High-mass new scalars at the LHC *with H in the final state*

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on behalf of the ATLAS and CMS Collaborations

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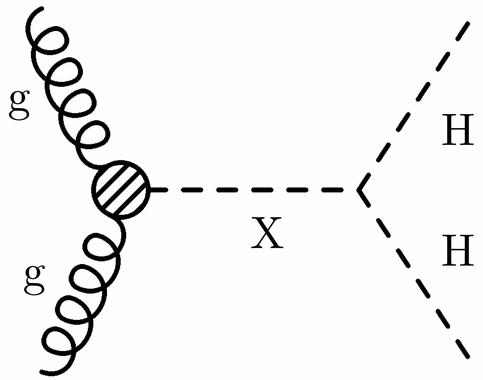
Searches for a high-mass scalar X decaying to H

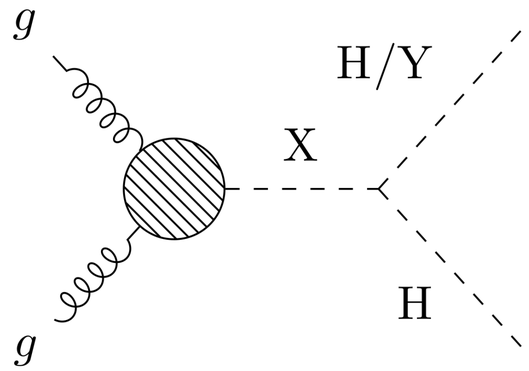
- Taking H to be an **SM-like 125 GeV Higgs boson**, we can consider several types of (pseudo)scalar decays:

X→HH



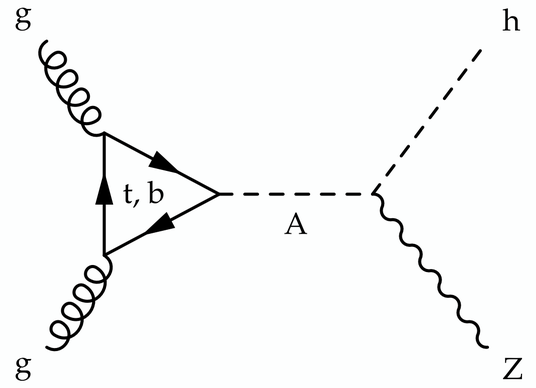
- Predicted in various different models, from very simple extended Higgs sector models (e.g. **real singlet model**) to warped extra dimension (**WED**) models

X→YH



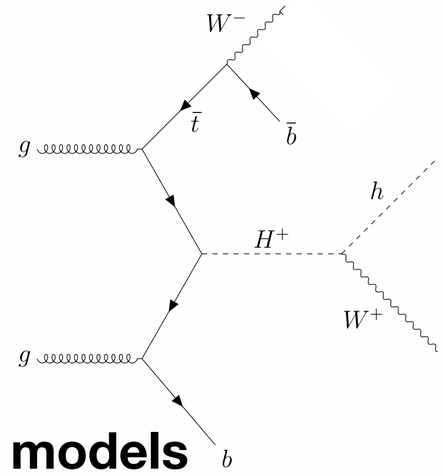
- Predicted in extended Higgs sector models, such as two-real-singlet model (**TRSM**), two-Higgs-doublet model with a compex singlet (**2HDM+S**), includig the **NMSSM**
- **Y** is a neutral BSM scalar or pseudoscalar

A→ZH



- Motivated by **2HDM**, **MSSM**

H⁺→WH

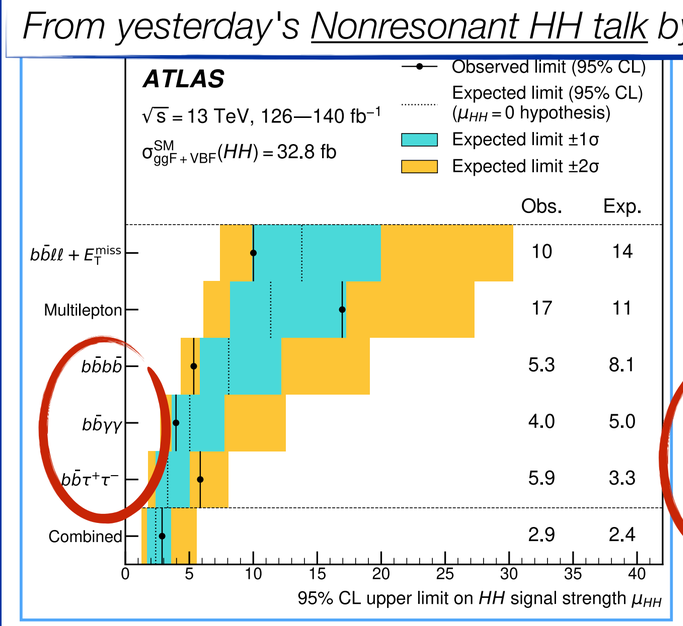


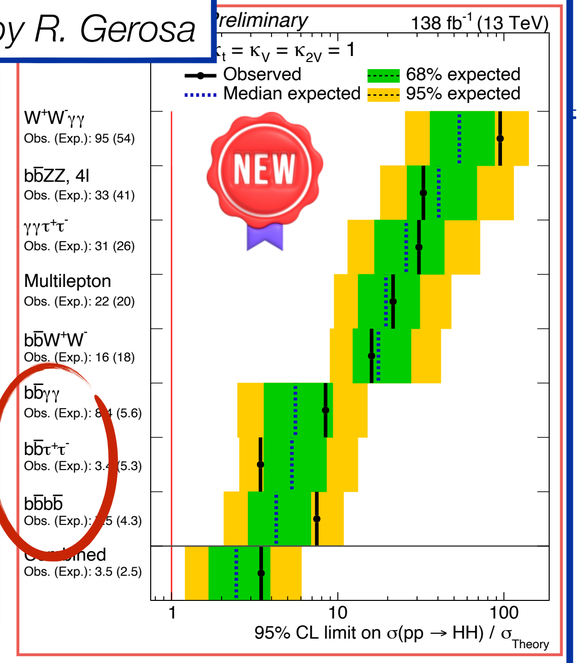
- Motivated by **3HDM**, **triplet models**

X→HH/YH at LHC

- Sensitivity for **X→HH** signals is driven by the **same 3 "golden channels" as the nonresonant HH** searches: **bbbb, bbττ, bbγγ**
  - Experimental **challenges** and analysis **strategies** & **techniques** are typically similar to the nonresonant HH searches
  - Both ATLAS and CMS have now performed analyses in these channels with the full Run-2 data set at 13 TeV, plus **statistical combinations**
- For more generic **X→YH** searches there are **no a priori golden channels**, since the branching fractions of Y are unknown
  - Many final states still uncovered, rapidly expanding search program
  - **Highlights** of recent results shown today

From yesterday's Nonresonant HH talk by R. Gerosa

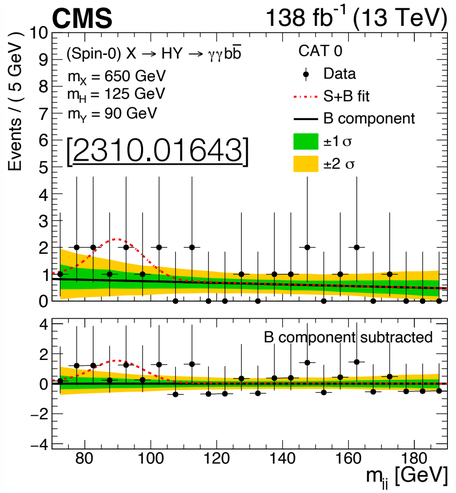


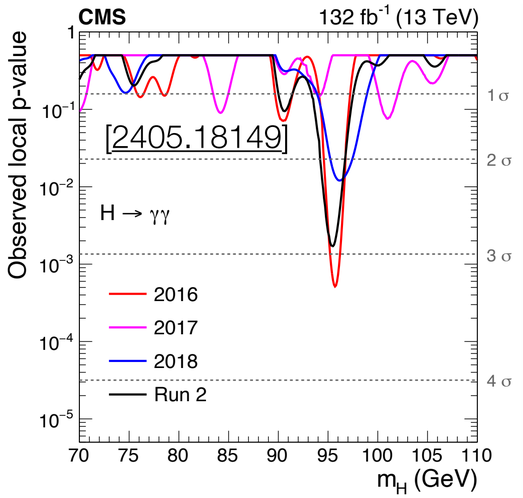


ATLAS: 95% CL on μ_{HH} is 2.9 (2.4) x SM

CMS: 95% CL on μ_{HH} is 3.4 (2.5) x SM

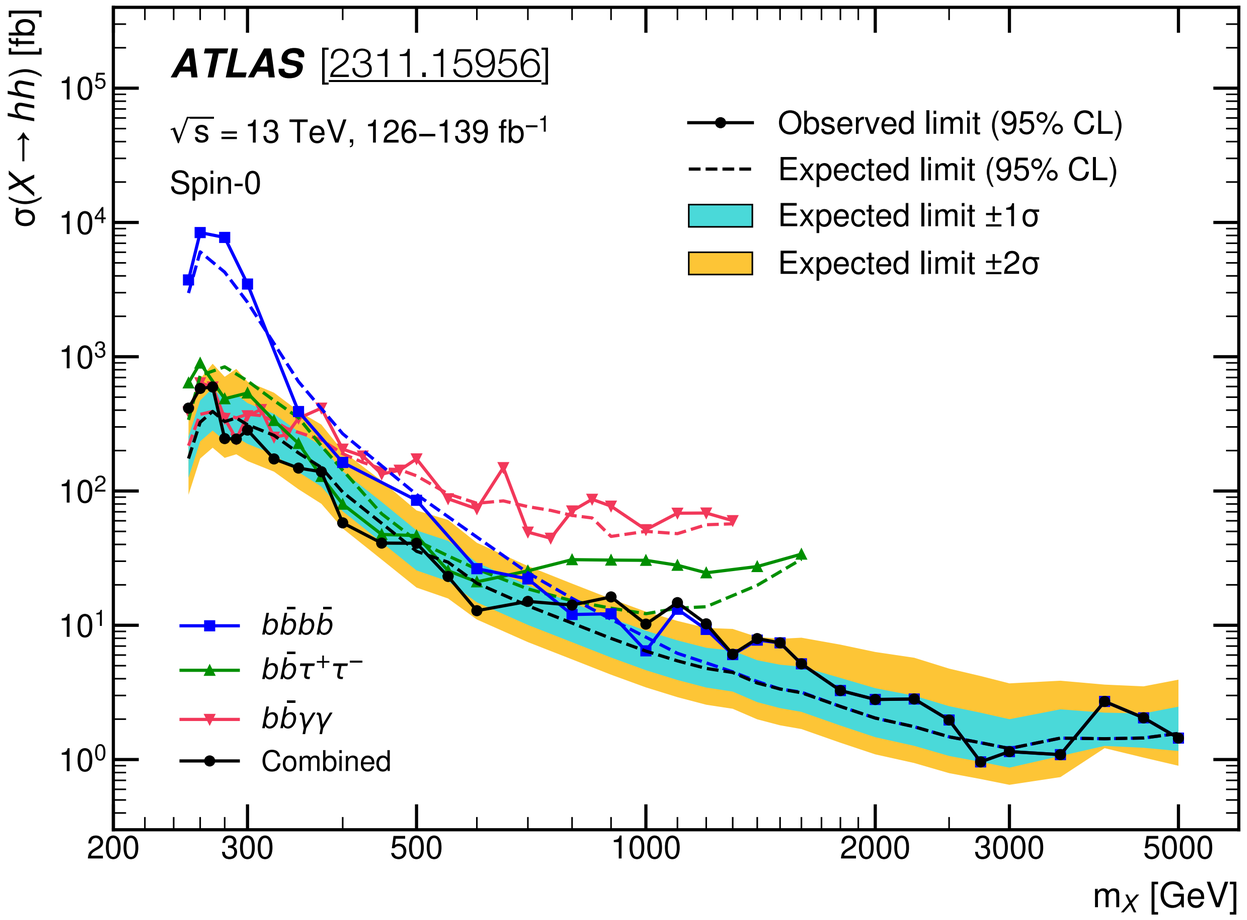
In 2022, CMS reported 3.8σ (<2.8σ local) excess in X→H(bb)Y(γγ) at ***(m_X,m_Y) = (650, 90)*** *GeV, consistent with 2.9σ (1.3σ) excess in Y→γγ*

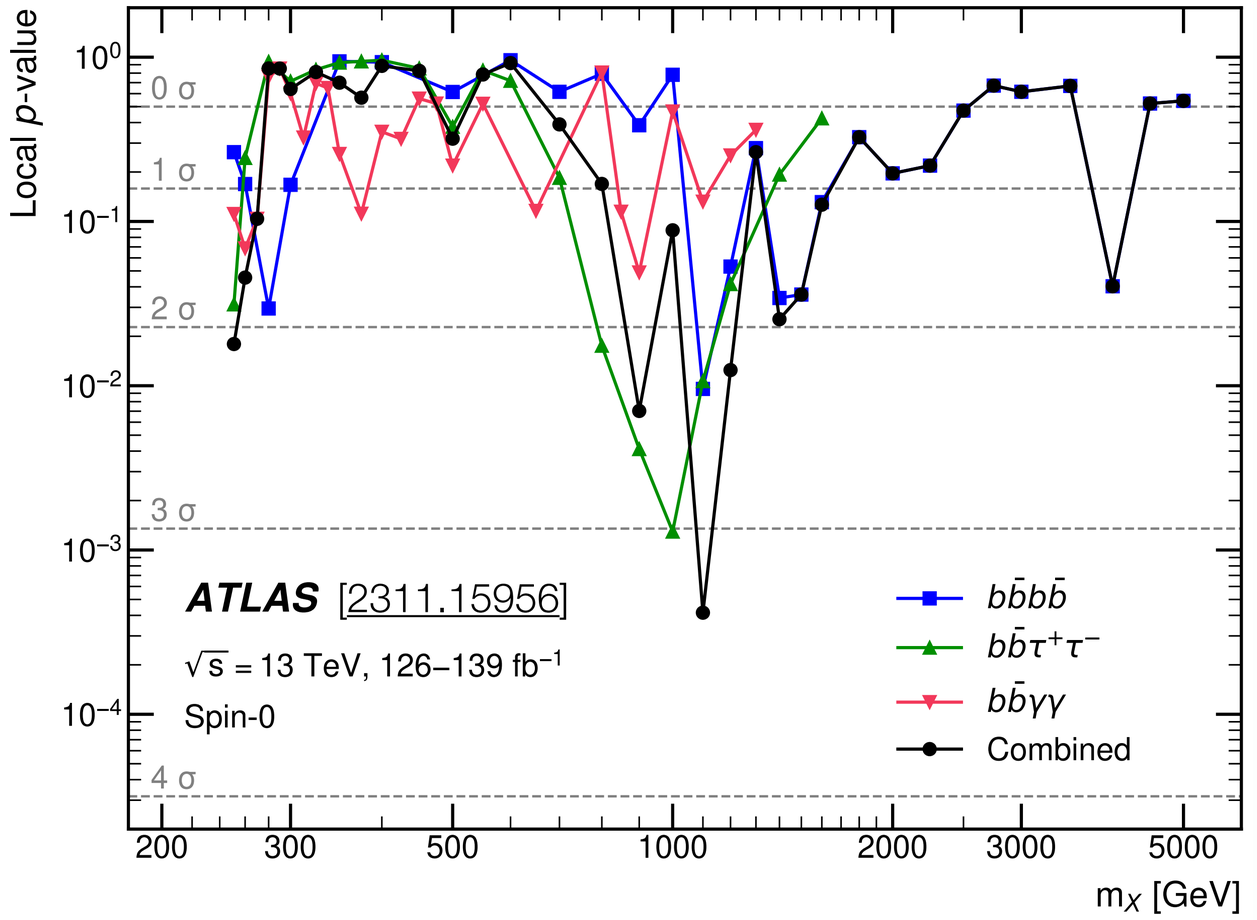




X→HH: Combinations & Interpretations

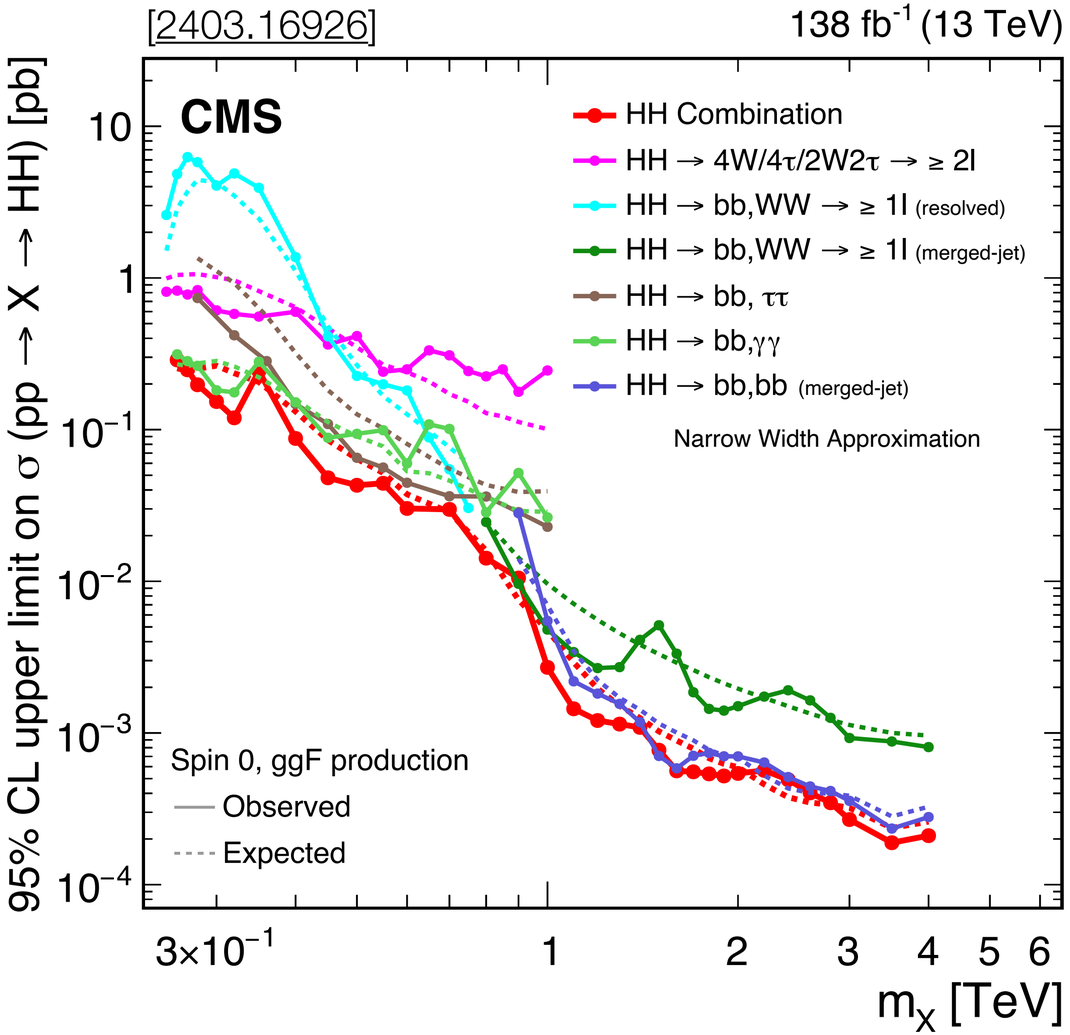
X→HH: ATLAS Combination

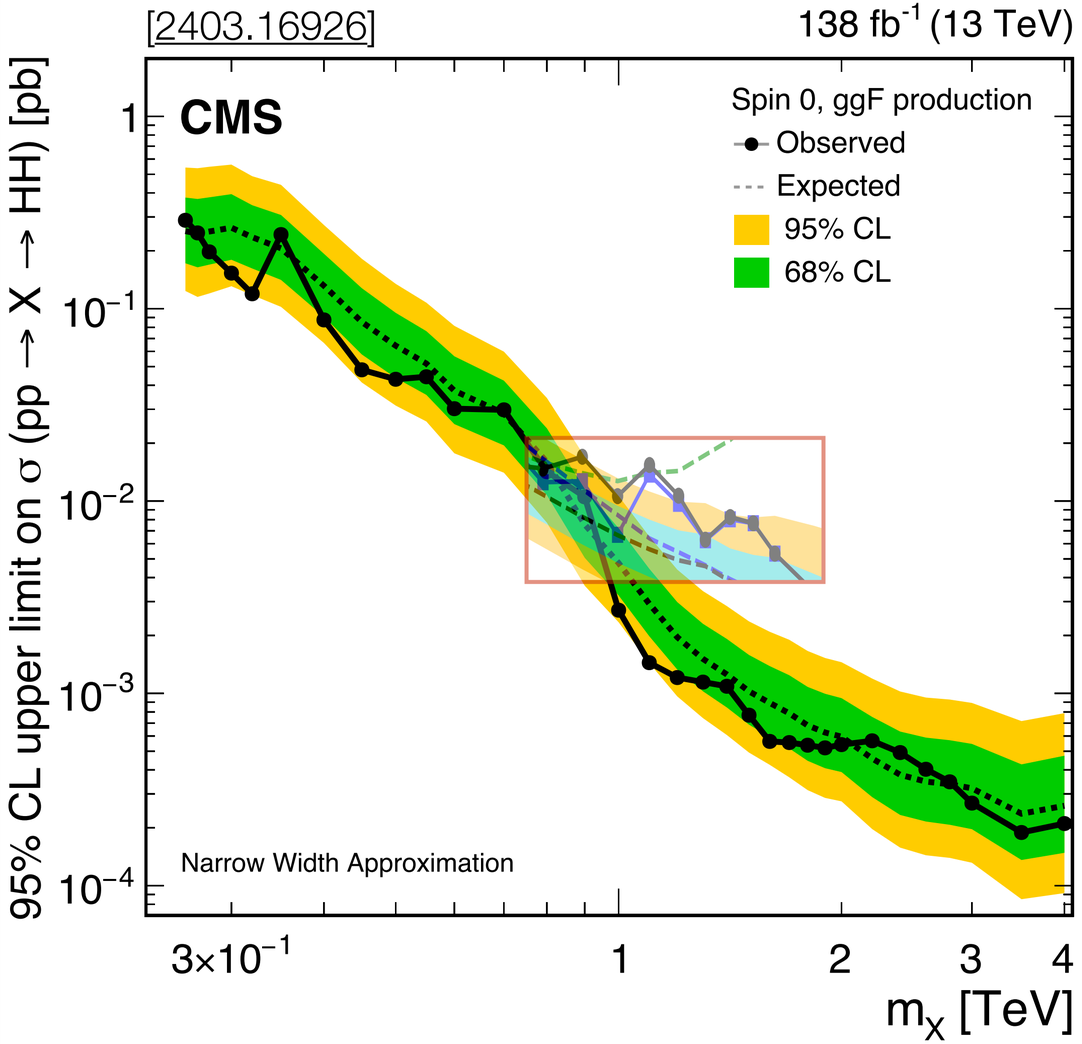




- Each of the golden channels **bbγγ**, **bbττ**, **4b** drives the sensitivity at **low** / **intermediate** / **high** m_X
- The largest excess at 1.1 TeV corresponds to a local (global) significance of **3.3σ** (2.1σ)
- **Narrow-width approximation** is used here and in all following results, unless stated otherwise

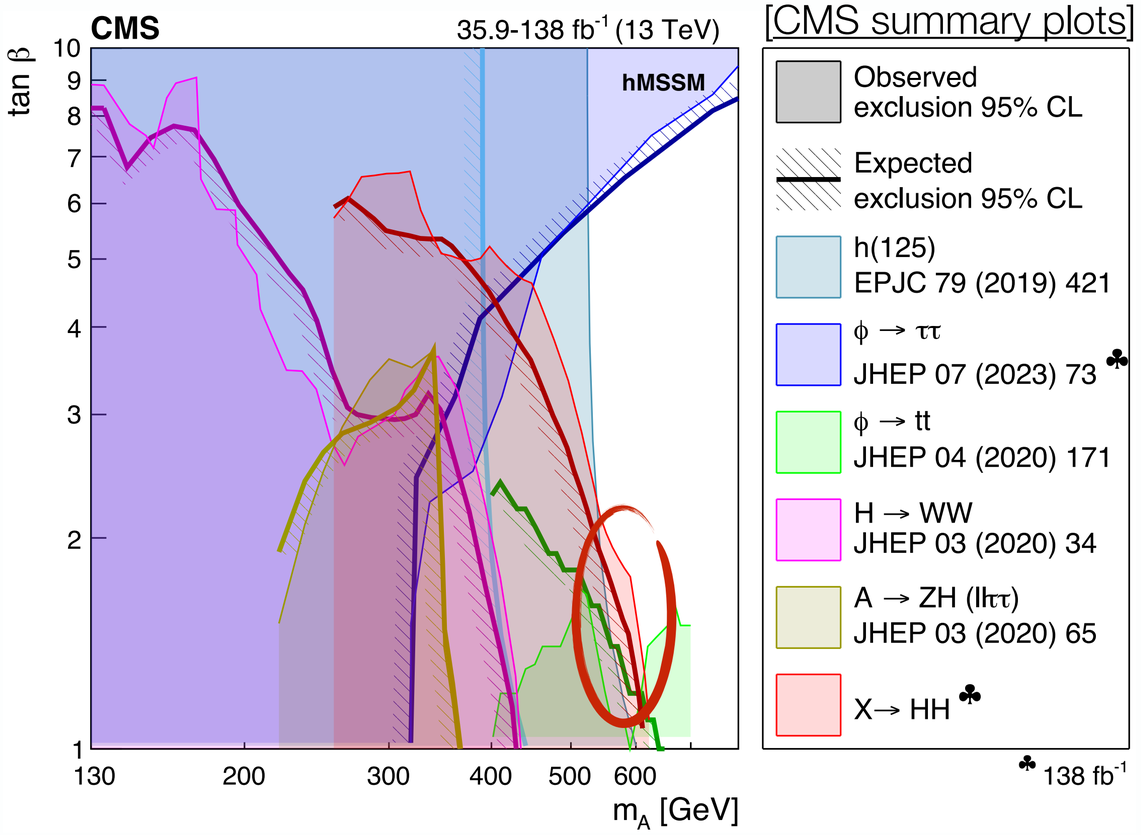
X→HH: CMS Combination

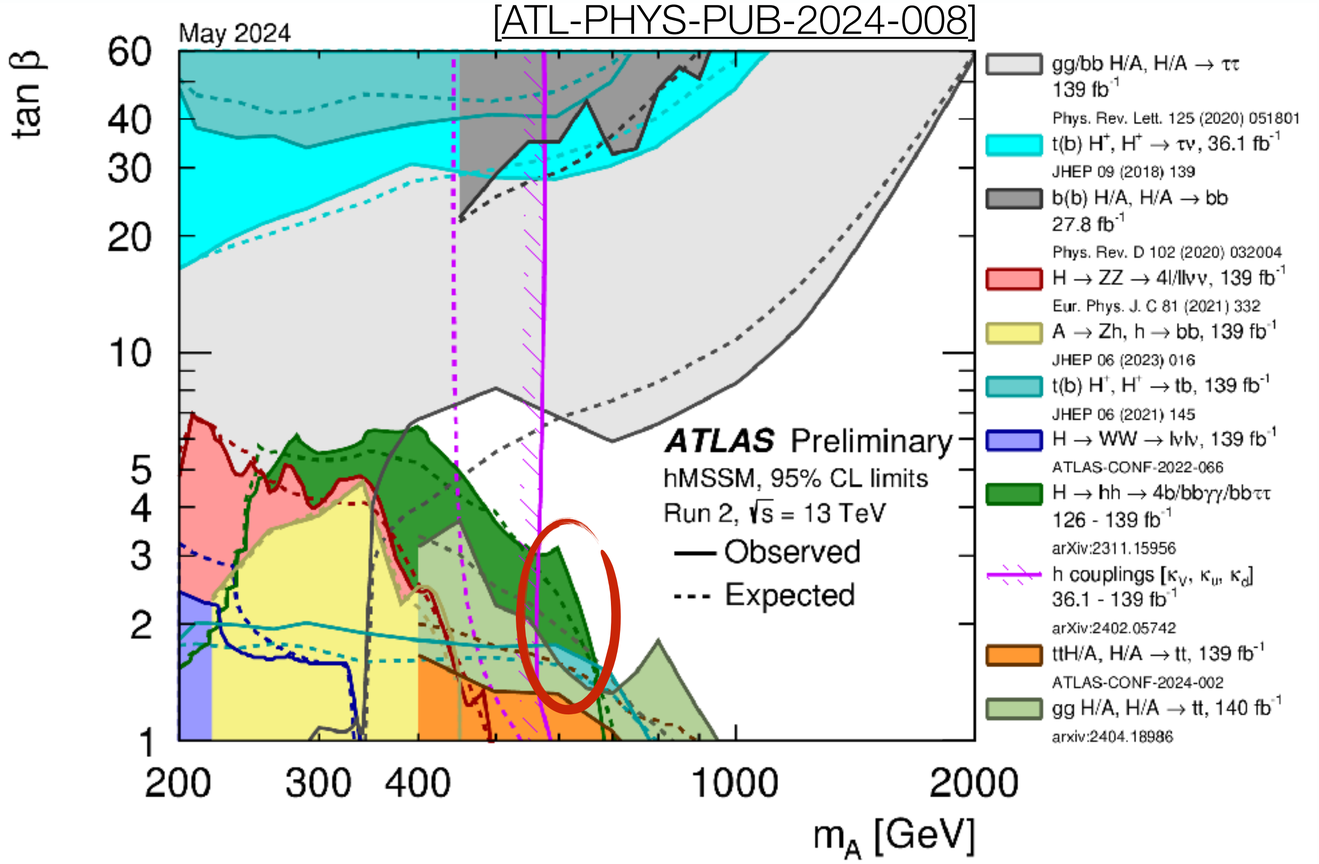




- Also here sensitivity driven by **bbγγ**, **bbττ**, **4b**
  - For X→HH→4b, only **merged-jet** topology included
- The excess observed by ATLAS around 1.1 TeV is **not** confirmed by CMS

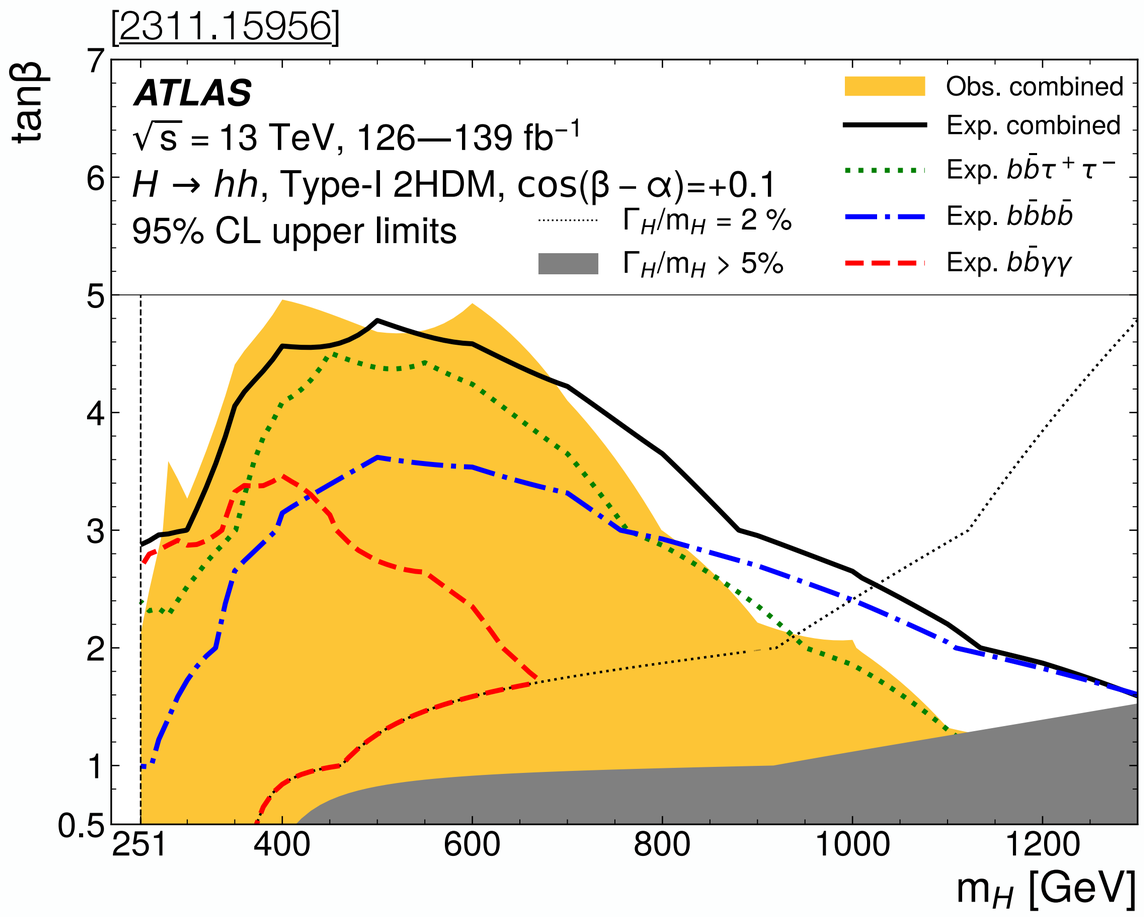
X→HH Interpretations: hMSSM

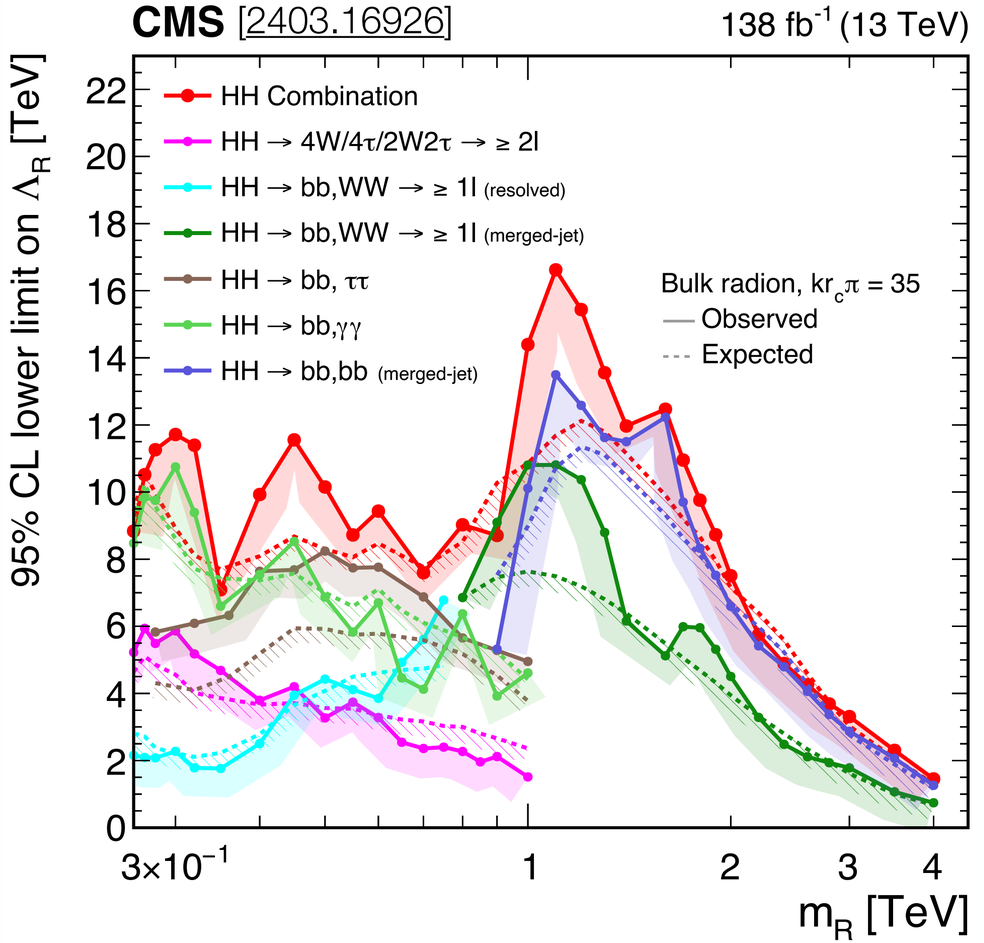




- **hMSSM** is a benchmark scenario designed to produce 125 GeV mass for the lightest MSSM scalar
  - Free parameters: **pseudoscalar mass m_A** and the **vacuum expectation value ratio tanβ**
- X→HH searches provide **some additional constraining power** in the hMSSM parameter space
  - Large **overlaps** with constraints from **H couplings** and **X→tt** searches

X→HH Interpretations: 2HDM, WED





- Both ATLAS and CMS provide interpretations in **2HDM**, assuming that X is the heavier scalar
  - More interpretations in the backup, including other 2HDM types & **MSSM** benchmark scenarios

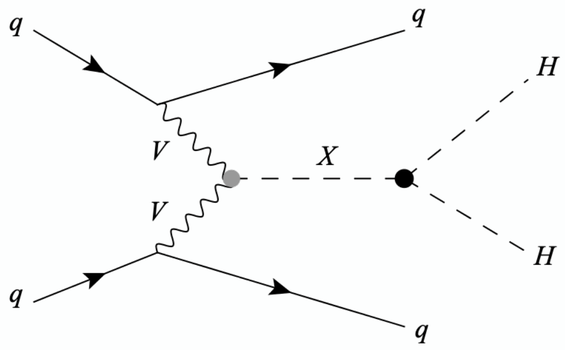
- CMS combination includes interpretation in WED, constraining the **bulk radion ultraviolet cutoff parameter λ_R**

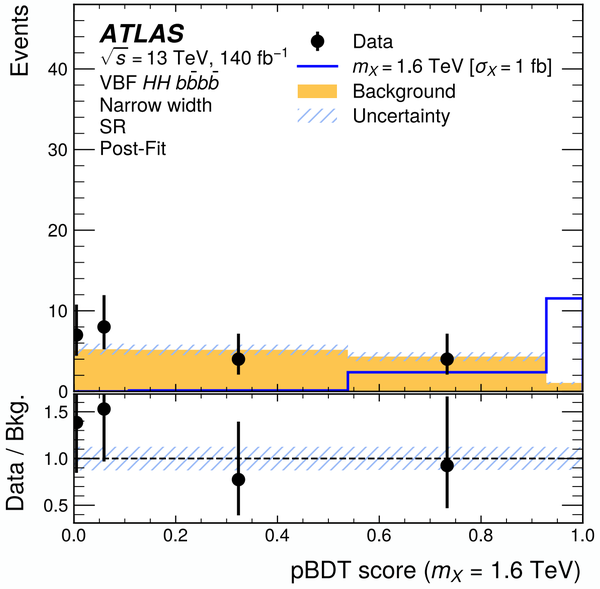
X→HH: Highlight

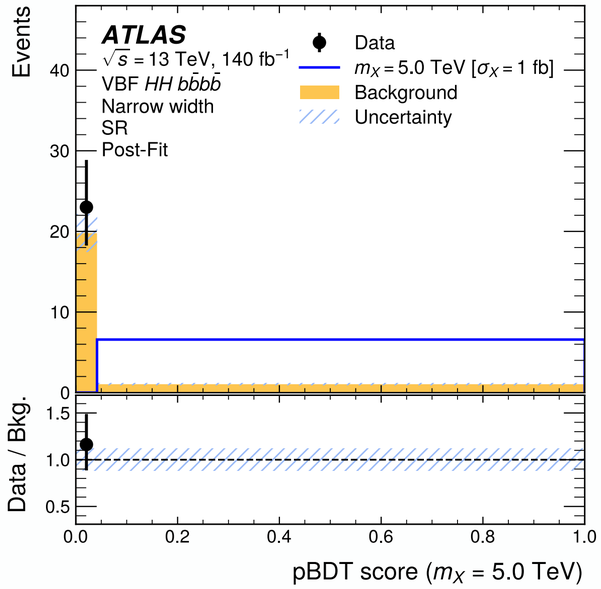
ATLAS VBF X→HH→4b [merged-jet]

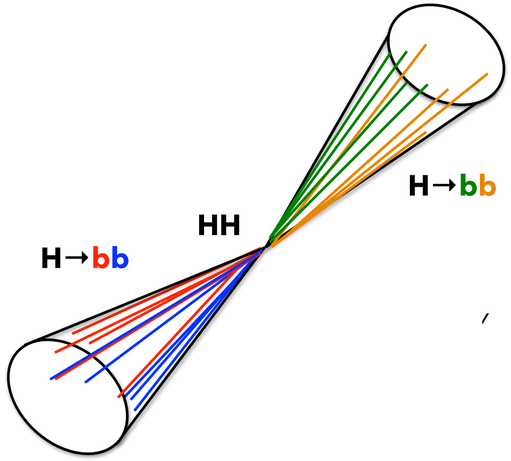
- Targeting **VBF production** of X→HH with **1 < m_X < 5 TeV**
- H bosons identified as **double-b-tagged large-radius jets**
- **VBF tag jets** reconstructed as small-radius jets
- **Data-driven background estimation** from single-bb-tag sample
- Signal extraction with **parametrised BDT**, conditional on m_X and using the kinematic features of H candidate jets and VBF tag jets

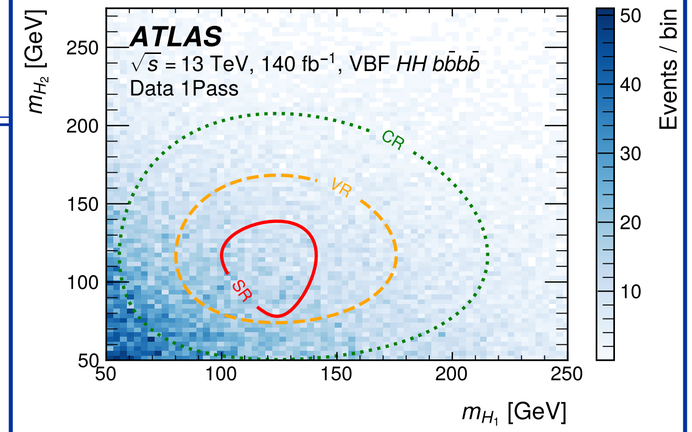
[2404.17193]

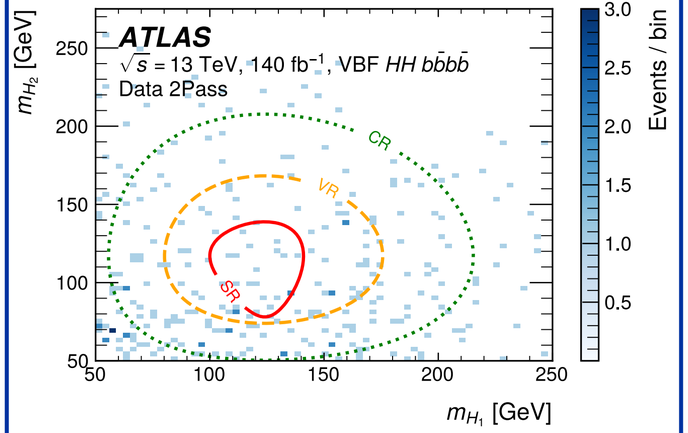


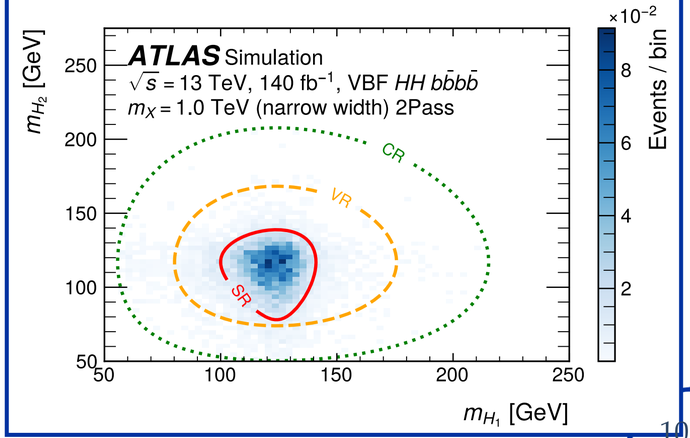




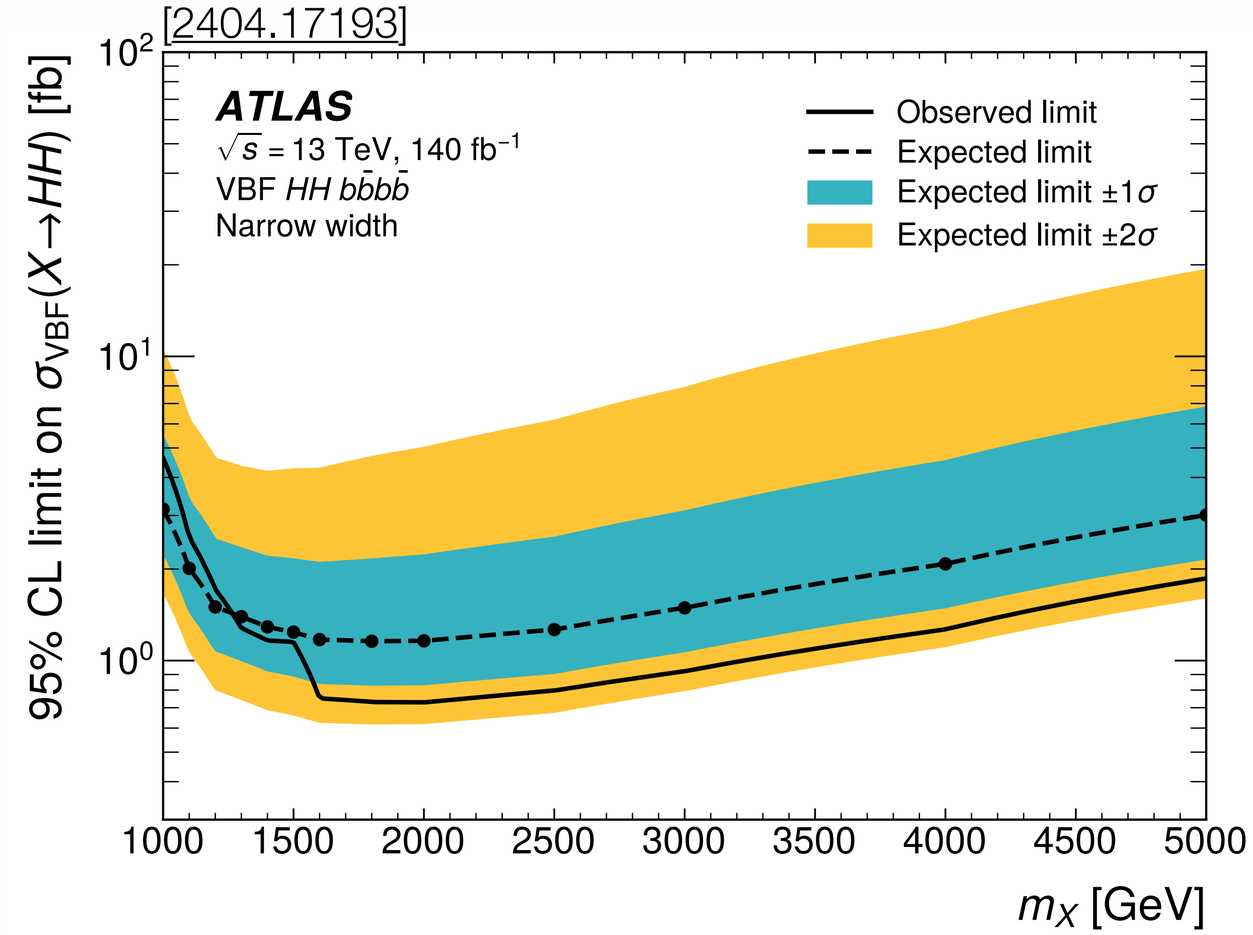


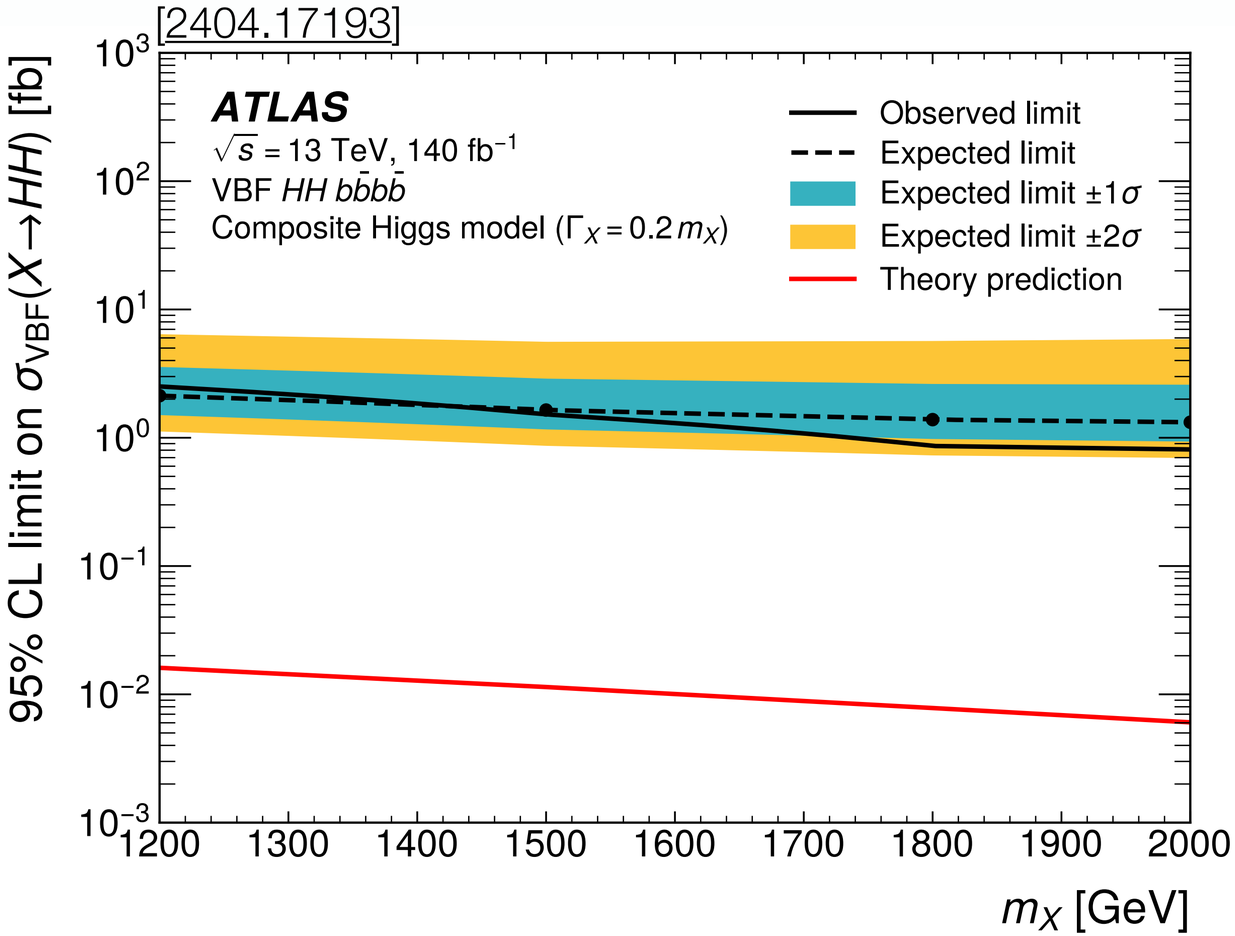






ATLAS VBF X→HH→4b [merged-jet]: Results



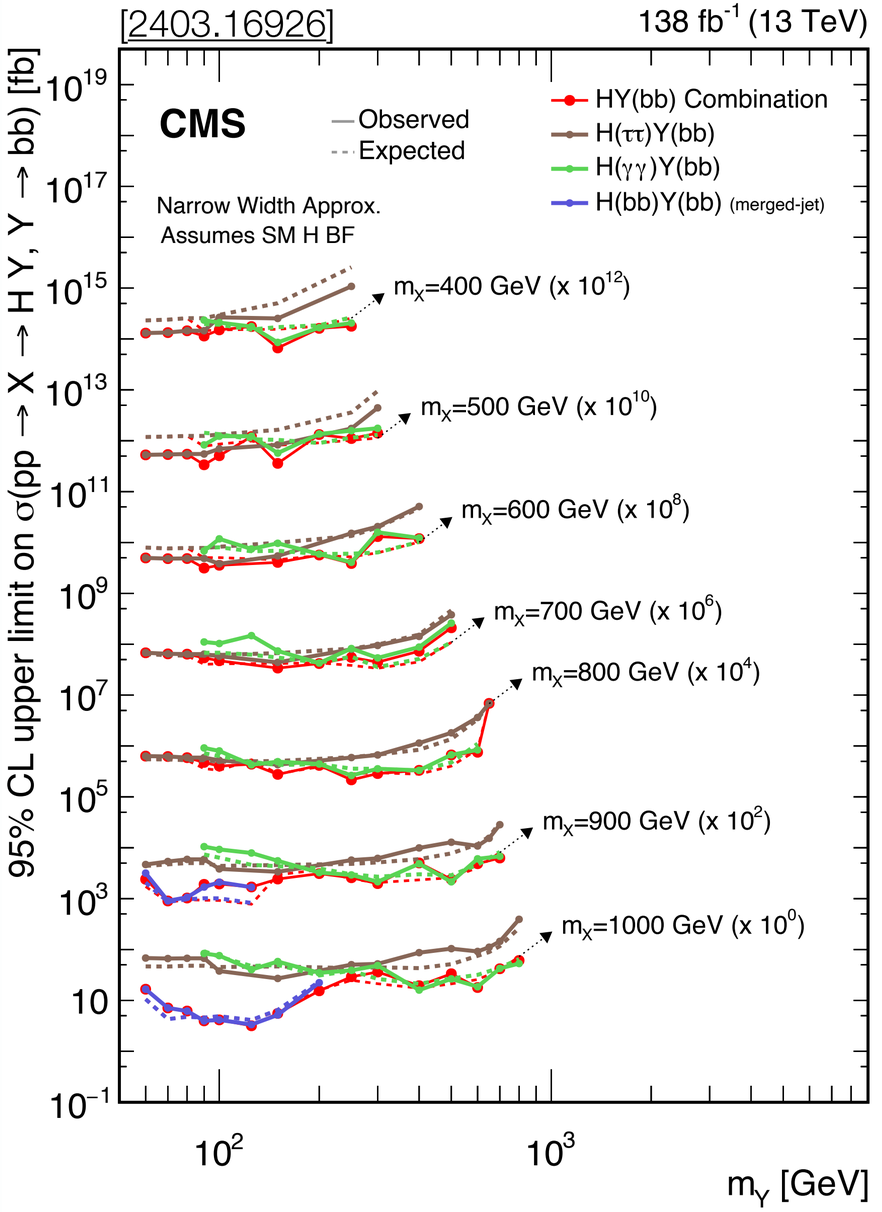


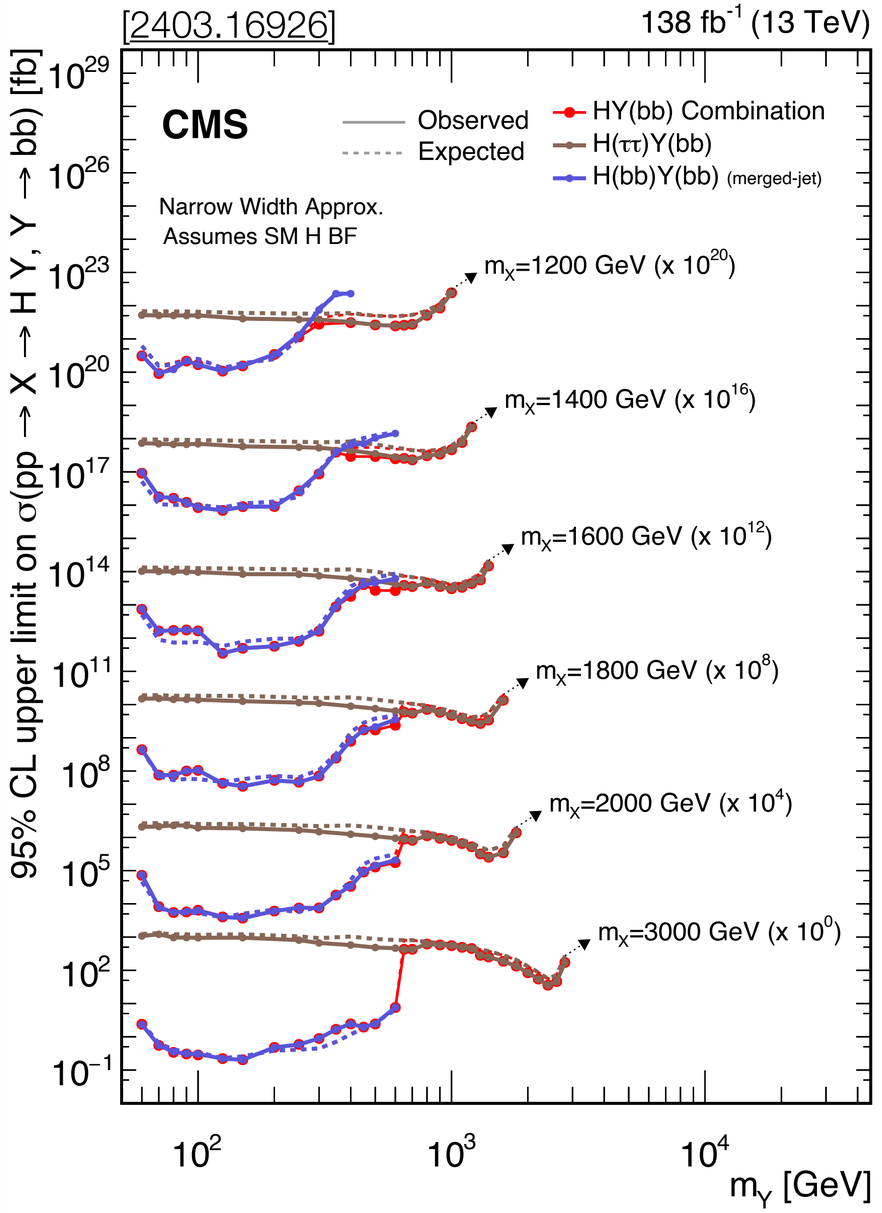
- Limits on VBF X→HH production set for both narrow-width and broad-width signal (Γ_X/M_X = 20%) cases

See also the talk by Maggie Chen

X→YH: Highlights

X→YH: CMS Combination





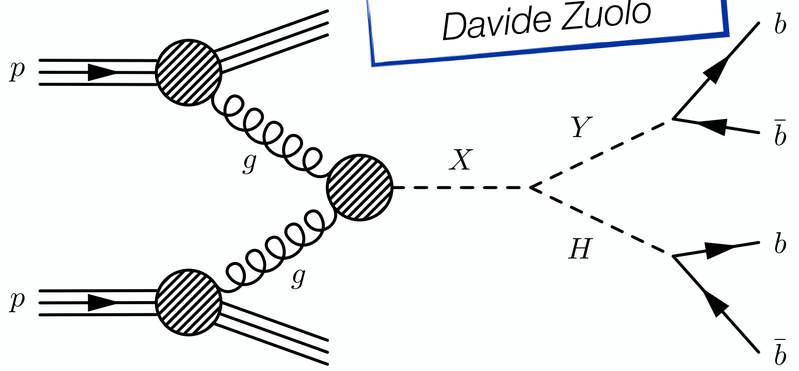
- CMS **combination** of 3 channels: **H(ττ)Y(bb)**, **H(γγ)Y(bb)**, and **H(bb)Y(bb)** [merged-jet]
  - Model-independent combination, i.e. **no assumption on Y branching fractions**
  - SM branching fractions assumed for H
- Sensitivity driven by one of the channels in most of the parameter space
- **Resolved-topology H(bb)Y(bb)** channel is not yet included

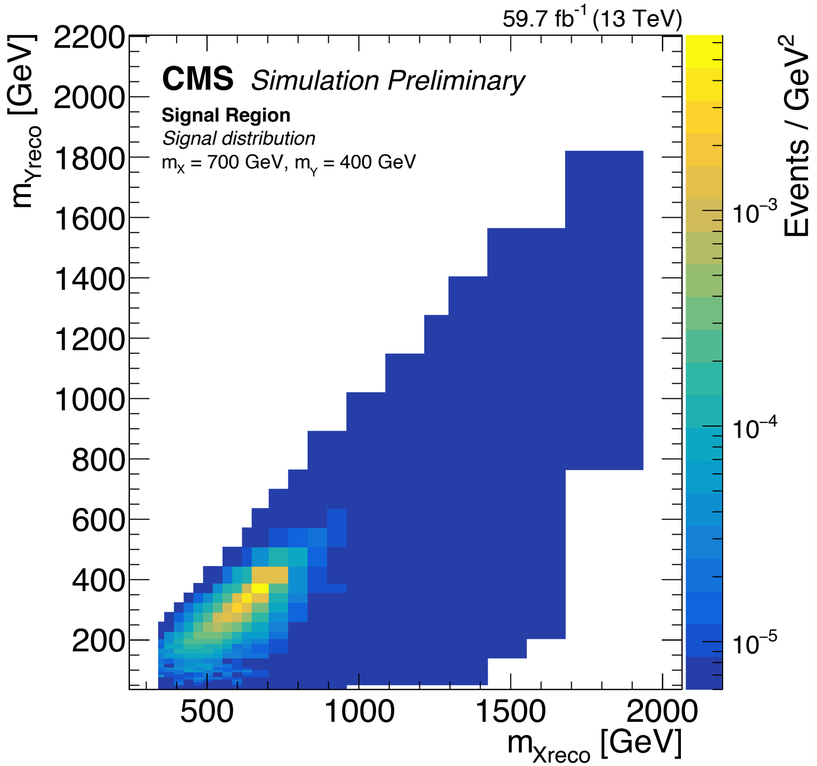
CMS X→YH→4b [resolved] [CMS-PAS-HIG-20-012]

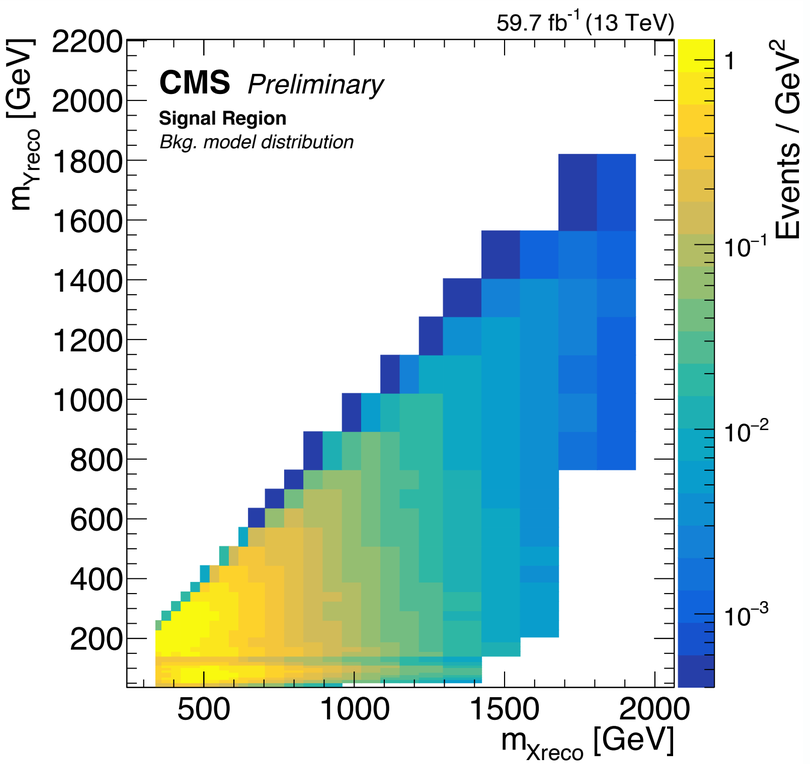
New for Higgs 2024

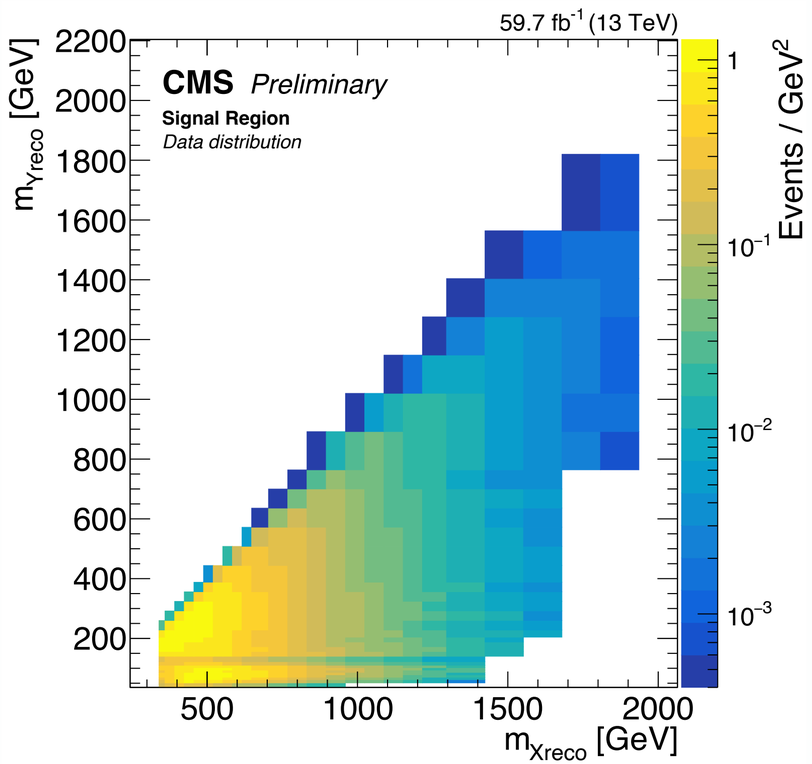
See also the talk by Davide Zuolo

- Targeting X→HY with **400<m_X<1600** GeV, **60<m_Y<1400** GeV
- Four jets with the highest **b-tag** scores used to reconstruct **H** and **Y**
  - Combinatorics solved by first finding the jet pair with mass closest to 125 GeV
- Data-driven QCD background estimation from 3b control region via **BDT reweighing technique** (similar to nonresonant 4b analysis)
- Signal extraction via **2D fit** of the reconstructed (**m_X ,m_Y**) distribution



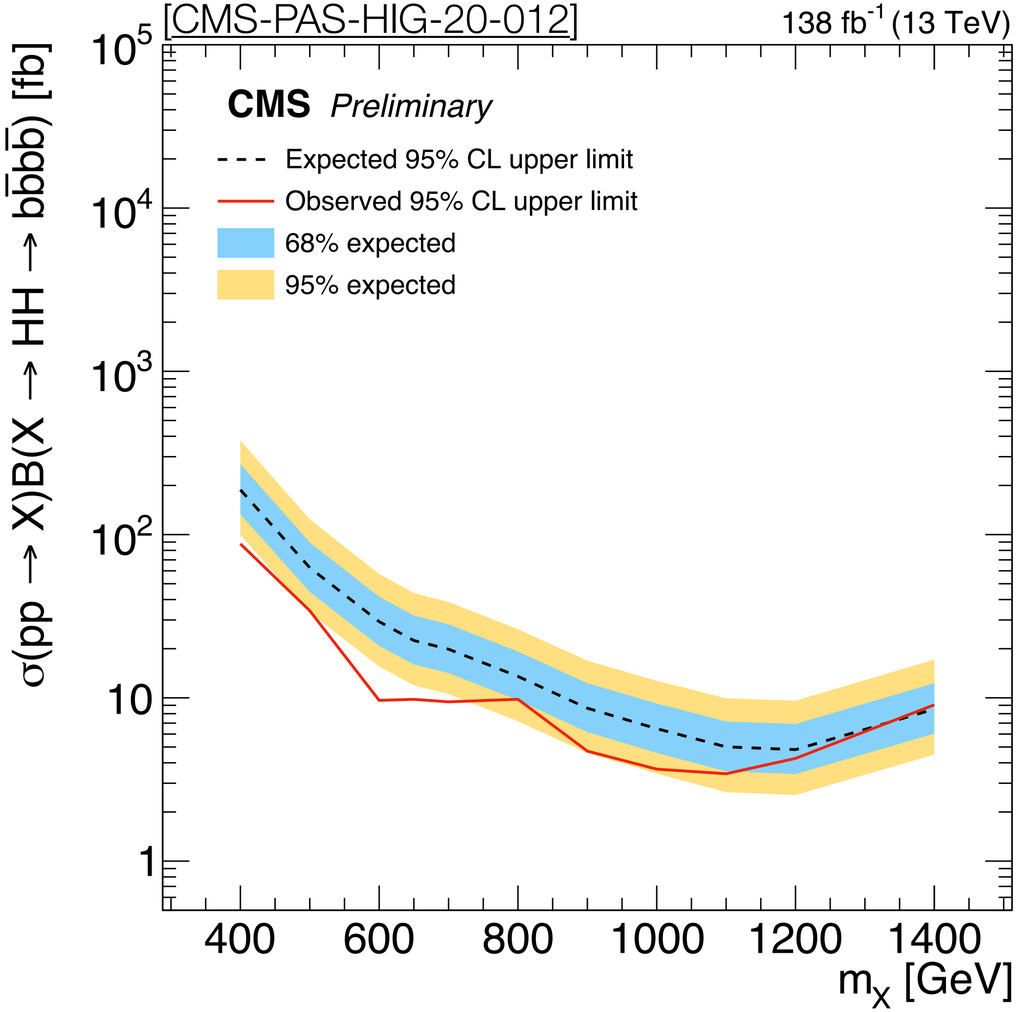


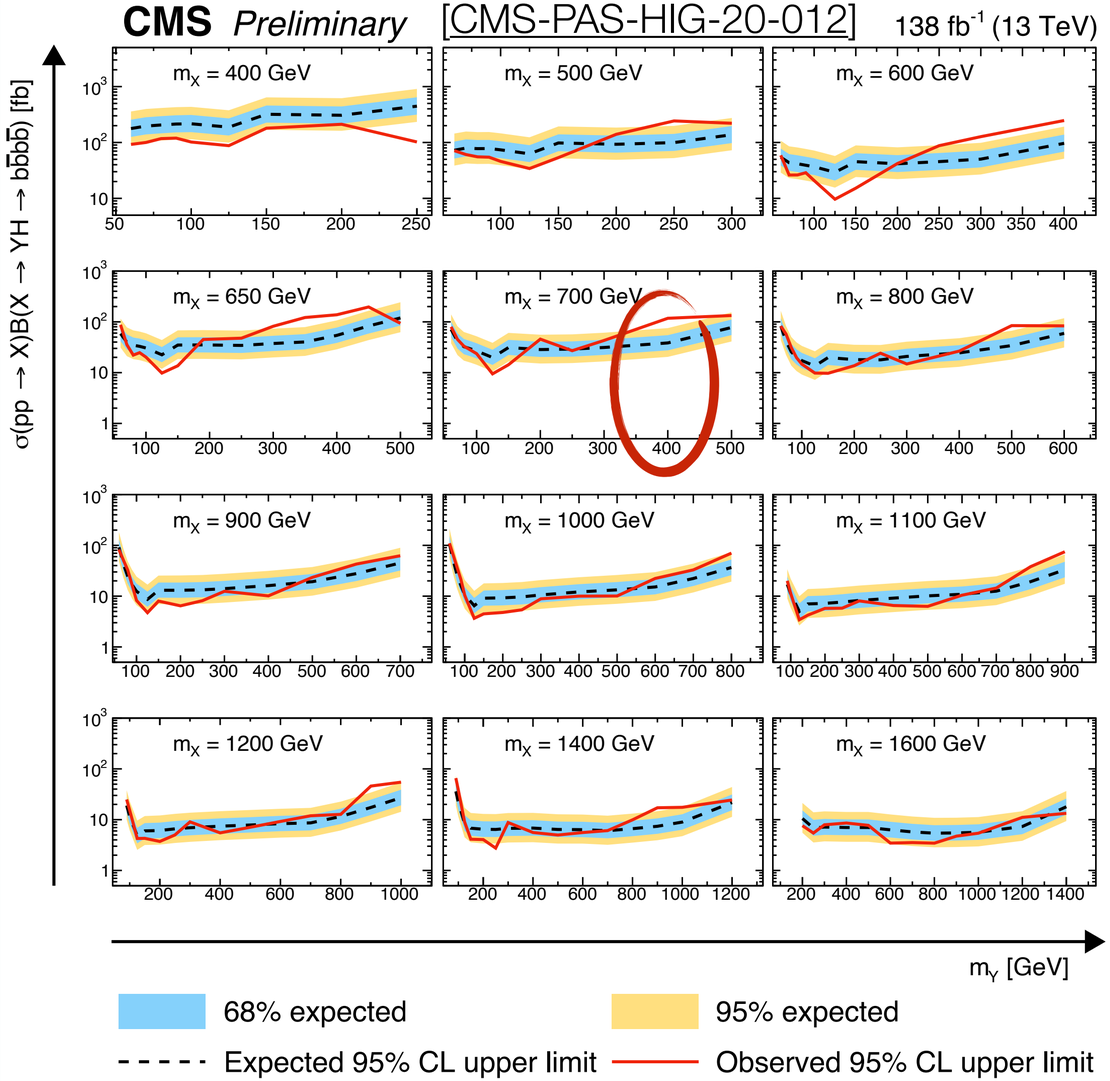




CMS X→YH→4b [resolved]: Results

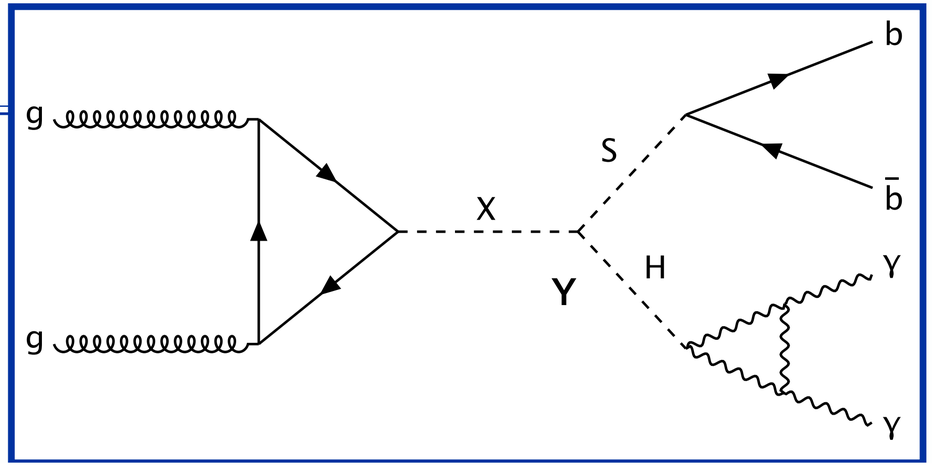
New for Higgs 2024



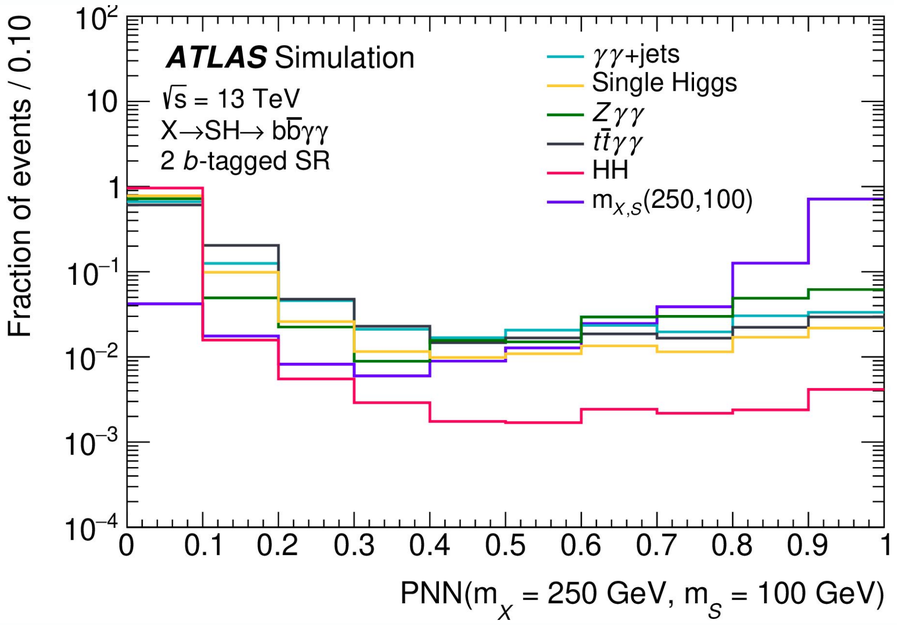


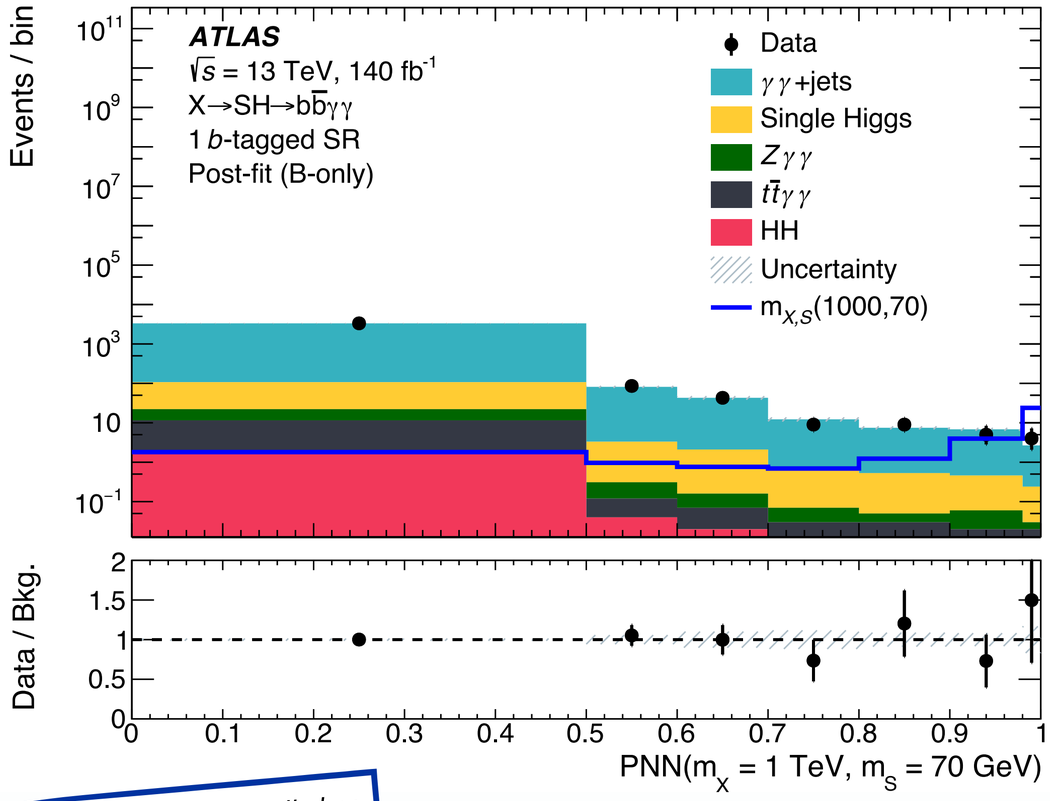
- **X→HH:** No excess observed
- **X→HY**: the excess at **(m$_X$,m$_Y$)=(700,400) GeV** has a local (global) significance of 4.1σ (2.8σ)

ATLAS X→YH→bbγγ [2404.12915]



- Targeting X→HY with **170<m_X<1000** GeV**, 15<m_Y<500** GeV
  - **H→γγ** pair enables efficient triggering and H mass reconstruction
  - **Y→bb** reconstructed both in **resolved** (2 b-tagged jets) and **merged-jet** (one b-tagged jet) topologies
- Data-driven background estimation from **$m_{\gamma\gamma}$ sidebands**
- **Signal extraction** with **parametrised neural network**
  - **Conditional on m_X and m_Y** (m_X only) in the resolved (merged-jet) region
  - Input features: reconstructed m_X and m_Y (m_X and p_T^X) in the resolved (merged-jet) region

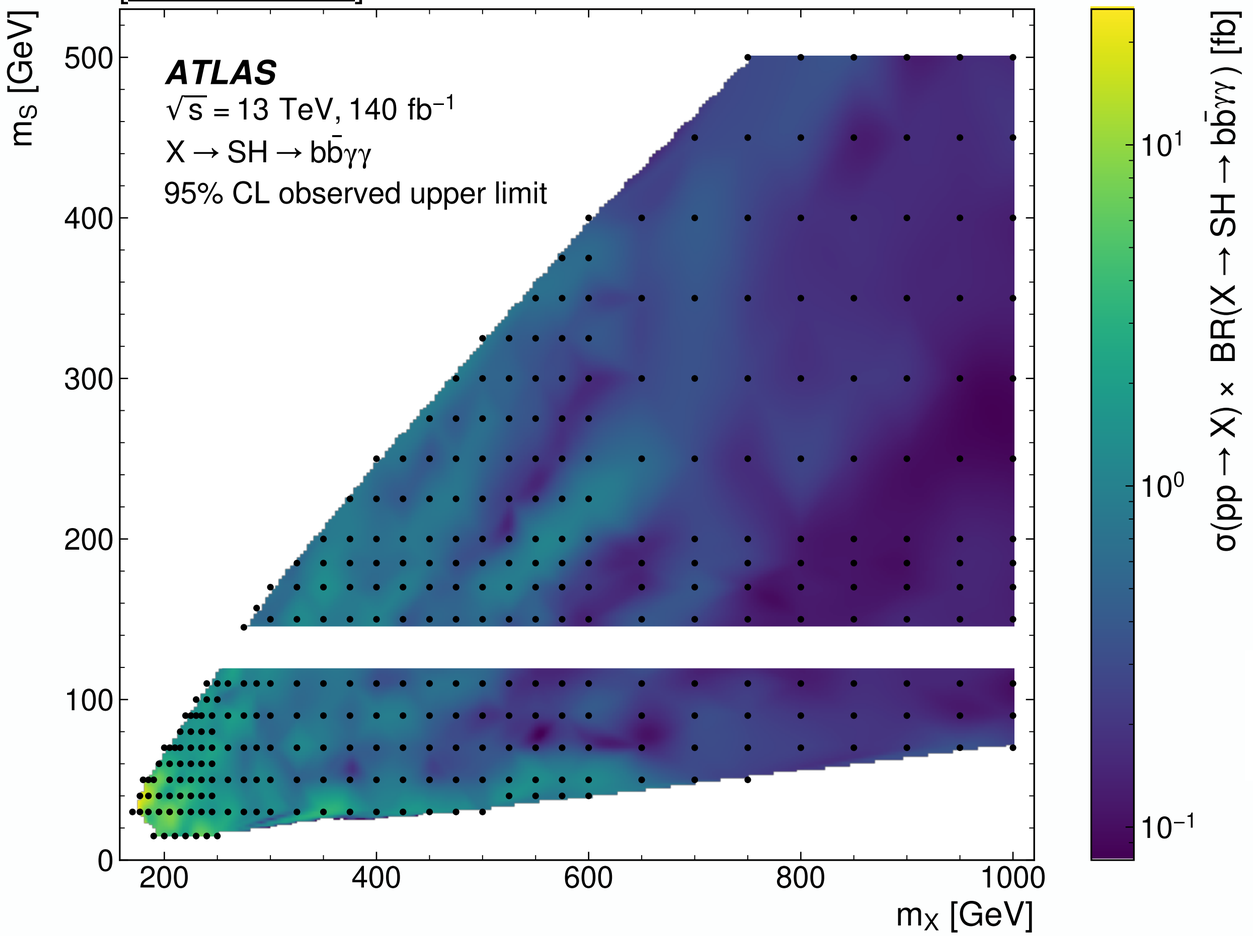




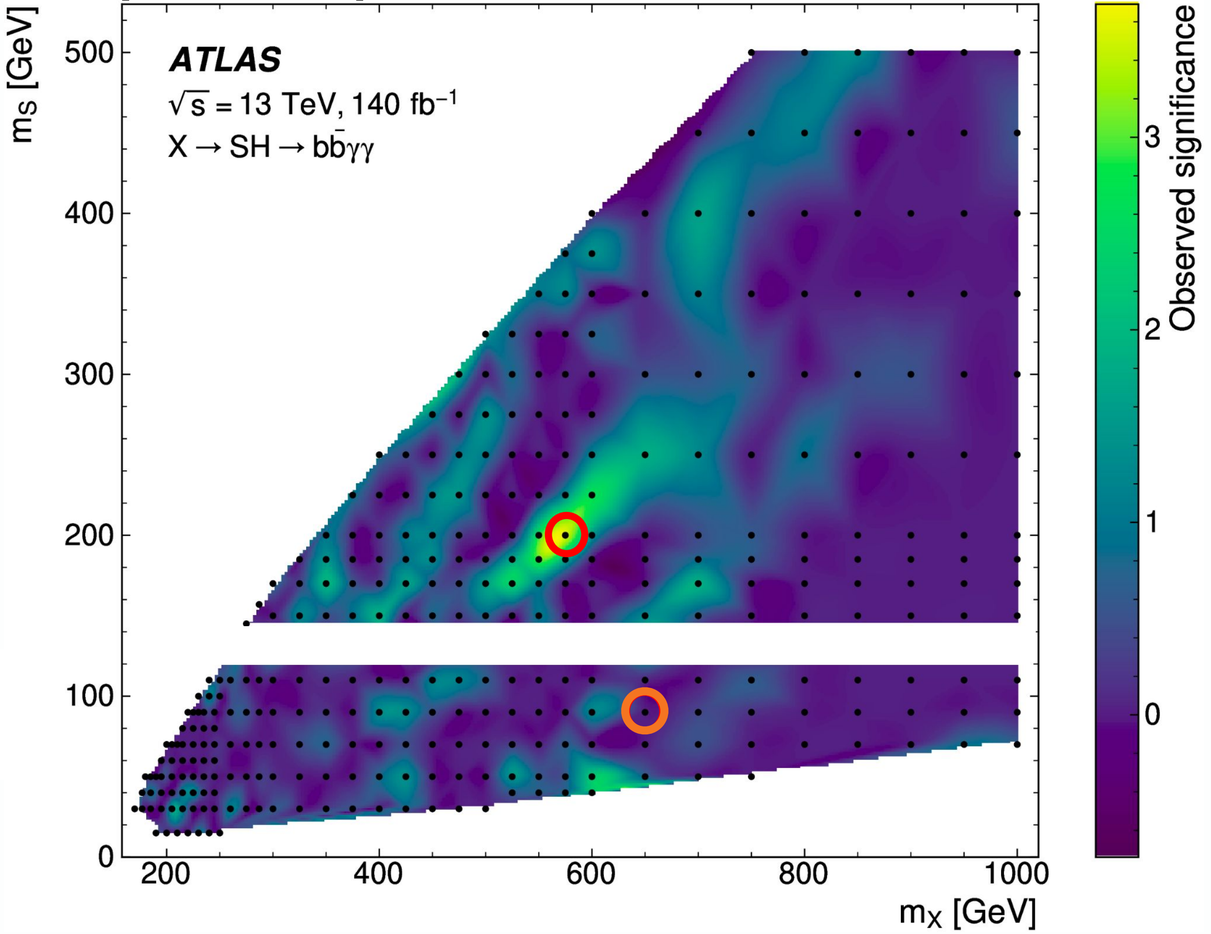
See also the talk by Maggie Chen

ATLAS X→YH→bbγγ: Results

[2404.12915]



[2404.12915]

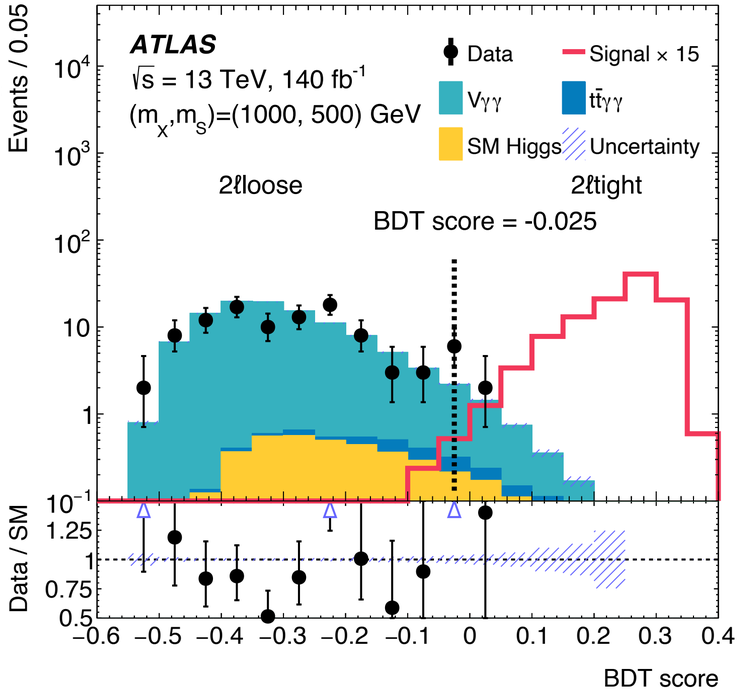


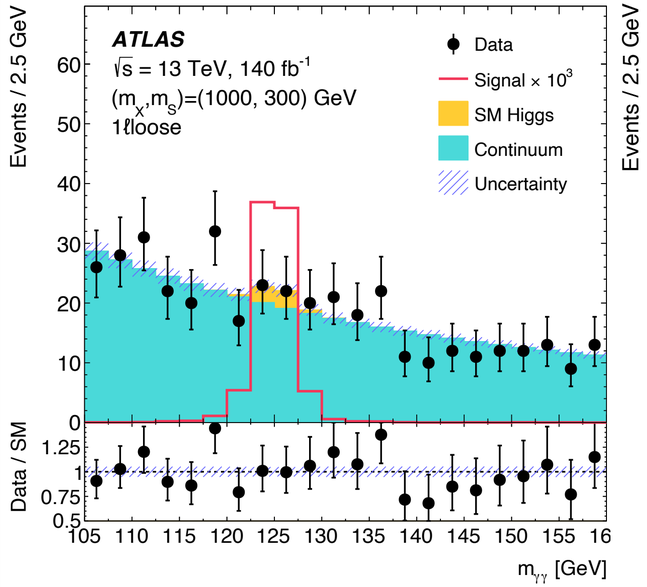
- Results for **X→HH** covered by an earlier dedicated analysis [2112.11876] with comparable sensitivity
- The largest excess at **(m_X,m_Y)=(575,200) GeV** has a local (global) significance of **3.5σ** (2.0σ)
- No deviation from background-only hypothesis around **(m_X,m_Y)=(650,90) GeV**, while a signal injection test indicates that a signal comparable to the CMS result would have an expected significance of 2.7σ

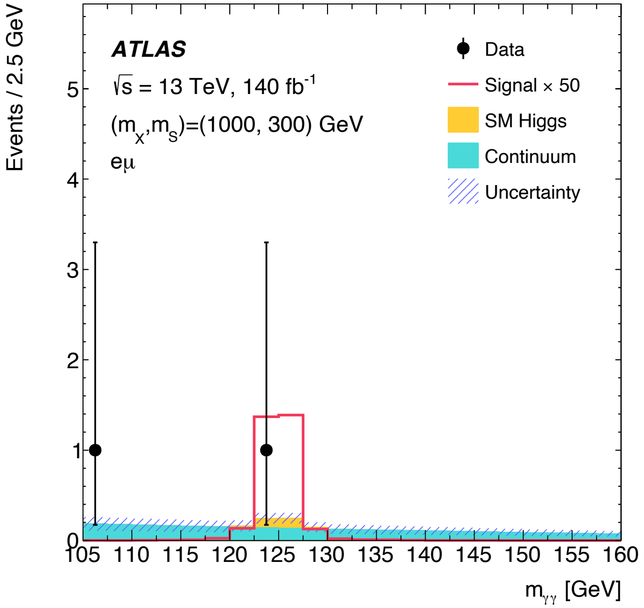
ATLAS X→YH→[WW/ZZ]γγ [2405.20926]

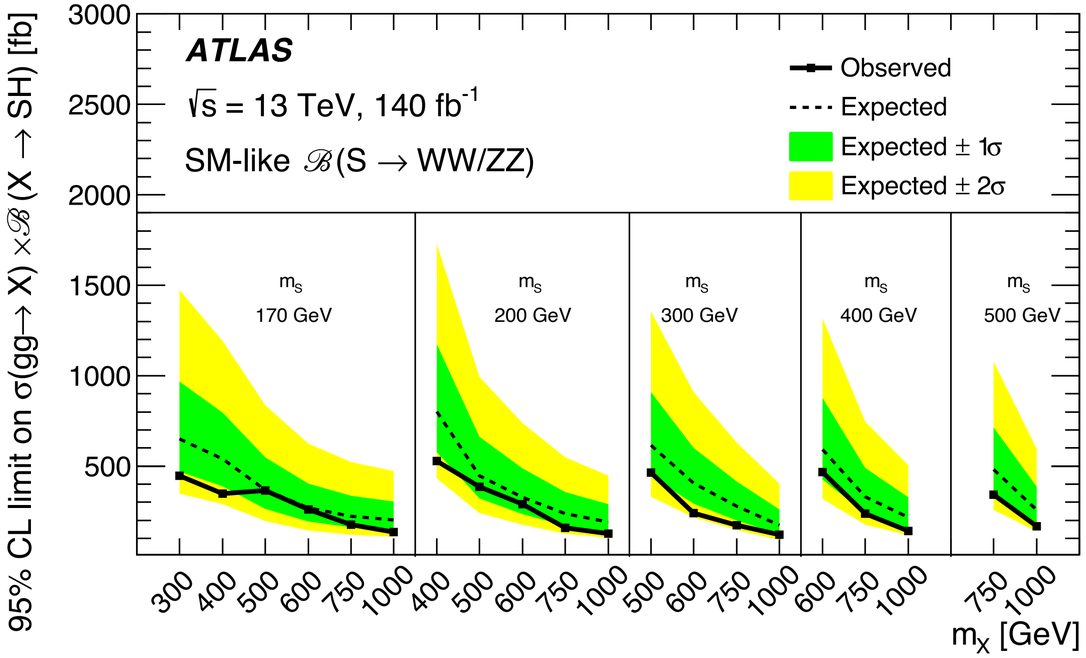
- Targeting X→HY with **300<m_X<1000** GeV**, 170<m_Y<500** GeV in a final states with **1 or 2 electrons/muons** (+jets) from W/Z decays
- Kinematic BDTs and lepton multiplicity used to **categorize** events
- Signal extraction from a simultaneous fit of **$m_{\gamma\gamma}$** distributions, with data-driven background estimation from $m_{\gamma\gamma}$ **sidebands**
- **No excess** observed
  - Limits set assuming Y decay exclusively to WW, exclusively to ZZ, or to both with SM-like branching fractions

See also the talk by Maggie Chen





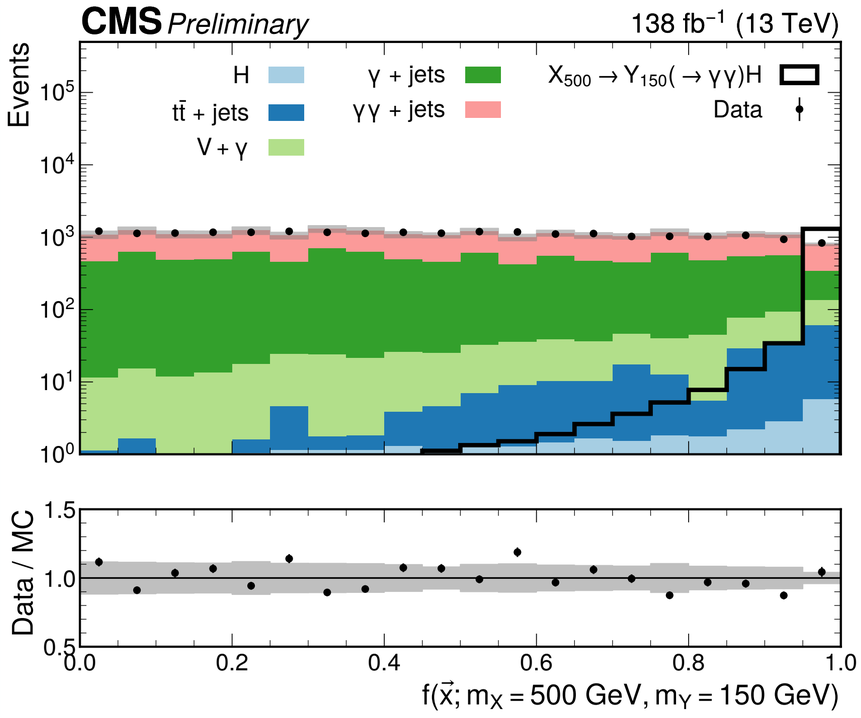


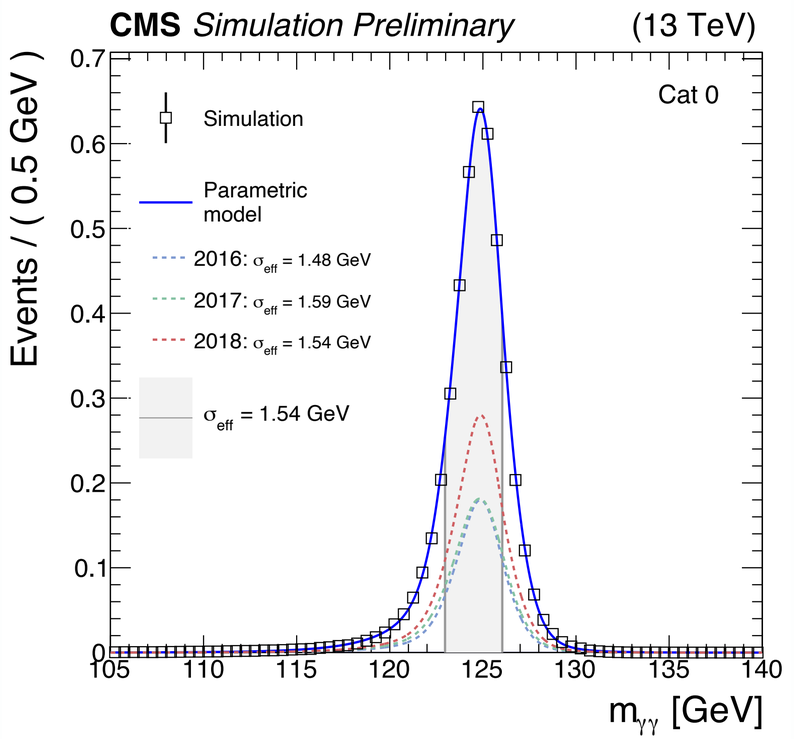


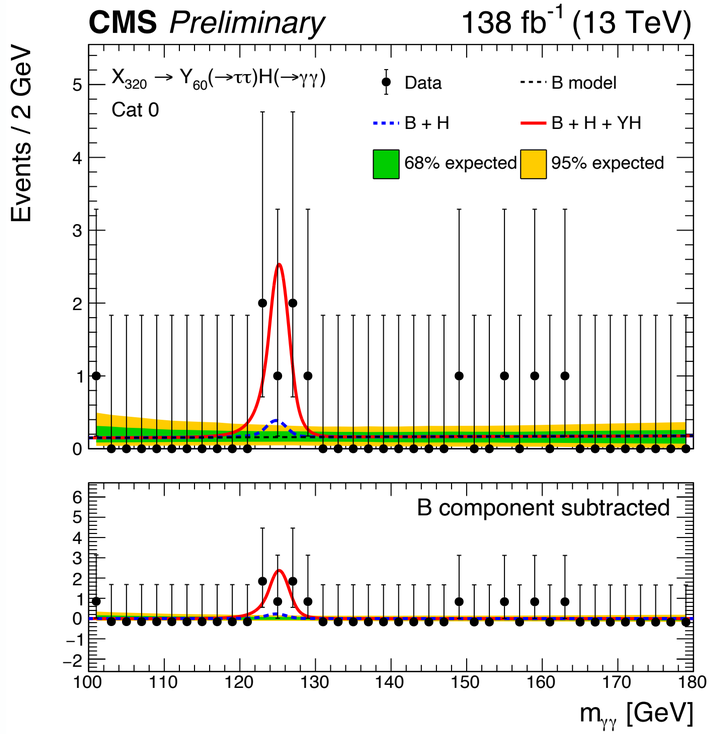
CMS X→YH→ττγγ/γγττ [CMS-PAS-HIG-22-012]

See also the talk by Davide Zuolo

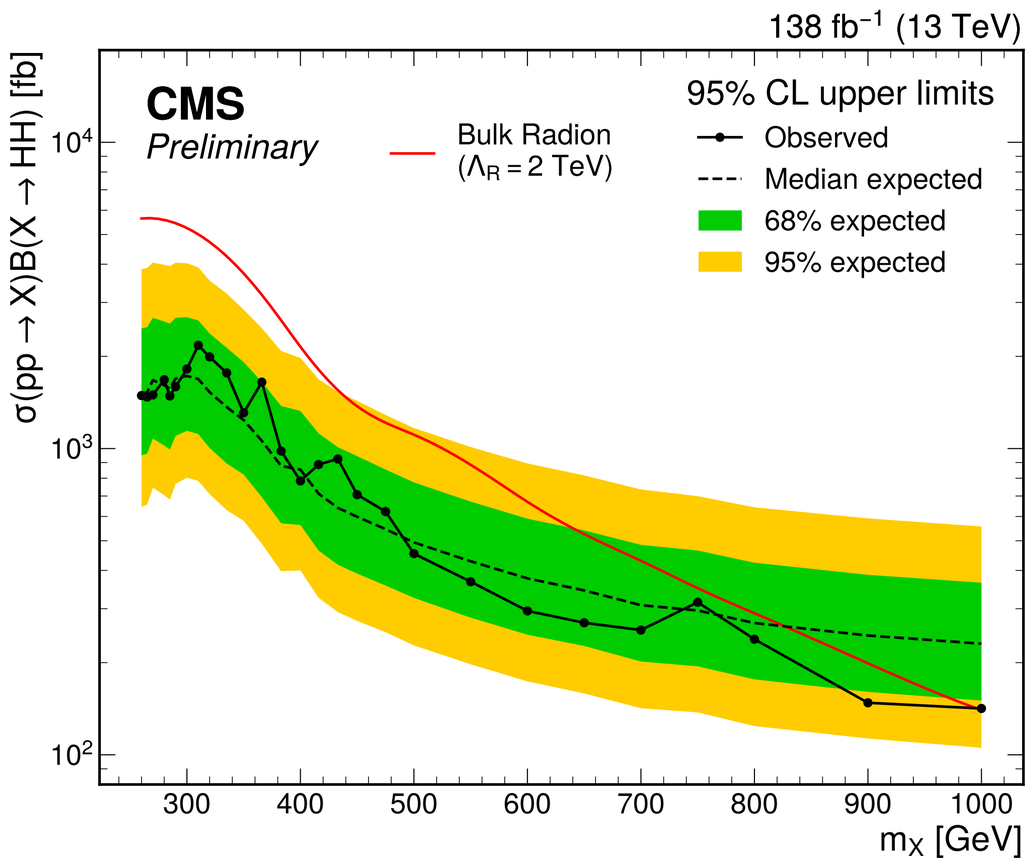
- Targeting X→HH (HY) with **260 (300) < m_X < 1600 GeV**
  - Covers both **Y(ττ)H(γγ)** with 50<m_Y<800 GeV, and **Y(γγ)H(ττ)** with 70<m_Y<800 GeV
- Event categorization with **parametrised neural network**, conditional on m_X and m_Y
  - Using the **kinematic features** or γ and τ candidates, p_T^{miss}, and jets; b-tagging, and angular separations
- Signal extraction using **$m_{\gamma\gamma}$**, with signal shape from simulation and **background shape from sidebands**



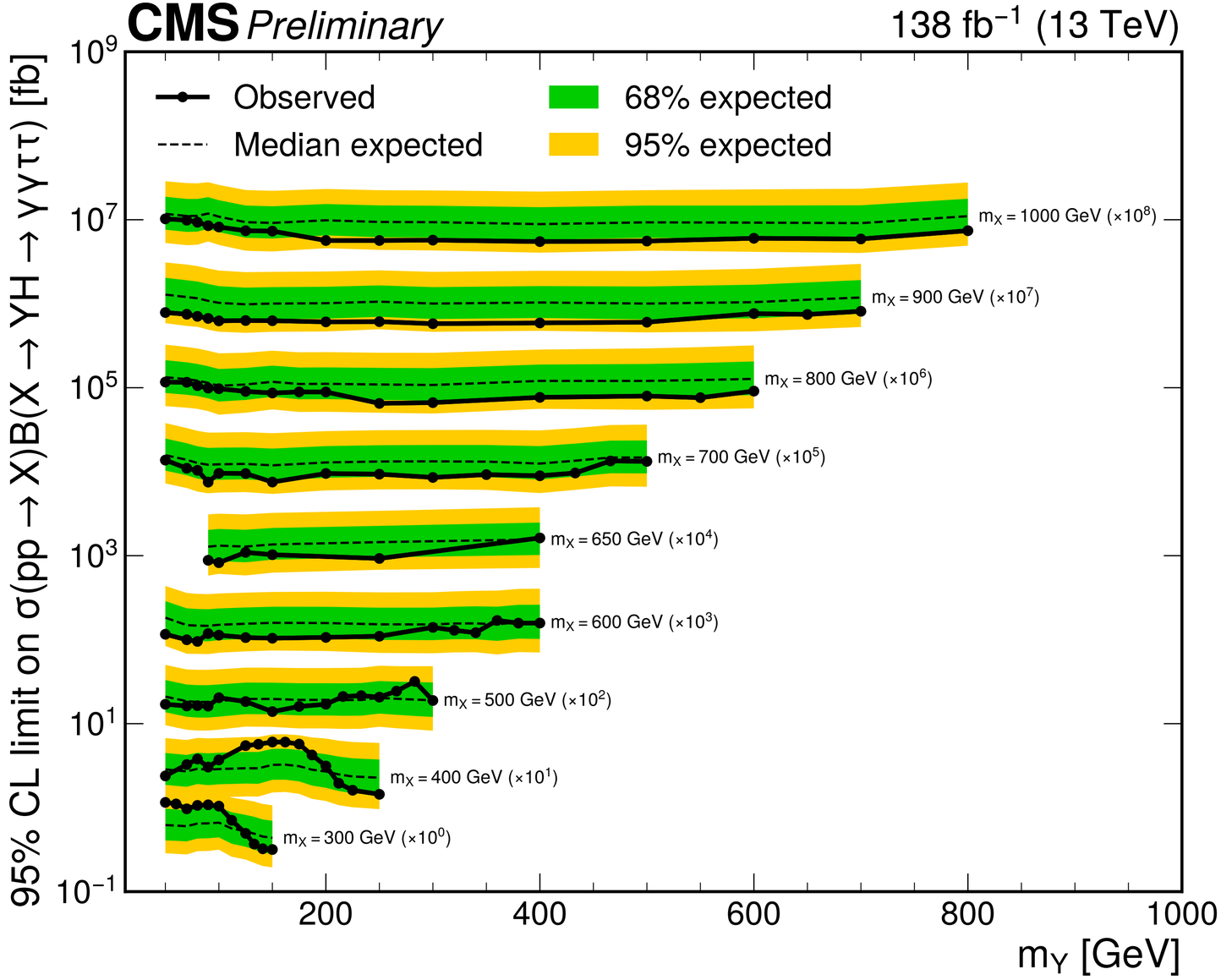




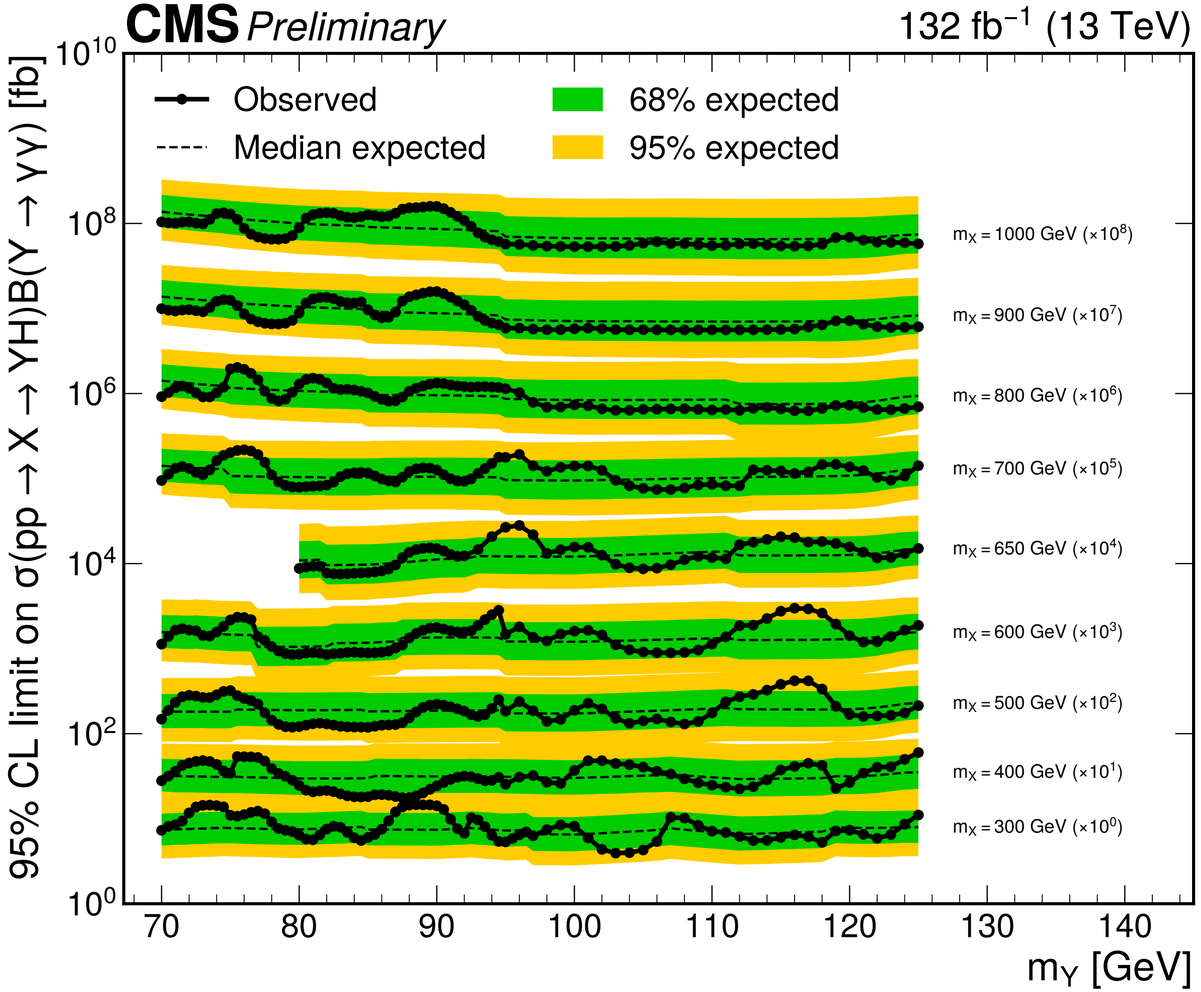
CMS X→YH→γγττ: Results [CMS-PAS-HIG-22-012]

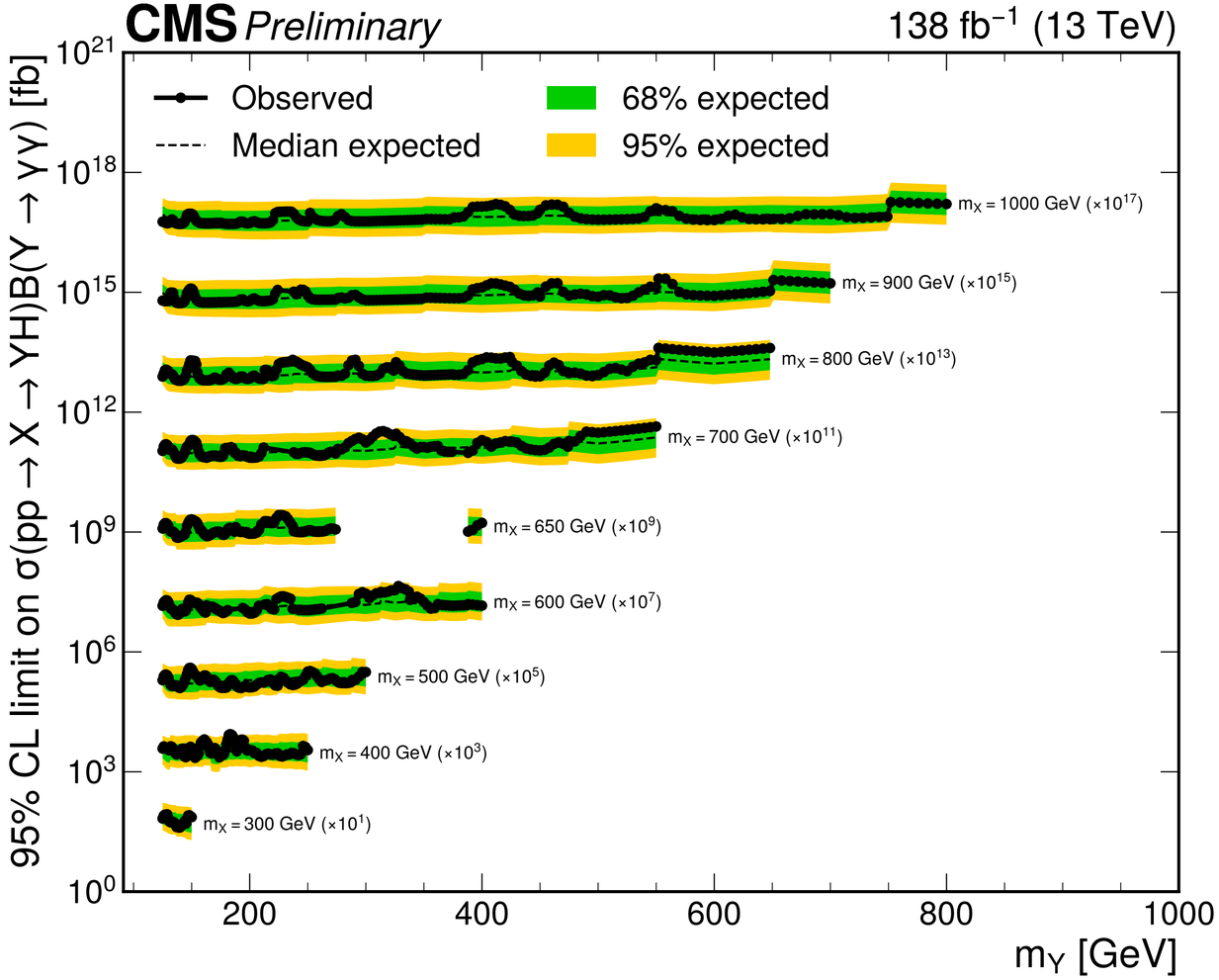


- No significant excess observed for **X→HH** or **X→Y(ττ)H(γγ)**



CMS X→YH→γγττ: Results [CMS-PAS-HIG-22-012]

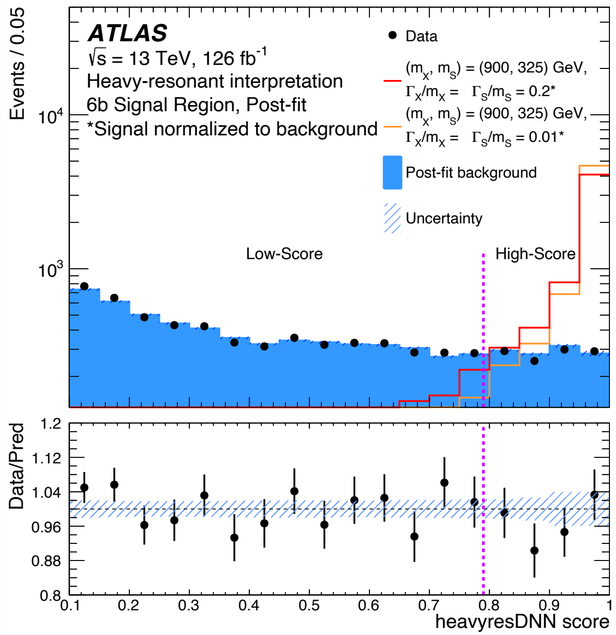




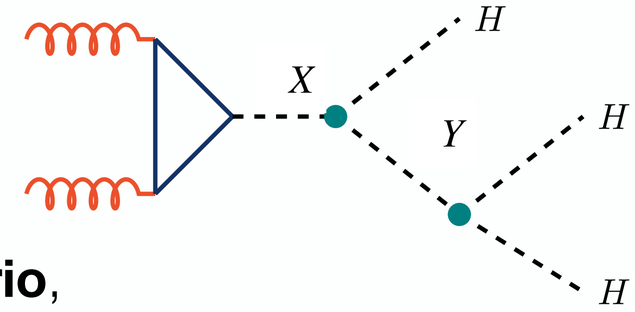
- **X→Y(γγ)H(ττ)**: the largest excess at **(m_X,m_Y)=(525,115) GeV** has a local significance of 3.4σ but the global significance of only 0.1σ

ATLAS X→YH→6b [2411.02040]

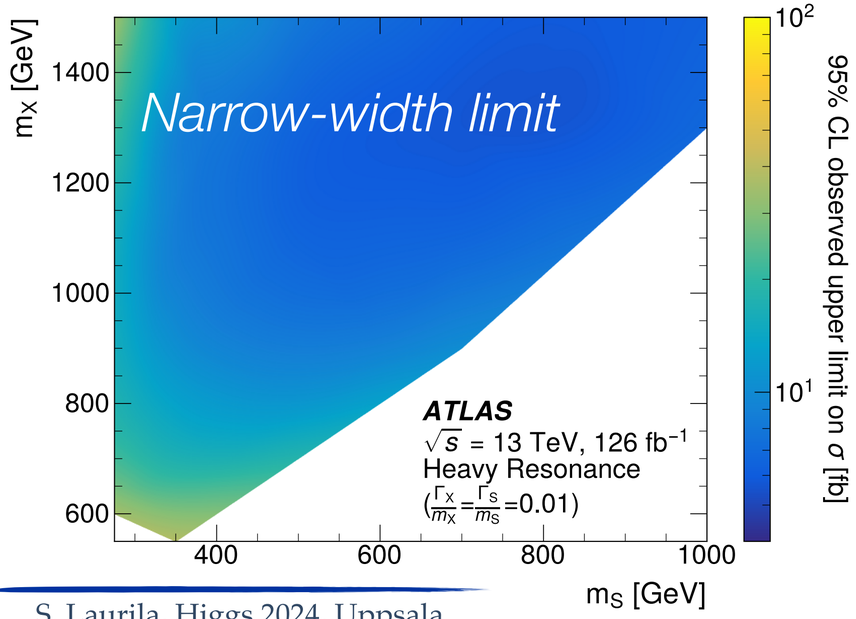
New for Higgs 2024

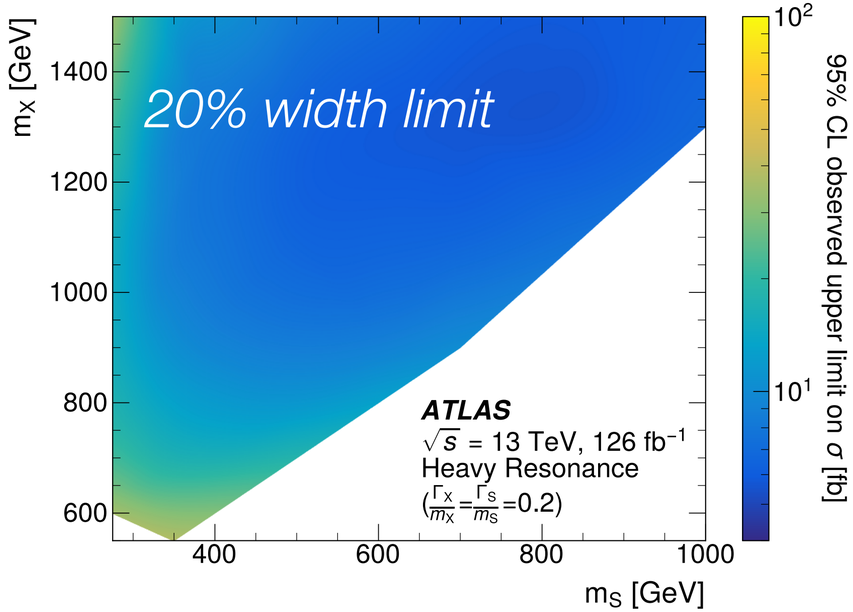


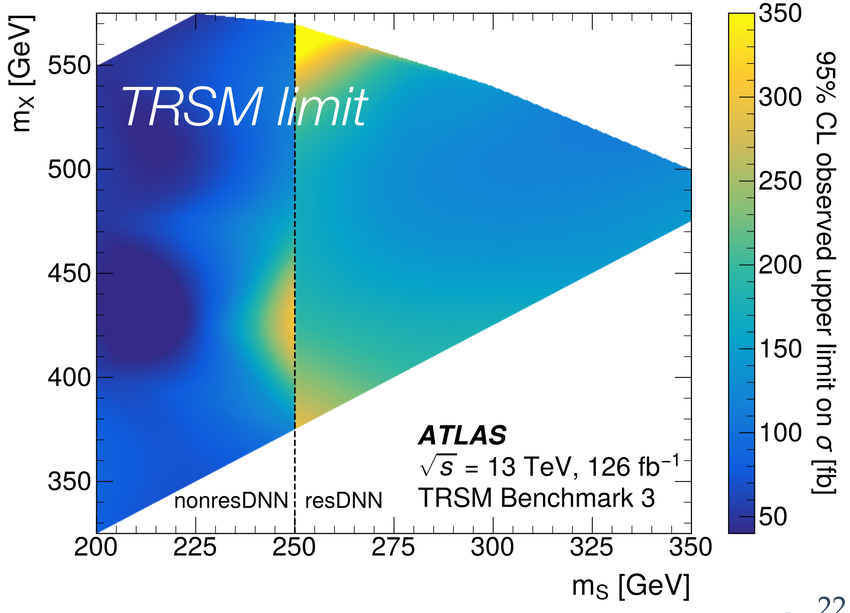
- In addition to the nonresonant interpretation, the new ATLAS 6b analysis considers **X→YH→HHH**
  - A **model-independent** X→YH search with **500<m_X<1500GeV**, **275<m_Y<1000 GeV**
  - An interpretation in an **TRSM benchmark scenario**, considering both resonant and nonresonant contributions
  - **Dedicated DNN** for resonant signal extraction
- **No excess** observed



See also the talks by Bill Balunas, Maggie Chen, and Raffaele Gerosa



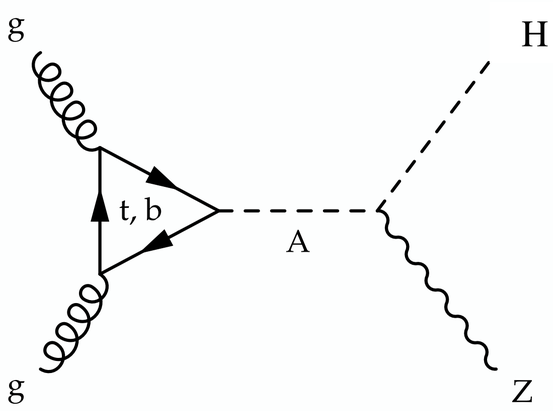


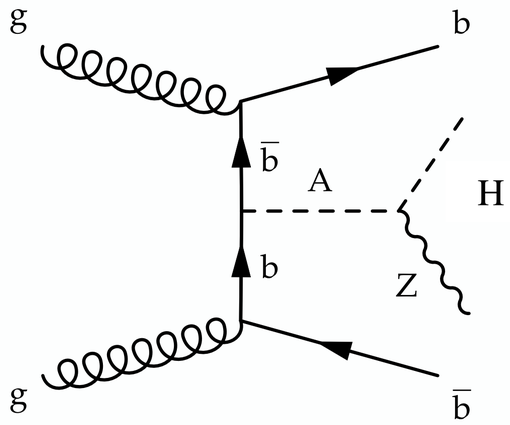


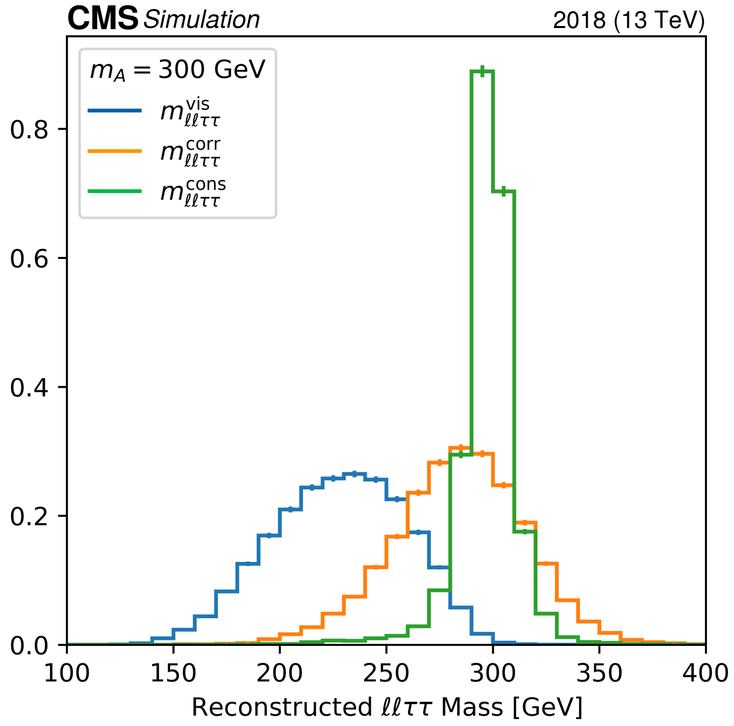
X→VH: Highlights

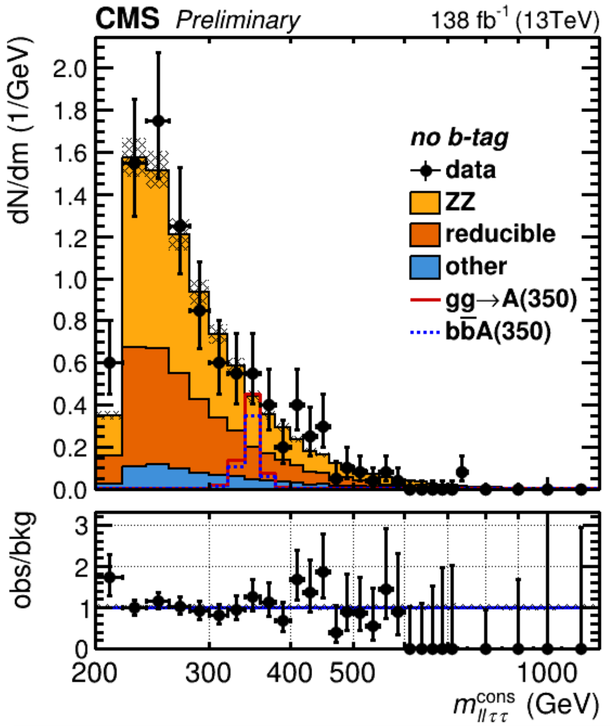
CMS A→ZH→llττ [CMS-PAS-HIG-22-004]

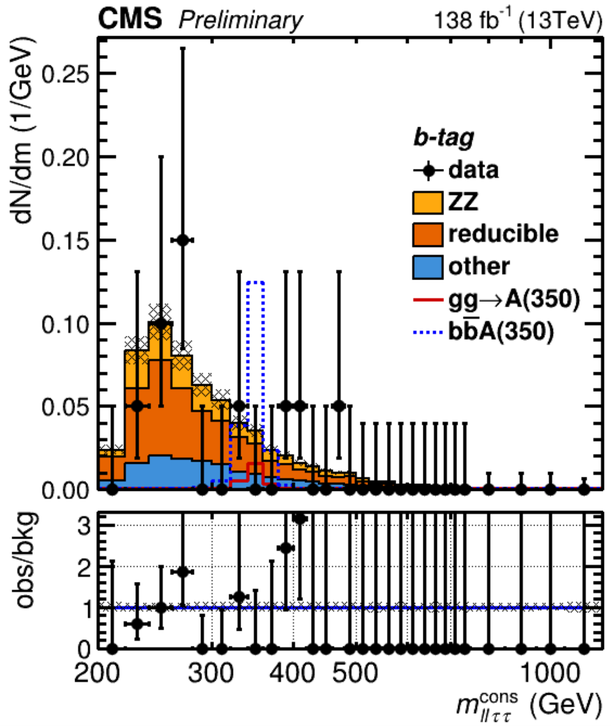
- 2HDM/MSSM-motivated search for pseudoscalar A with **225<m_A<800** GeV, produced via **gluon fusion** or in **association with b quarks**
- Final states considered: Z→ee/μμ, **H→eτh/μτh/τhτh**
- A candidate mass resolution improved by imposing **125 GeV mass constraint**
- Data-driven estimation of reducible background from jet→tau misidentification



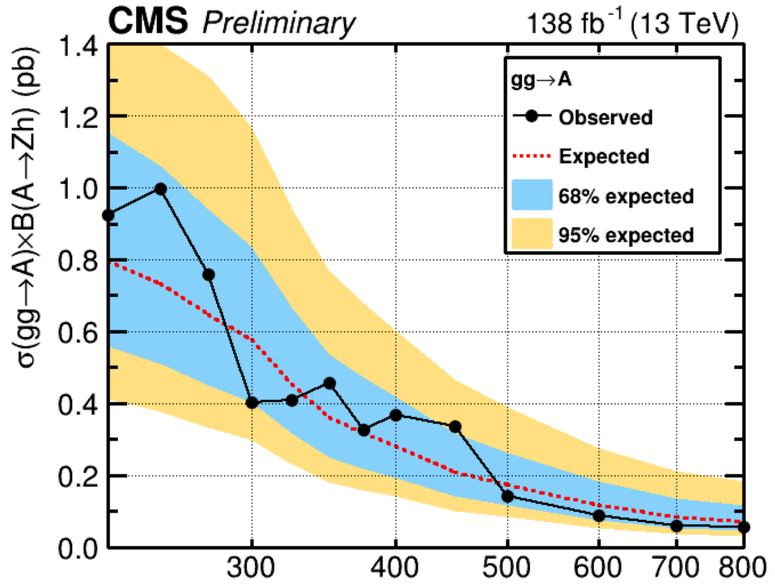


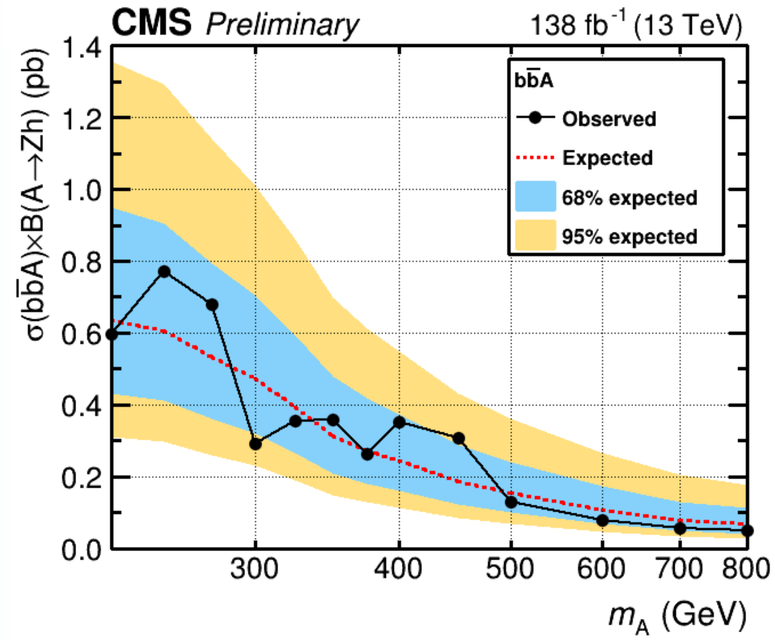


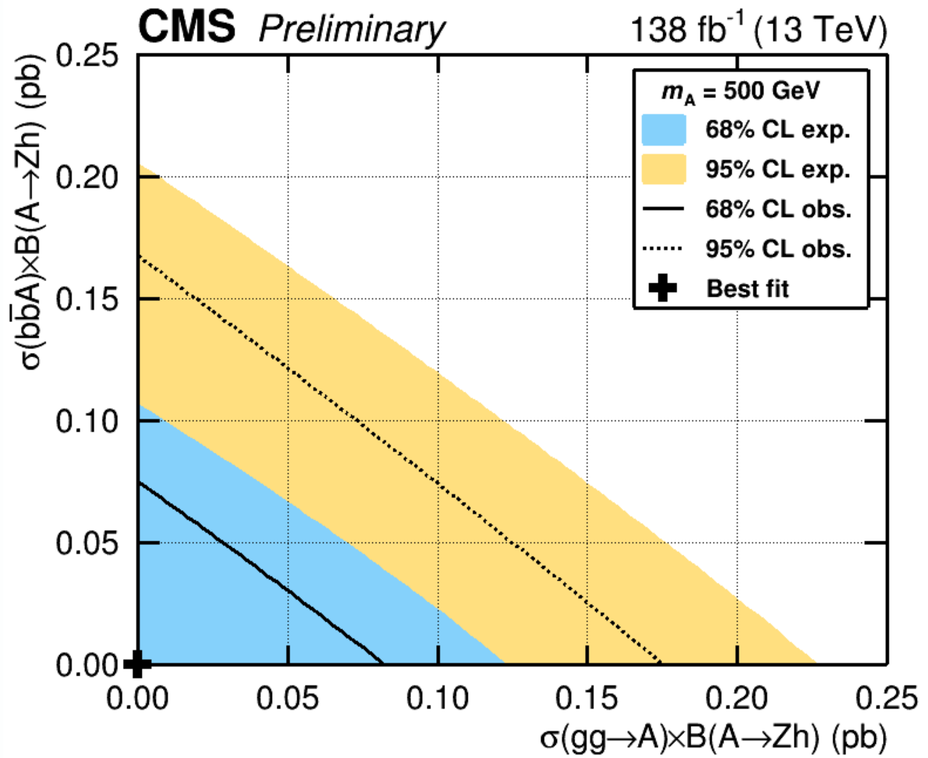




CMS A→ZH→llττ: Results [CMS-PAS-HIG-22-004]

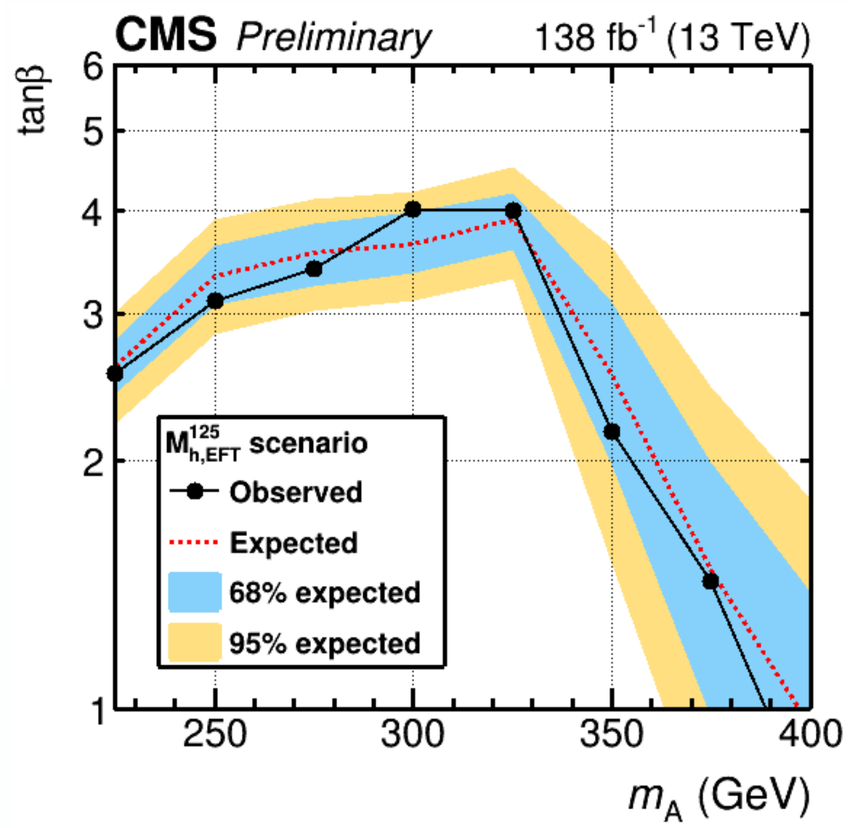






- Limits set on both production modes separately and together

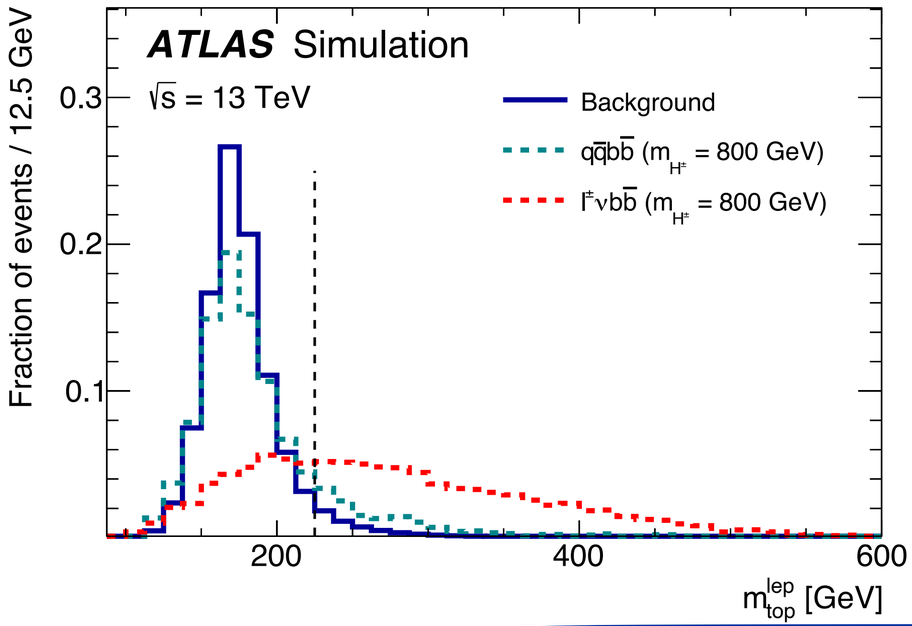
- Interpretation in **MSSM**

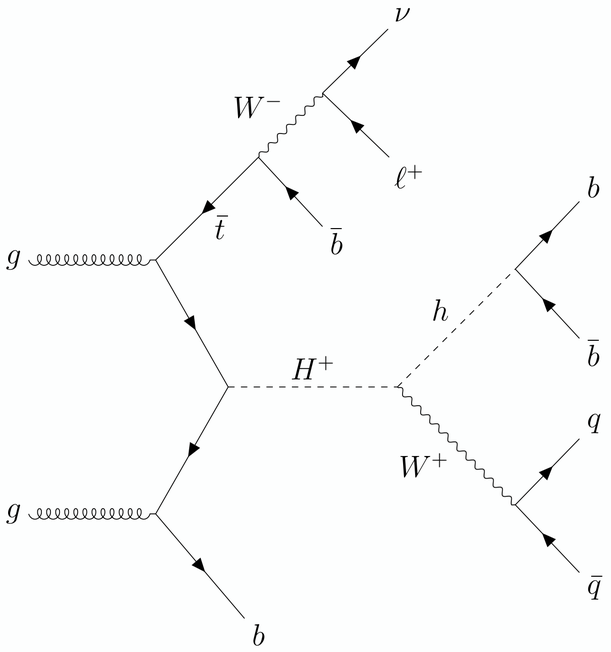


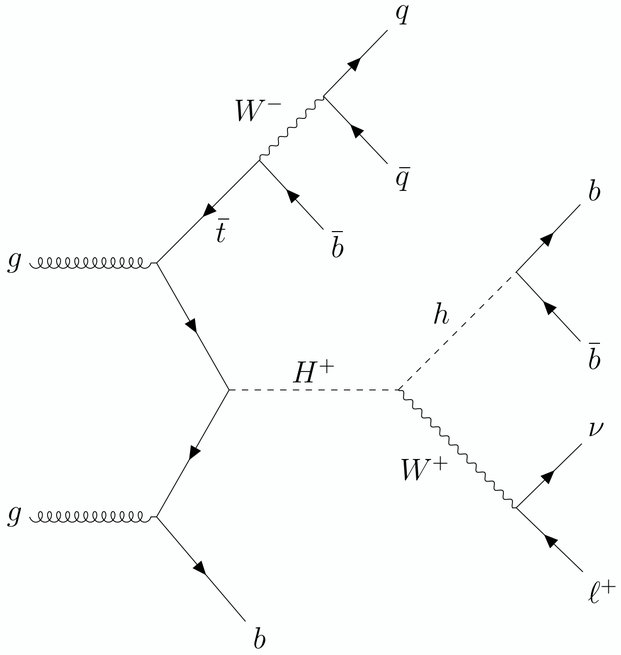
ATLAS $H^+ \to WH \to [qq/l\nu]bb$ [HMBS-2024-45]

New for Higgs 2024

- The **first LHC search** for a charged Higgs boson (**250<m_{H^+}<3000** GeV) decaying to W + H (125 GeV)
  - Focus on **single-lepton** final states and top associated production





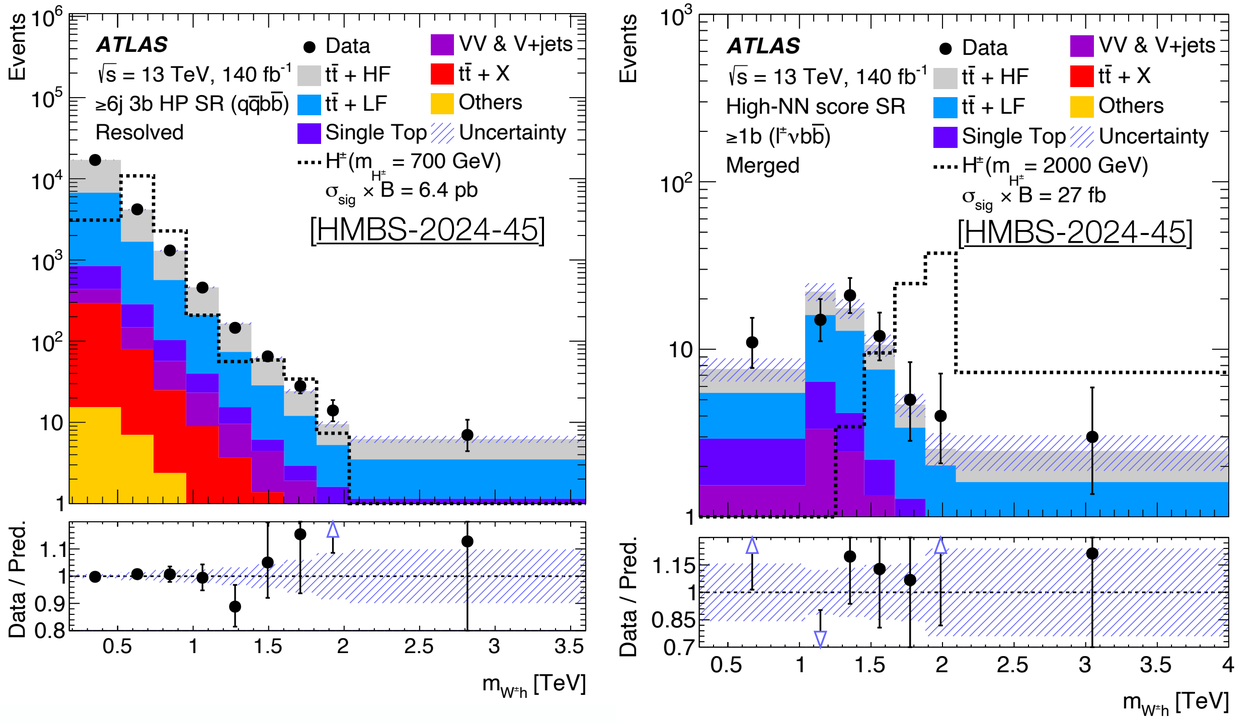


	qqbb channel	**lvbb channel**
Resolved topology	✤ **BDT** to solve combinatorics (kinematics + b-tags)	✤ BDT + **W mass constraint** to reconstruct $p_z(\nu)$
Merged-jet topology	✤ **2 large-R jets**, **H tagging** with variable-radius track jets	✤ **1 H-tagged large-R jet** + e/μ + ν candidate

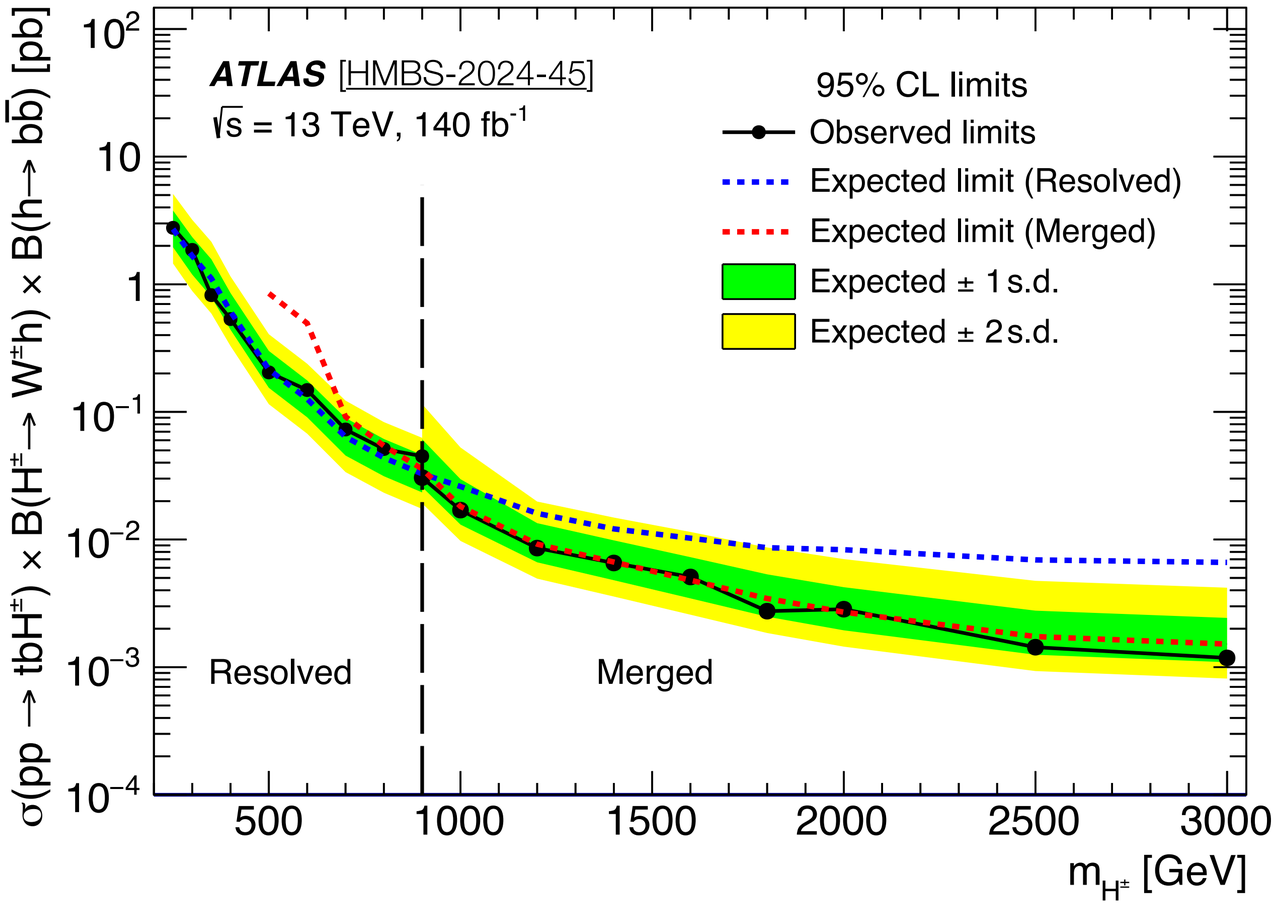
+kinematic DNN for background suppression

ATLAS $H^+ \to WH \to [qq/l\nu]bb$: Results

New for Higgs 2024



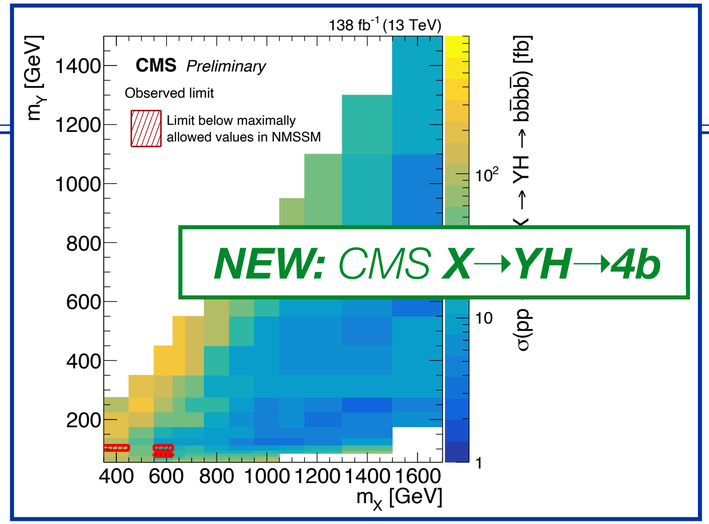
- Signal extraction using **reconstructed H^+ invariant mass** distributions
- **Categorizatation** by channel, decay BDT/DNN score, and (b-)jet multiplicity
- Backgrounds estimated from simulation, with in-situ corrections from **control regions**

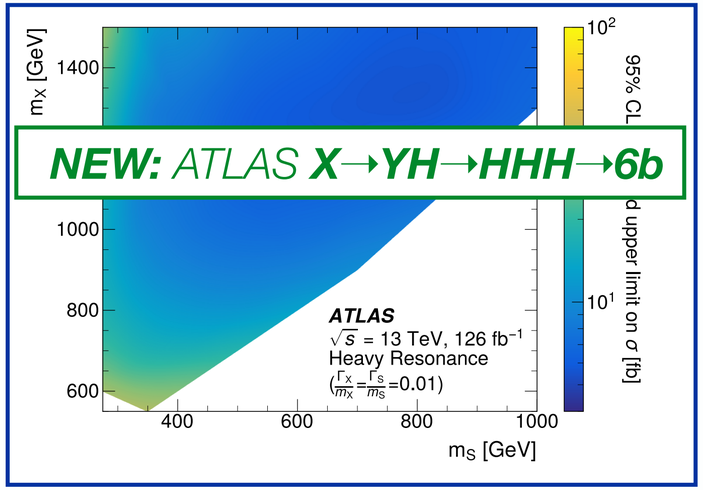


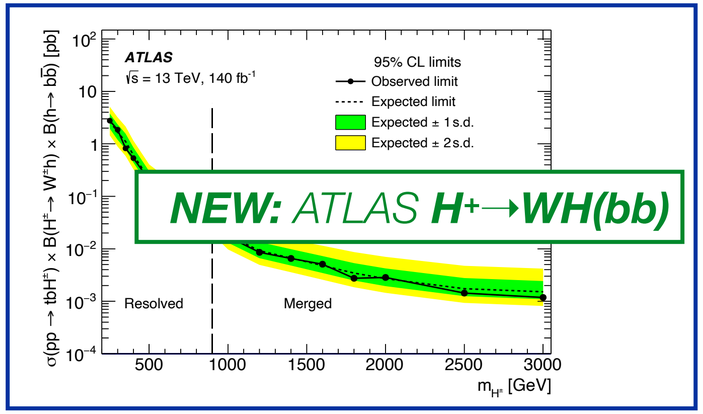
- The resolved and merged-jet analyses are not orthogonal → take the best limit of the two
- **No excess observed**
- These are the first LHC limits on this process

Summary & Outlook

- **X→HH**:
  - Driven by the 3 **golden channels**, for which the Run 2 analyses are now fully finalized by both experiments
  - Statistical **combinations** with full Run 2 shown today, with various interpretations
  - Next: dedicated analyses/categories for different **production modes**
- **X→YH**:
  - Various final states to cover, the work to **fill the gaps** continue
  - First statistical **combination** performed by CMS, with Y(bb)H(bb/ττ/γγ)
- **The two experiments cross-check each other efficiently:**
  - ATLAS m_{HH} = 1.1 TeV excess **not** confirmed by CMS
  - CMS (m_X,m_Y) = (650,90) GeV γγbb excess **not** confirmed by ATLAS
- **Run-3 improvements** in triggering, flavour tagging, etc. will push the sensitivity for the future resonant searches beyond the statistics increase



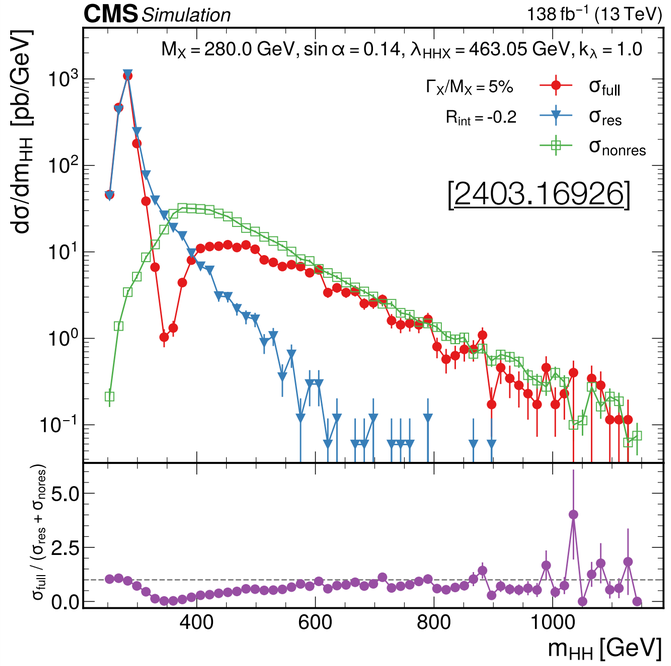


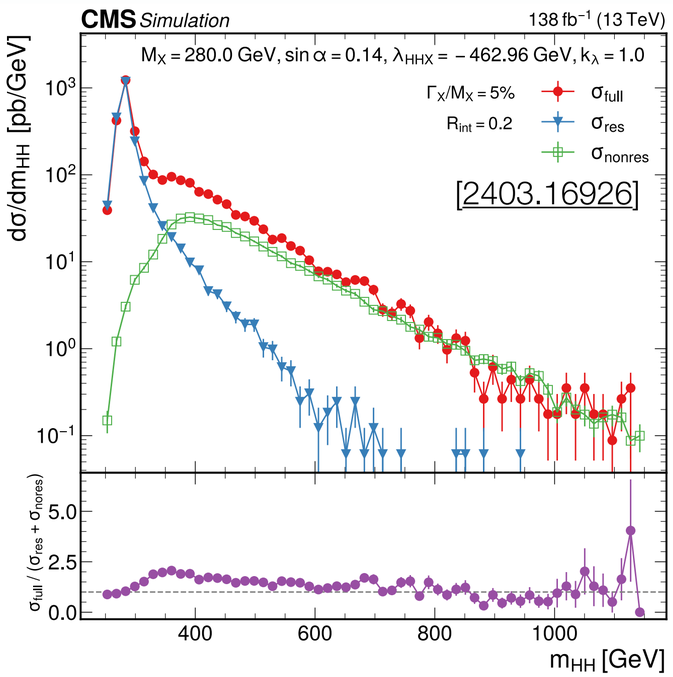


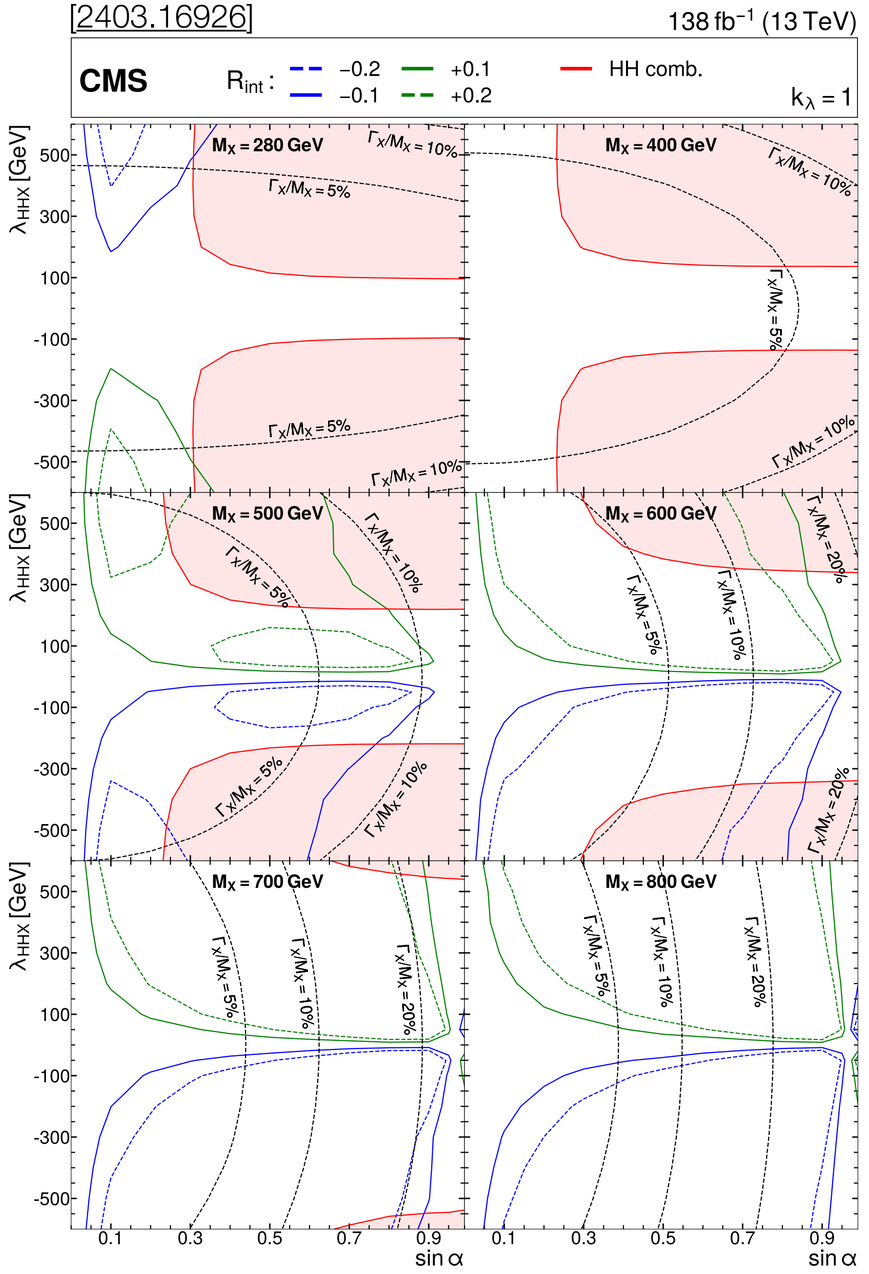
Thank you!

More results

CMS X→HH: Sensitivity to Interference Effects







- So far the X→HH searches have **not** considered the possible **interference with nonresonant HH** (constructive or destructive)
- CMS has conducted a study of the interference effects, with the goal of **identifying phase space regions where NWA is valid**
- Real singlet model used to produce benchmarks with **Γ_X/M_X** = 5 / 10 / 20% and **relative interference effect R_{int}** = ±10% or ±20%

$$R_{\text{int}} = \frac{\sigma^{\text{full}} - \left(\sigma^{\text{resonant-only}} + \sigma^{\text{nonresonant}}\right)}{\sigma^{\text{resonant-only}} + \sigma^{\text{nonresonant}}}$$

ATLAS X→HH: Limits in 2HDM & MSSM [2311.15956]

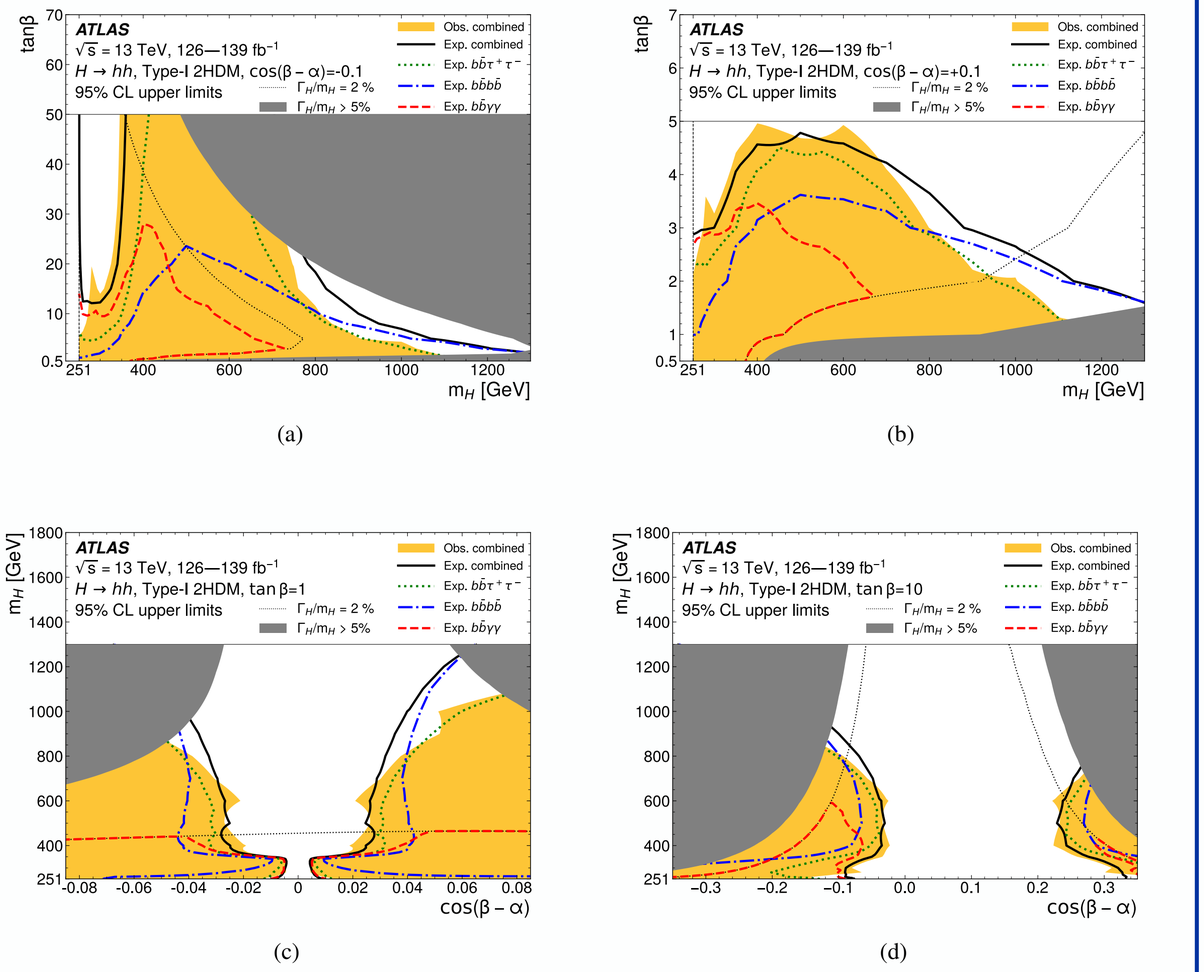


Figure 2: Exclusion limits at the 95% CL on the Type-I 2HDM parameter space. Observed and expected limits for the combination of all channels and expected limits for each of the individual channels are presented. The 2HDM parameters are shown in the m_H–$\tan\beta$ plane for (a) $\cos(\beta-\alpha) = -0.1$ and (b) $\cos(\beta-\alpha) = 0.1$, and in the $\cos(\beta-\alpha)$–m_H plane for (c) $\tan\beta = 1$ and (d) $\tan\beta = 10$. The $b\bar{b}\gamma\gamma$ channel limits are valid for H boson natural widths $\Gamma_H/m_H < 2\%$, so limits from this channel are quoted for the parameter space that satisfies this requirement. The limits in the $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ channels are only valid for $\Gamma_H/m_H < 5\%$, so no limits are quoted in the dark shaded regions, where the width exceeds this value.

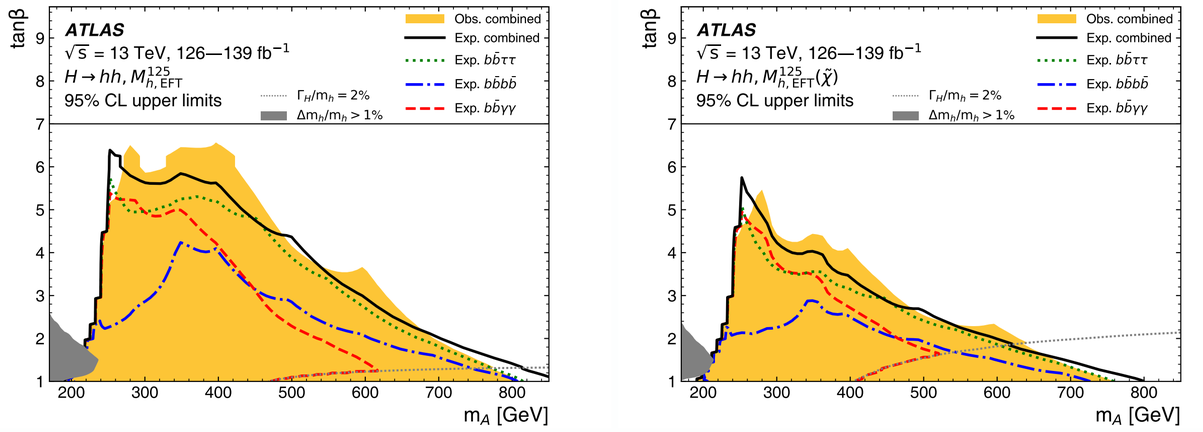


Figure 3: Observed and expected exclusion limits at the 95% CL on the MSSM parameter space for the (a) $M^{125}_{h,\mathrm{EFT}}$ and (b) $M^{125}_{h,\mathrm{EFT}}(\tilde{\chi})$ benchmark scenarios for each of the individual channels and their combination. The $b\bar{b}\gamma\gamma$ channel limits are valid for H boson natural widths $\Gamma_H/m_H < 2\%$, so limits from this channel are quoted for the parameter space that satisfies this requirement. The limits do not apply in the dark shaded regions, where the mass of the lightest CP-even Higgs boson, h, is not compatible with 125 GeV within the experimental mass resolution.

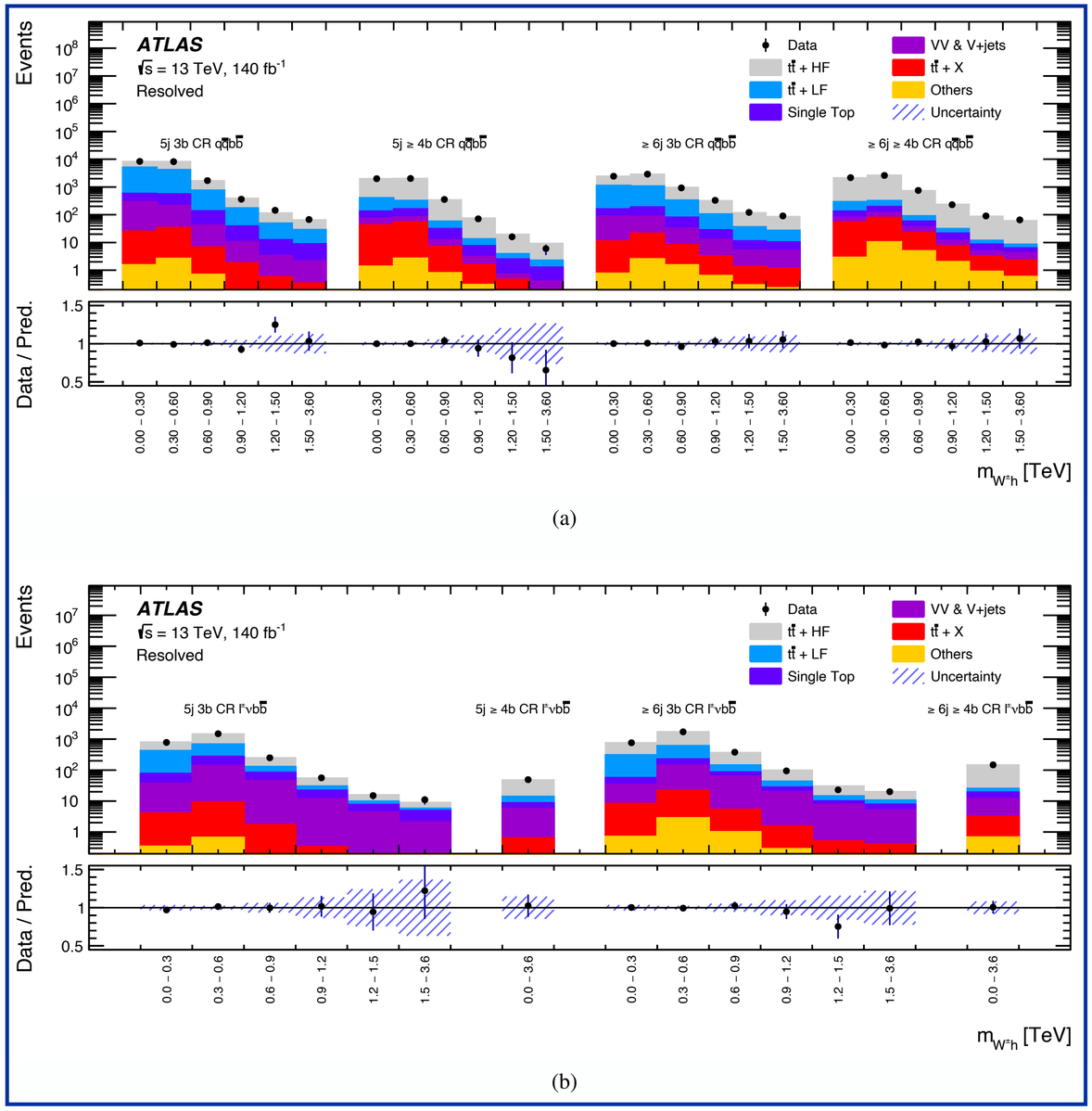
ATLAS $H^+ \to WH \to [qq/l\nu]bb$: Selections

[HMBS-2024-45]

	Resolved analysis		Merged analysis	
Decay channel	$\ell^{\pm}\nu b\bar{b}$	$q\bar{q}b\bar{b}$	$\ell^{\pm}\nu b\bar{b}$	$q\bar{q}b\bar{b}$
Preselection	$N^{\ell} = 1$ $E_{\mathrm{T}}^{\mathrm{miss}} > 30\,\mathrm{GeV}$ $N^{\text{small}-R\,\text{jets}} \geq 5$ $N^{b-\text{tags}} \geq 2$		$N^{\text{large}-R\,\text{jets}} \geq 1$ $N^{h-\text{tags}} = 1$	
Classification requirement	$m_{\text{top}} > 225\,\mathrm{GeV}$ $5j3b$, $5j \geq 4b$, $\geq 6j3b$, and $\geq 6j \geq 4b$	$m_{\text{top}} < 225\,\mathrm{GeV}$	$N^{W-\text{tags}} = 0$ $0b$ and $\geq 1b$	$N^{W-\text{tags}} = 1$

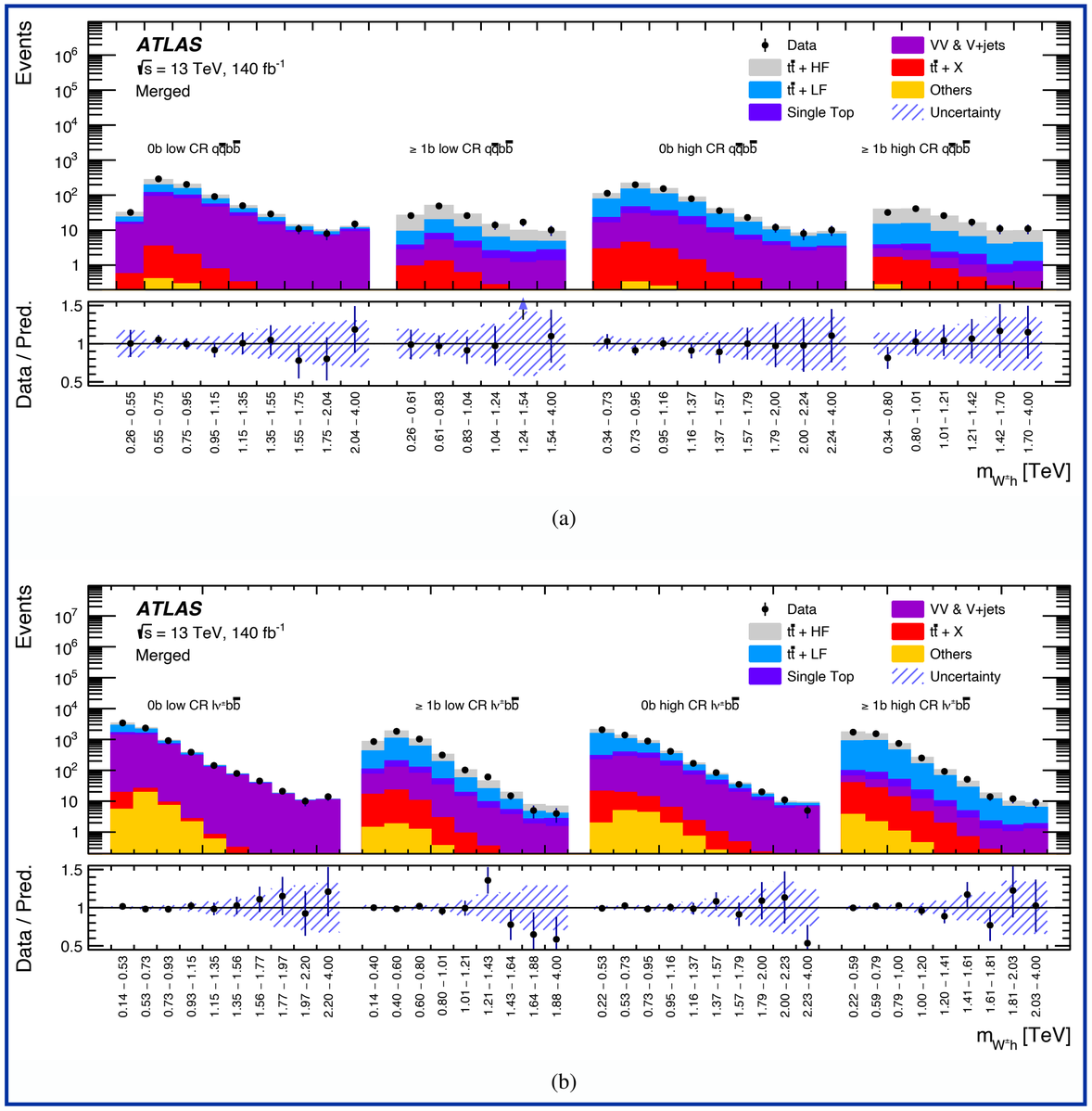
Region	Requirement	$\ell^{\pm}\nu b\bar{b}$ channel	$q\bar{q}b\bar{b}$ channel
Resolved			
Signal regions	Jet & b-tag multiplicity		$5j3b$, $5j \geq 4b$, $\geq 6j3b$, $\geq 6j \geq 4b$
	BDT score	$w_{\text{BDT}}^{\text{max}} \geq 0.7$	$w_{\text{BDT}}^{\text{max}} \geq 0.9$
Low-purity signal regions	Jet & b-tag multiplicity		$5j3b$, $5j \geq 4b$, $\geq 6j3b$, $\geq 6j \geq 4b$
	BDT score	–	$0.0 \leq w_{\text{BDT}}^{\text{max}} < 0.9$ (for events with $5j3b$ or $\geq 6j3b$) $0.6 \leq w_{\text{BDT}}^{\text{max}} < 0.9$ (for events with $5j \geq 4b$ or $\geq 6j \geq 4b$)
Control regions	Jet & b-tag multiplicity		$5j3b$, $5j \geq 4b$, $\geq 6j3b$, $\geq 6j \geq 4b$
	BDT score	$-0.5 \leq w_{\text{BDT}}^{\text{max}} < 0.5$	$-0.5 \leq w_{\text{BDT}}^{\text{max}} < 0.0$ (for events with $5j3b$ or $\geq 6j3b$) $-0.5 \leq w_{\text{BDT}}^{\text{max}} < 0.6$ (for events with $5j \geq 4b$ or $\geq 6j \geq 4b$)
Merged			
High-NN score signal region	b-tag multiplicity		$0b$, $\geq 1b$
	Mass window		$95\,\mathrm{GeV} \leq m_J < 140\,\mathrm{GeV}$
	NN score	$w_{\text{NN}} \geq 0.83$	$w_{\text{NN}} \geq 0.2$ (for events with $0b$) $w_{\text{NN}} \geq 0.1$ (for events with $\geq 1b$)
Medium-NN score signal region	b-tag multiplicity		$0b$, $\geq 1b$
	Mass window		$95\,\mathrm{GeV} \leq m_J < 140\,\mathrm{GeV}$
	NN score	$0.4 \leq w_{\text{NN}} < 0.83$	–
Low-NN score signal region	b-tag multiplicity		$0b$, $\geq 1b$
	Mass window		$95\,\mathrm{GeV} \leq m_J < 140\,\mathrm{GeV}$
	NN score	$w_{\text{NN}} < 0.4$	$w_{\text{NN}} < 0.2$ (for events with $0b$) $w_{\text{NN}} < 0.1$ (for events with $\geq 1b$)
Low-mass control region	b-tag multiplicity		$0b$, $\geq 1b$
	Mass window		$m_J < 95\,\mathrm{GeV}$
	NN score		–
High-mass control region	b-tag multiplicity		$0b$, $\geq 1b$
	Mass window		$m_J \geq 140\,\mathrm{GeV}$
	NN score		–

ATLAS $H^+ \to WH \to [qq/l\nu]bb$: Control Regions



(a)

(b)



(a)

(b)