
- Use of a **DNN** to classify the events and a **Heavy Mass Estimator** (HME) to reconstruct the resonance for DL



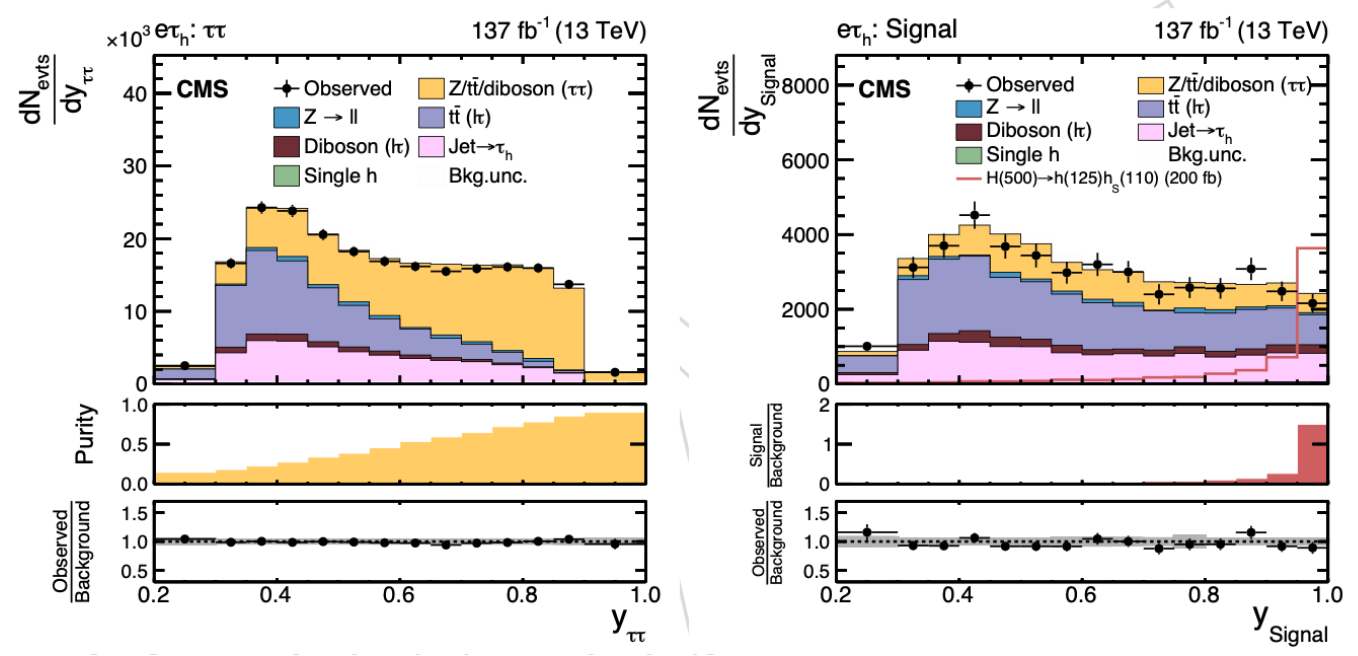


- **$b\bar{b} + l$  final states in the  $bbWW$  and  $bb\tau\tau$  HH decay modes**
- Selection : one AK8 jet ( $H \rightarrow bb$ ) and 1 (SL : 1 more AK8 jet is required) or 2 (DL) leptons
- Additional b-tagged AK4 jets (DeepJet) are vetoed
- **ML fit to the 2D  $m_X/m_{bb}$  distribution with 4 background and 1 signal template**

# bbττ

JHEP11(2021)057

- $Y \rightarrow b\bar{b} + H \rightarrow \tau\tau$
- $bb(\tau_h\tau_h + e\tau_h + \mu\tau_h)$  final states (largest sensitivity to searched signature)



- **Selection** : At least 1(b jet + jet) + 1 ττ pair
- τ identification using DeepTau
- b-Jet identification using DeepJet
- Selected events are passed to a NNs to distinguish signal from 4 background classes