

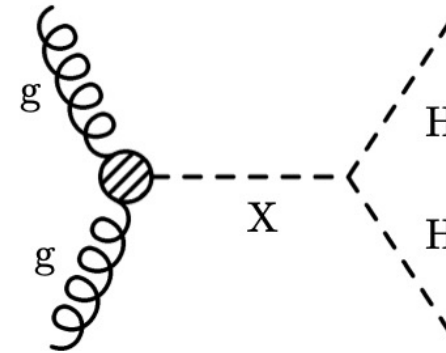
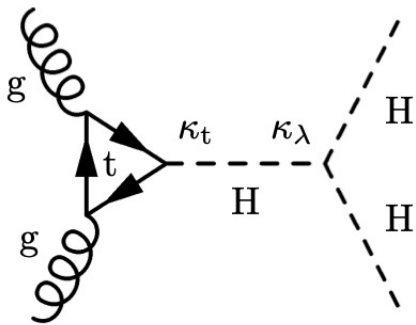
Searches for heavy resonance decaying into two Higgs bosons ($X \rightarrow HH$) at CMS

15 th FCPPL workshop

Elise Jourdhuy , on behalf of the $X \rightarrow HH/HY$ combination team

Higgs to probe new physics

- Higgs sector as a tool to probe physics beyond the SM
- **HH** production probes the shape of the Higgs potential



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

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) : $X \rightarrow HY$ possible

▪ Parameters :

- Ratio of vev $\tan \beta = v/\langle S \rangle$
- Mixing angle α
- Masses

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See Chu Wang's presentation

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➤ 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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▪ Parameters :

- Ratio of vev $\tan \beta$
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- Masses
- m_{12} : Z_2 symmetry breaking parameter

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Extended Higgs Sectors

Minimal supersymmetric standard model (MSSM)

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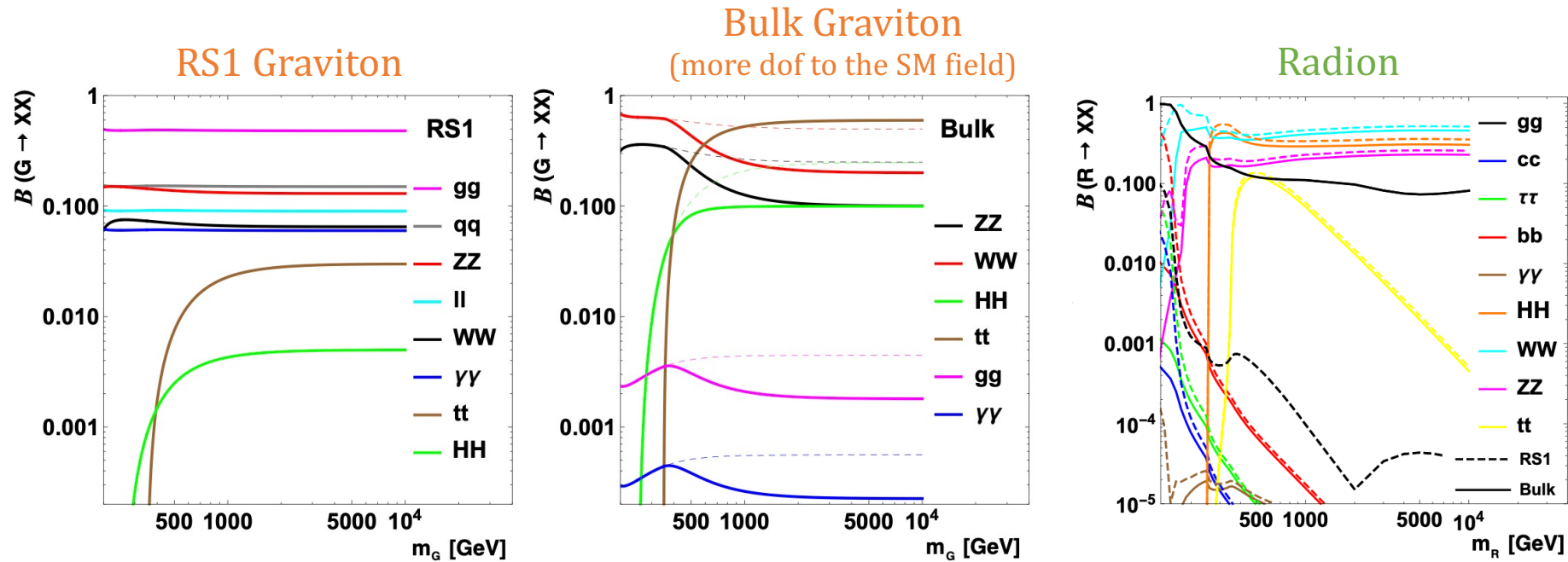
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 - Ratio of v $\tan \beta$
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Warped Extra Dimension (WED)

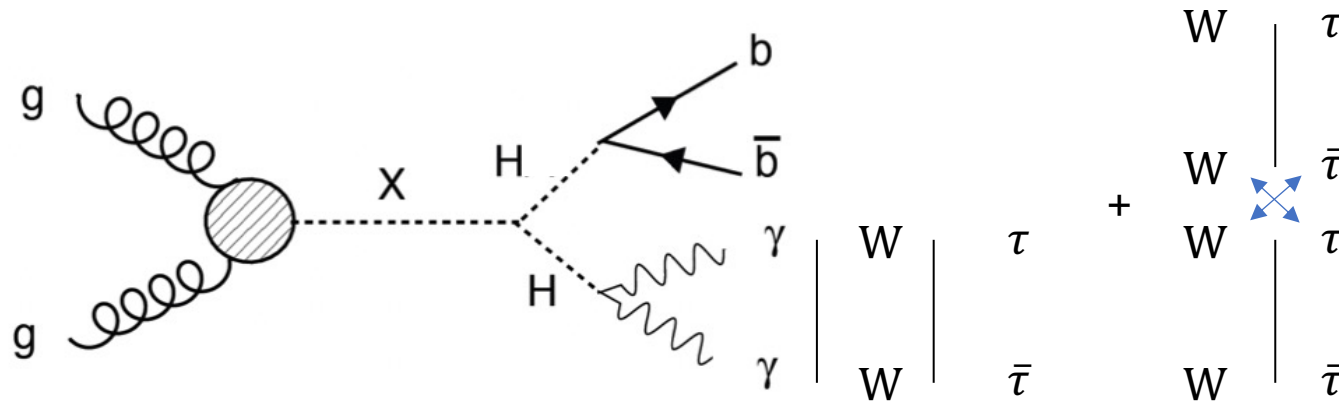
Warped Extra Dimension by Randall and Sundrum (RS) → Existence of an **extra spatial dimension**

- Existence of a **spin 0 Radion** and a **spin 2 Kaluza-Klein (KK) Graviton**
- Parameters : mass scale Λ_R (= UV cut-off of the model) / k/\overline{M}_{pl} (k : Warp factor, \overline{M}_{pl} : reduced Planck mass),
- HH is among the **highest Branching Ratios** for the **Bulk scenario**

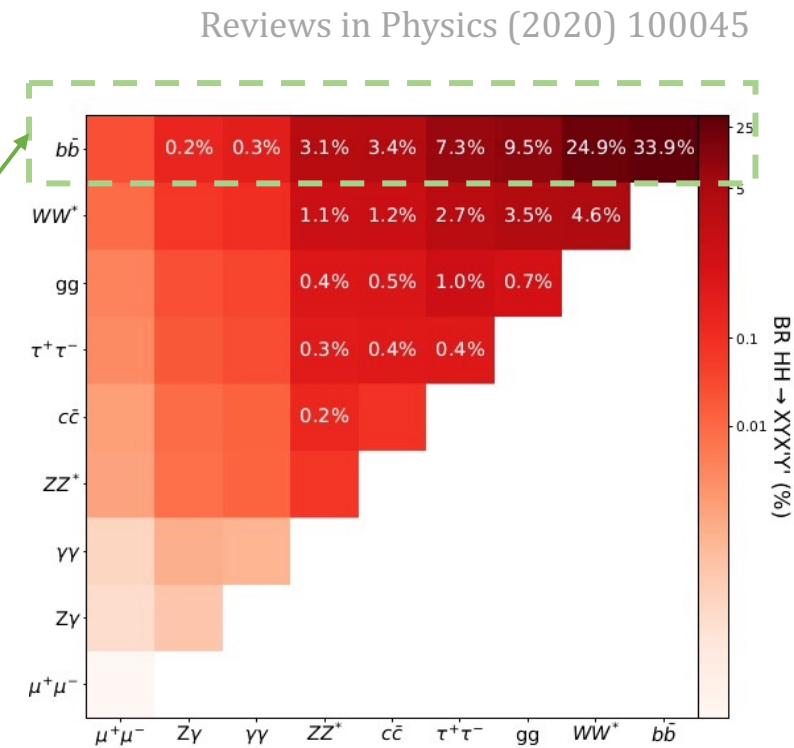


Involved analyses

Channels considered : $bby\gamma$, $bbWW$ (resolved and boosted), $bbbb$ boosted, $bb\tau\tau$, multilepton



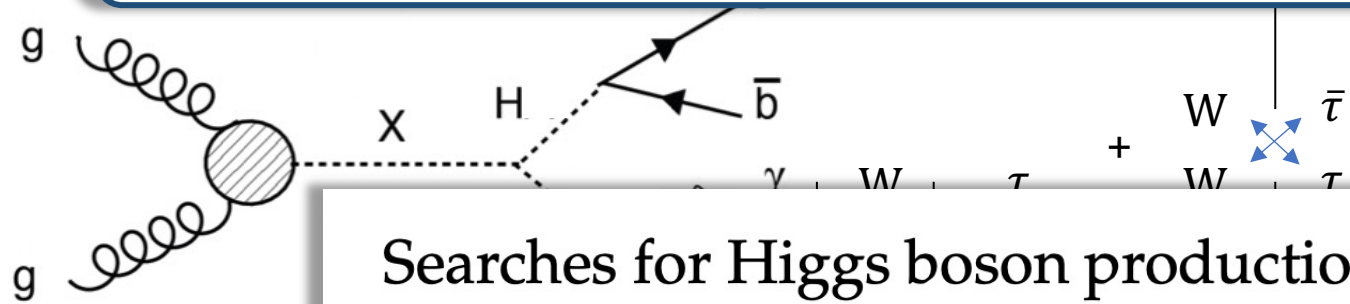
Most channels take advantage of the high b-quark Branching ratio



Involved analyses

Channels considered: $hh\gamma$, $hhVV$ (resolved and boosted), $hhbb$ boosted, $hh\tau\tau$, multilepton

Combining different analyses will result in a **more sensitive** « final result »

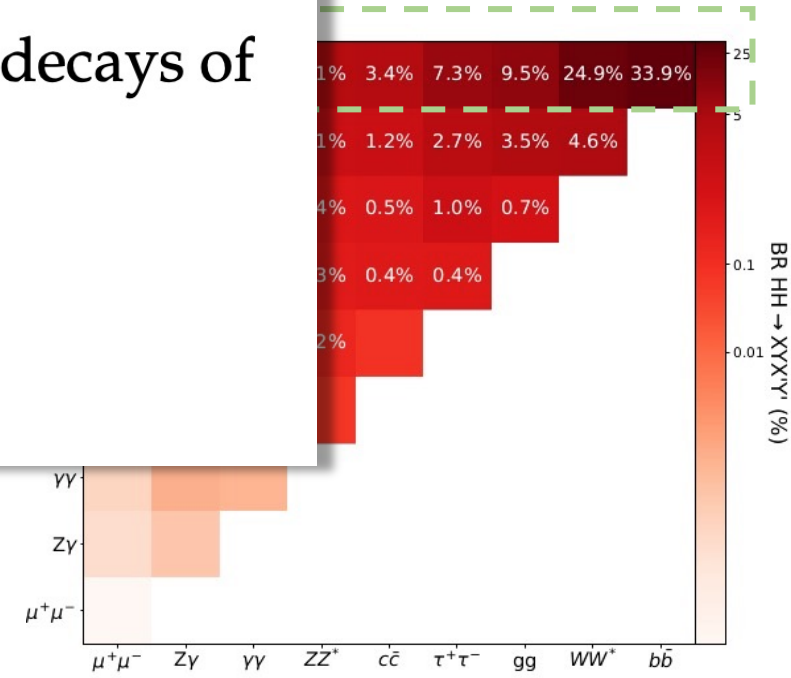


Reviews in Physics (2020) 100045

Searches for Higgs boson production through decays of heavy resonances

The CMS Collaboration*

Most cl



Combination procedure

✓ One event cannot appear in two different analyses

H	H		m_χ		
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	H		m_χ	m_γ	
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

Overlap between *bbWW resolved* and *boosted analyses* → **removed the overlapping mass points of *bbWW resolved*** (least sensitive)

b-veto to avoid overlap with other analyses

Hadronic decays of τ only

✓ Systematics alignment

✓ Same normalization for all analysis

✓ Stastical tests

Combination procedure

✓ **One event cannot appear in two different analyses**

✓ **Systematics alignment**

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

✓ **Same normalization for all analysis**

✓ **Stastical tests**

Combination procedure

✓ **One event cannot appear in two different analyses**

✓ **Systematics alignment**

✓ **Same normalization for all analysis**

Each analysis is normalized to its BR

✓ **Stastical tests**

Combination procedure

✓ **One event cannot appear in two different analyses**

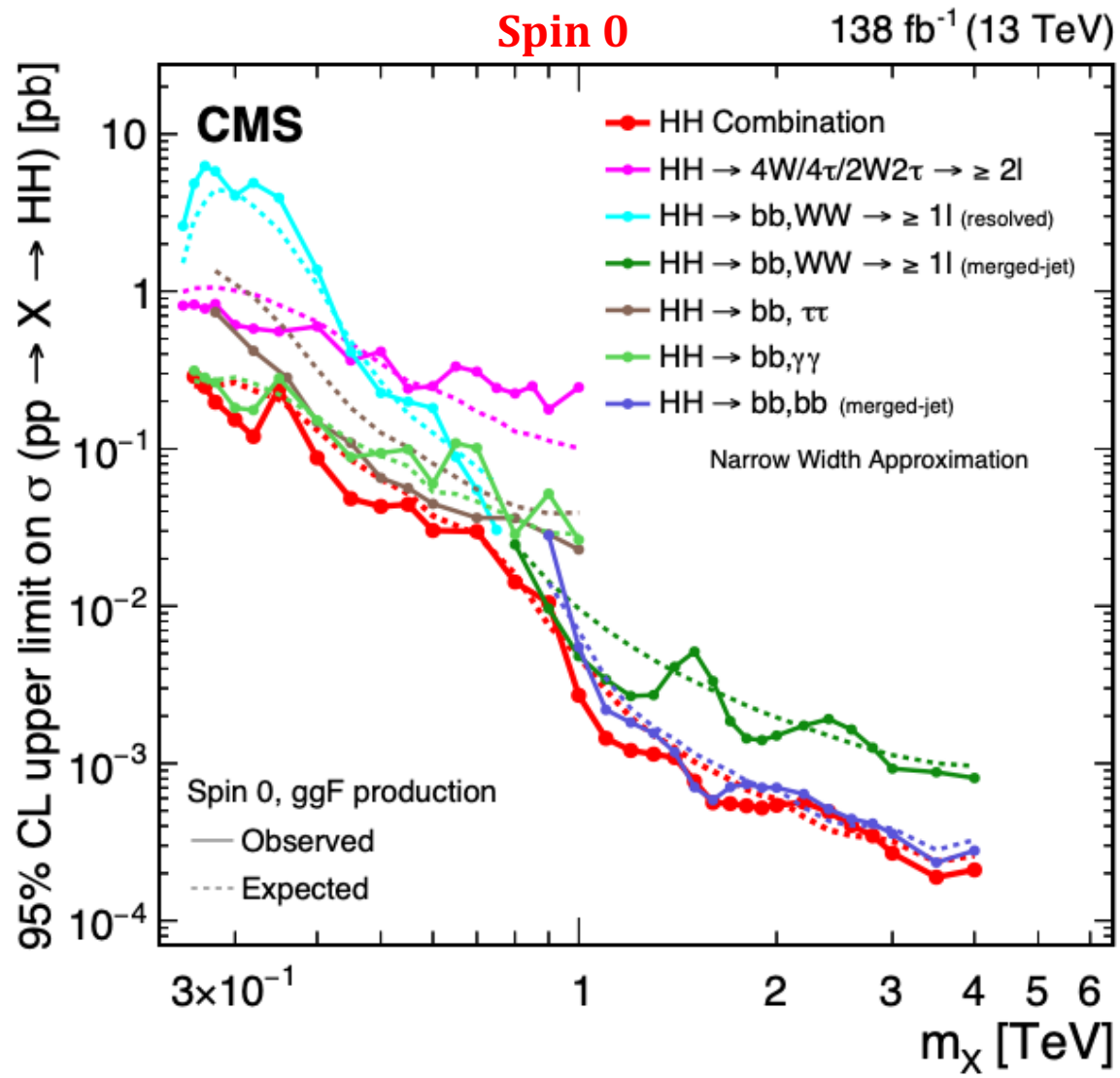
✓ **Systematics alignment**

✓ **Same normalization for all analysis**

✓ **Statistical tests**

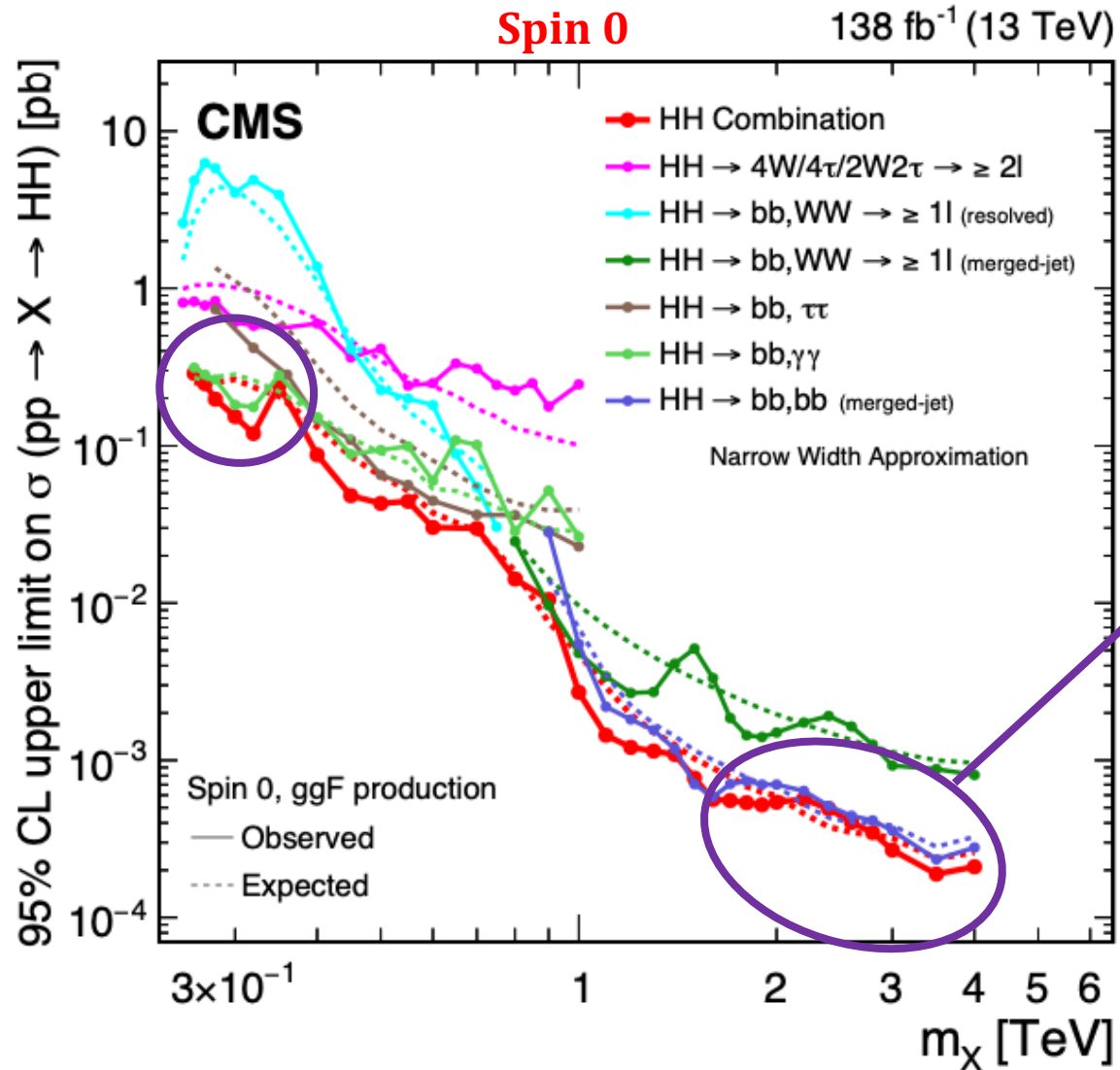
Performed statistical tests to check the sanity of the statistical combination : goodness of fit, pulls and impacts of nuisance parameters , bias test

Results



Wide mass range \rightarrow Wide range of sensitivity

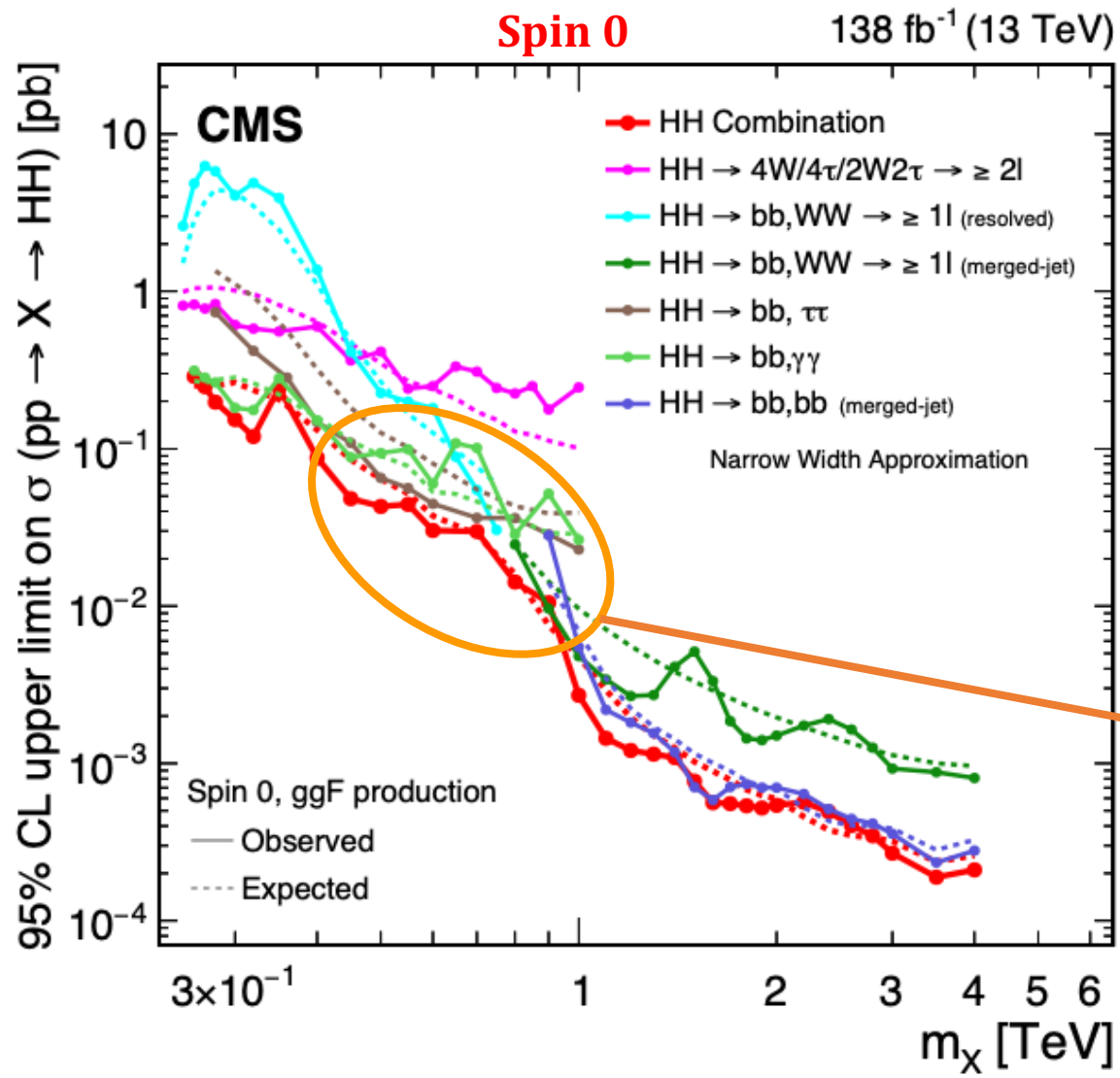
Results



Wide mass range \rightarrow Wide range of sensitivity

Combination dominated by one channel

Results

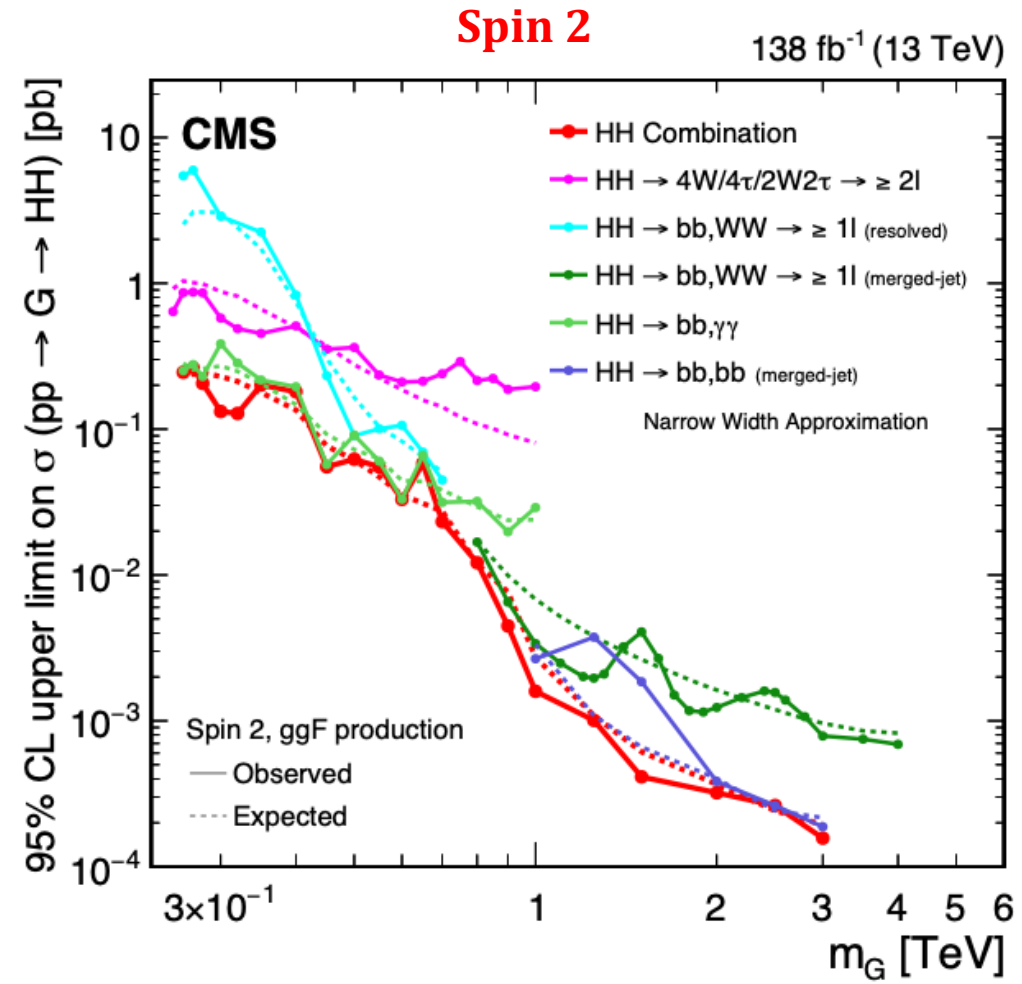
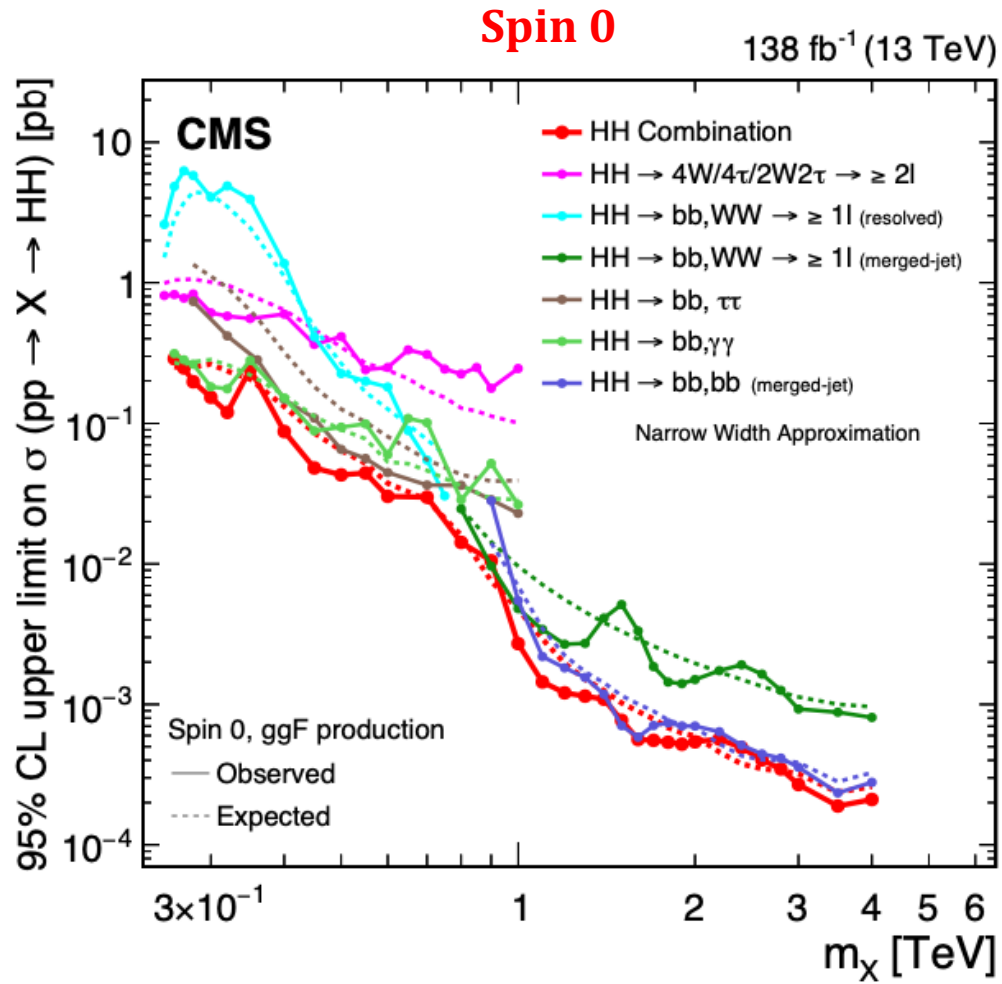


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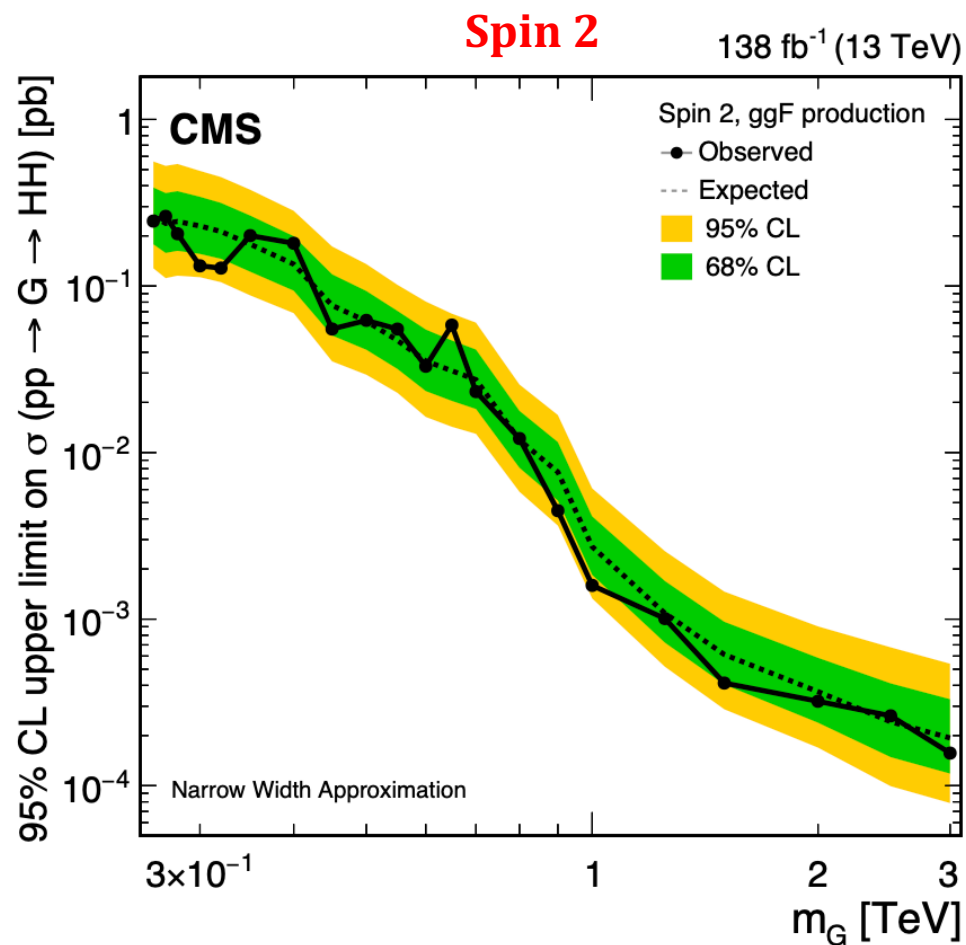
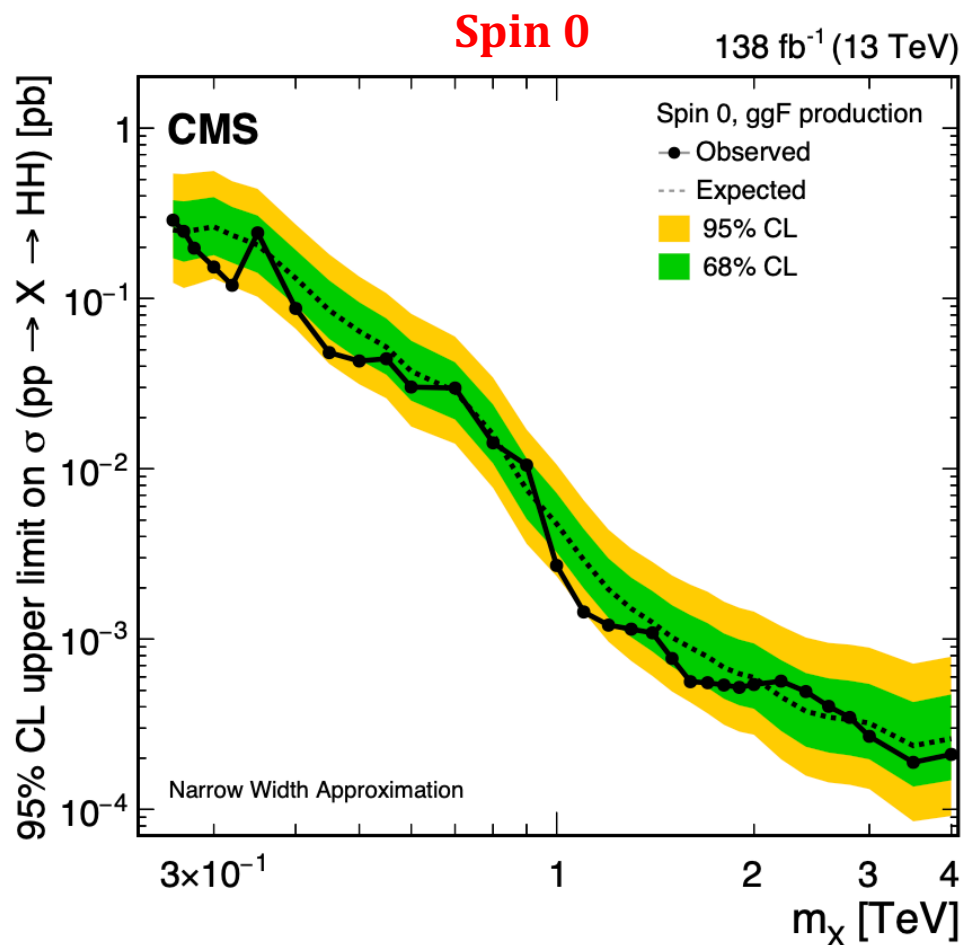
Combination dominated by one channel

Gain in sensitivity
(400-700 GeV)

Results

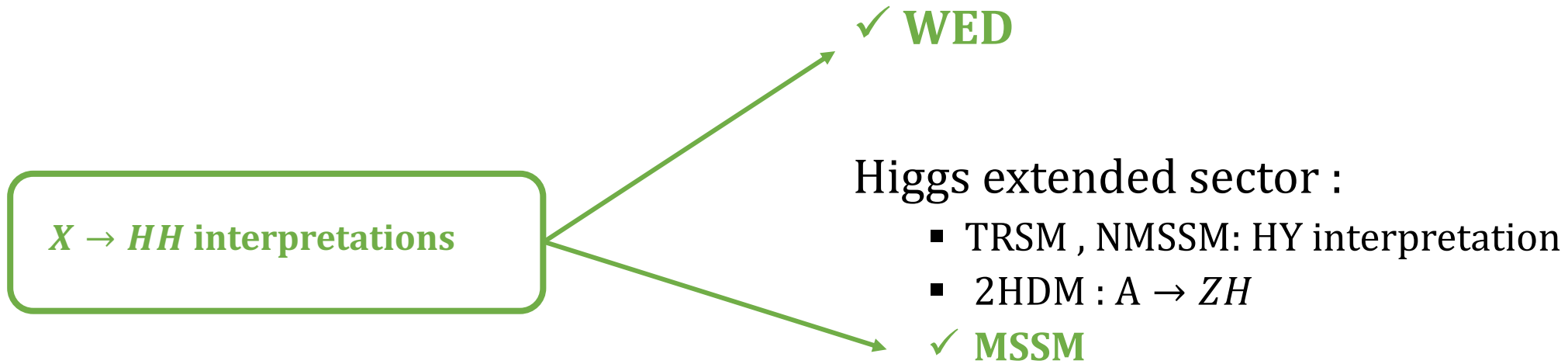


Results



No excess observed

Interpretations

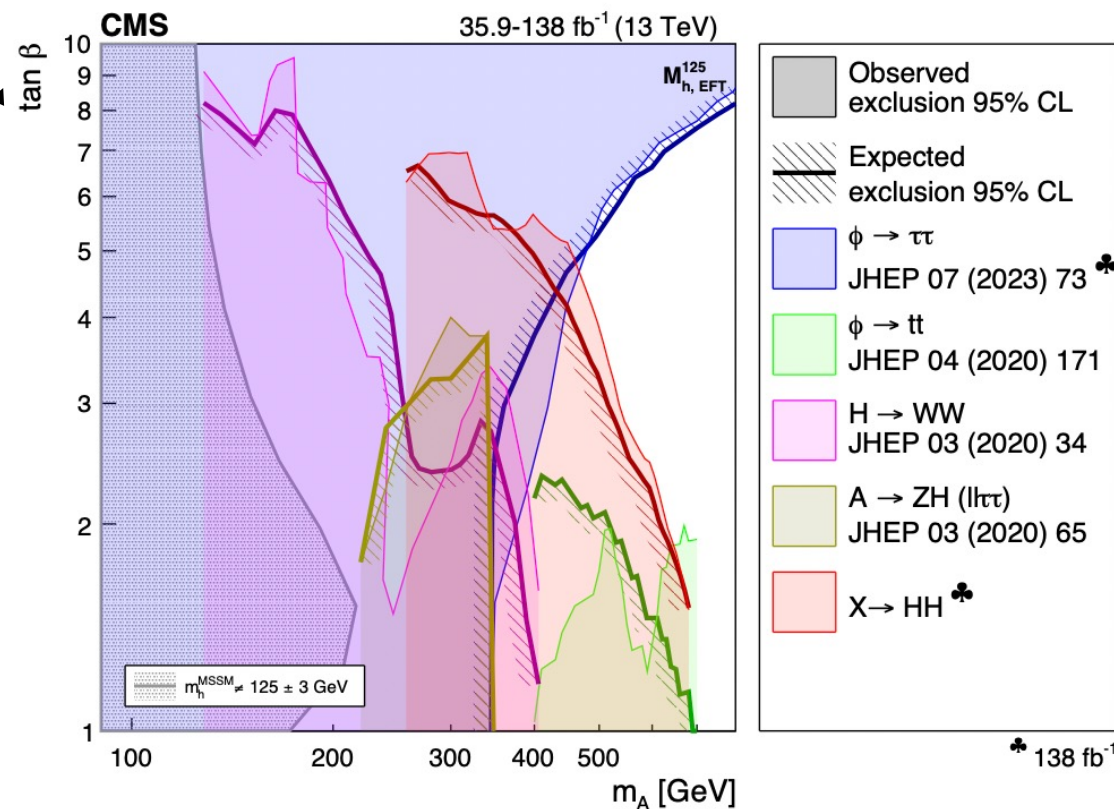
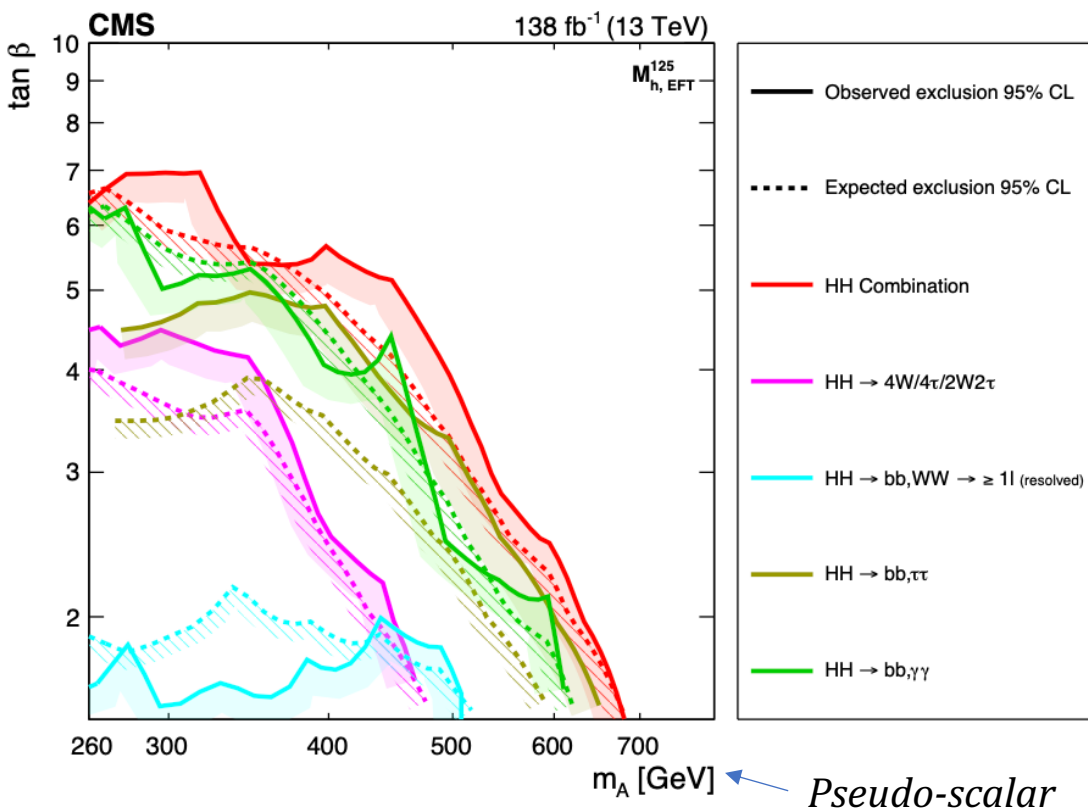


Interpretation - MSSM

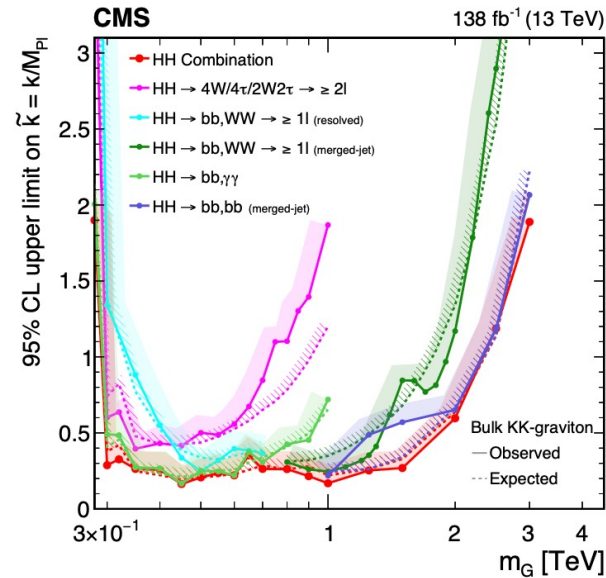
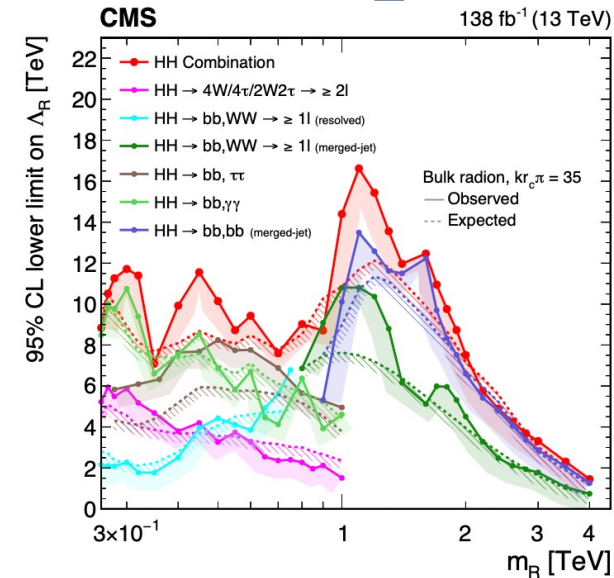
hMSSM model in backup

Particularly interesting when $m_A < 700$ GeV
 → Where we **gain sensitivity from the combination**

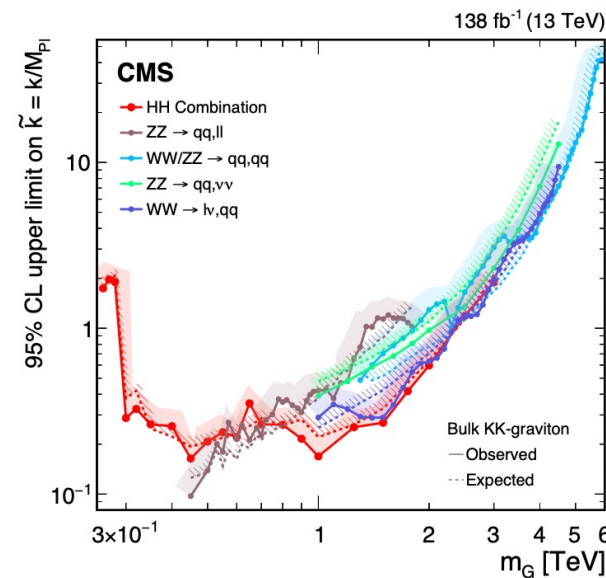
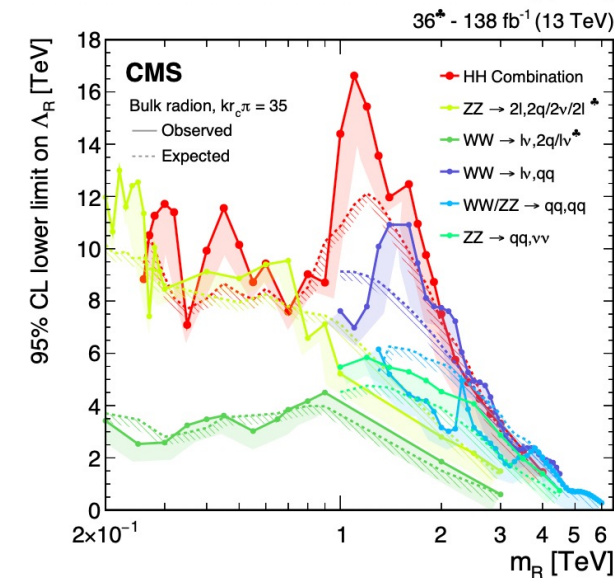
Unique exclusion limits for $m_A > 400$ GeV !



Interpretation - WED



HH decay channels vs combination



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

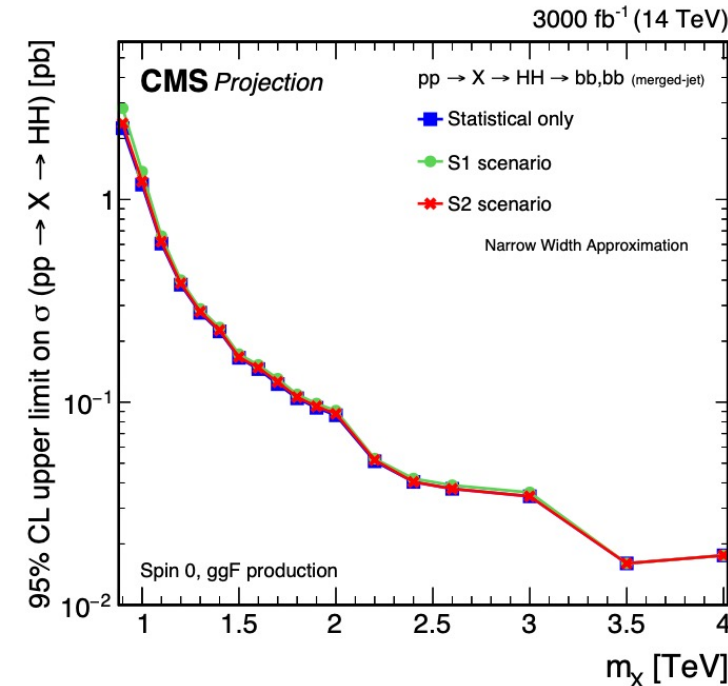
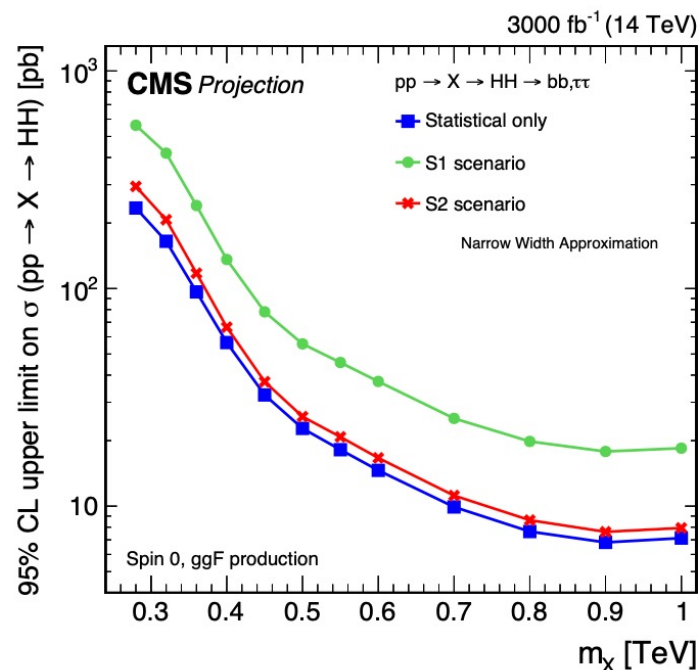
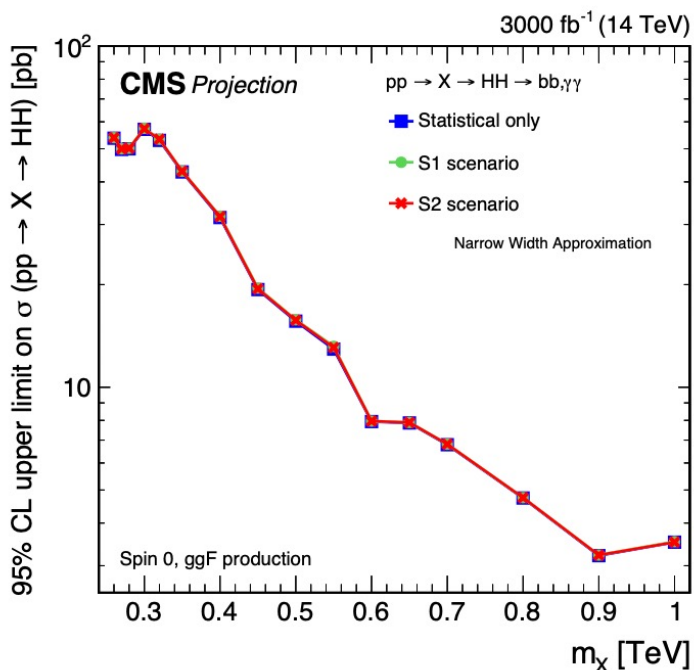
HH combination vs Other Diboson searches

HH Projections for HL-LHC

High luminosity LHC (2029) plans to increase the integrated luminosity up to 3000 fb^{-1}

- S1** : Same systematics as Run 2
- S2** : Theoretical systematics are halved and experimental systematics are set to YR18/snowmass recommendations
- S3** : Only statistical uncertainties

- Projection of the 3 most sensitive channel : $bb\gamma\gamma$, $bb\tau\tau$ and $bbbb$
- $bbbb$ and $bb\gamma\gamma$ are still **statistics-dominated**
- The improvement of the systematics benefits $bb\tau\tau$

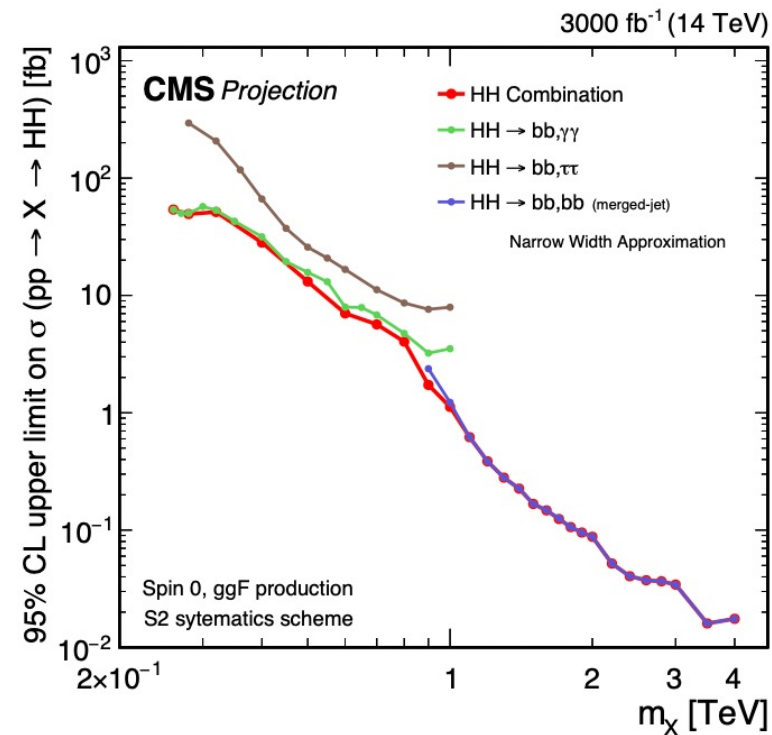
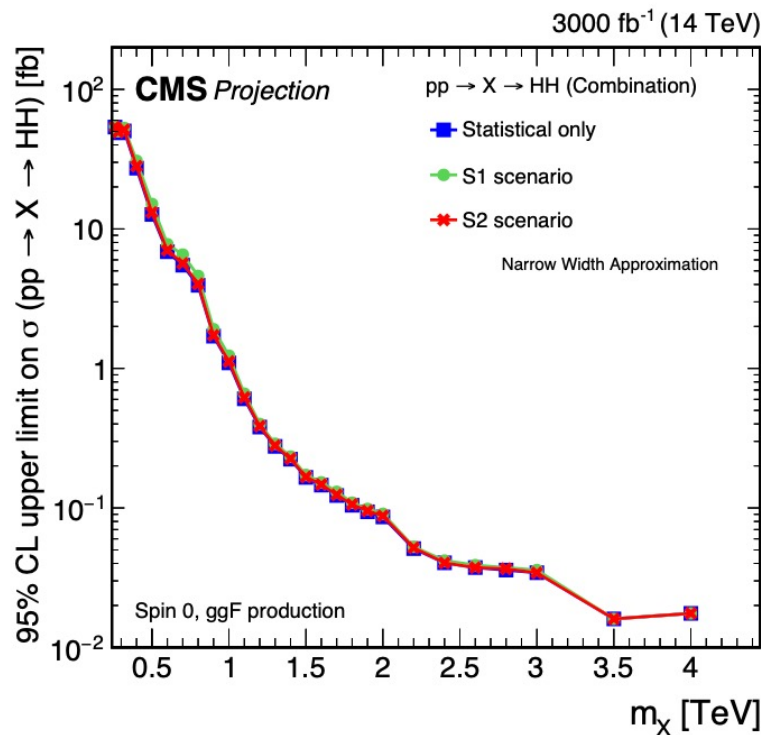


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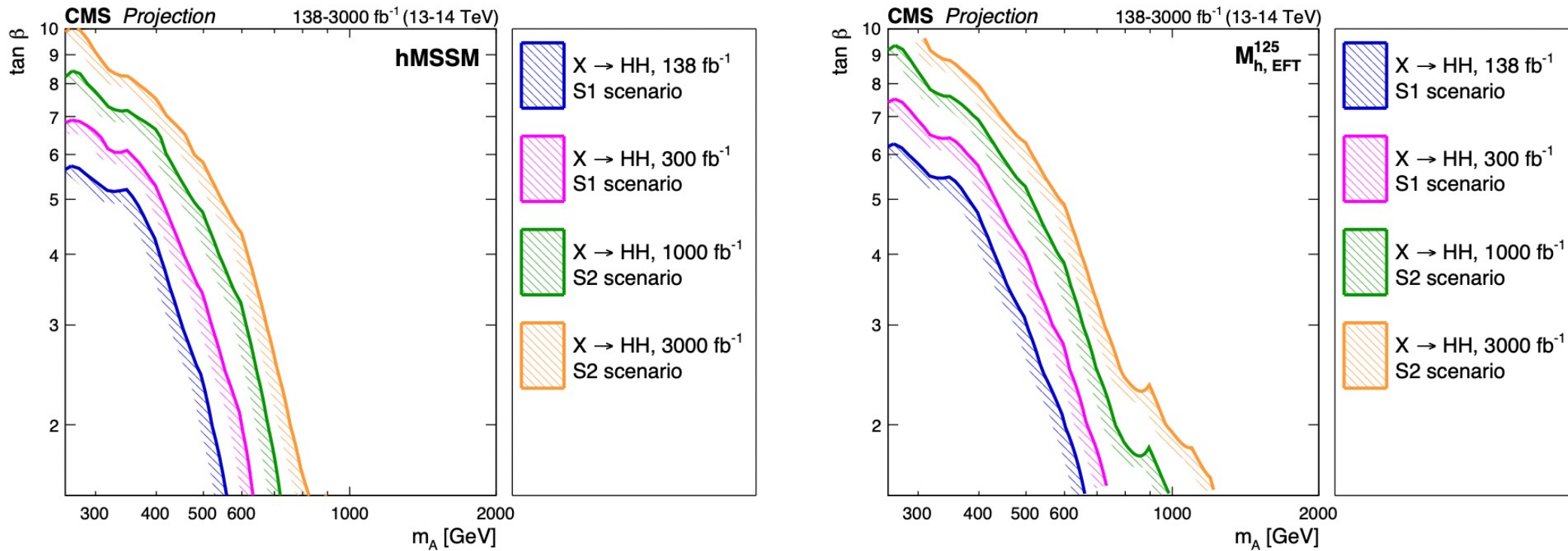
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- $bbbb$ and $bby\gamma$ dominates the combination
- The combination will still be **statistics-dominated**

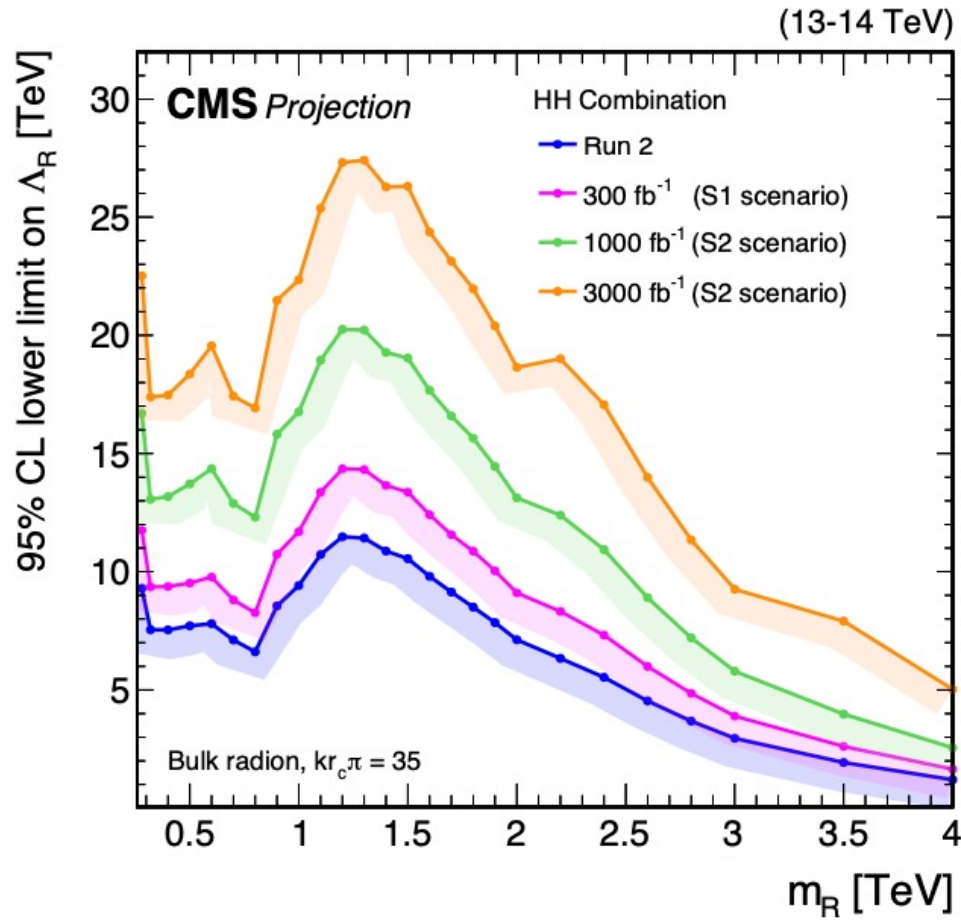


Projection – MSSM

Exclusion in m_A increased of $\approx 250\text{-}300$ GeV with HL-LHC



Projection - WED



Exclusion limits are expected to at least double

- **A Combination of $X \rightarrow HH$ searches was performed with LHC Run 2 data**
 - Combination offered a **great gain of sensitivity** for masses between 0.5 and 1 TeV
 - No excess was observed
 - Below masses of 0.32 TeV and above 0.8 TeV, this combination gives the **strongest observed limits to date**
- Interpretation with Higgs Extended sector and Warped Extra Dimension models
- Projections for HL-LHC

The review also features $X \rightarrow YH$ searches, stay tuned for next talk by Chu Wang!

Thank you !

Backup

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

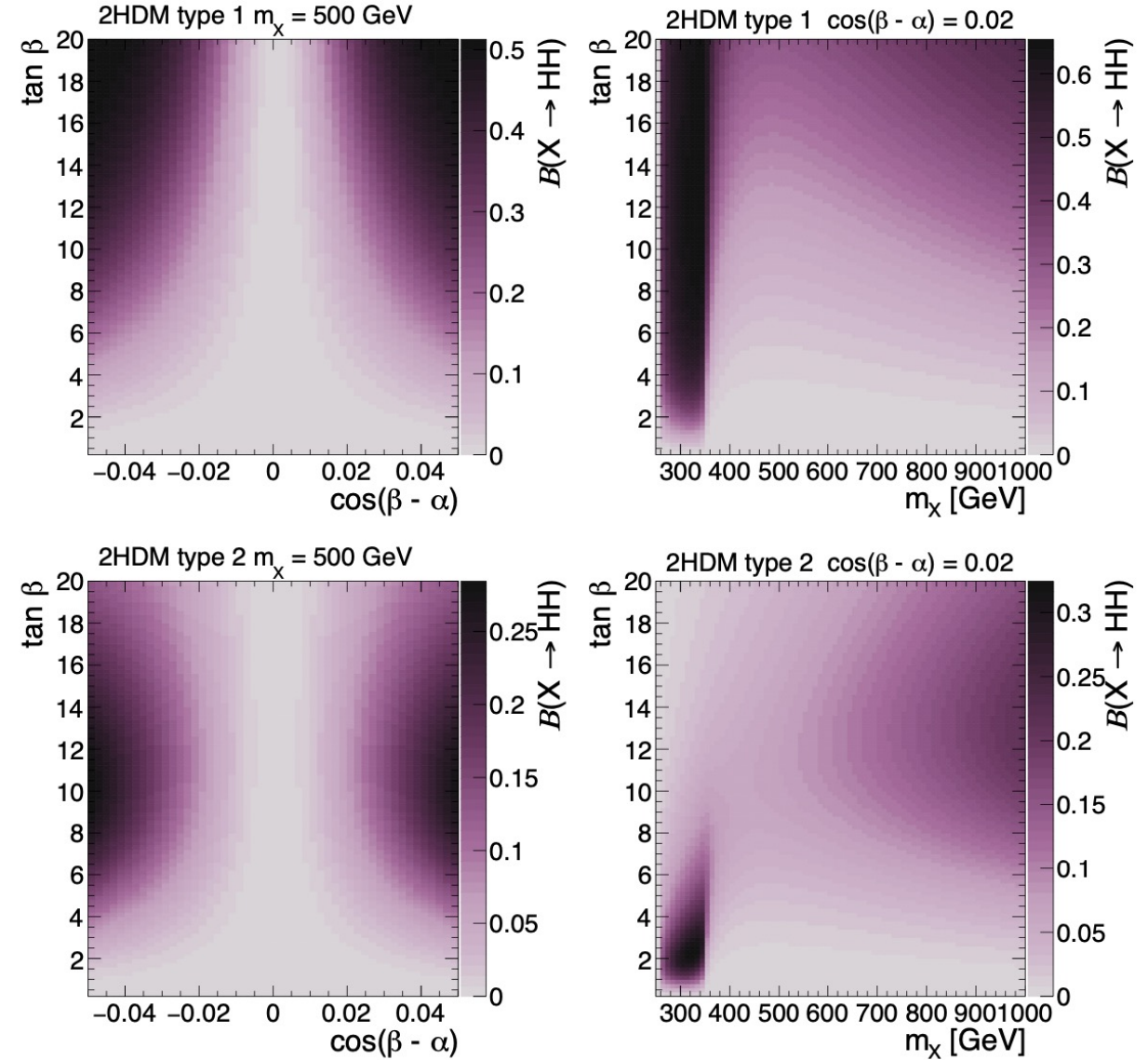


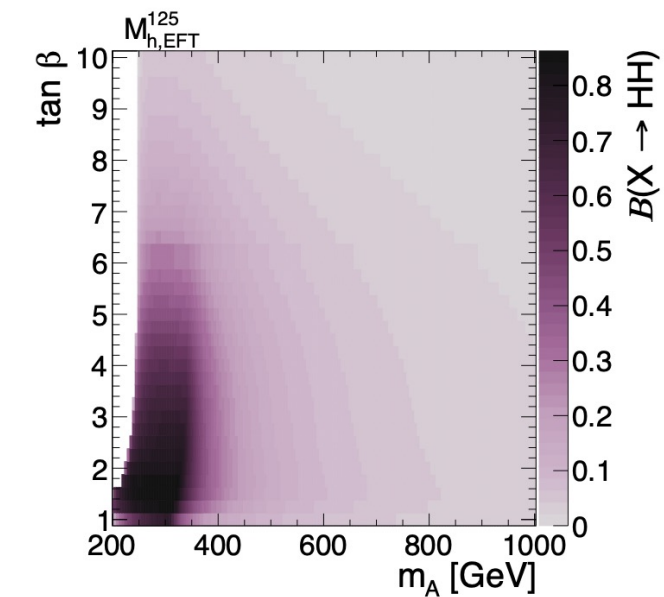
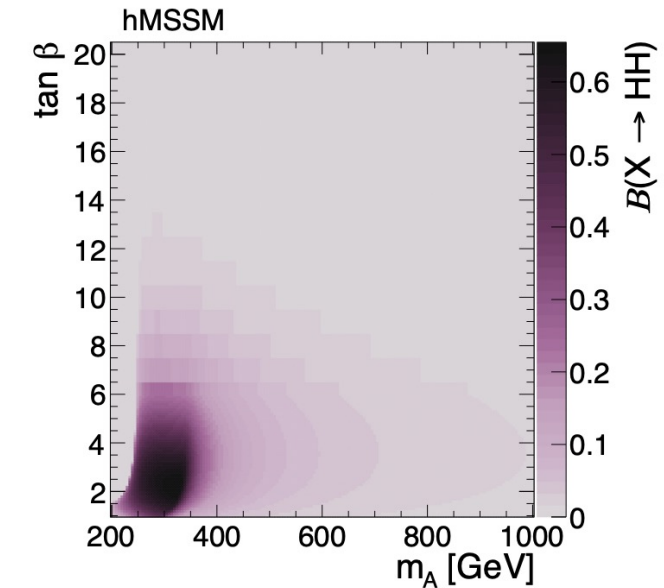
Figure 5: Branching fractions of $X \rightarrow HH$ decays in 2HDMs of Type I (upper) and Type II (lower) in the $\cos(\beta - \alpha)$ - $\tan \beta$ plane for $m_X = 500$ GeV (left) and in the m_X - $\tan \beta$ plane for $\cos(\beta - \alpha) = 0.02$ (right). The masses of all non-SM-like Higgs bosons 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

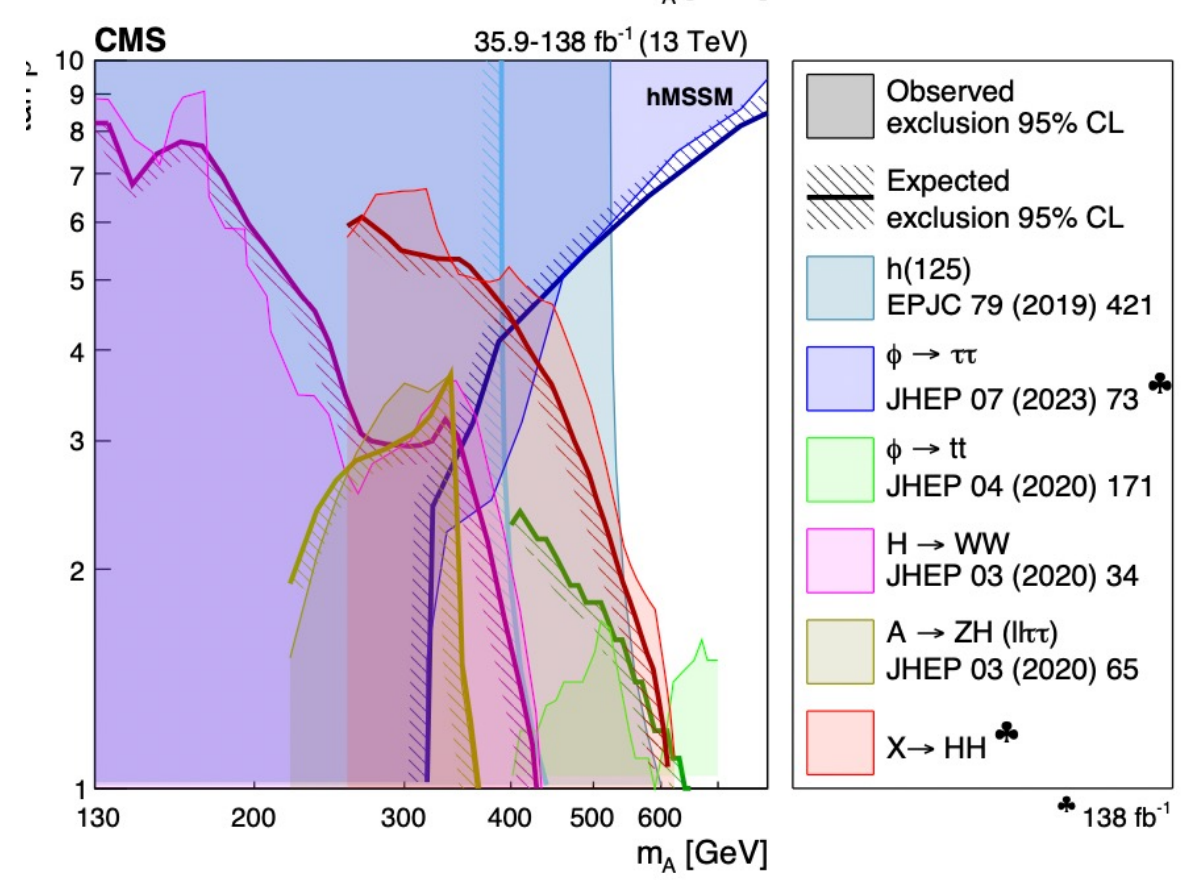
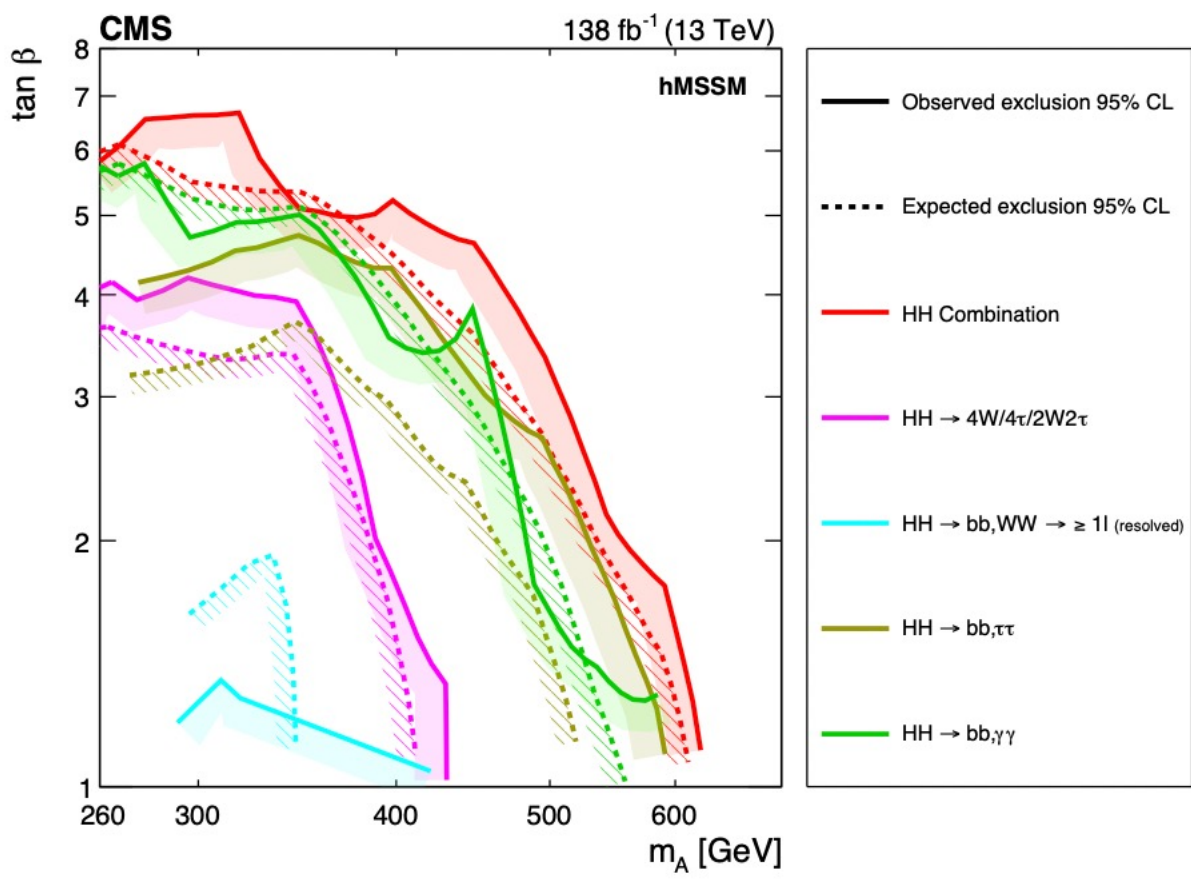
Minimal supersymmetric standard model (MSSM)

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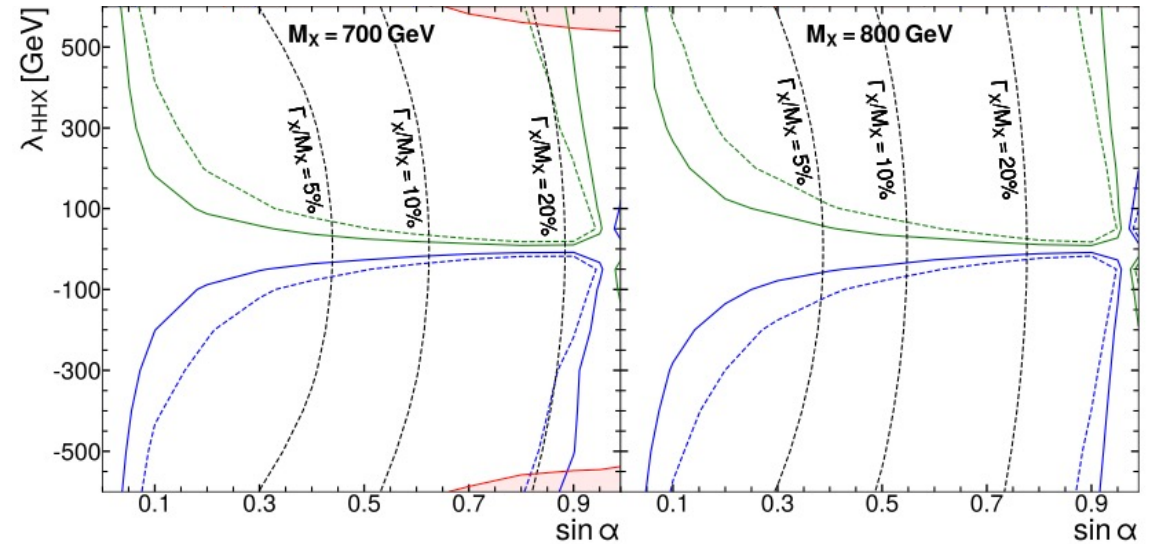
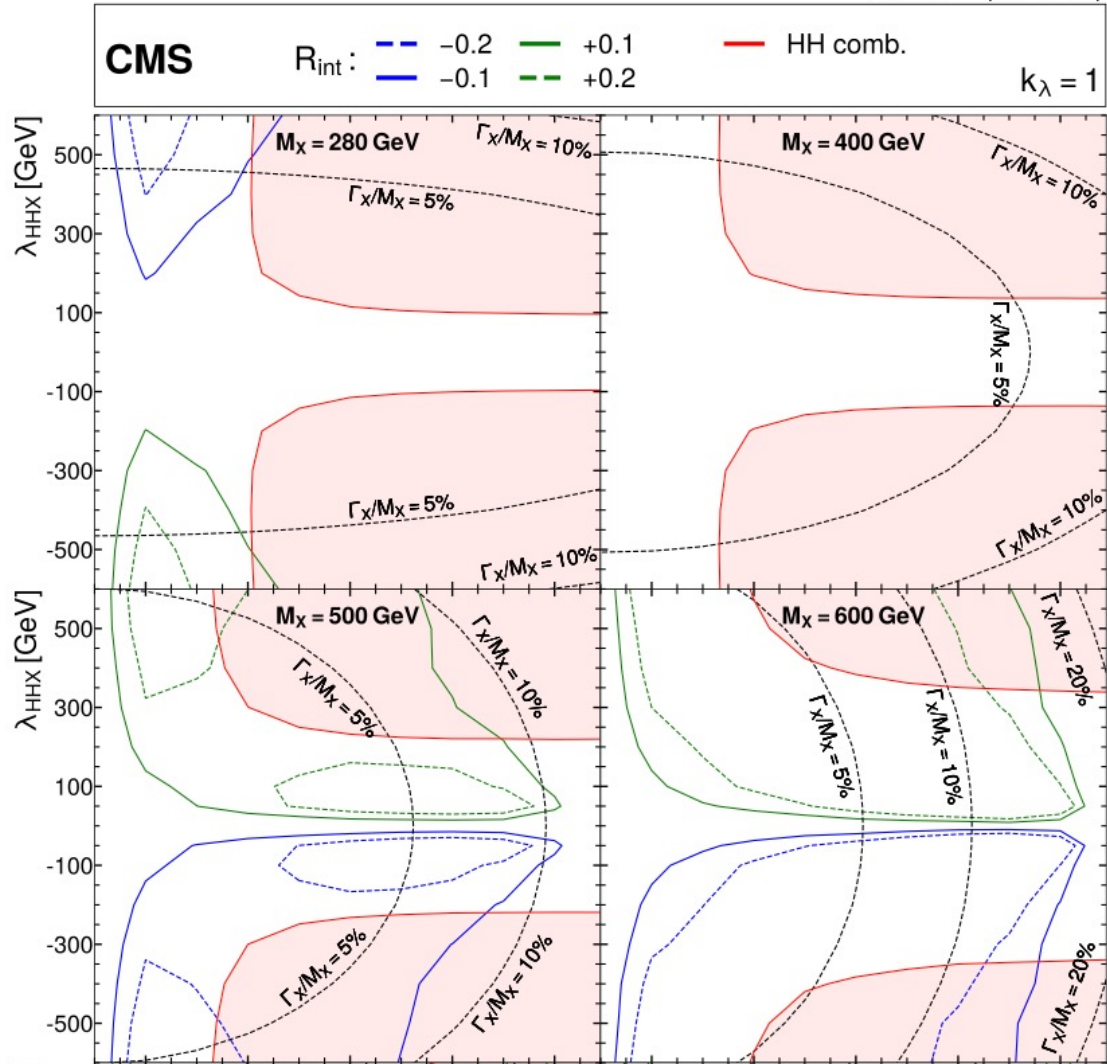


Interpretation - hMSSM



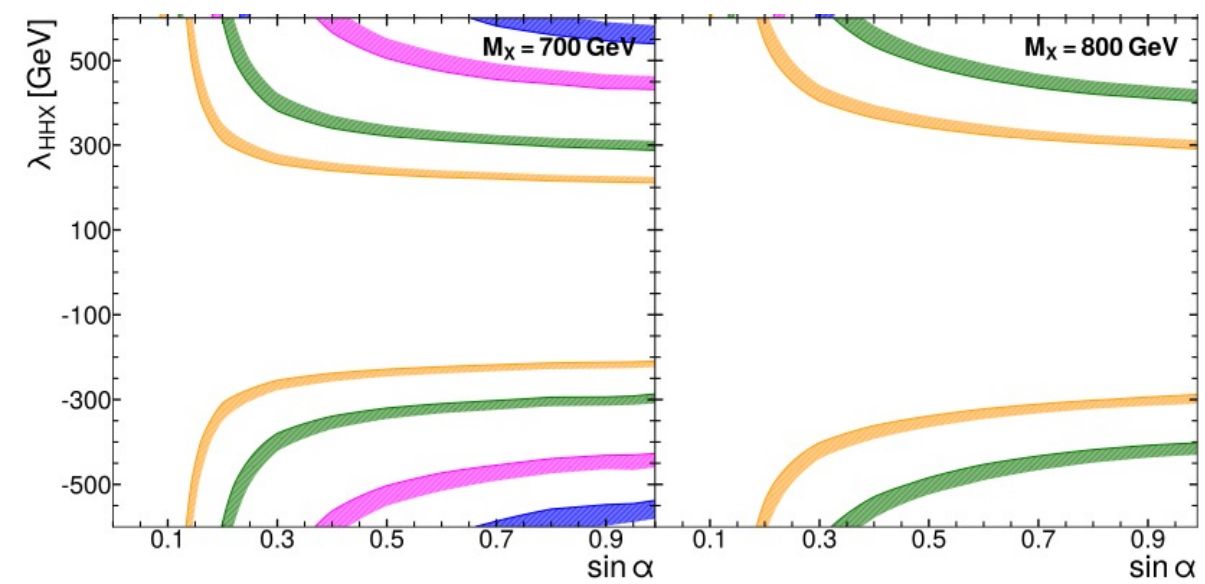
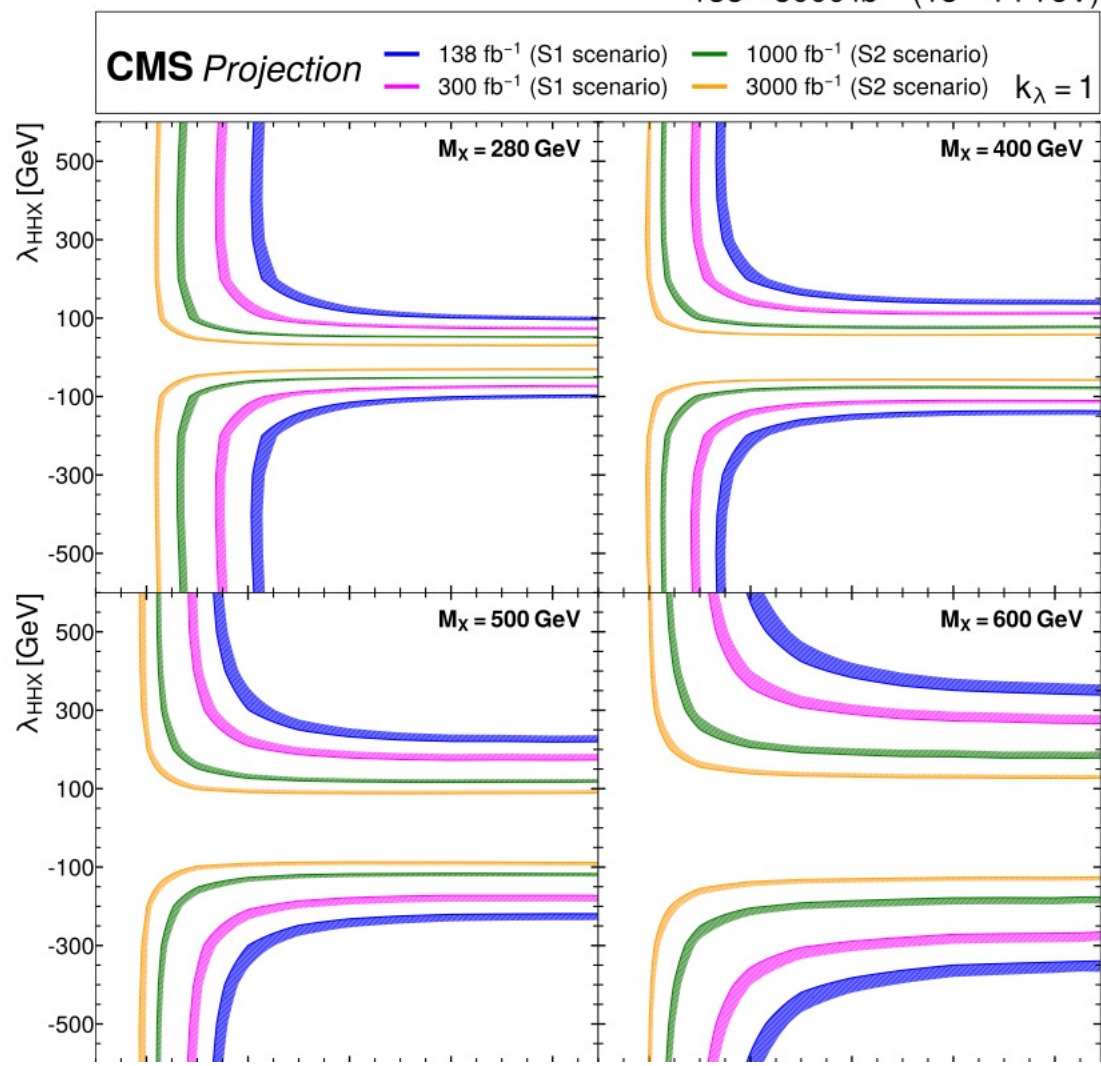
Singlet model

138 fb⁻¹ (13 TeV)

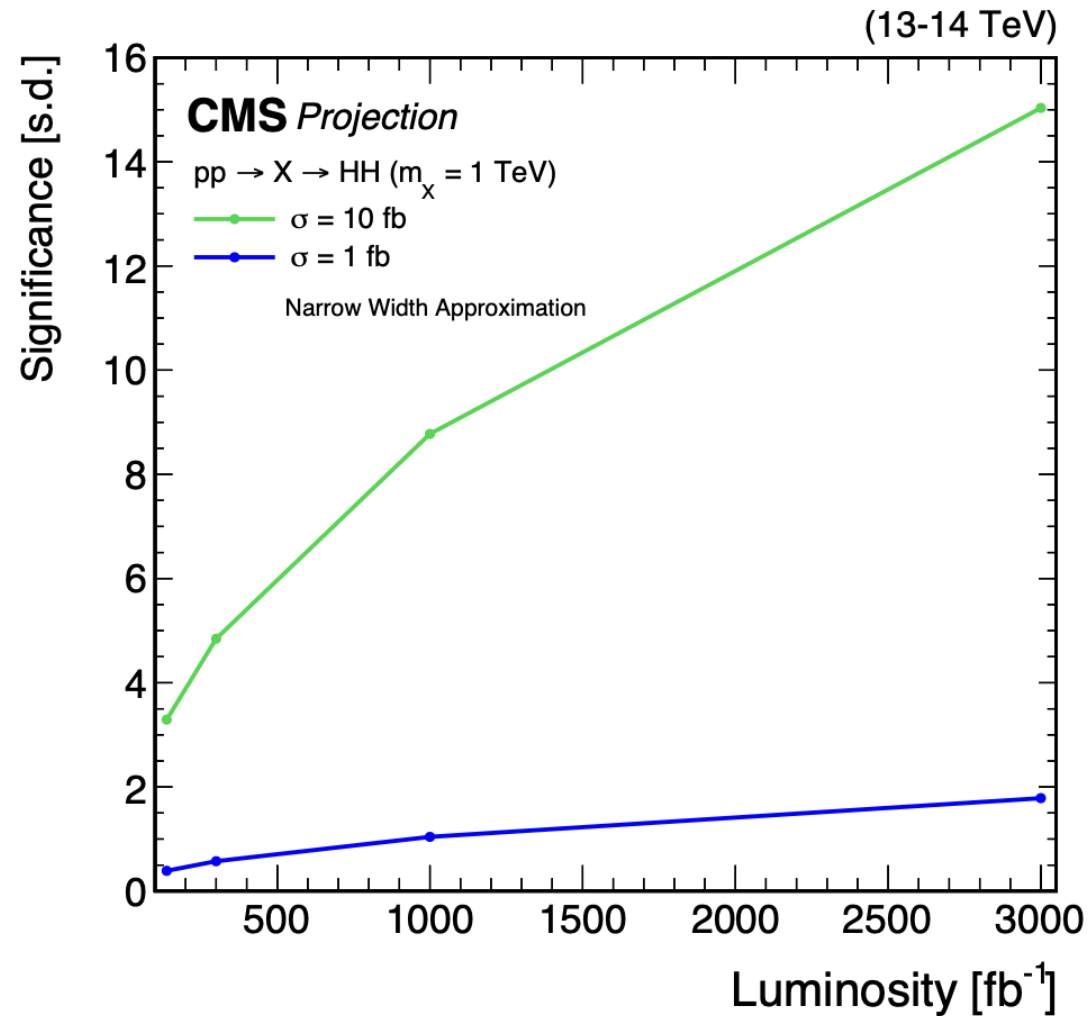


Projection - Singlet

138 - 3000 fb⁻¹ (13 - 14 TeV)



Projection – Discovery potential

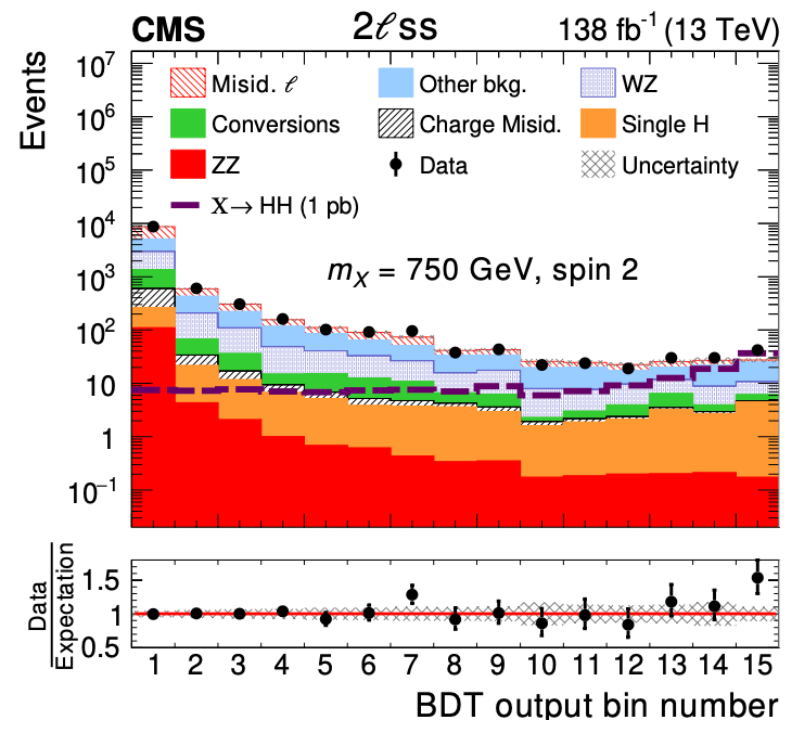
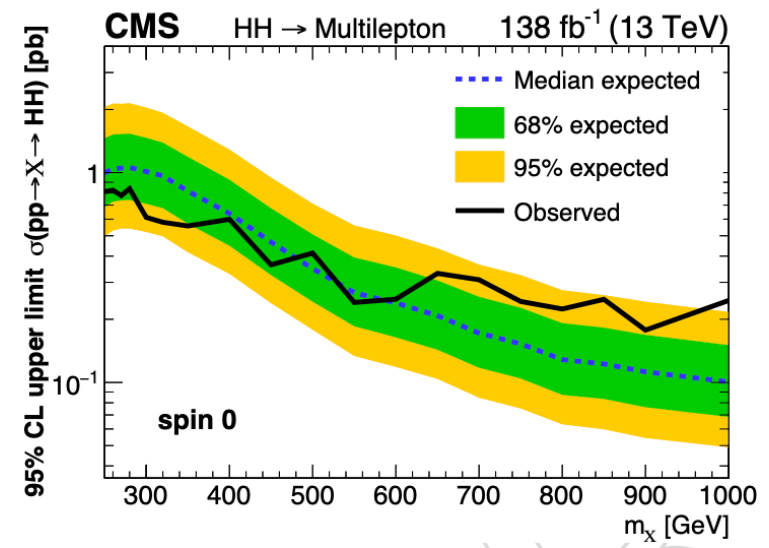


Multilepton : HIG-21-002

$$X \rightarrow HH$$

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- $WWWW$, $WW\tau_h\tau_h$ 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.

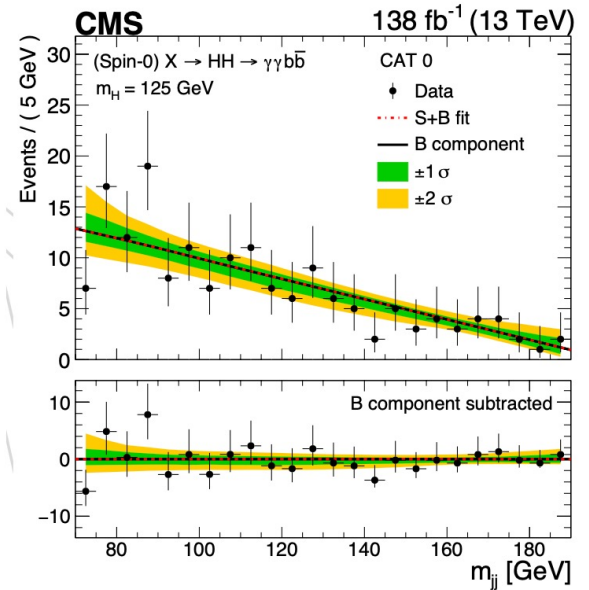
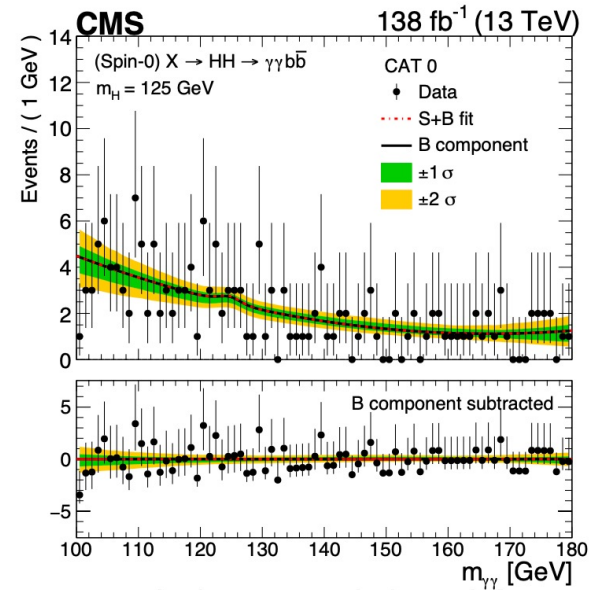
$b\bar{b}\gamma\gamma$: HIG-21-011

$X \rightarrow HH/HY$

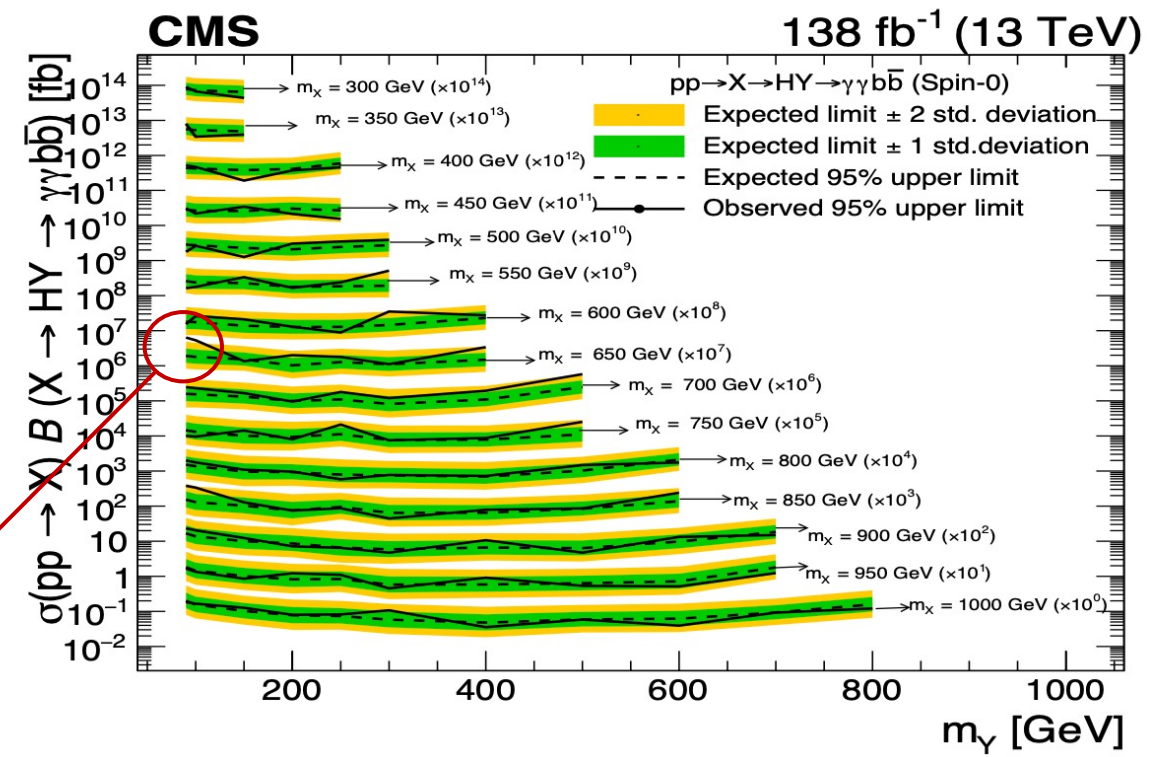
- Very low BR but **small background** contamination
- **2D fit** on the mass distributions of $H \rightarrow \gamma\gamma$, $H/Y \rightarrow b\bar{b}$

Selection :

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



Excess of 3.8 (2.8) σ found at $m_X = 650$ GeV and $m_Y = 90$ GeV

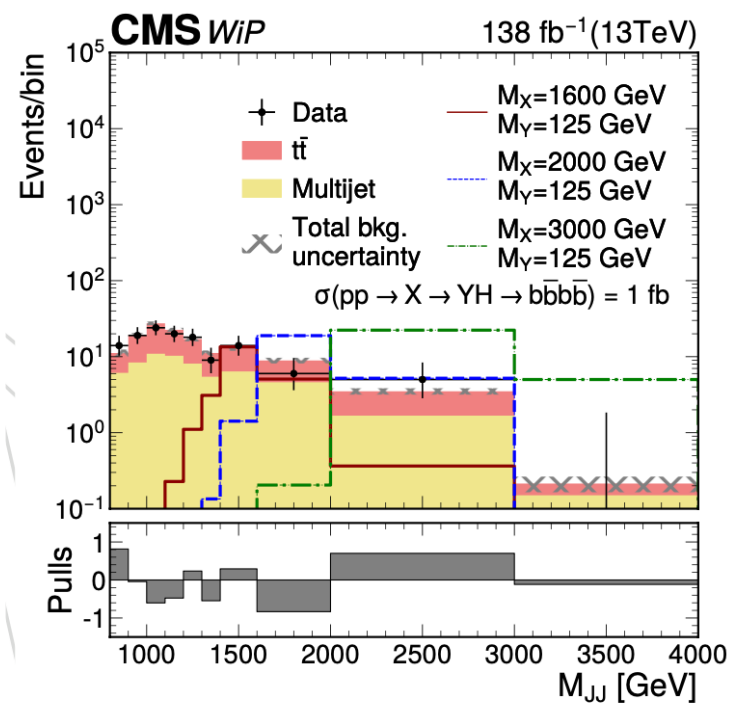
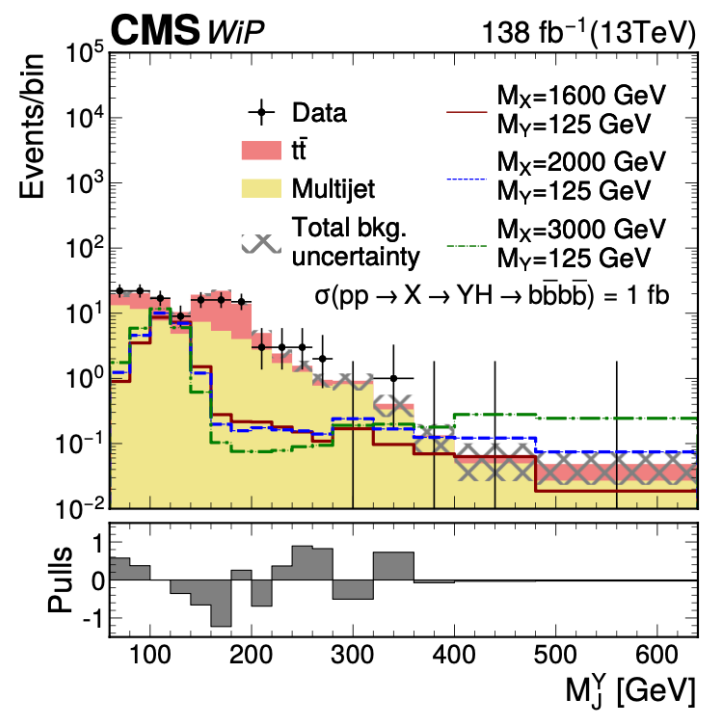


$X \rightarrow HH/HY$

[Physics Letters B 842 \(2023\) 137392](#)

4b boosted : B2G-21-003

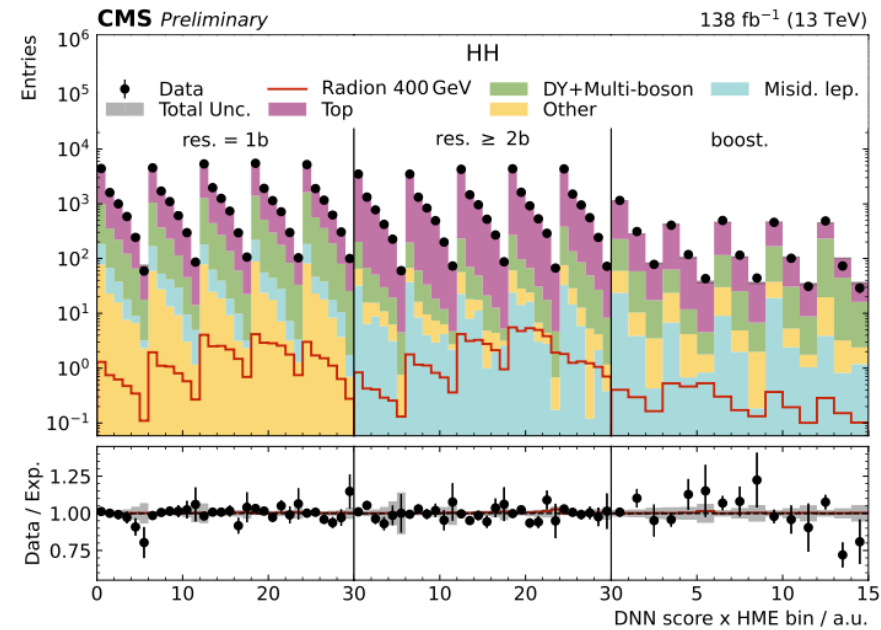
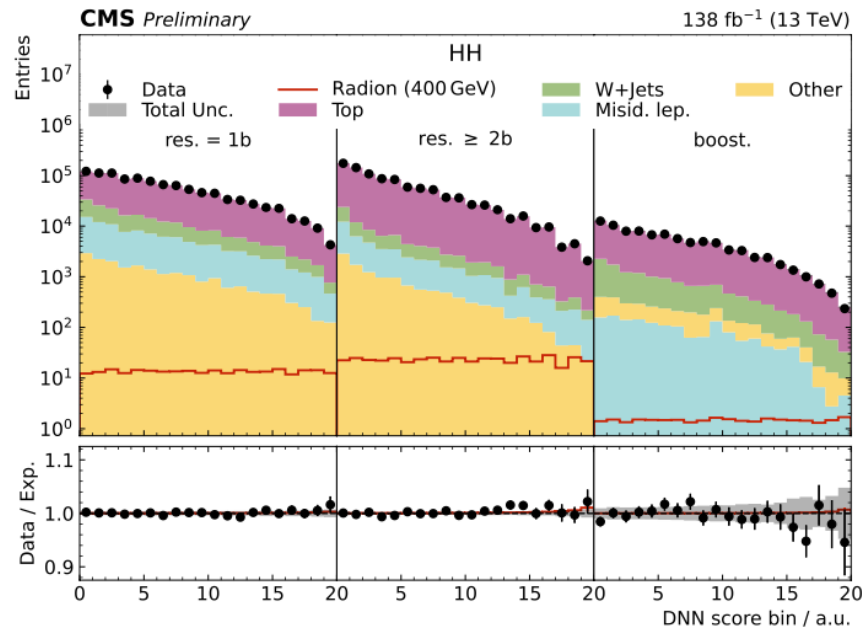
- 4b analysis at **high M_X** . Very **high BR** . **Low background** search.
- **Jet substructure tagging**
- ParticleNet is employed to discriminate the decays of a boosted H boson to a pair of b quarks against a background of other jets




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

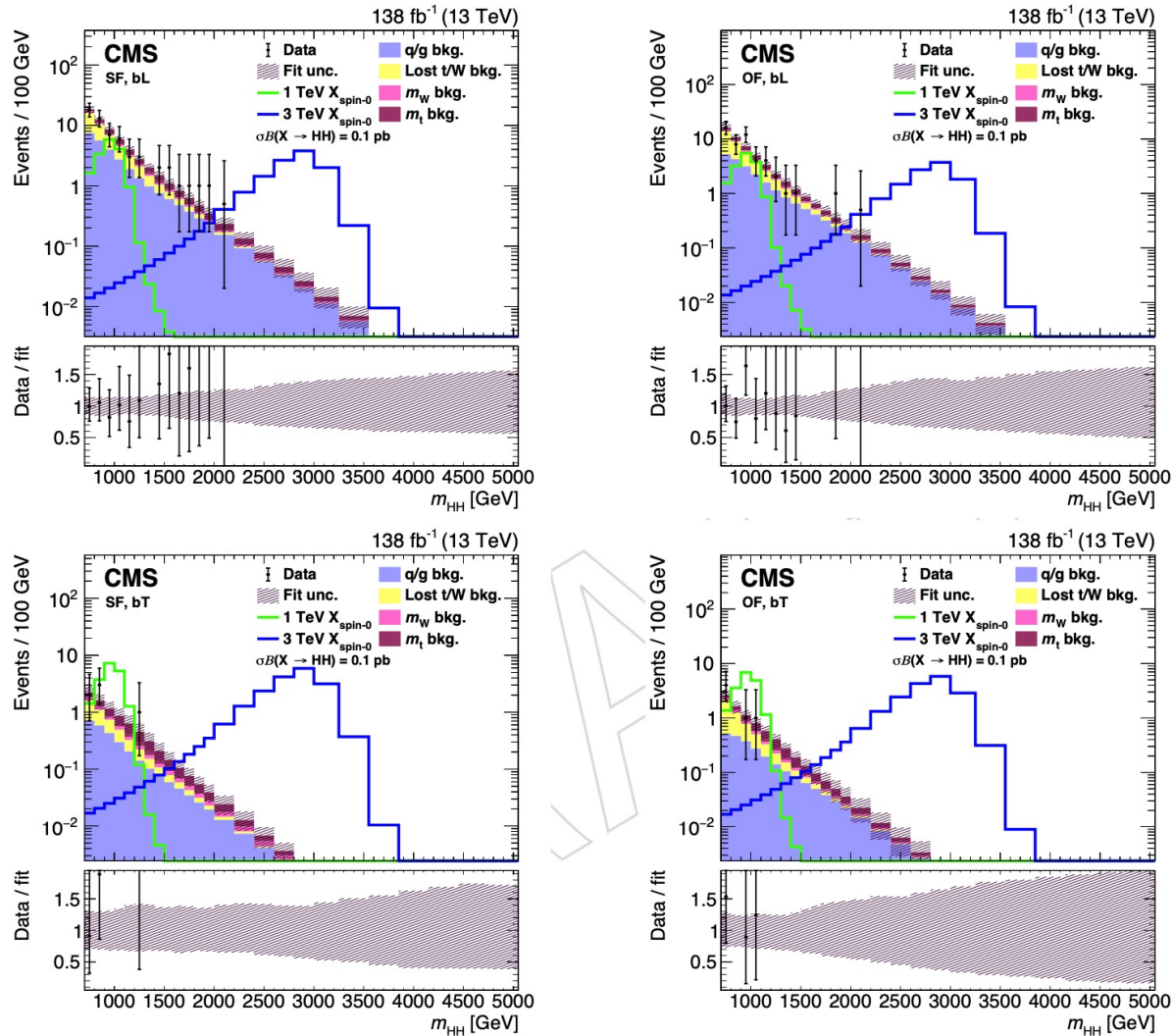
bbVV resolved : HIG-21-005

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



bbVV boosted : B2G-20-007

JHEP05(2022)005



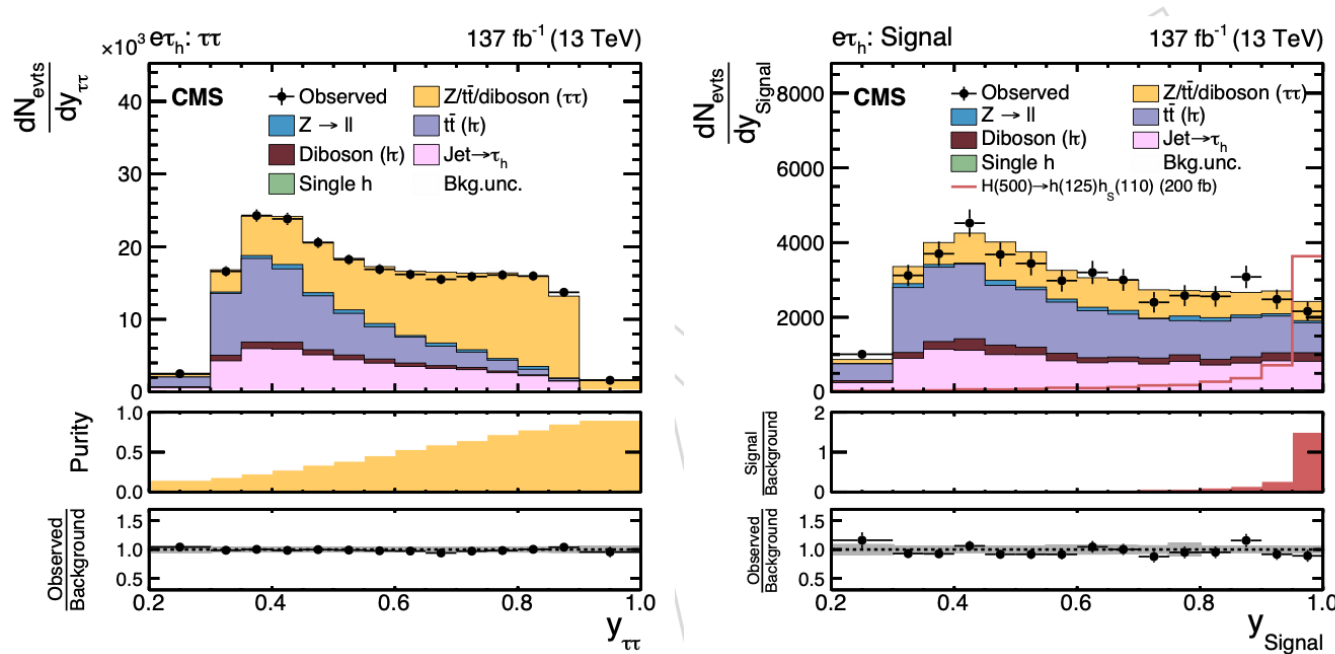
- $b\bar{b} + l$ final states in the $bbWW$ and $bb\tau\tau$ HH decay modes
- Selection : one AK8 jet ($H \rightarrow bb$) and 1 (SL : 1 more AK8 jet is required) or 2 (DL) leptons
- Additional b-tagged AK4 jets (DeepJet) are vetoed
- ML fit to the 2D m_X/m_{bb} distribution with 4 background and 1 signal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

$bb\tau\tau$: HIG-20-014

$X \rightarrow HY$

[JHEP11\(2021\)057](#)

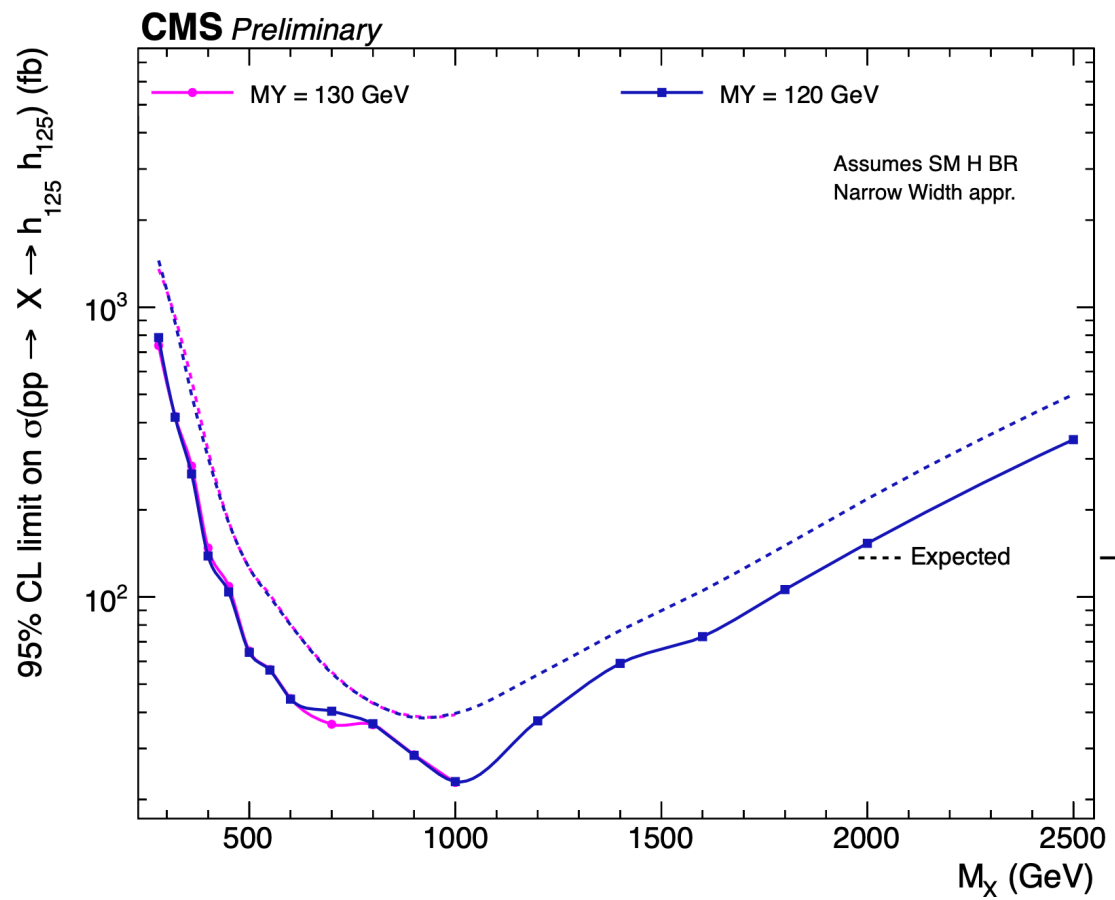
- $Y \rightarrow b\bar{b} + H \rightarrow \tau\tau$
- $bb(\tau_h\tau_h + e\tau_h + \mu\tau_h)$ final states (largest sensitivity to searched signature)



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

bb $\tau\tau$ analysis is soon to be obsolete, the future three ongoing teams are working in HH and HY in different mass ranges

$bb\tau\tau$: HIG-20-014



No symmetric analysis :
 $(m_Y = 125$ GeV)

No significant difference between the limits
in $m_Y = 120$ and 130 GeV

**We take the $m_Y = 130$ GeV to emulate the
 $m_H = 125$ GeV mass point**