

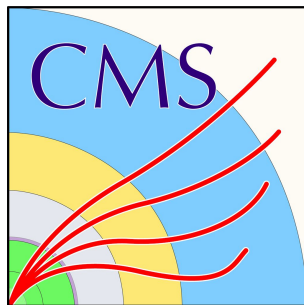
# Search for new high-mass scalars at the LHC

Higgs 2024 conference

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On behalf of the the ATLAS and CMS collaborations

8th November 2024



# Introduction

- The SM Higgs sector is the simplest solution to achieve electroweak symmetry breaking
  - **There is no guarantee that the Higgs sector is actually minimal**
- The SM Higgs sector can be easily extended with additional singlets, doublets, or triplets, or combinations of them
- An extended Higgs sector can solve some of the shortcomings of the SM:
  - Facilitate baryogenesis to explain the large asymmetry between matter and antimatter
  - Enhance vacuum stability
  - Provide dark matter candidates
  - Provide a solution to the strong CP problem (i.e. predict axions)

# Extended Higgs sector

2 Higgs doublets (i.e. 2HDM)  $\xrightarrow{\text{EWSB}}$   $h, H, A, H^\pm$

- **Relevant model parameters:**

- Mixing angle  $\alpha$  between neutral states
- $\tan \beta$  (ratio of VEVs)
- Masses:  $m_h, m_H, m_A, m_{H^\pm}$

[Phys.Rev.D 67 \(2003\) 075019](#)

1 Higgs doublet + 2 triplets (Georgi-Machacek model)  $\xrightarrow{\text{EWSB}}$   $h, H, H_3, H_3^\pm, H_5, H_5^\pm, H_5^{\pm\pm}$

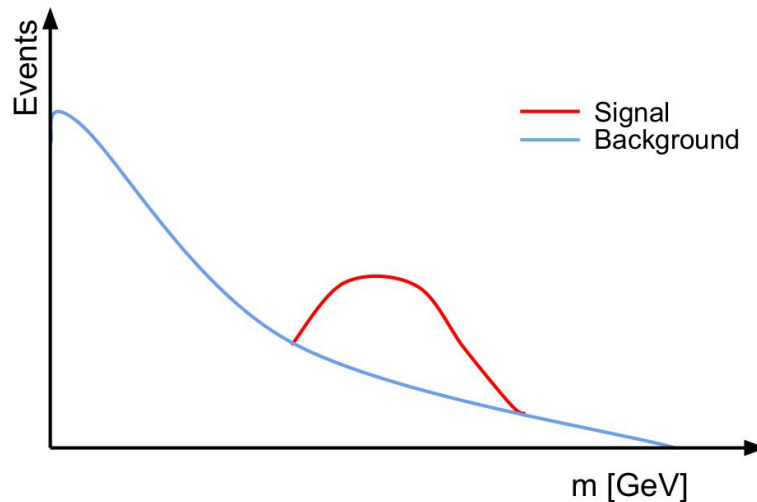
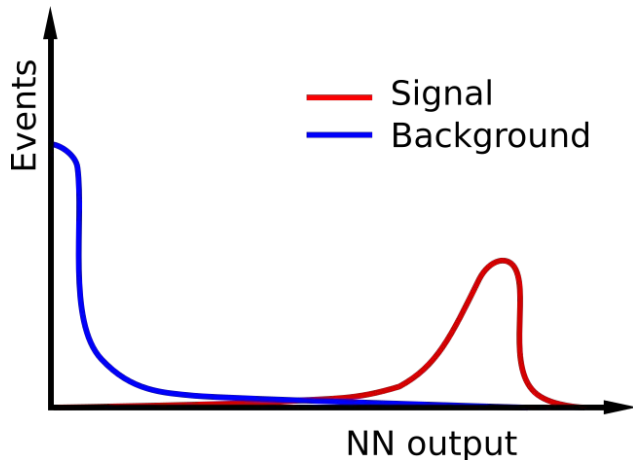
- **Relevant model parameters:**

- Mixing angle  $\alpha$  between neutral states
- $s_H = \sin \theta_H$  (ratio of doublet and triplet VEVs)
- Masses:  $m_h, m_H, m_{H_3}, m_{H_5}$

[Phys.Rev.D 90 \(2014\) 1](#)

# Search strategy

- Most analyses are designed to perform (quasi) **model-independent searches for a bump in a smoothly falling mass spectrum**
  - Perform maximum likelihood fit to **set upper limits** on production cross section and/or branching fraction
  - Interpretation in a large variety of different models

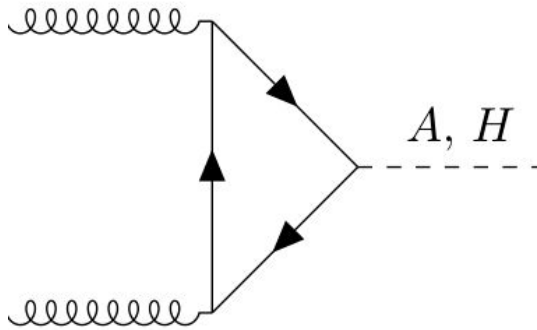


- For complicated final states, train neural networks (NNs) or boosted decision trees (BDTs) to separate signal from backgrounds
  - Probe BDT/NN response distribution

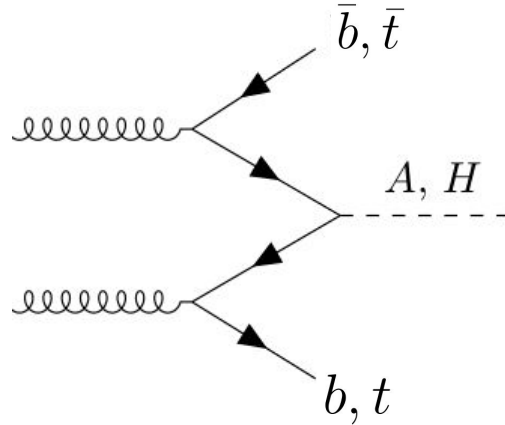
# Outline

- Neutral Higgs bosons searches
- Singly charged Higgs boson searches
- Doubly charged Higgs bosons searches
- Interpretations

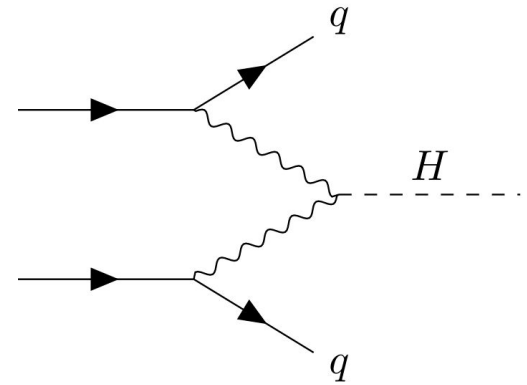
# Neutral Higgs bosons



gluon-gluon fusion (ggF)



b/t-associated production



Vector boson fusion (VBF)

## Considered decay modes:

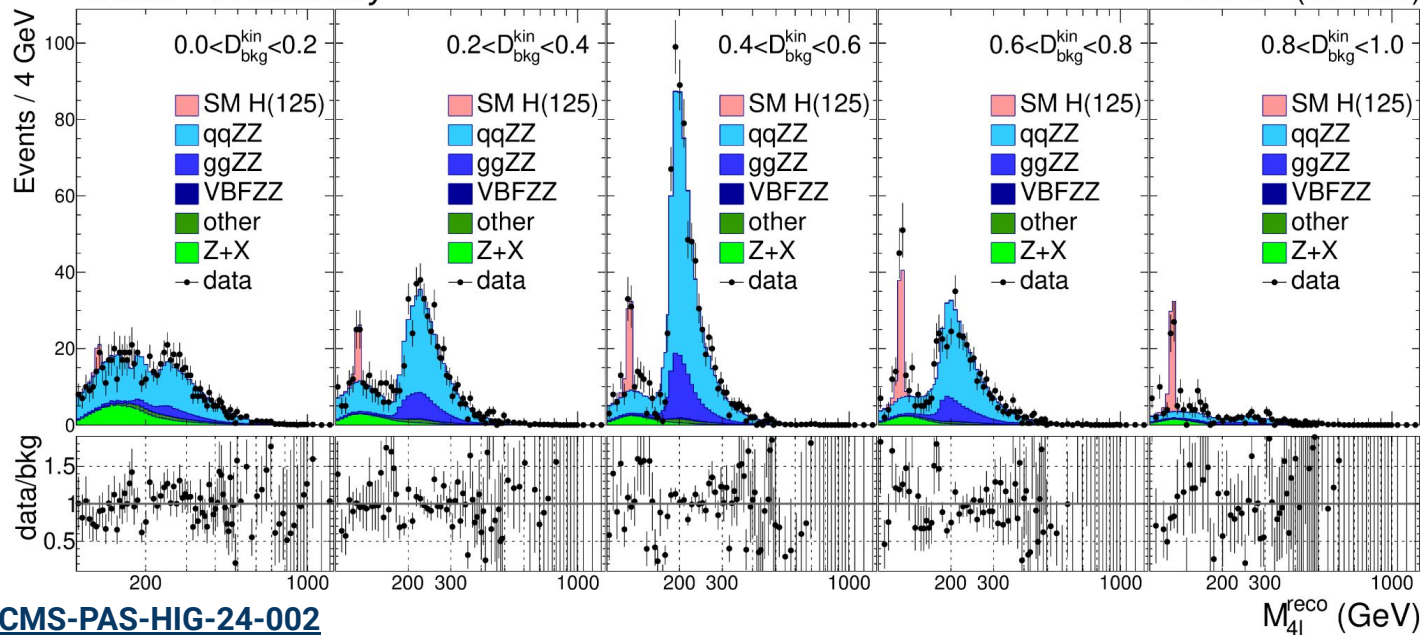
- $A/H \rightarrow \tau\tau, \mu\mu, tt, bb$
- $H \rightarrow ZZ, WW, \gamma\gamma, Z\gamma, hh$
- $A \rightarrow Zh, ZH$

# Search for $X \rightarrow ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^-$

- Motivated by:
  - **2HDMs**
  - **Models predicting extra dimensions (predicting radions)**
- Classify events based on topology of jets (ggF vs. VBF)

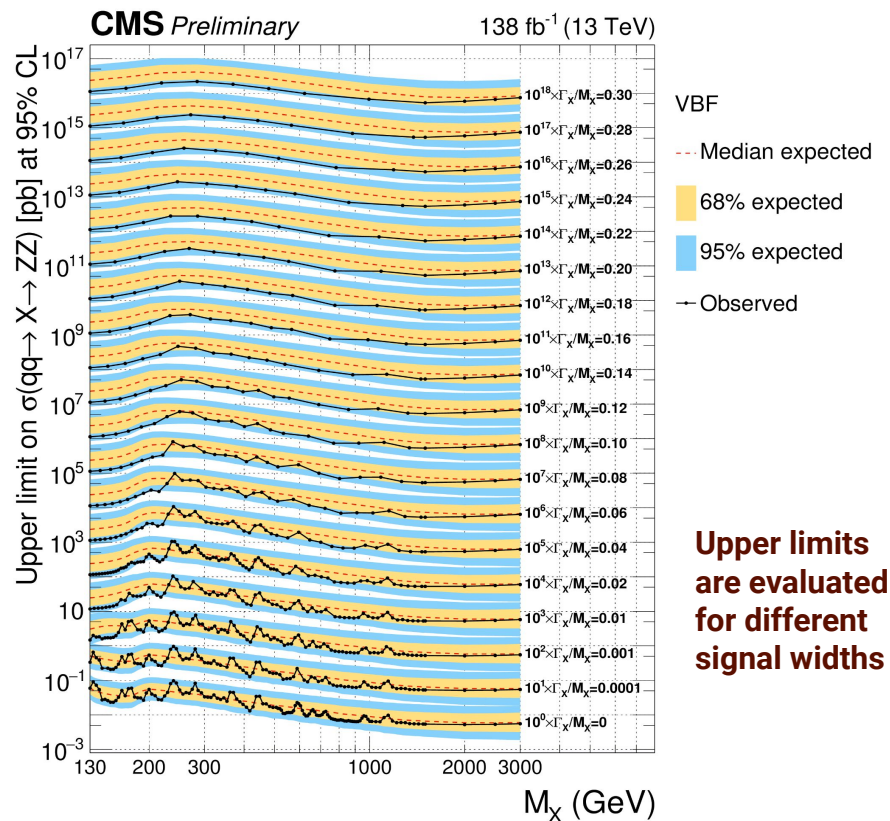
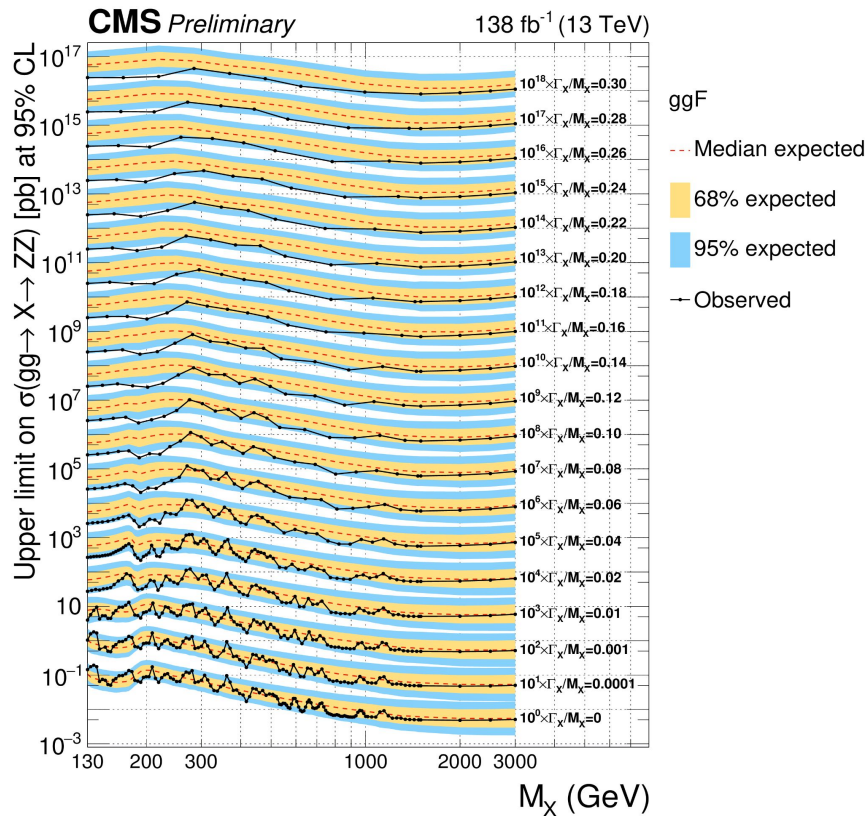
**CMS** Preliminary

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



Fit inv. mass ( $M_{4\ell}$ ) in bins of a kinematic discriminant computed using MELA

# Search for $X \rightarrow ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^-$



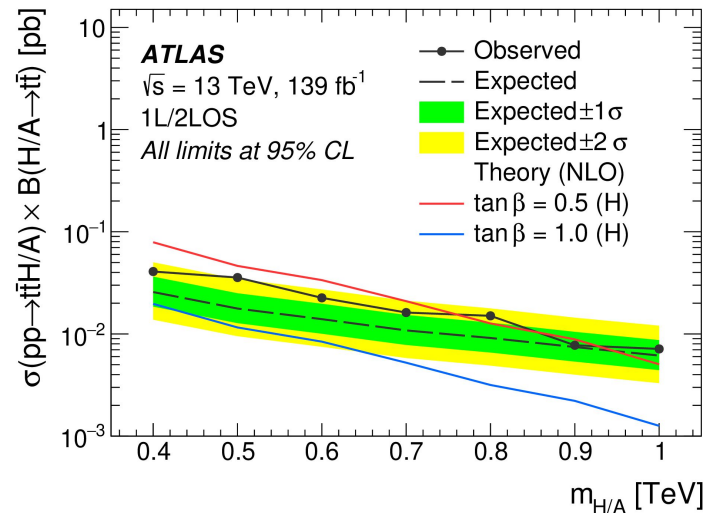
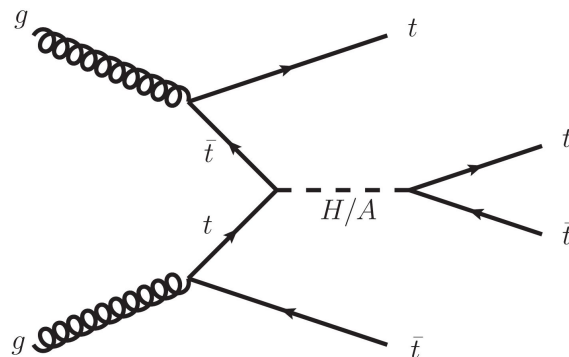
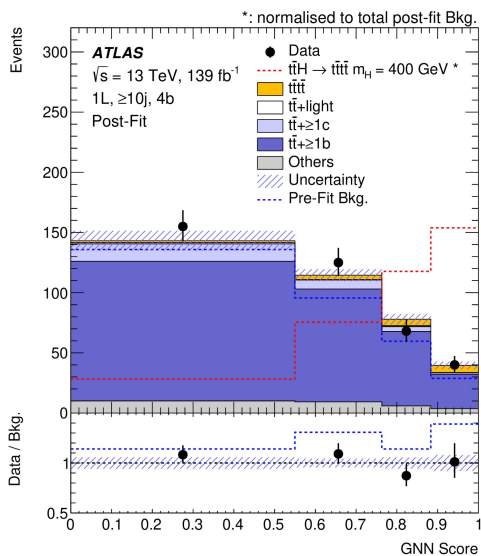
**Largest excess found for a mass around 138 GeV reaching a local (global) significance of  $3.0\sigma$  ( $1.9\sigma$ ) for the lowest width hypotheses**



# Search for H/A in 4 top events

arXiv:2408.17164

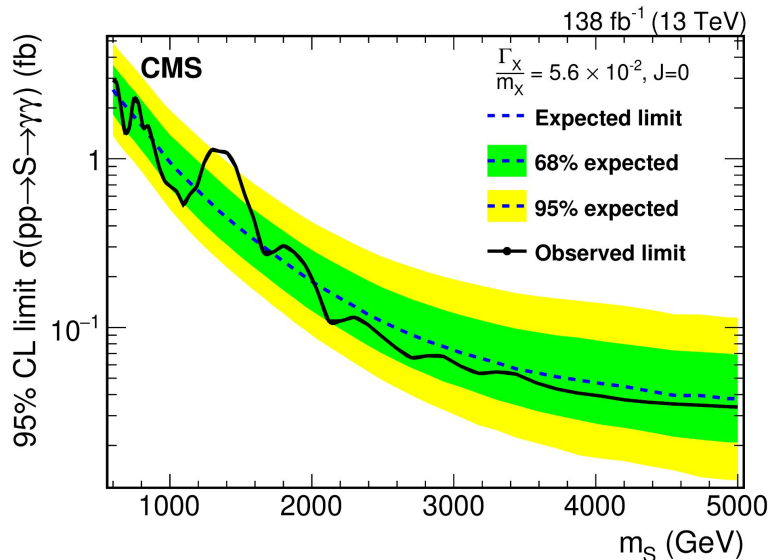
- Motivated by:
  - 2HDMs (for  $m_{H/A} > 500$  GeV and moderate  $\tan \beta$  values)
  - Models predicting pair production of colour-octet scalars
  - Excess ( $1.8\sigma$ ) in 4 top XSec measurement (arXiv:2303.15061)
- Use  $m_{H/A}$ -parameterised multivariate discriminant
- Classify events based on lepton & (b-)jet multiplicity



- Complimentary to searches for  $gg \rightarrow A/H \rightarrow t\bar{t}$ 
  - Suffer from destructive interference effects with the SM continuum

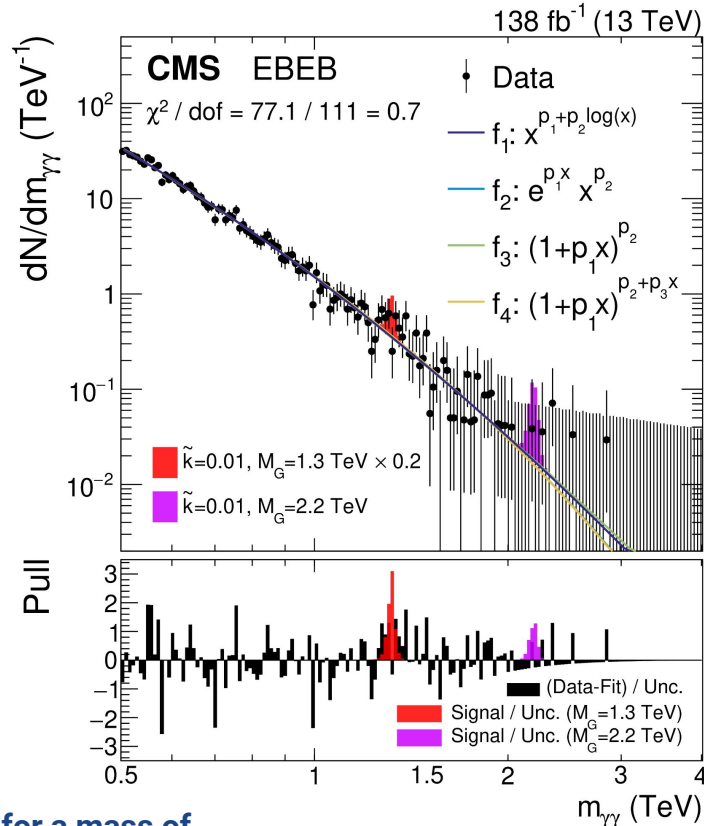
# Search for new physics in high-mass di-photon events

- Motivated by:
  - Basically any extended Higgs sector model
  - Models predicting extra dimensions
- Events are classified based on the photon location in the ECAL: distinguishing barrel (EB) and end-cap (EE)
- Parametrised functions are fit to the  $m_{\gamma\gamma}$  spectrum



Obtain results for various widths hypotheses

Largest excess found for a mass of 1.3 TeV reaching a local (global) significance of  $2.6\sigma$  ( $0.5\sigma$ )

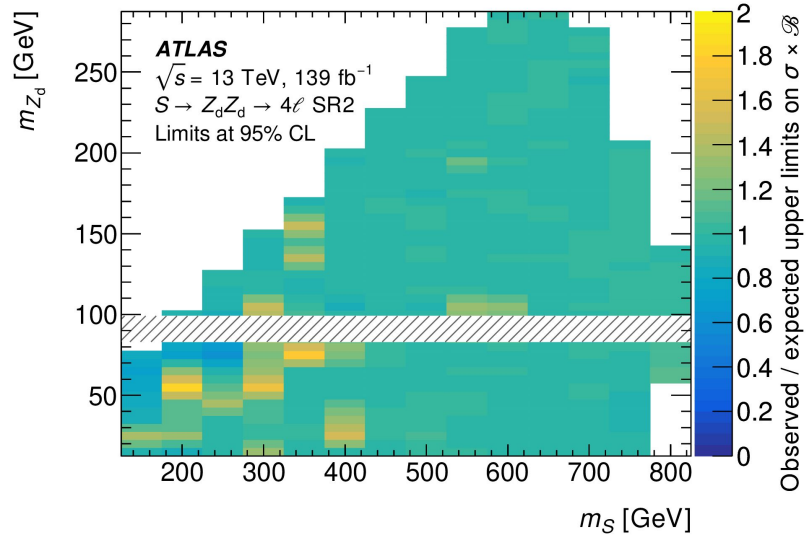
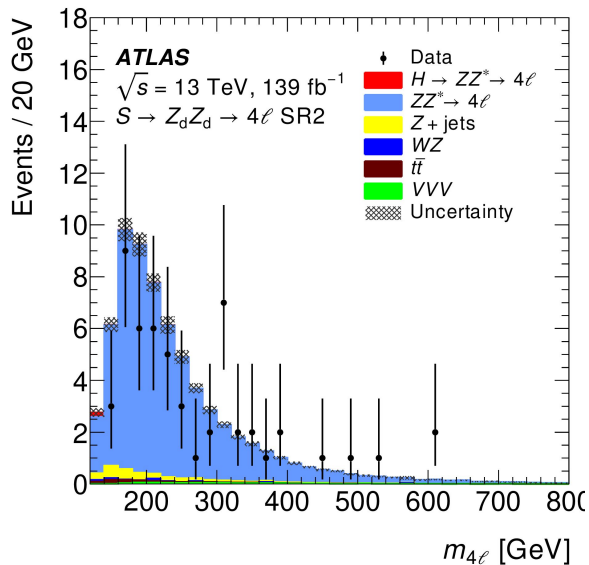
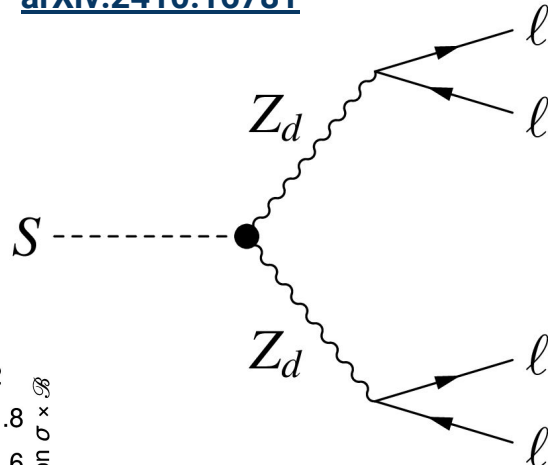


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# Search for new scalars in $\ell^+\ell^-\ell^+\ell^-$

[arXiv:2410.16781](https://arxiv.org/abs/2410.16781)

- Motivated by:
  - **Hidden Abelian Higgs Model**
    - With mixing of  $U(1)_d$  the SM  $U(1)_Y$
- Events are classified (in two SRs) based on requirements on  $m_{4\ell}$  and  $m_{2\ell}$

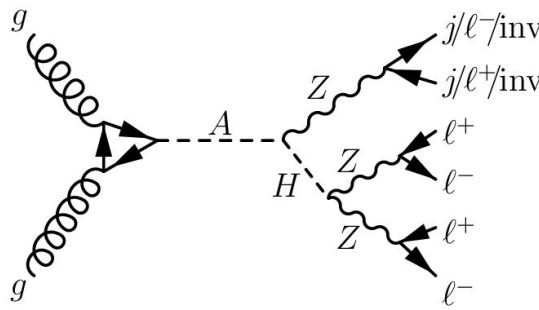
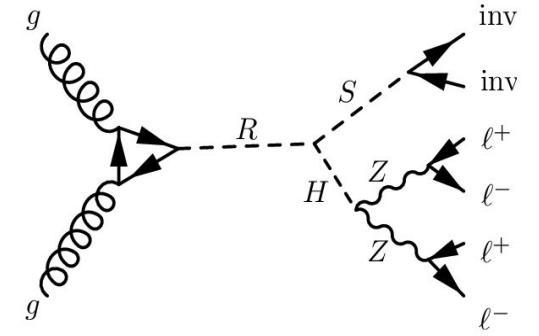
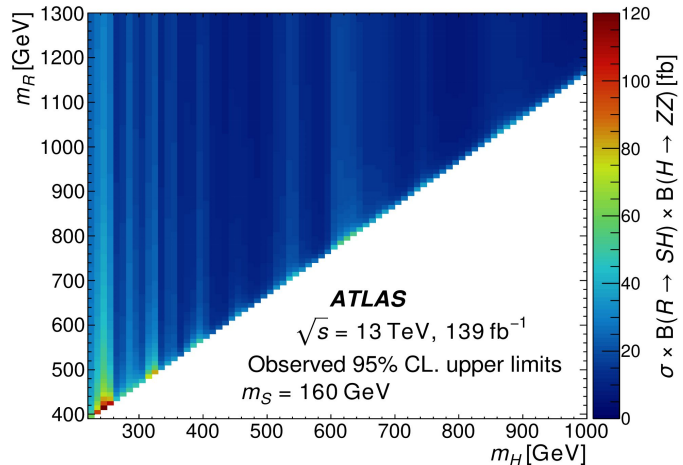
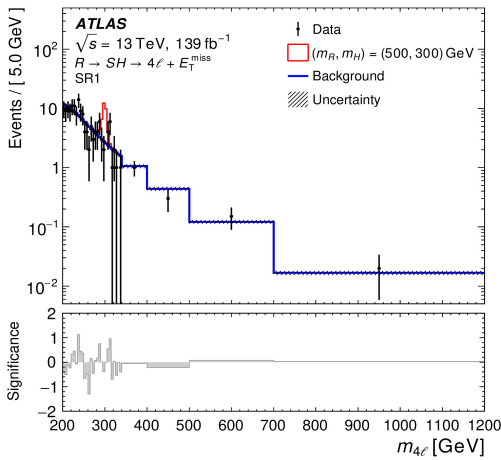


**Largest excess found for  $(m_S, m_{Z_d}) = (350 \text{ GeV}, 75 \text{ GeV})$  reaching a local (global) significance of  $2.8\sigma$  ( $0.5\sigma$ )**

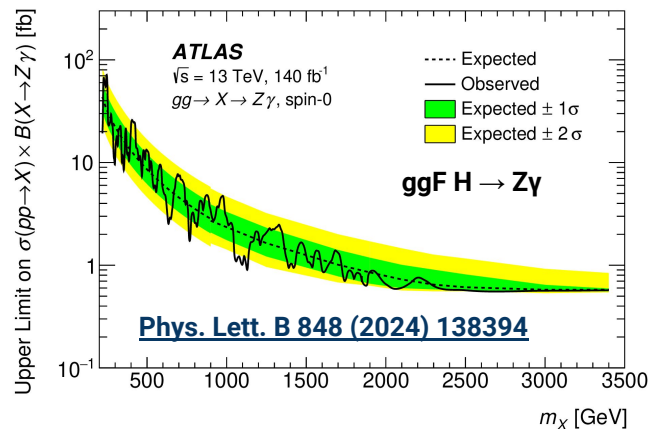
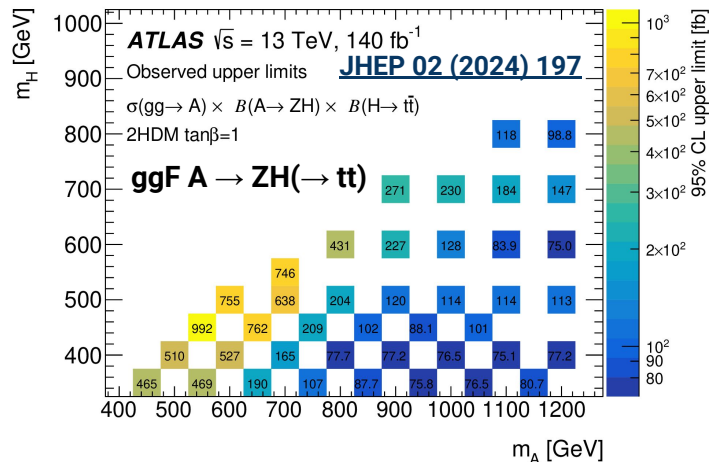
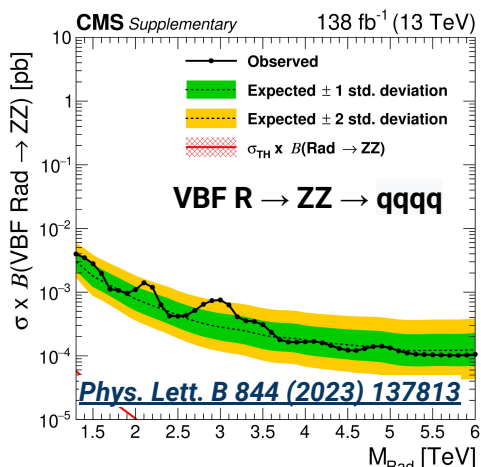
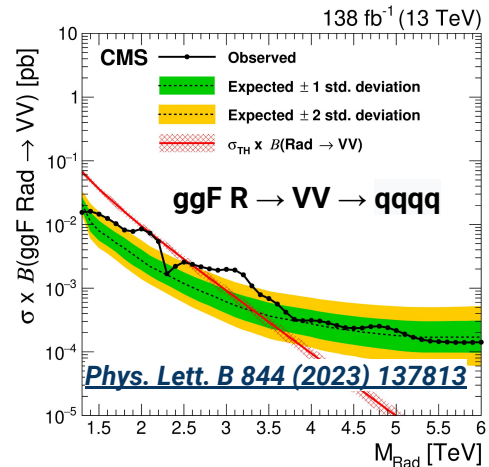
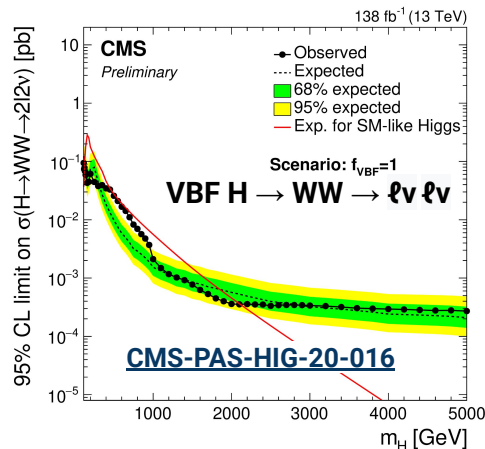
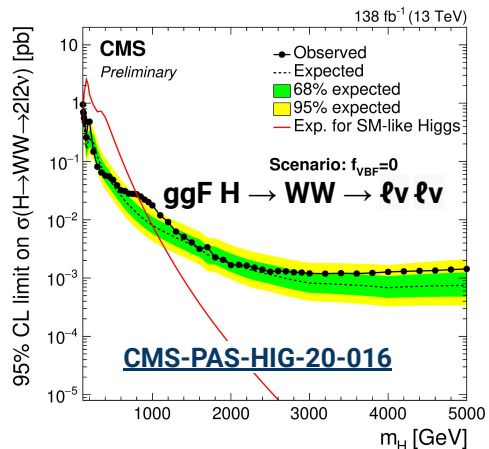
# Search for new scalars in $\ell^+\ell^-\ell^+\ell^- + \text{MET}/\text{jets}$ final states

[arXiv:2401.04742](https://arxiv.org/abs/2401.04742)

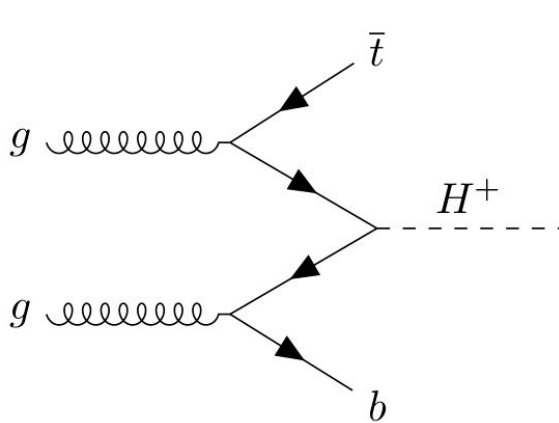
- Motivated by:
  - 2HDM + S (with S being a dark matter portal)
  - 2HDM (for  $A \rightarrow ZH$ )
- Events are classified (in 7 SRs) based on:
  - Jet multiplicity
  - MET significance
- Parametrised functions are fit to the  $m_{4\ell}$  spectrum



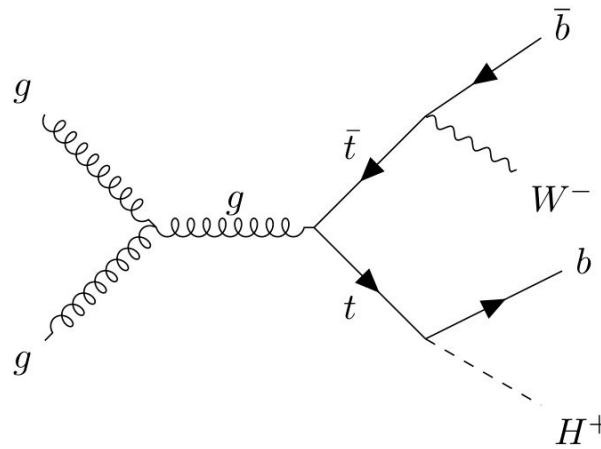
# Some more Results



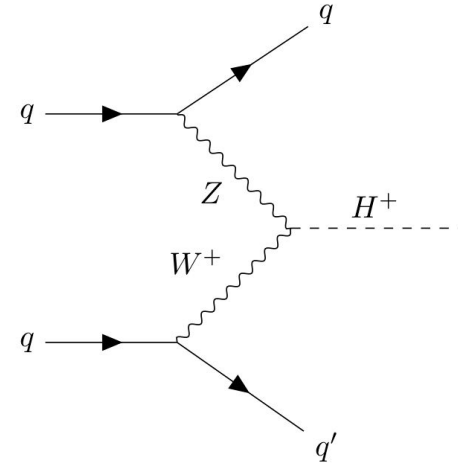
# Singly charged Higgs bosons



Associated production



Top quark decays



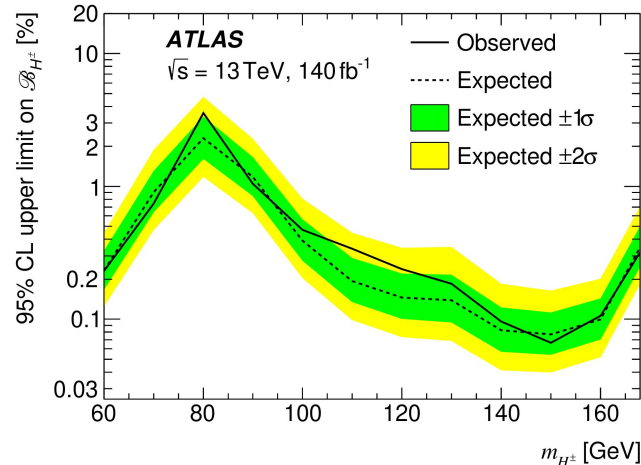
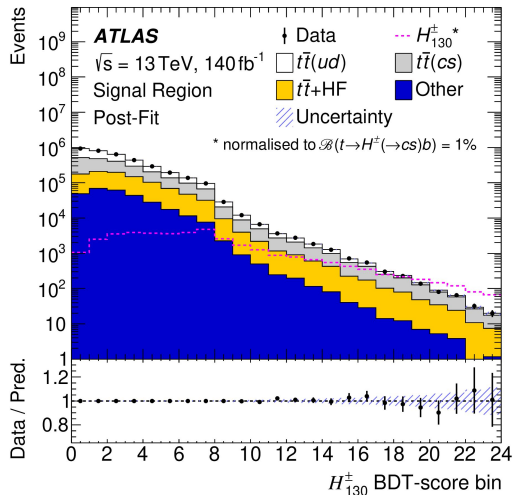
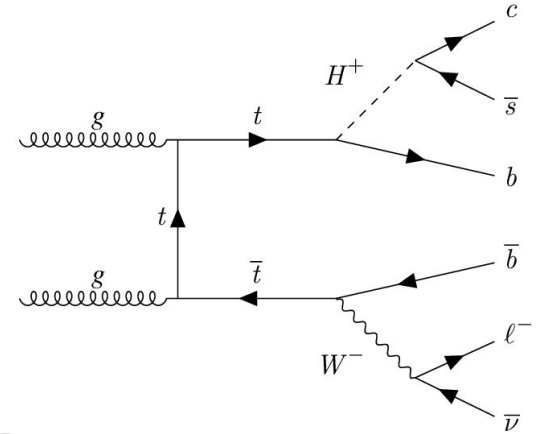
Vector boson fusion

## Considered decay modes:

- $H^\pm \rightarrow \tau\nu, tb, cb, cs$
- $H^\pm \rightarrow W^\pm Z, W^\pm\gamma, W^\pm A, W^\pm H$

# Search for $H^\pm \rightarrow cs$ decays

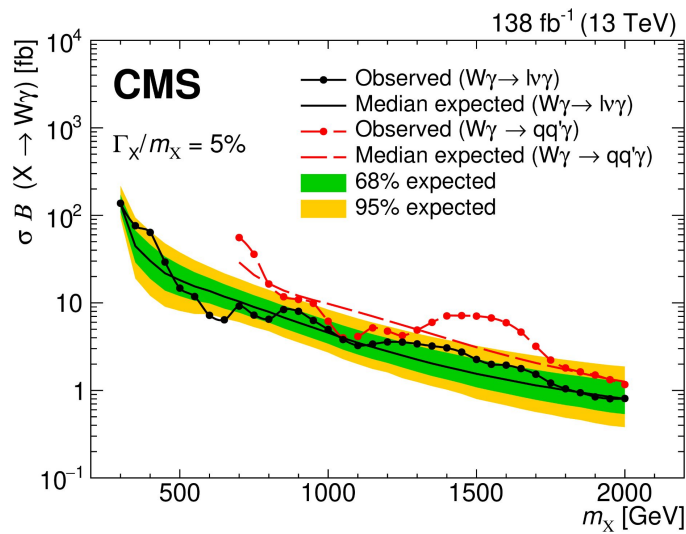
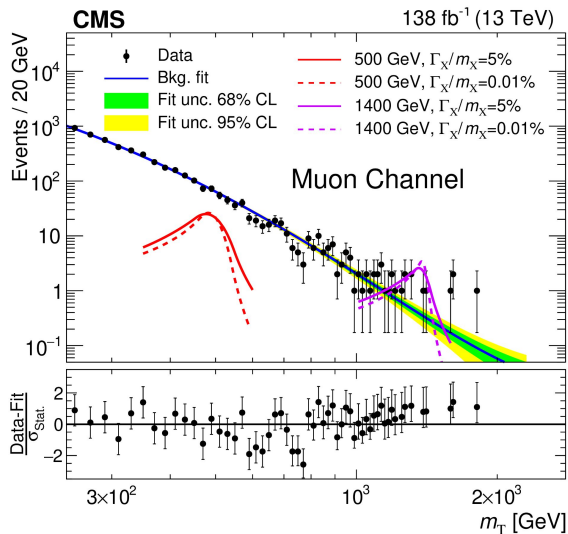
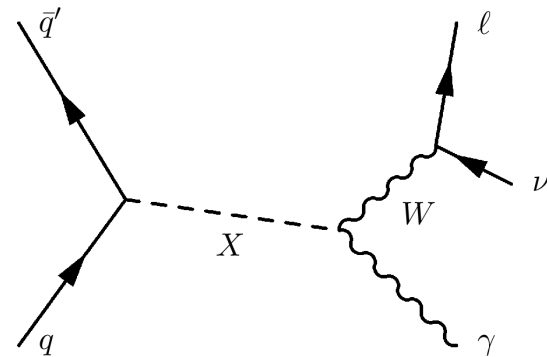
- Decay is relevant (or even dominant) for low masses in:
  - Type-I 2HDMs
  - Type-II and lepton-specific 2HDMs for  $\tan \beta < 1$
  - Flipped 2HDMs for  $\tan \beta > 5$
- Deploy boosted decision trees using kinematic event properties and the flavour composition
  - Simultaneous tagging of  $b$ -jets and  $c$ -jets



Most stringent limits for masses between 120GeV and 160GeV

# Search for $H^\pm \rightarrow W^\pm \gamma$ decays

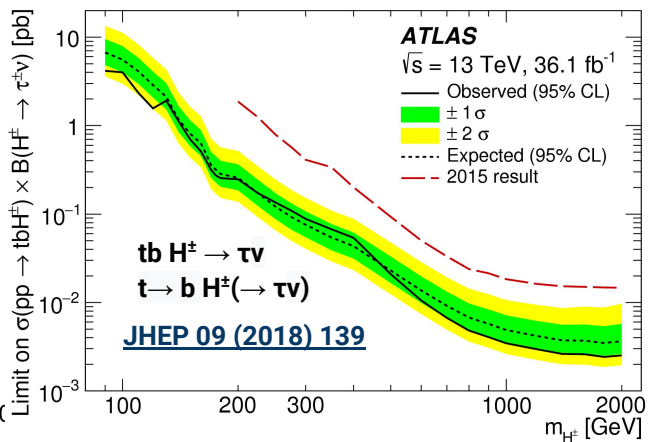
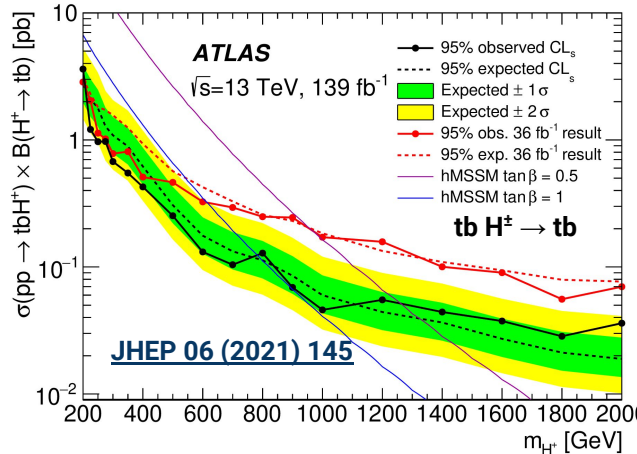
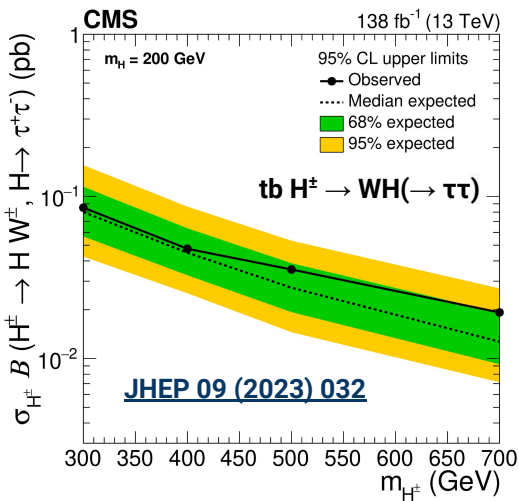
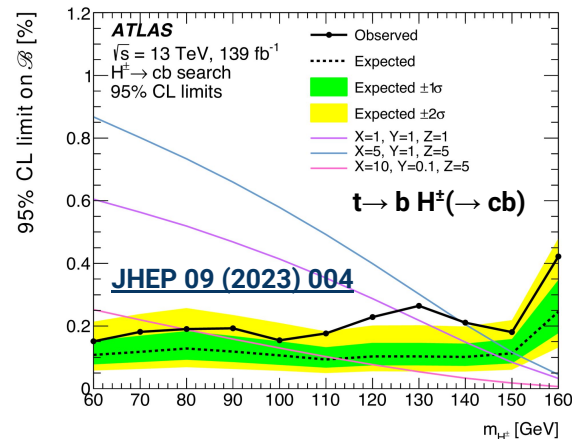
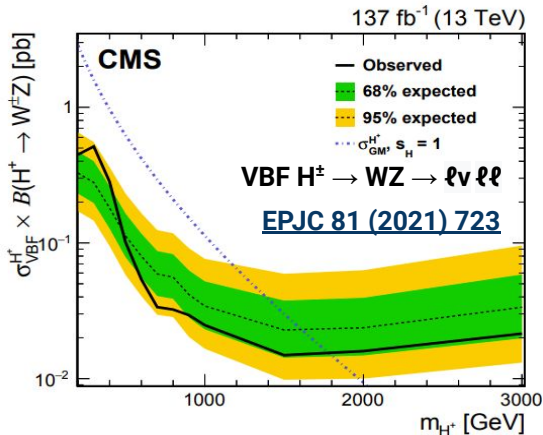
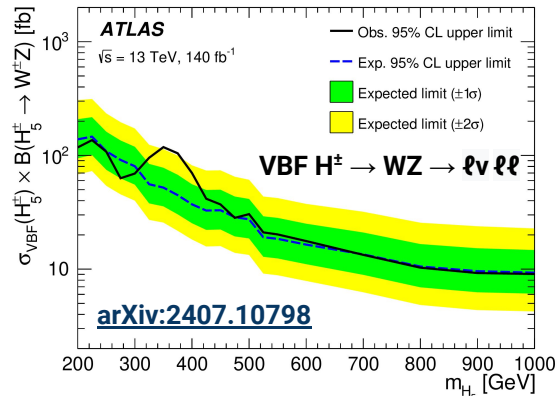
- Motivated by:
  - Georgi-Machacek model
  - Folded-supersymmetry models
- Parametrised functions are fit to the transverse mass ( $m_T$ ) spectrum



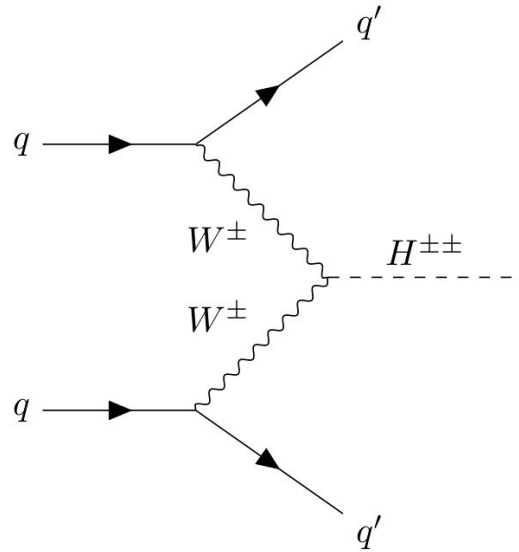
No significant excess is observed in contrast to a previous search for  $W \rightarrow (qq)\gamma$  resonances ( $3.1\sigma$ )



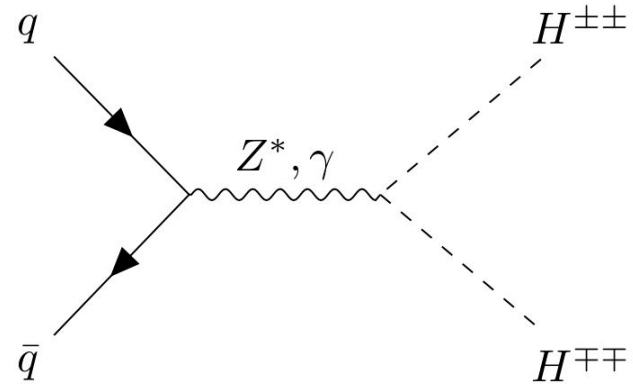
# Some more Results



# Doubly charged Higgs bosons



Vector boson fusion

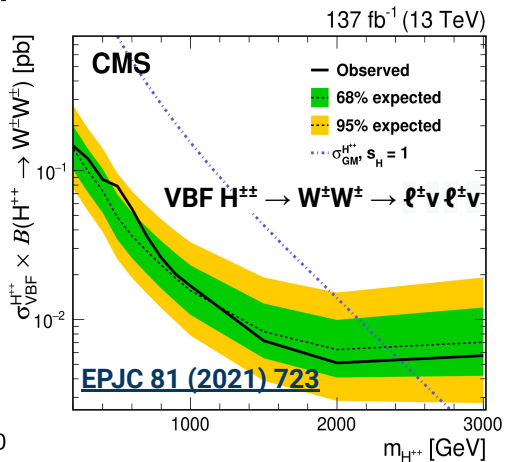
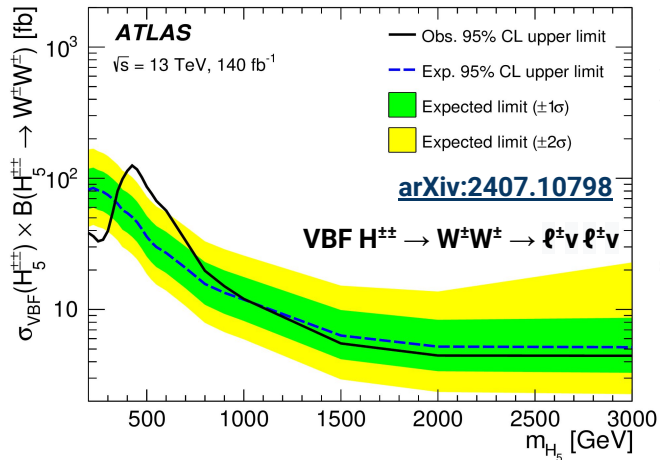
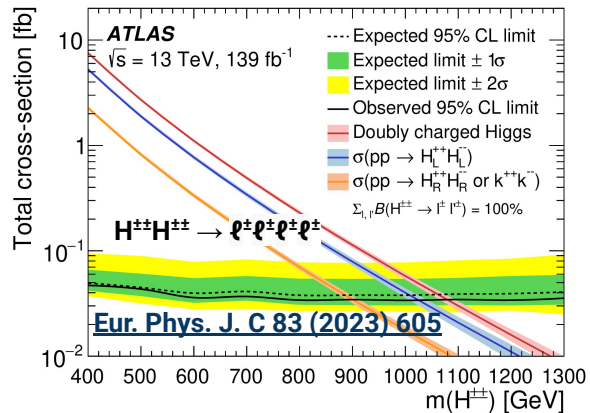
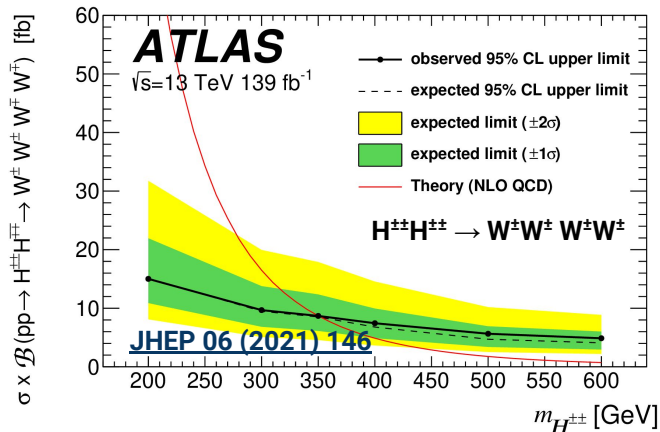


Pair production

## Considered decay modes:

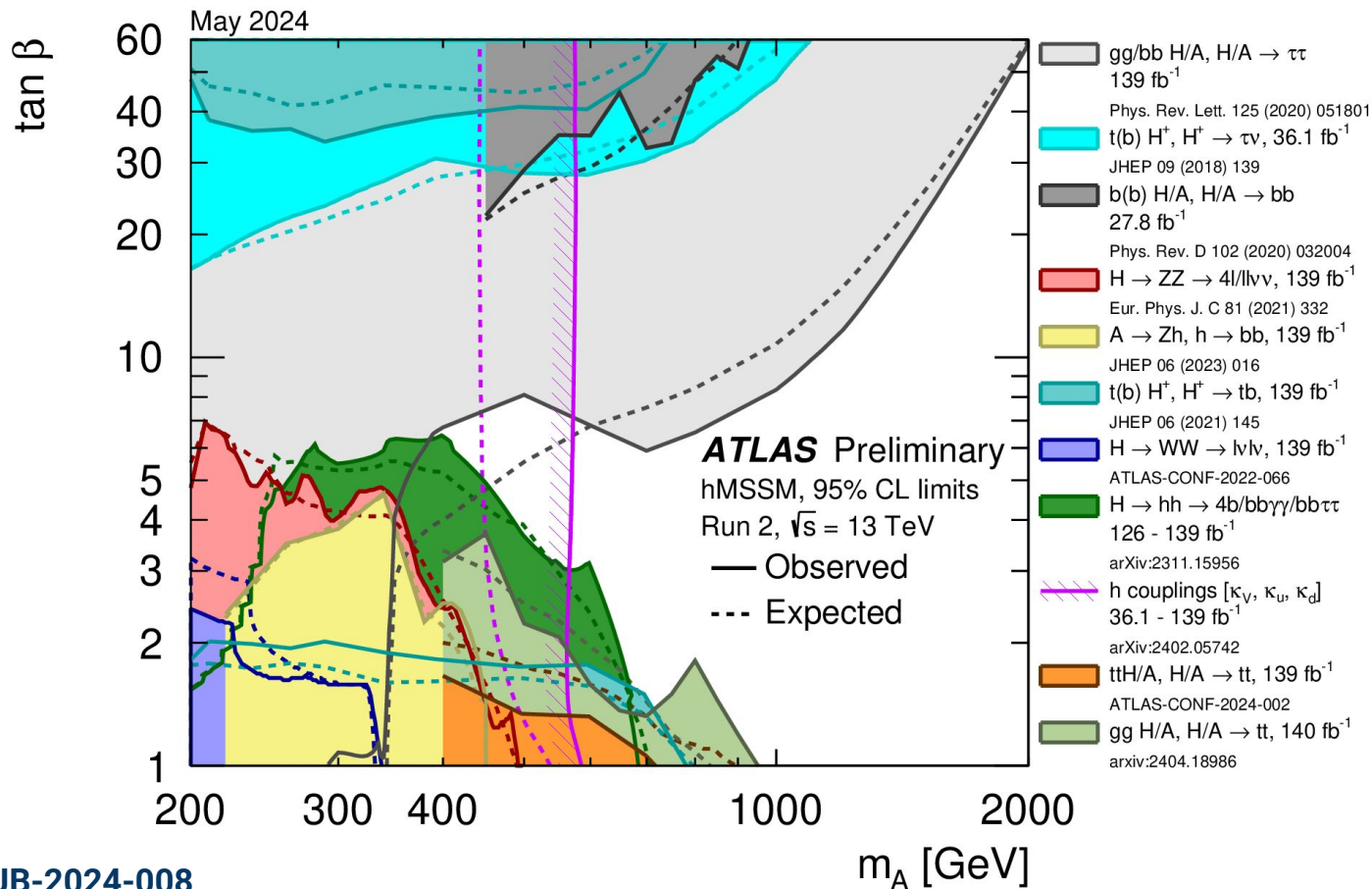
- $H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm$
- $H^{\pm\pm} \rightarrow W^\pm W^\pm$

# Latest Results

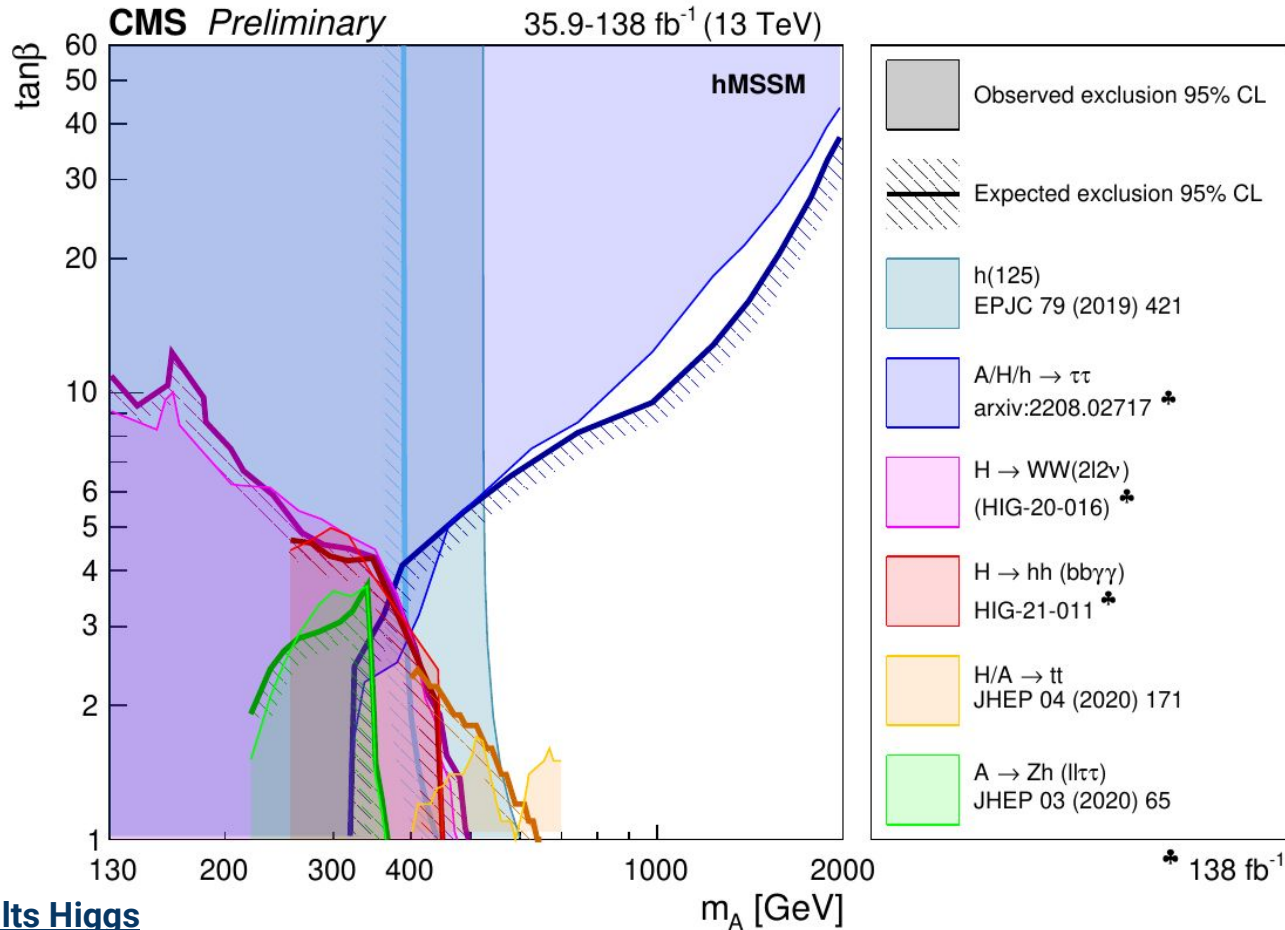


# Interpretations

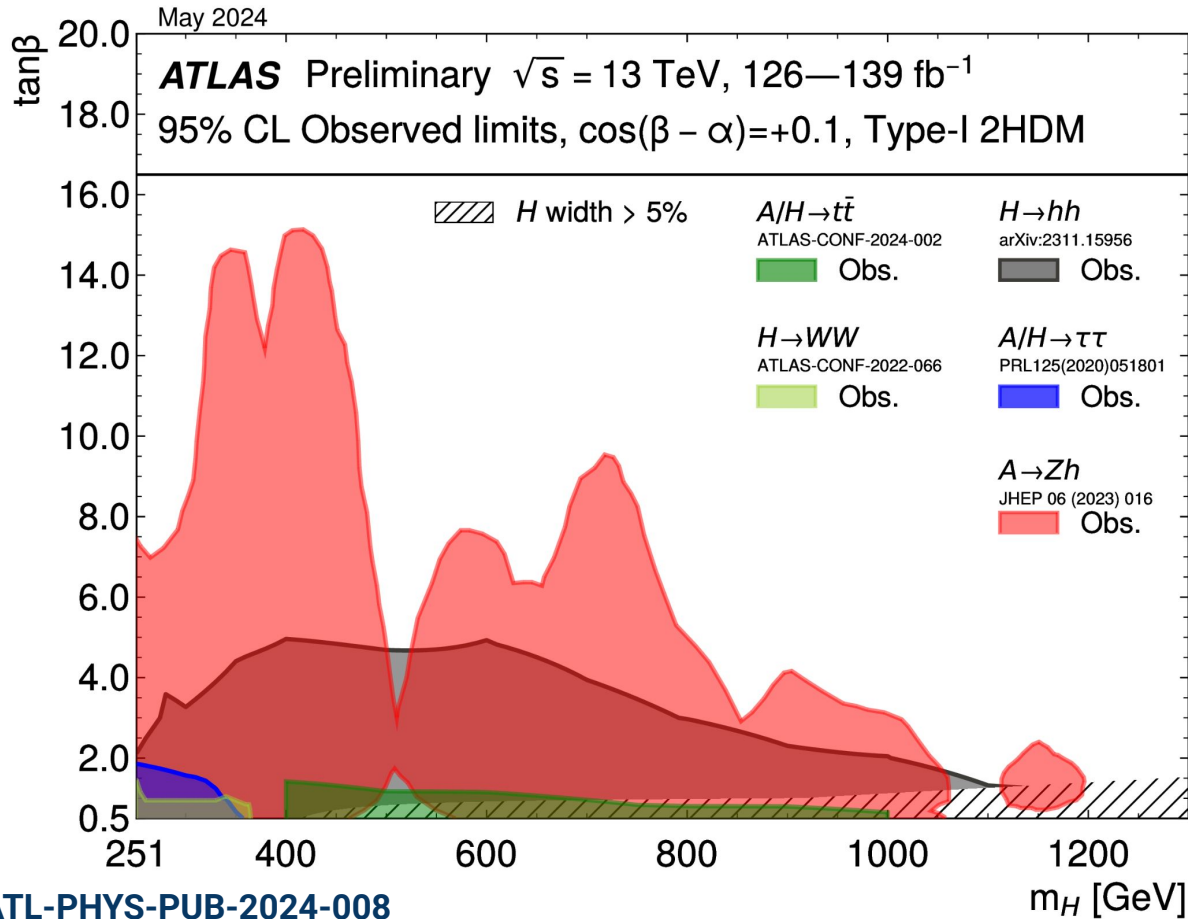
# Exclusion contours on the hMSSM parameter space



# Exclusion contours on the hMSSM parameter space

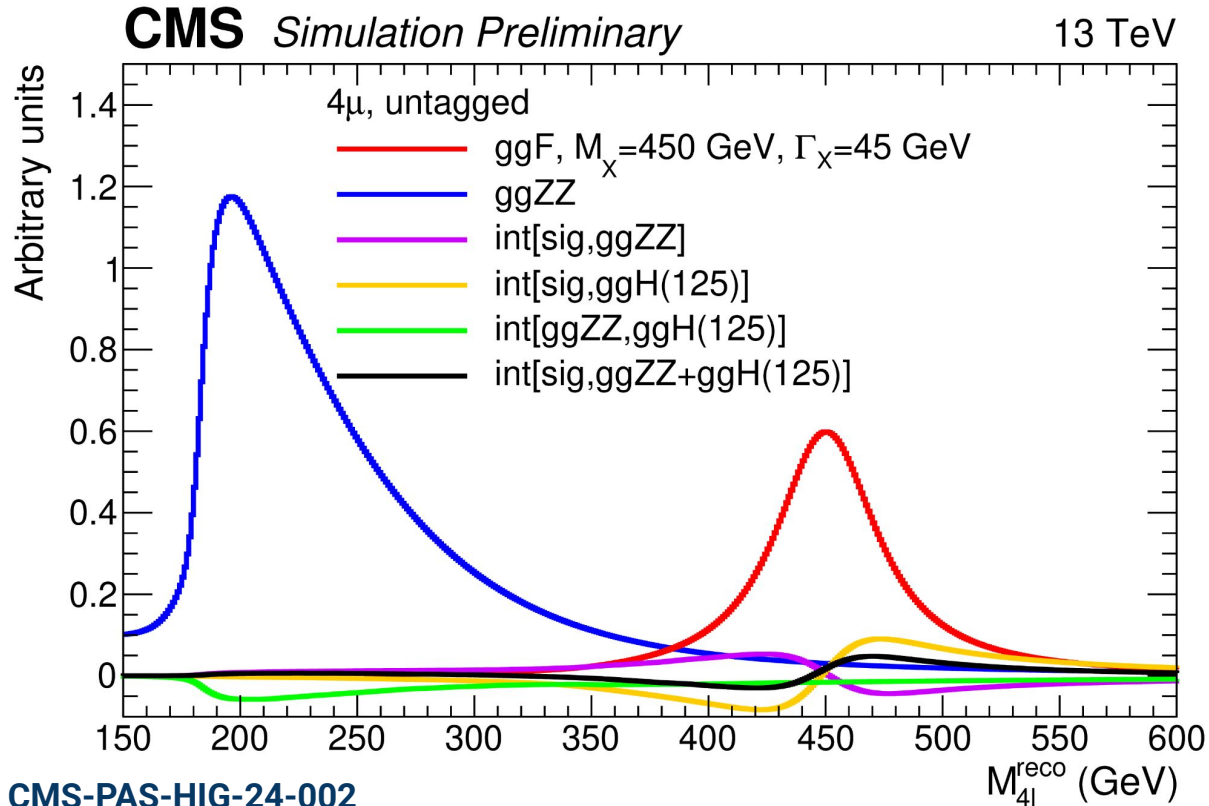


# Exclusion contours on the Type-I 2HDM parameter space



- Relevance of individual analysis channels varies between the selected benchmark models
  - Channels subdominant in one interpretation may be dominant in another
- **Underlines importance to cover full spectrum of different production and decay modes**

# Interpretations (interference effects)



- Large width effects and interference effects are too often ignored in searches at the LHC
  - Of course very model-dependent

**Have some good examples from recent  $X \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$  search**



# Concluding remarks

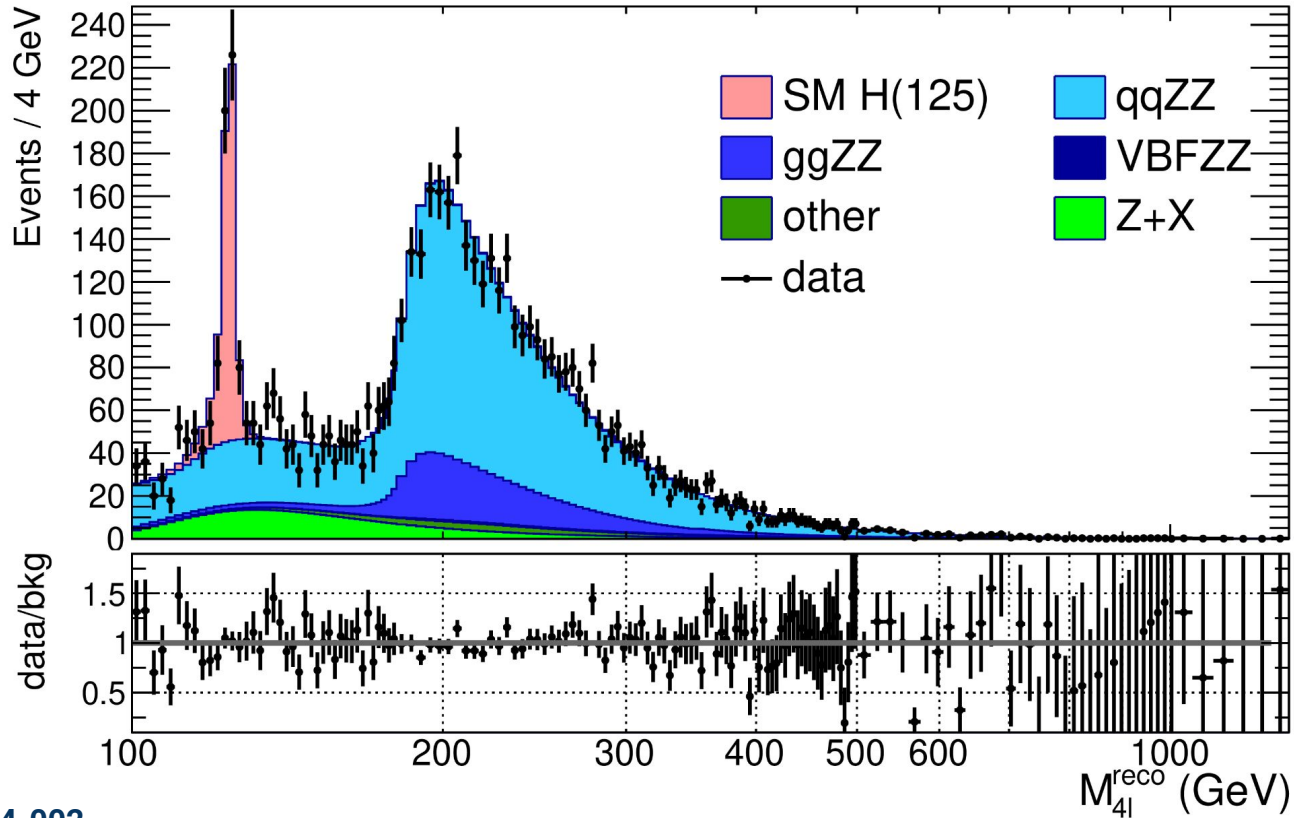
- **Extended Higgs sector is promising to find new physics**
- CMS and ATLAS have recently published several exciting experimental results on searches for additional Higgs bosons (still only based on Run-2 data)
  - Cover extensive list of production and decay modes in searches for neutral/charged heavy/light Higgs bosons
  - Presented only a few highlights of available results.
    - Additional results can be found via the [ATLAS](#) and [CMS](#) publication pages
    - More results (including Wh, Zh and hh searches) to be presented by [Santeri Laurila](#)
  - No significant hint for physics beyond the SM has been observed so far
    - **But there are several small deviations that have to be followed up**
  - Many more results based on the full Run-2 and partial Run-3 dataset are expected in the next month/years
    - **New production and decay channels will become available with increasing statistics**

# Back-up

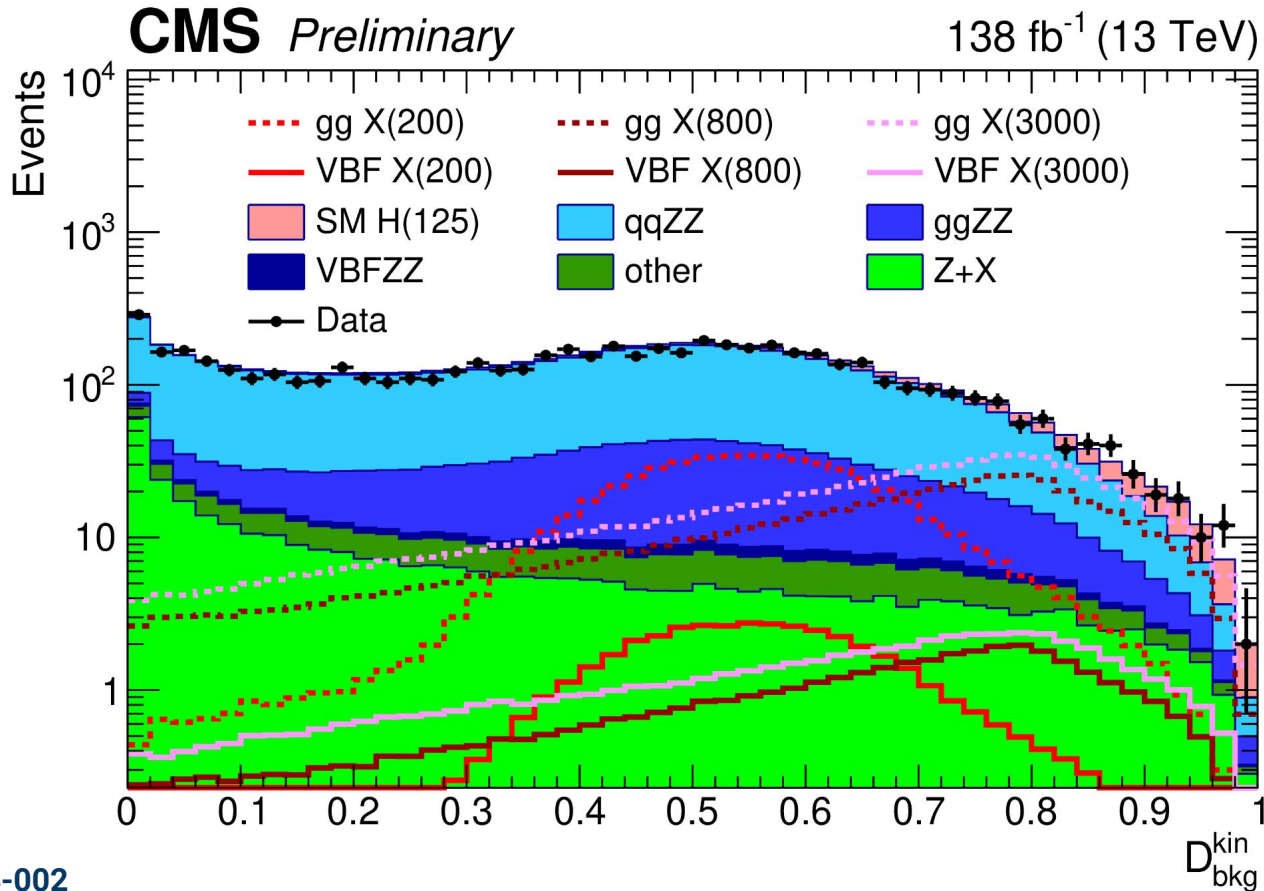
# Search for $X \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$

**CMS** Preliminary

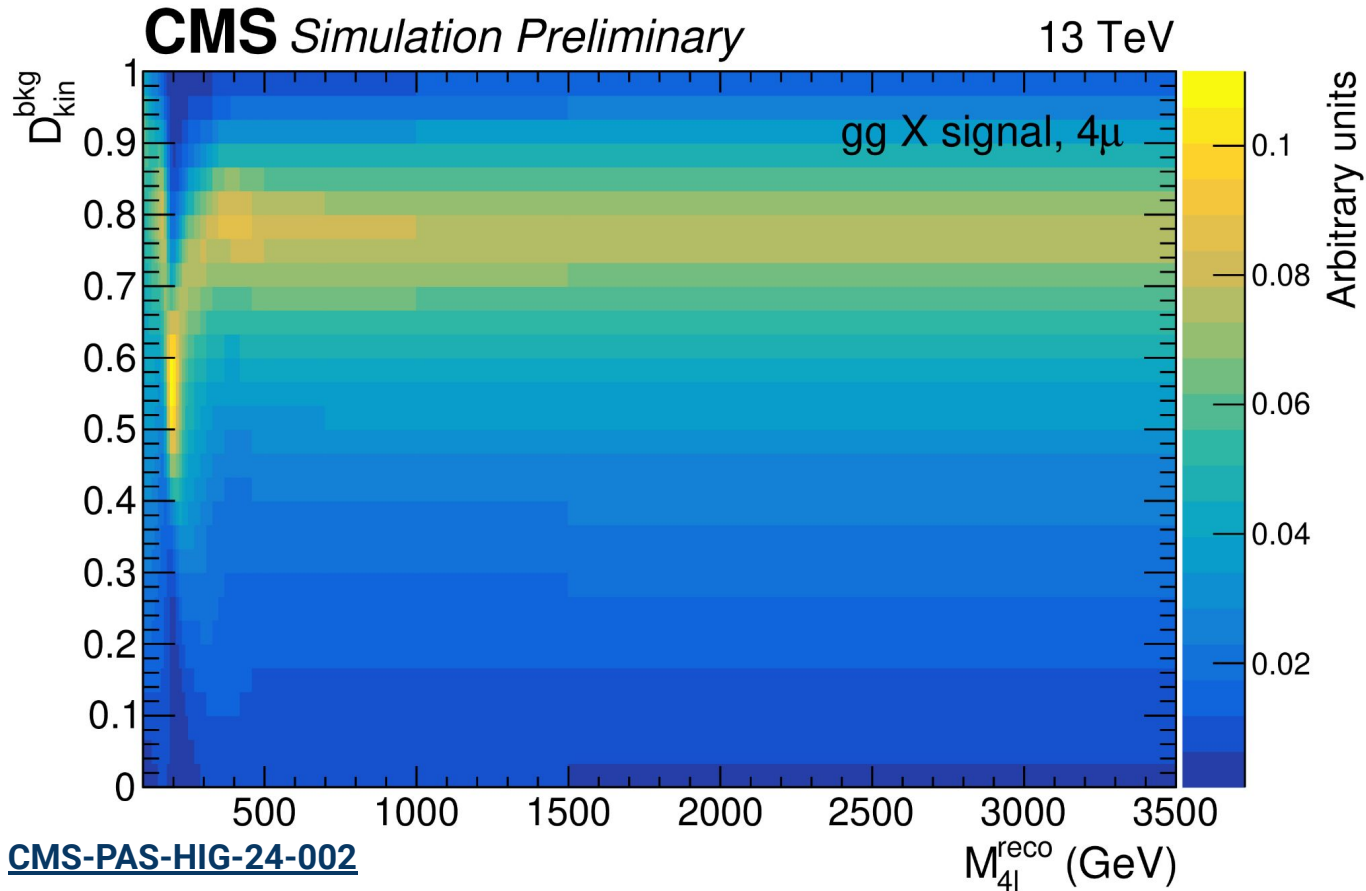
138 fb<sup>-1</sup> (13 TeV)



# Search for $X \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$



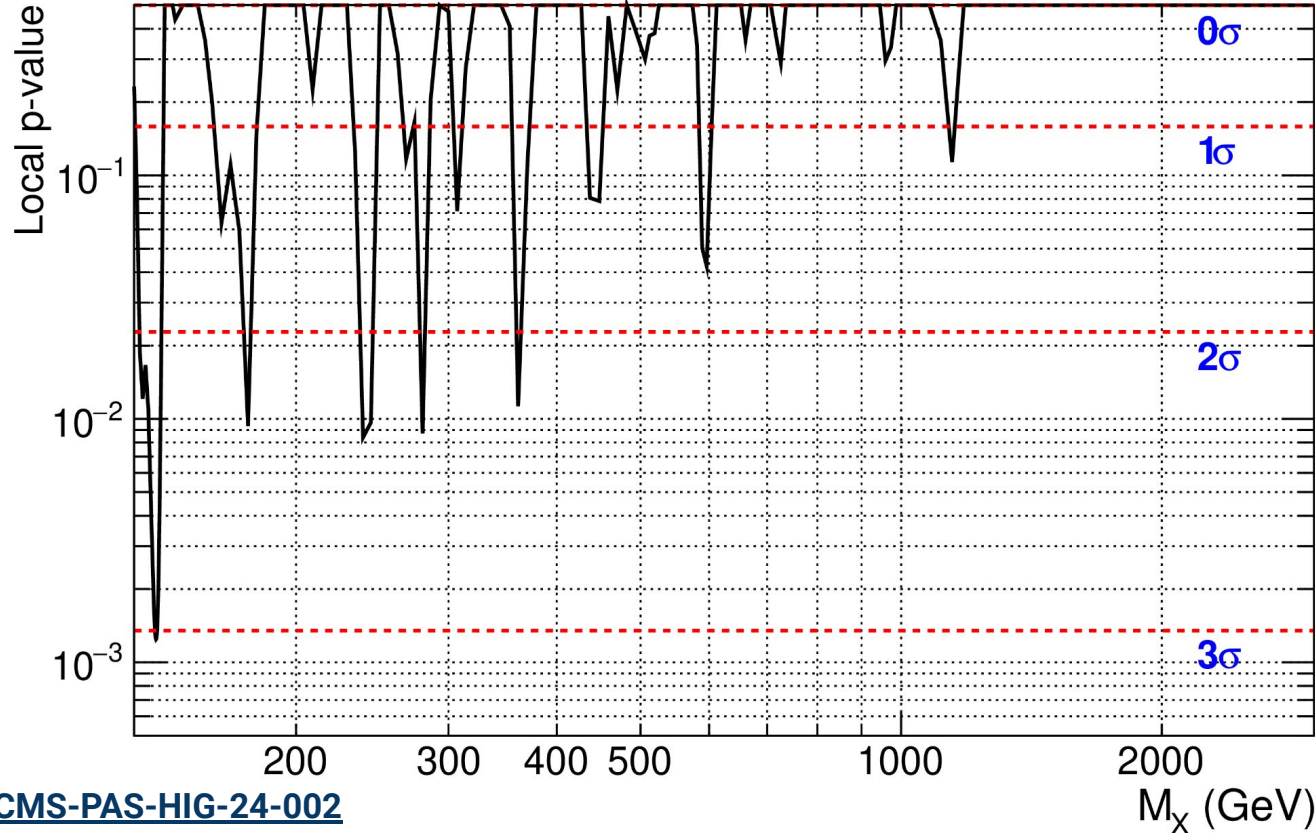
# Search for $X \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$



# Search for $X \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$

**CMS** Preliminary

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

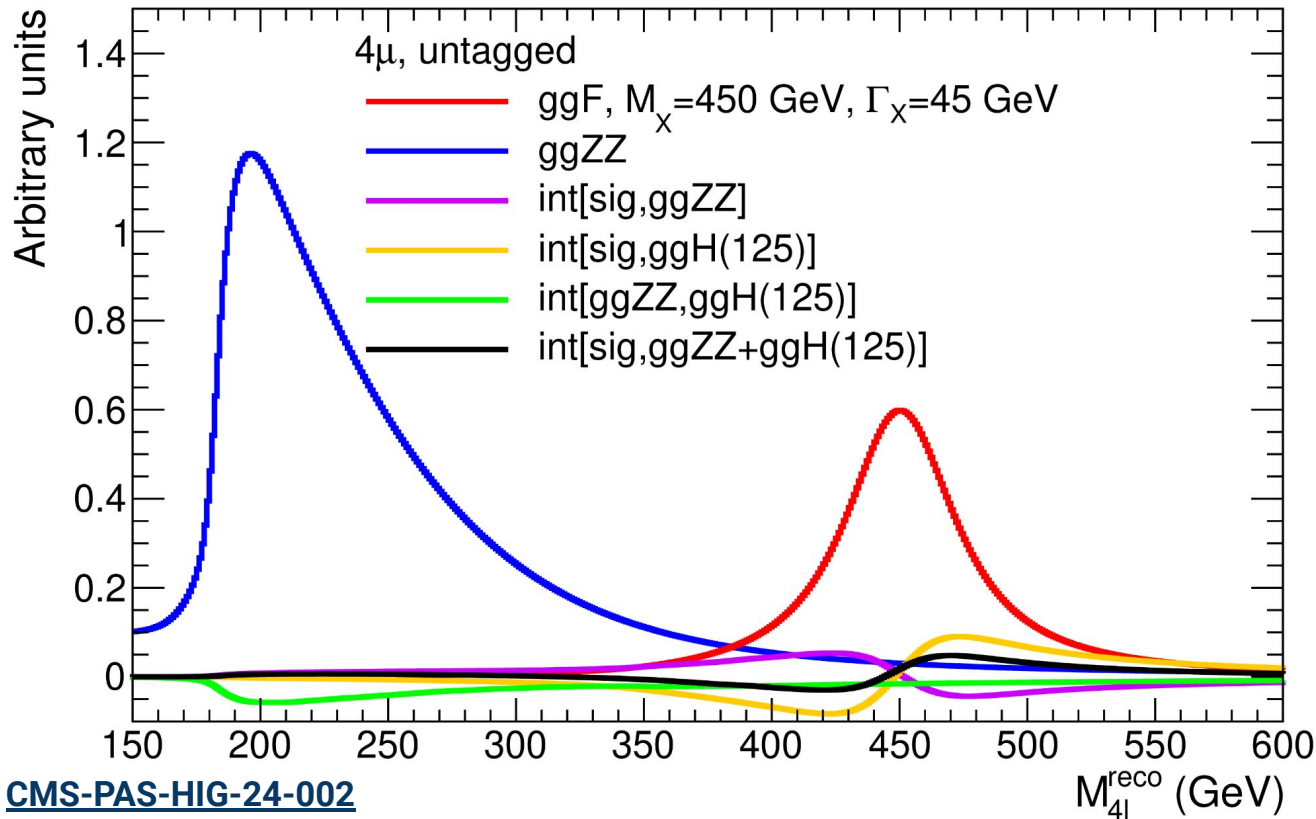


The local p-value as a function of  $M_X$  with  $f_{\text{VBF}}$  floating

# Search for $X \rightarrow ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^-$

**CMS** *Simulation Preliminary*

13 TeV

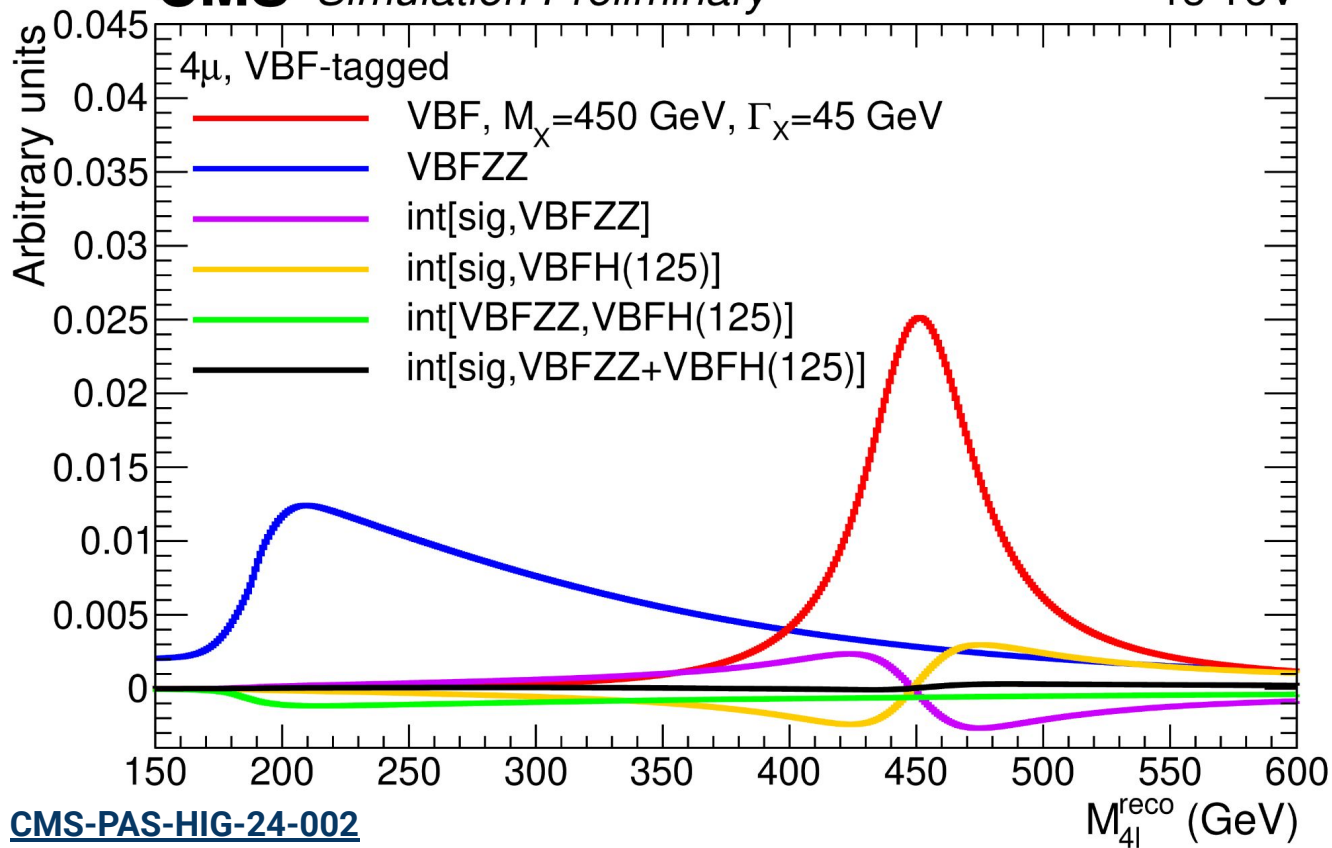


**Examples of interference lineshapes.** The lineshape of the ggF signal with  $M_X = 450$  GeV,  $\Gamma_X = 45$  GeV in the red curve, the lineshape of the  $gg \rightarrow ZZ$  background in the blue curve, and the lineshapes of the three interferences in the violet, orange and green curves.

# Search for $X \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$

**CMS** Simulation Preliminary

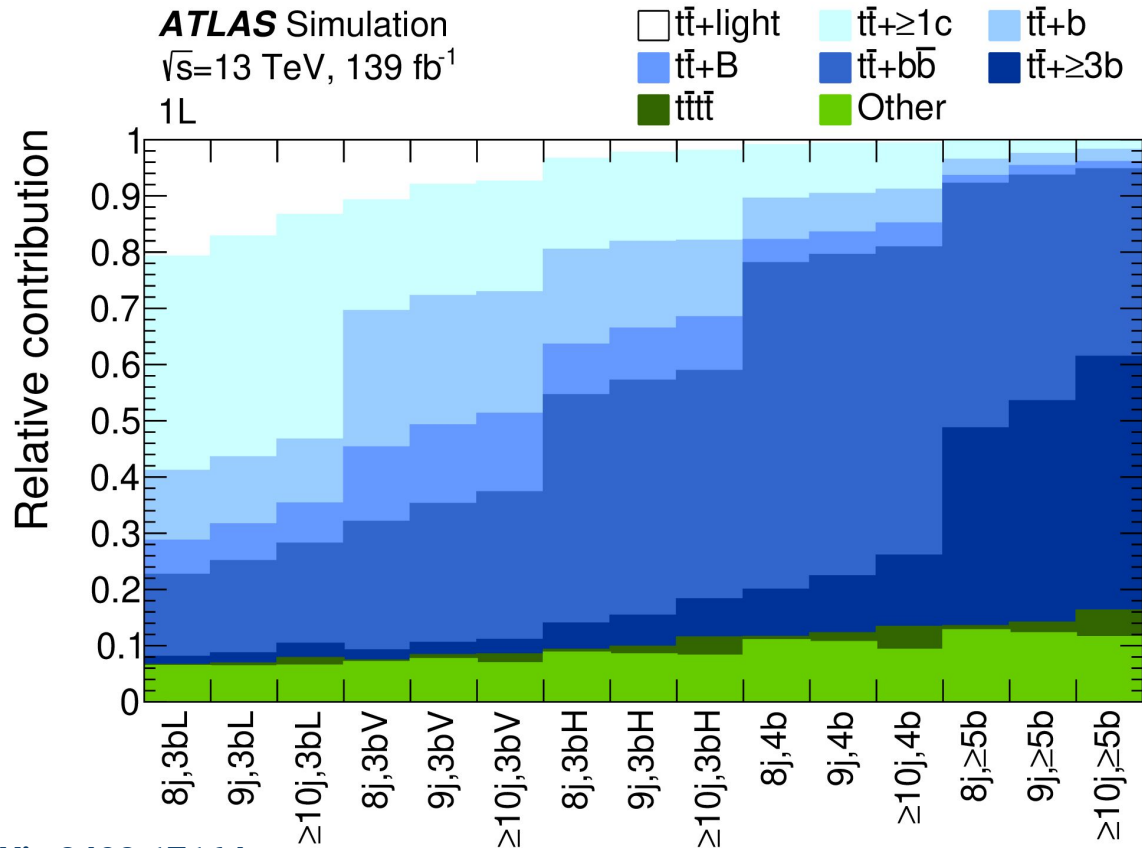
13 TeV



Examples of interference lineshapes. The lineshape of the VBF signal with  $M_X = 450$  GeV,  $\Gamma_X = 45$  GeV in the red curve, the lineshape of the VBF ZZ background in the blue curve, and the lineshapes of the three interferences in the violet, orange and green curves.



# Search for H/A in 4 top events

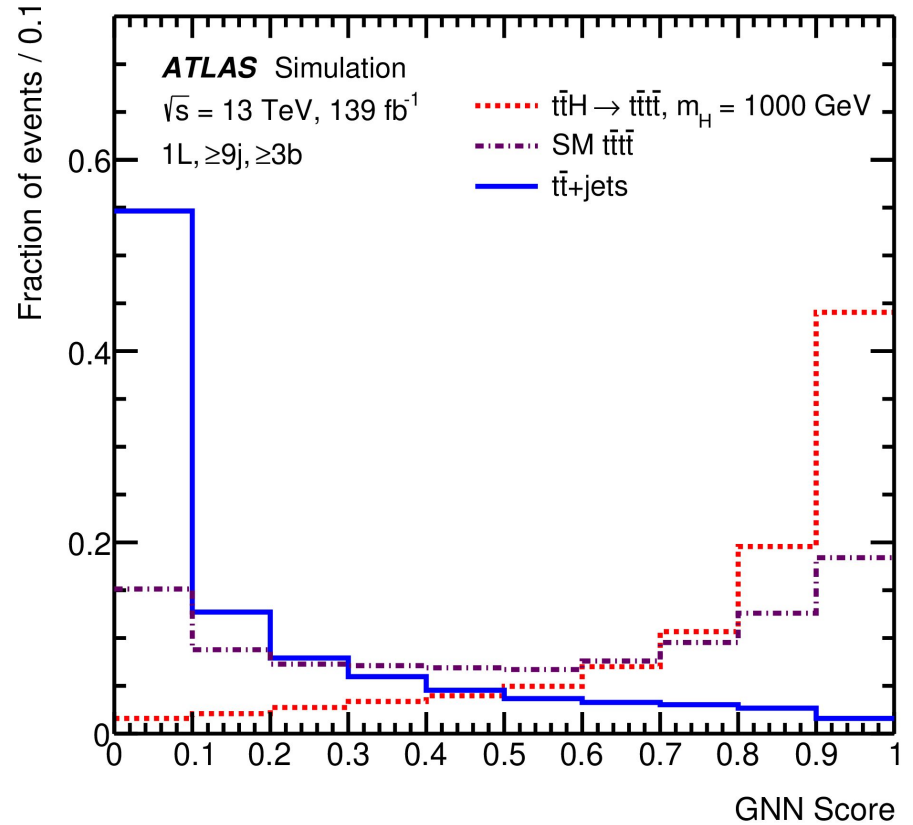
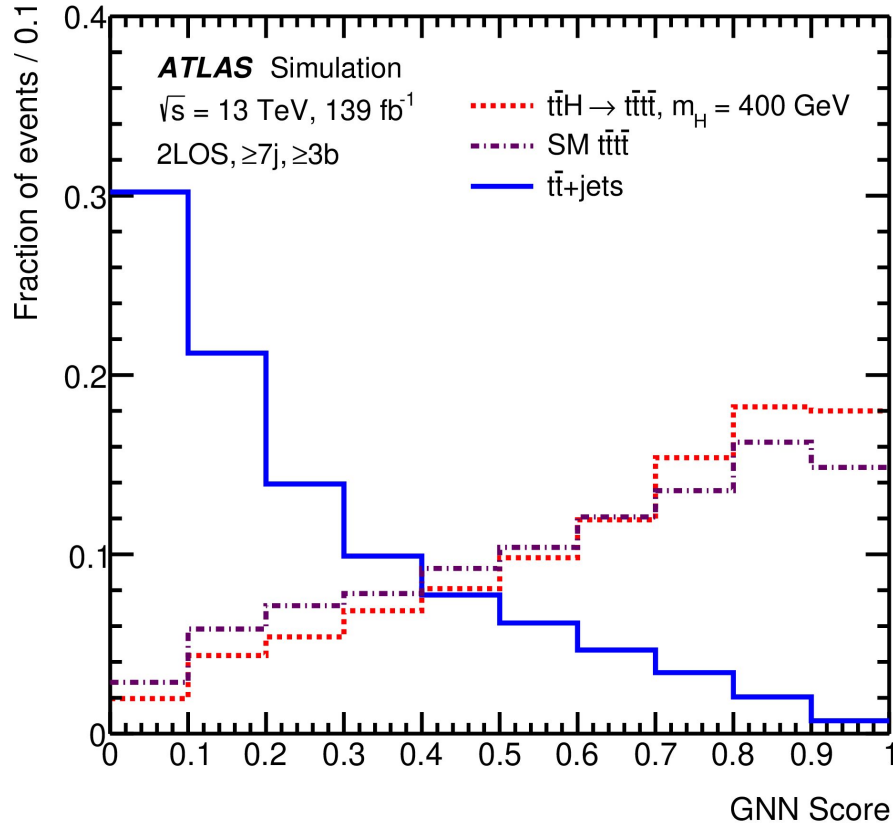


The relative contribution of the different background classes in the control, validation and signal regions in the 1L channels.

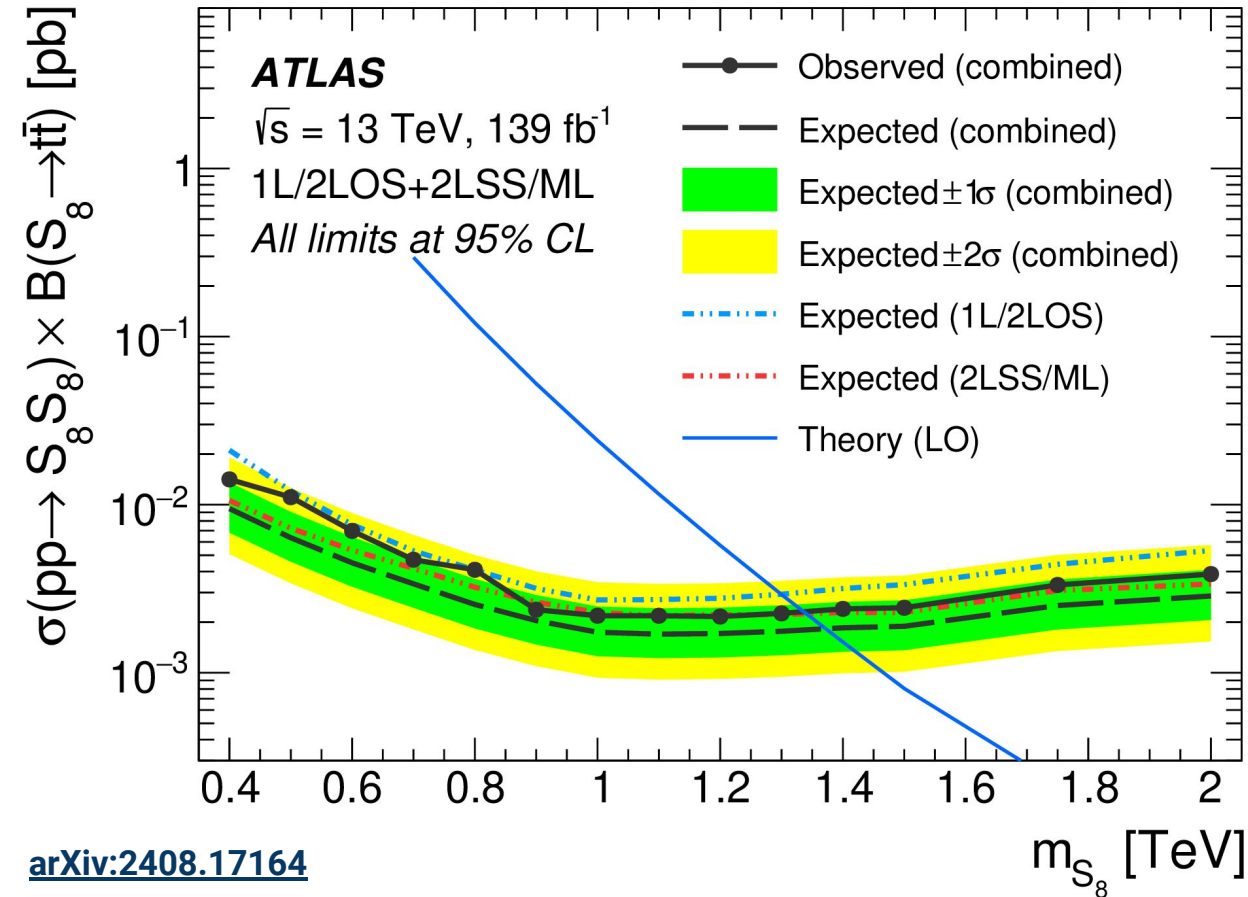
# Search for H/A in 4 top events

Variable	Description	
$\sum_{i \in [1,6]} \text{pcb}_i$	Sum of the pcb scores of the six jets with the highest scores	<b>The list of global features used in the GNN training in descending order of importance in the training of the 1L GNN</b>
$H_T$	$p_T$ sum of all reconstructed leptons and jets	
$N_{\text{jets}}$	Number of jets	
$H_T^{\text{ratio}}$	$p_T$ sum of the four leading jets in $p_T$ divided by the $p_T$ sum of the remaining jets	
$dR_{jj}^{\text{avg.}}$	Average $\Delta R$ across all jet pairs	
$m_T^W$	$W$ boson transverse mass calculated using the lepton four-momenta and $E_T^{\text{miss}}$ (1L only)	
$\Delta R_{bb}^{\text{min.}}$	Minimum $\Delta R$ between any pair of jets $b$ -tagged at the 70% OP	
$\Delta R_{\ell b}^{\text{min.}}$	Minimum $\Delta R$ between any pair of lepton and jet $b$ -tagged at the 70% OP	
$m_{bbb}^{\text{avg.}}$	Average invariant mass of all triplets of jets $b$ -tagged at the 70% OP	
$m_{jjj}^{\text{avg.}}$	Average invariant mass of all triplets of jets with an angular separation of $\Delta R < 3$	
$\sum d_{12}$	Sum of the first $k_t$ splitting scale $d_{12}$ over all large- $R$ jets	
$\sum d_{23}$	Sum of the second $k_t$ splitting scale $d_{23}$ over all large- $R$ jets	
$N_{\text{LR-jets}}$	Number of large- $R$ jets with a mass greater than 100 GeV	
Centrality	$\sum_i p_T^i / \sum_i E_i$ where the sums are performed over all reconstructed jets and leptons	
$m_{\ell\ell}$	Invariant mass of the two leptons (2LOS only)	<a href="https://arxiv.org/abs/2408.17164">arXiv:2408.17164</a>

# Search for H/A in 4 top events



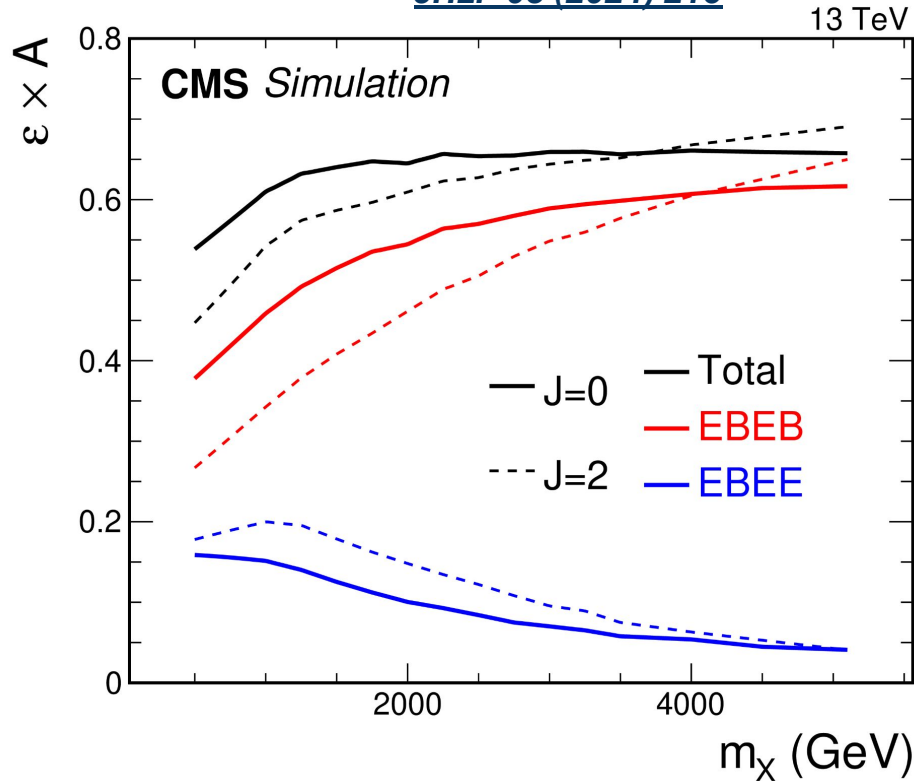
# Search for H/A in 4 top events



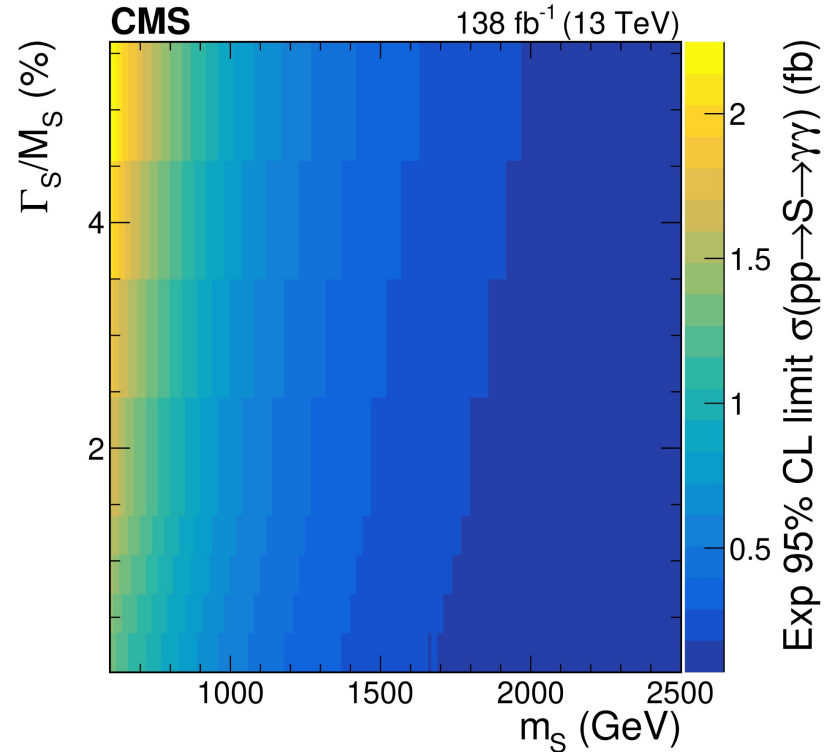
Expected and observed 95% CL upper limits on the  $S_8 S_8 \rightarrow 4 \text{ top}$  production cross-section as a function of  $m_{S_8}$ , obtained from the combination of the 1L/2LOS and 2LSS/ML final states. The expected limits from the individual 1L/2LOS and 2LSS/ML analyses are also shown. The predicted production cross-section is shown with the solid blue curve.

# Search for new physics in high-mass diphoton events

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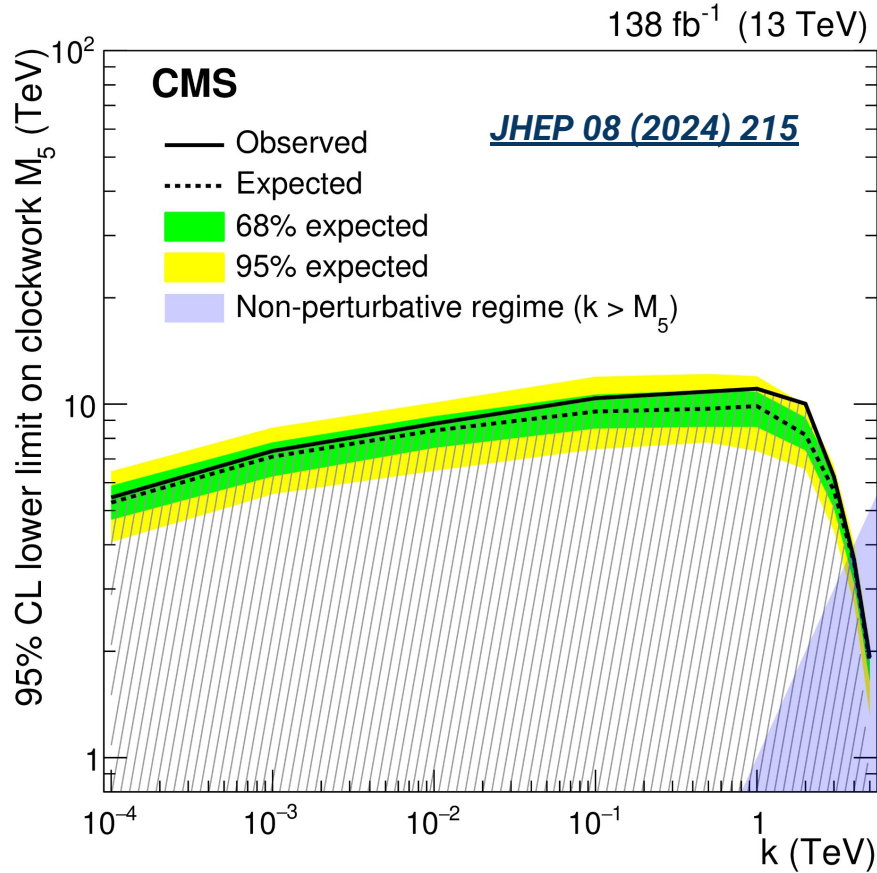


The product of the acceptance and the event selection efficiency is shown as a function of the signal resonance mass for the narrow signal width hypothesis



Observed 95% CL upper limits on the product of the cross section and branching fraction as a function of the Higgs boson mass versus the resonance width

# Search for new physics in high-mass diphoton events



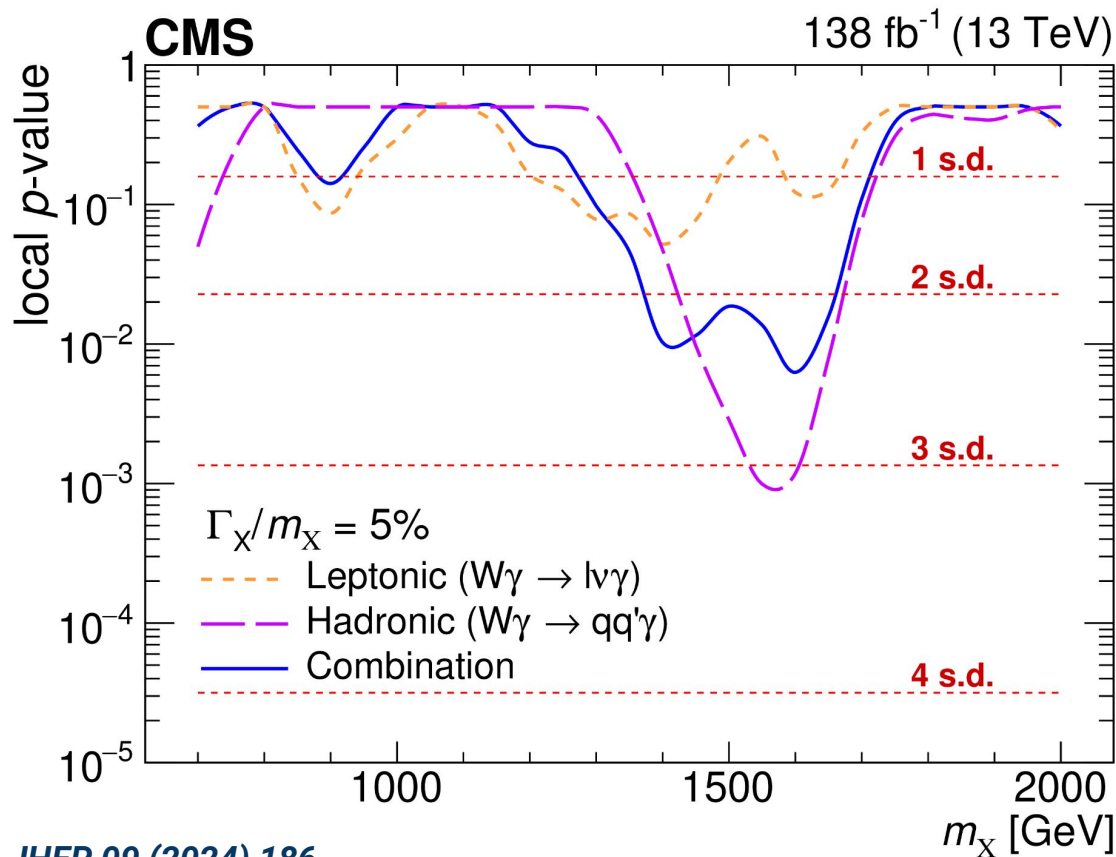
The exclusion limit for the clockwork framework over the  $k$ - $M_5$  parameter space. The darker shaded region denotes where the theory becomes nonperturbative. The region below the solid line constitutes the excluded region. Expected 68% and 95% limit bands are shown in green and yellow, respectively.

# Search for $H^\pm \rightarrow cs$ decays

Variable type	Variable name	Definition
<b>Top-quark kinematic variables</b>		
$t_{\text{had}}$	$j_1 p_T$	$p_T$ of $j_1$ -labelled jet
	$j_2 p_T$	$p_T$ of $j_2$ -labelled jet
	$b_{\text{had}} p_T$	$p_T$ of $b_{\text{had}}$ -jet
	$b_{\text{had}}^{t_{\text{had}}\text{-rest}} p$	Momentum of $b_{\text{had}}$ -jet in $t_{\text{had}}$ rest frame
	dijet mass	Invariant mass of $j_1+j_2$ jets
	$(j_1+b_{\text{had}})$ mass	Invariant mass of $j_1+b_{\text{had}}$ jets
	$(j_2+b_{\text{had}})$ mass	Invariant mass of $j_2+b_{\text{had}}$ jets
	$\cos \theta$	Boson spin sensitive variable
$t_{\text{lep}}$	$b_{\text{lep}} p_T$	$p_T$ of $b_{\text{lep}}$ -jet
	Lepton $p_T$	$p_T$ of reconstructed lepton
	$W$ mass	Invariant mass of reconstructed $W$ boson
	$t_{\text{lep}}$ mass	Invariant mass of reconstructed $t_{\text{lep}}$
	$t_{\text{lep}} p_T$	$p_T$ of reconstructed $t_{\text{lep}}$
$t\bar{t}$ -system	$\Delta R(b_{\text{lep}}, b_{\text{had}})$	$\Delta R$ between the $b_{\text{lep}}$ -jet and $b_{\text{had}}$ -jet
	$t\bar{t}$ mass	Invariant mass of $t_{\text{had}}+t_{\text{lep}}$
<b>Event variables</b>		
Event level	$N_{\text{jets}}$	Number of jets in the event
	$S_T$	Scalar $p_T$ sum of all calibrated objects
	$P_{t\bar{t}}$	Normalised probability of correct jet labelling
<b>Flavour-tagging variables</b>		
Flavour-tagging score	$j_1$ PCFT	PCFT score of $j_1$
	$j_2$ PCFT	PCFT score of $j_2$
	$b_{\text{had}}$ PCFT	PCFT score of $b_{\text{had}}$ -jet
	$b_{\text{lep}}$ PCFT	PCFT score of $b_{\text{lep}}$ -jet
Number of tags	$N_{c\text{-tagLo}}$	Number of jets passing loose $c$ -tag WP ( $b$ -veto)
	$N_{c\text{-tagTi}}$	Number of jets passing tight $c$ -tag WP ( $b$ -veto)
	$N_{b\text{-tag70}}$	Number of jets passing 70% $b$ -tag WP
	$N_{b\text{-tag60}}$	Number of jets passing 60% $b$ -tag WP

**Final list of input variables used in the training of the boosted decision trees**

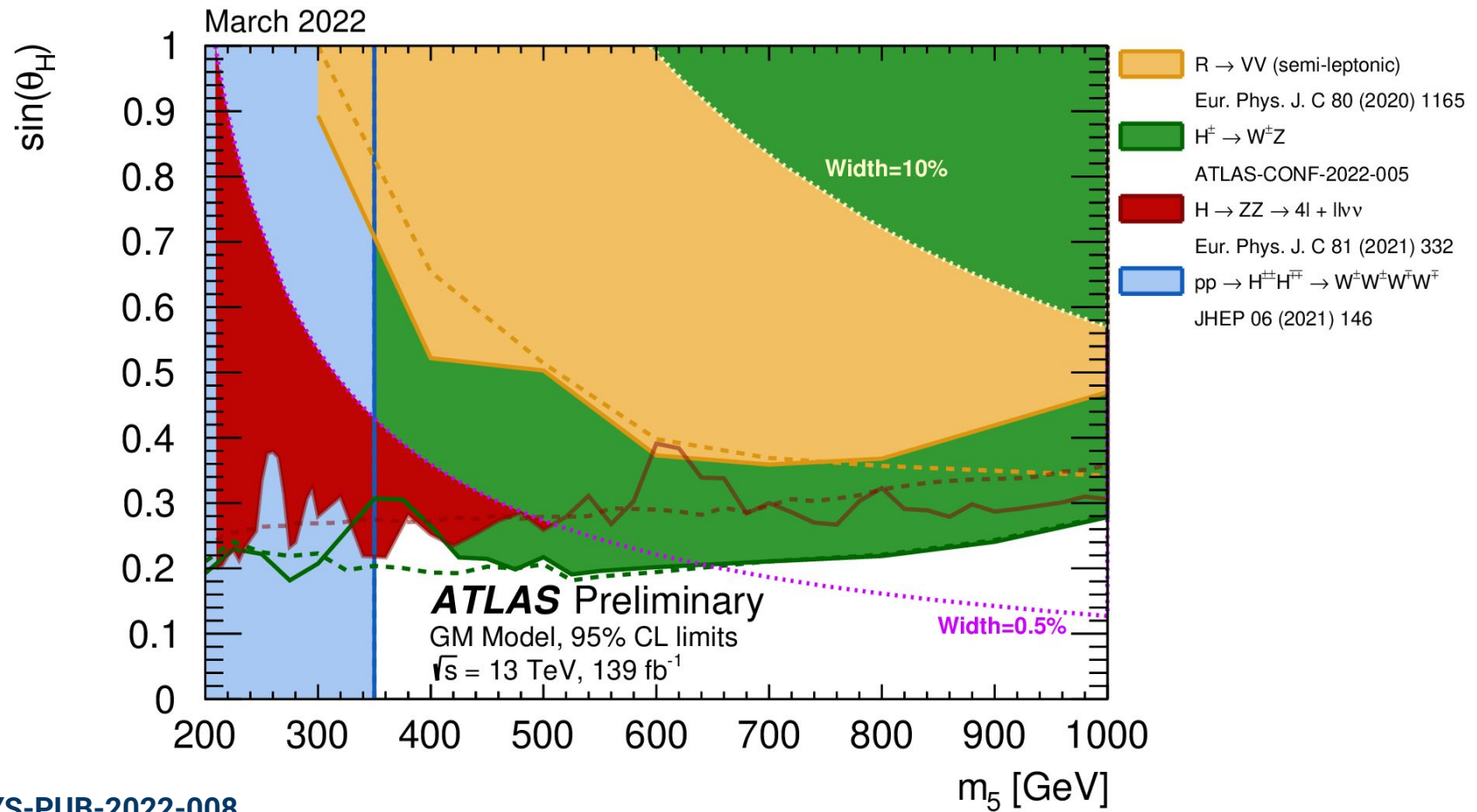
# Search for $H^\pm \rightarrow W^\pm \gamma$ decays



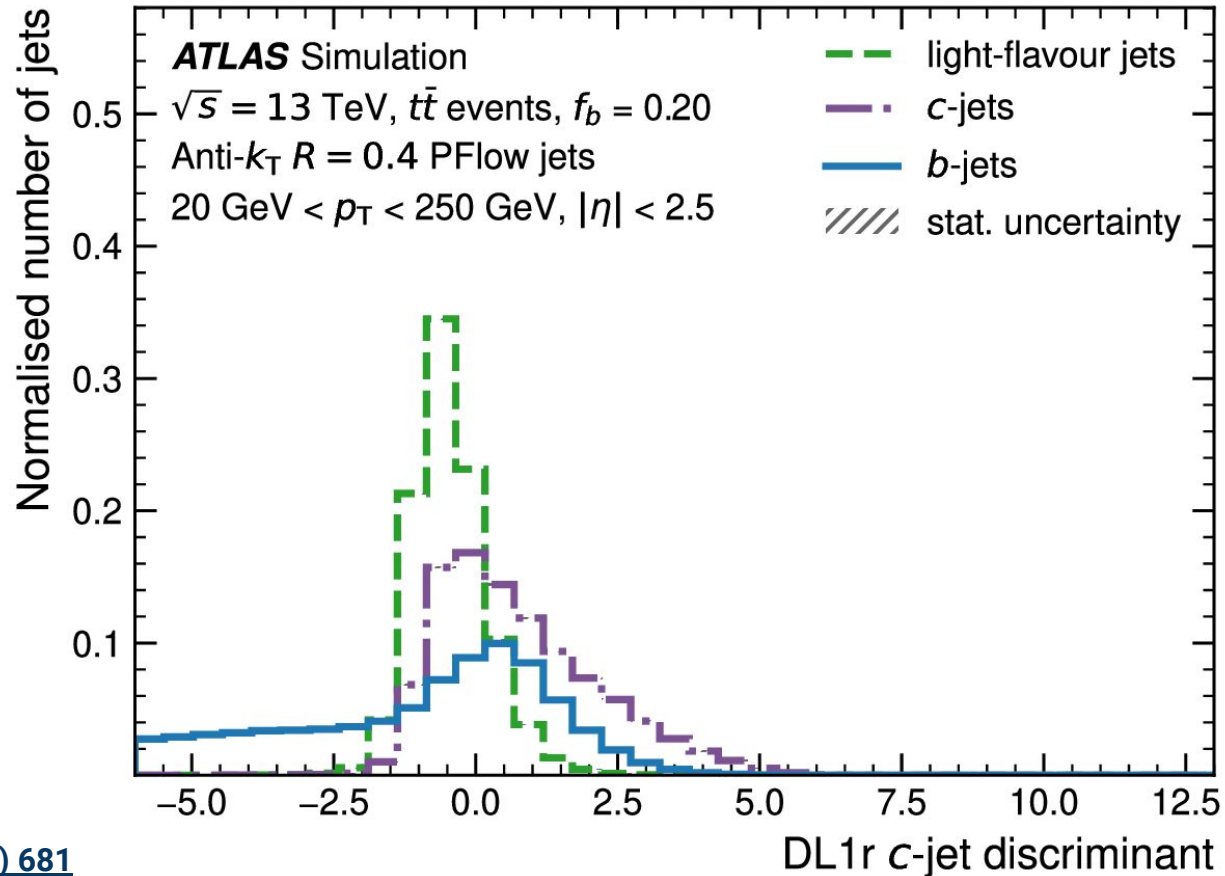
Observed local  $p$ -values for broad resonance width hypotheses with the background-only fit in the hadronic and leptonic channels. The blue line shows the observed local  $p$ -values after their combination. In the hadronic channel (violet line), the largest excess corresponds to a local significance of 3.1 s.d. In the leptonic channel (orange line), the largest local significance is 1.6 s.d.. After combining with the leptonic channel, the largest excess is 2.5 s.d.



# Exclusion contours on the parameter space of the Georgi-Machacek model



# ATLAS c-jet tagging



# Interference pattern in $t\bar{t}$ resonance searches

