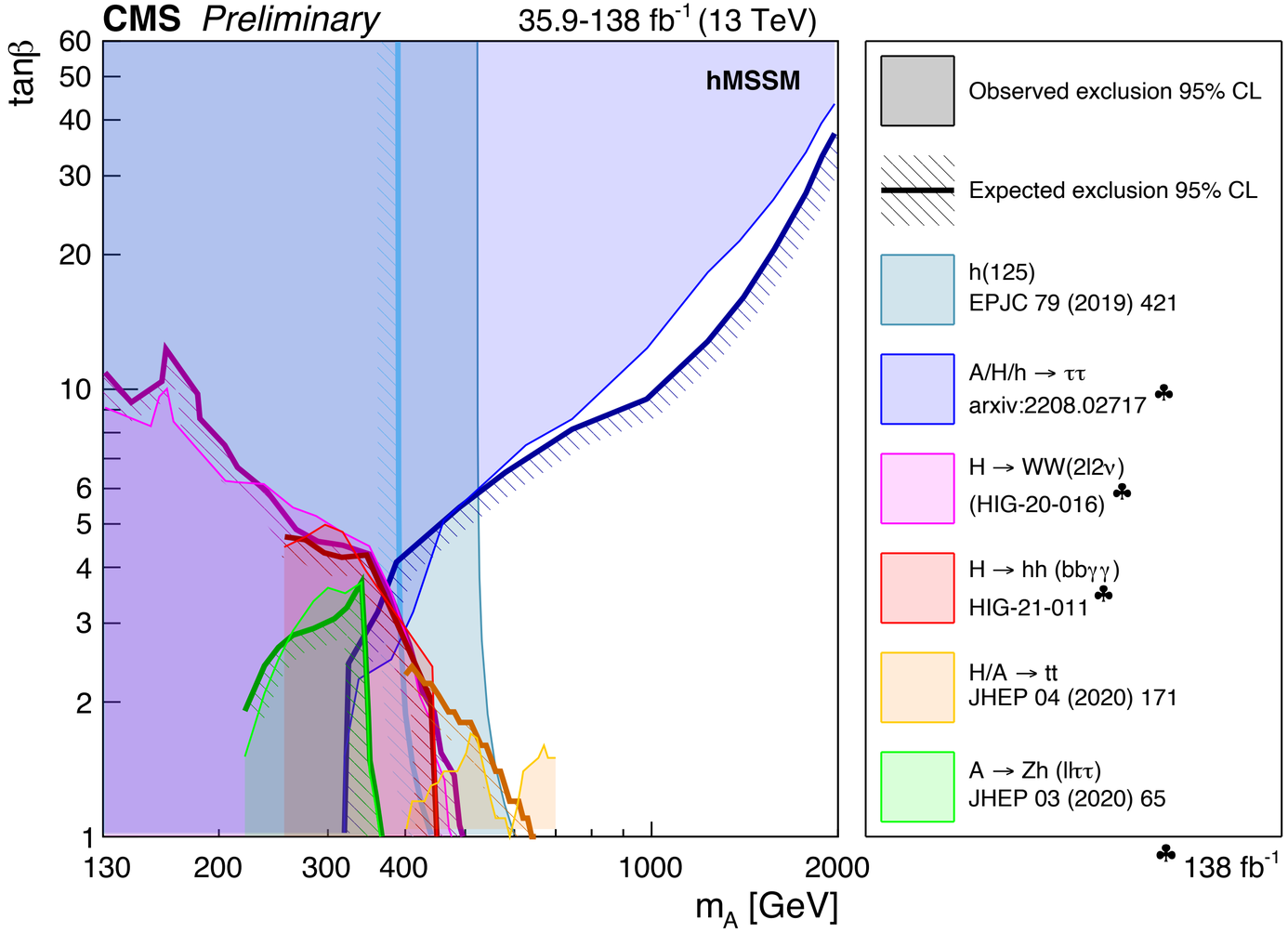
# Extended Higgs sector *experimental status*




Roberto Salerno

# The role of H in searches for BSM

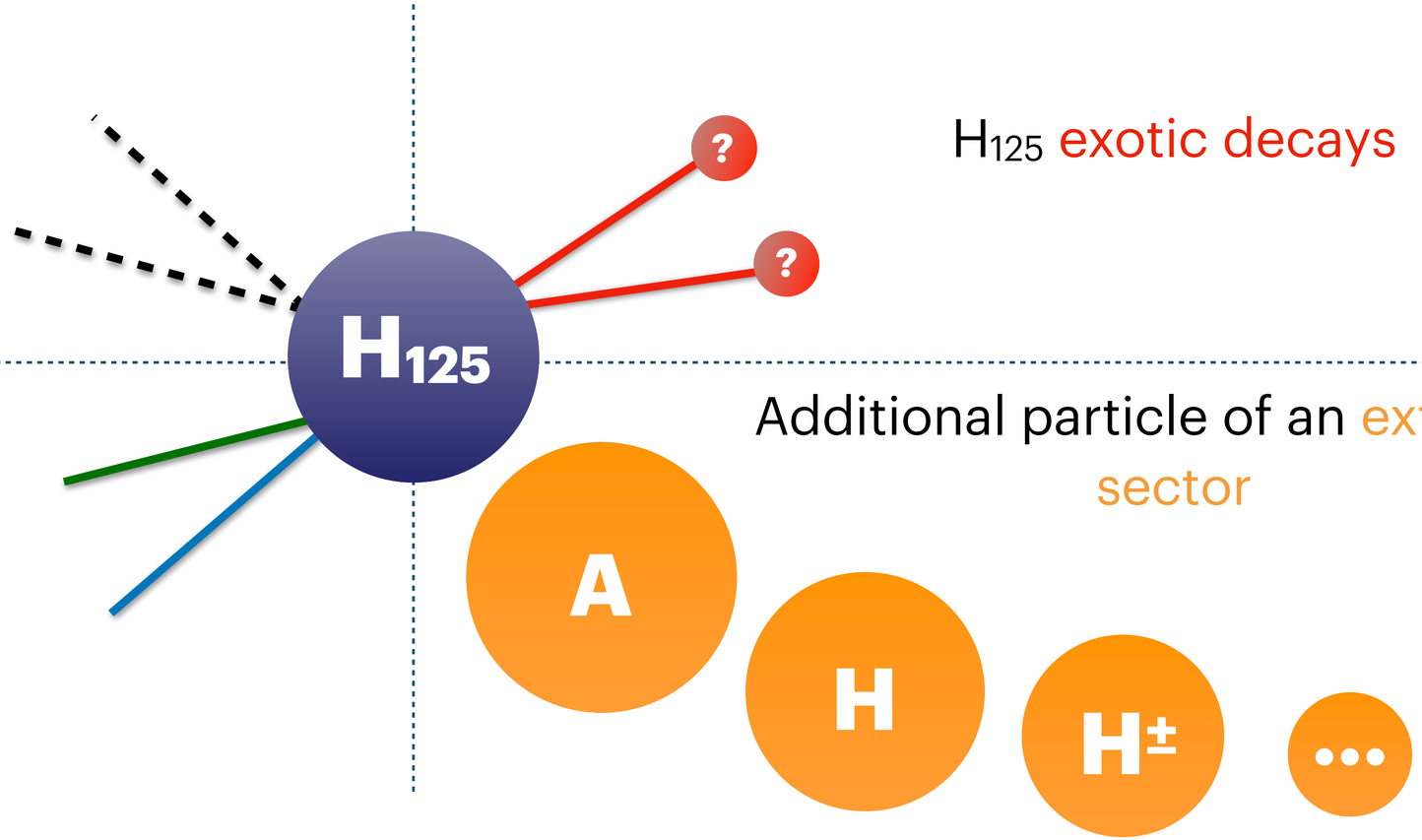
**>10 years after its discovery**, the Higgs boson plays a fundamental role in searches for physics beyond the Standard Model

# The role of H in searches for BSM

**>10 years after its discovery**, the Higgs boson plays a fundamental role in searches for physics beyond the Standard Model

invisible decay

$H_{125}$ invisible and undetected decays




$H_{125}$ exotic decays

exotic decays

flavour violating decays

$H_{125}$ flavour violating decays

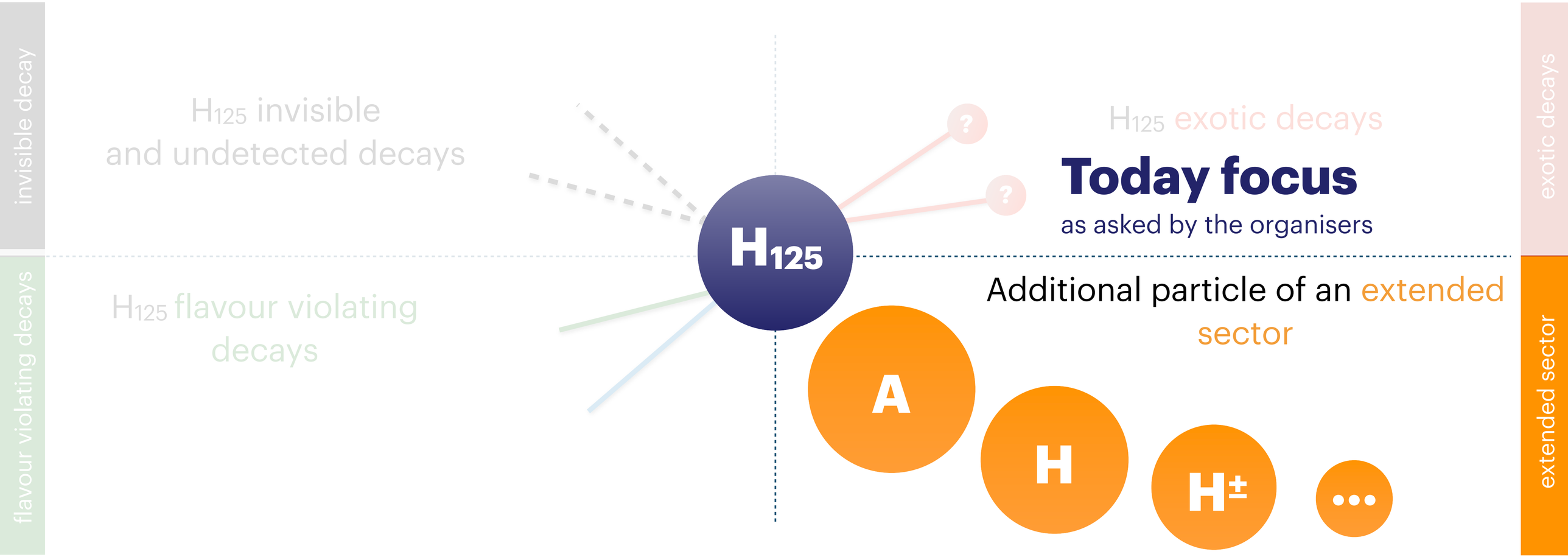
Additional particle of an extended sector

extended sector

Very large physics program pursued by both ATLAS and CMS!

# The role of H in searches for BSM

**>10 years after its discovery**, the Higgs boson plays a fundamental role in searches for physics beyond the Standard Model




Very large physics program pursued by both ATLAS and CMS!

# Extended Higgs sector - *3 groups of searches*

A **light resonance X** ($m_X < m_{H125}$) decaying to SM particles

- $X \to \gamma\gamma$, $X \to \tau\tau$

A **heavy resonance X** ($m_X > m_{H125}$) decaying to SM particles

- $X \to VV$, $X \to H_{125}H_{125}$

A **heavy resonance X** ($m_X > m_{H125}$) decaying to at least a new particle

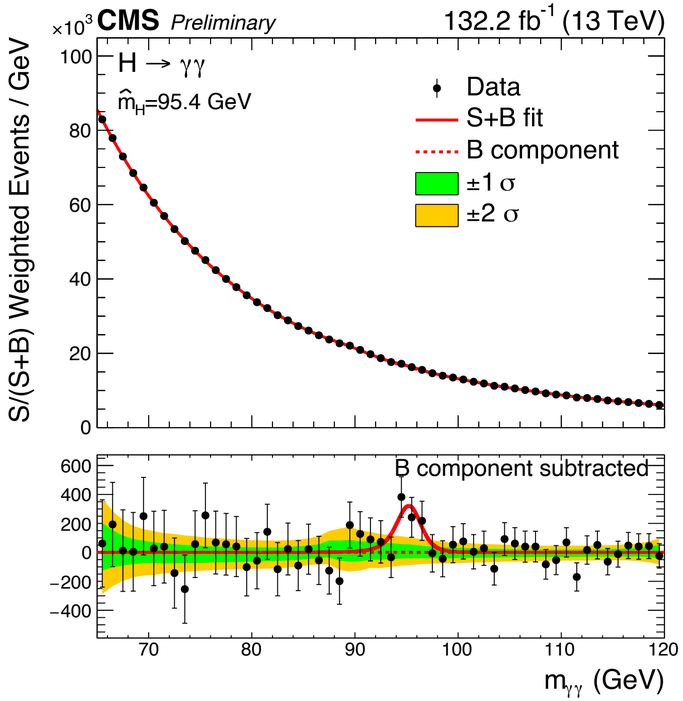
- $X \to YH_{125}$, $X \to ZA$

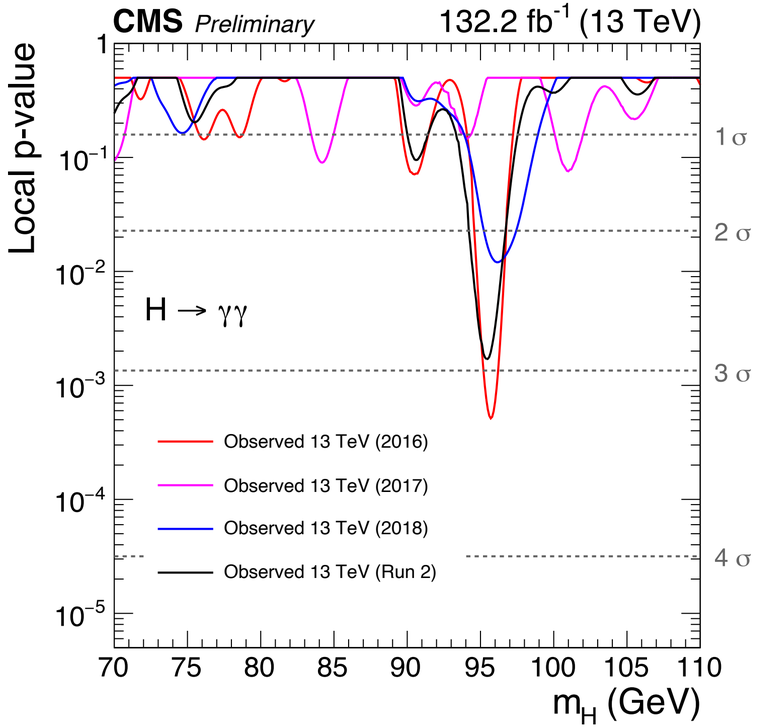
All the analyses presented are using the LHC (full) Run2 dataset
Experiments are not yet covering the whole matrix of final states

# Light resonance: X → $\gamma\gamma$



One of the flagship searches




As written in the paper :

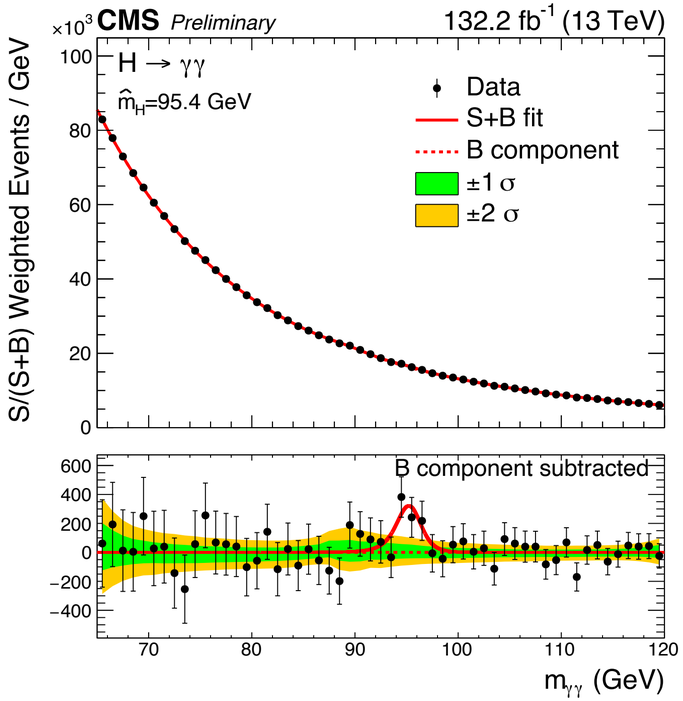
"In the case of the combined data set, one excess with approximately 2.9$\sigma$ local (1.3$\sigma$ global) significance is observed for a mass hypothesis of 95.4 GeV "

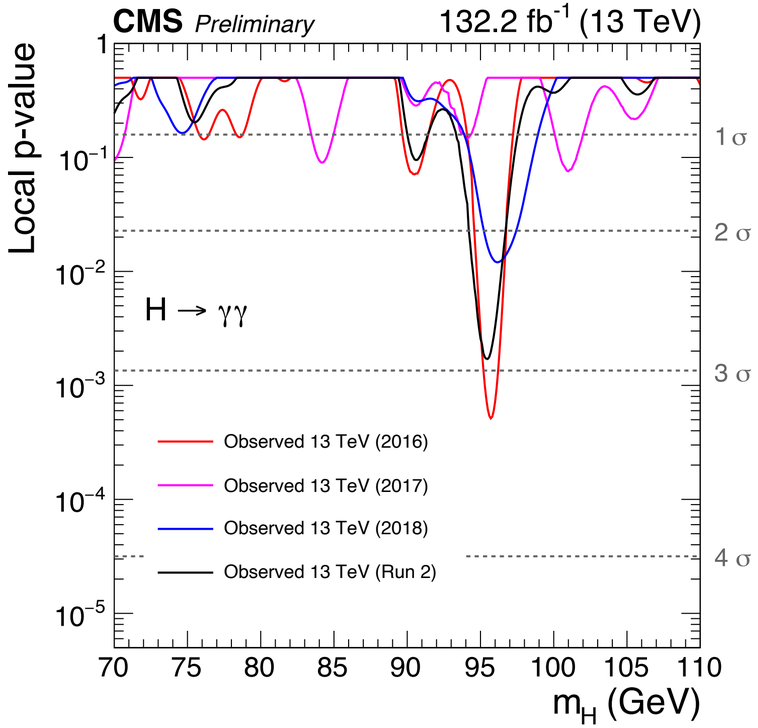
# Light resonance: X → $\gamma\gamma$

CMS PAS HIG-20-002

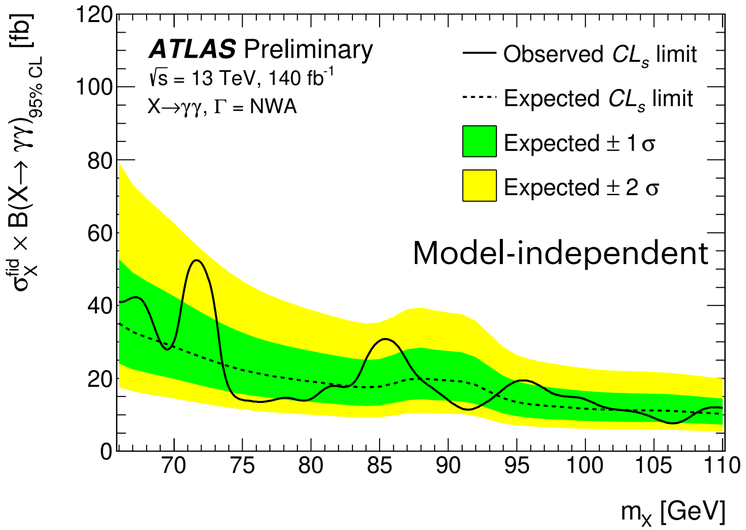
ATLAS-CONF-2023-035

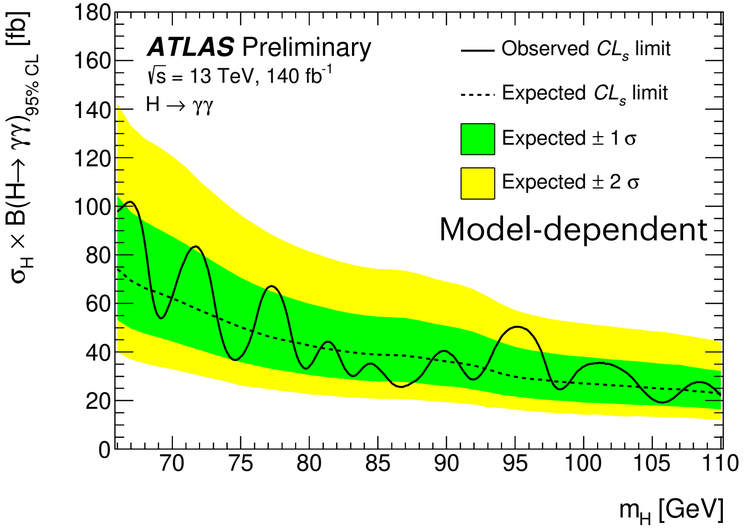
One of the flagship searches




ATLAS search cannot confirm the CMS excess

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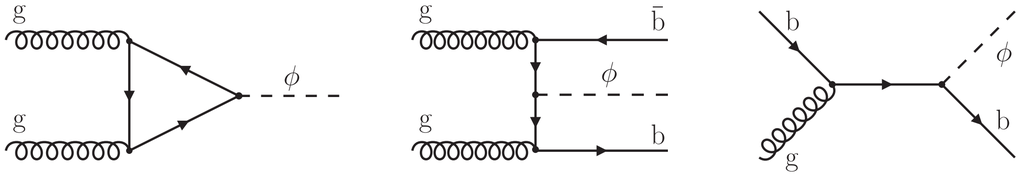
"In the case of the combined data set, <u>one excess</u> with approximately 2.9$\sigma$ local (1.3$\sigma$ global) significance is observed for a mass hypothesis of 95.4 GeV "

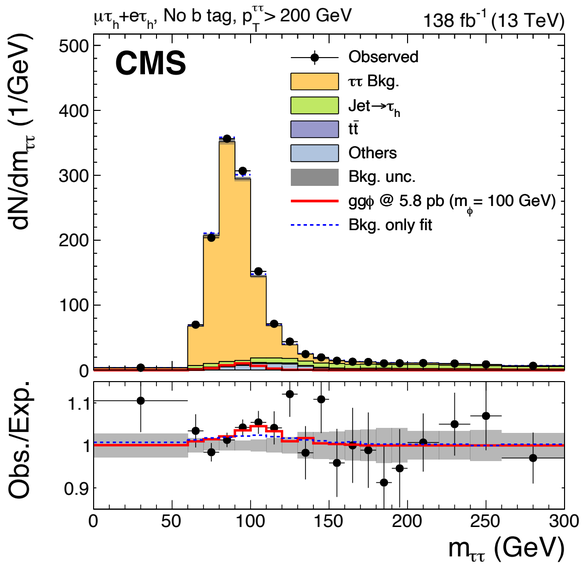
# Light/Heavy resonance: A/H→$\tau\tau$

JHEP 07 (2023) 073

4 ττ final states ($\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, $e\mu$)
b-tag/no b-tag category




Fit $m_{\tau\tau}$
in various Higgs $p_T$ categories

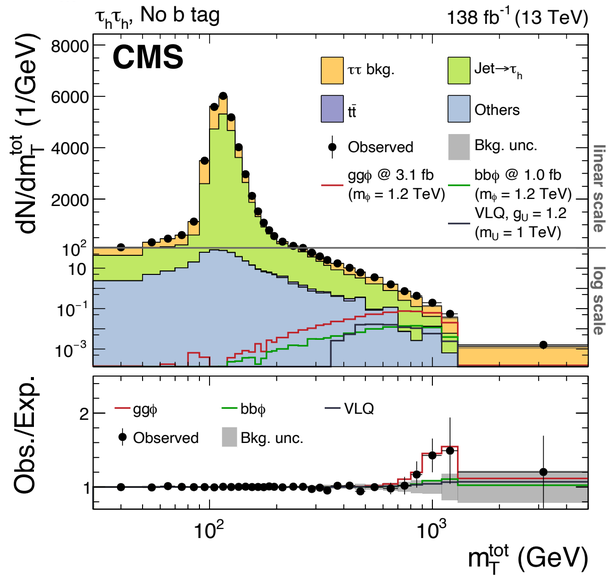



**Low-mass analysis**

$m_\phi < 250$ GeV

**High-mass analysis**

$m_\phi > 250$ GeV

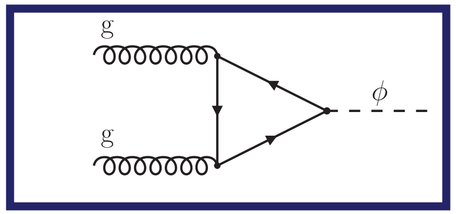


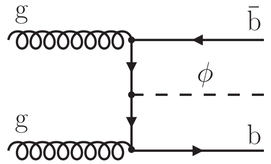

Fit transverse mass variable
Few $m_T$ categories

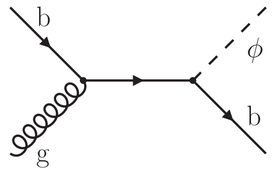
# Light/Heavy resonance: A/H→ττ

JHEP 07 (2023) 073

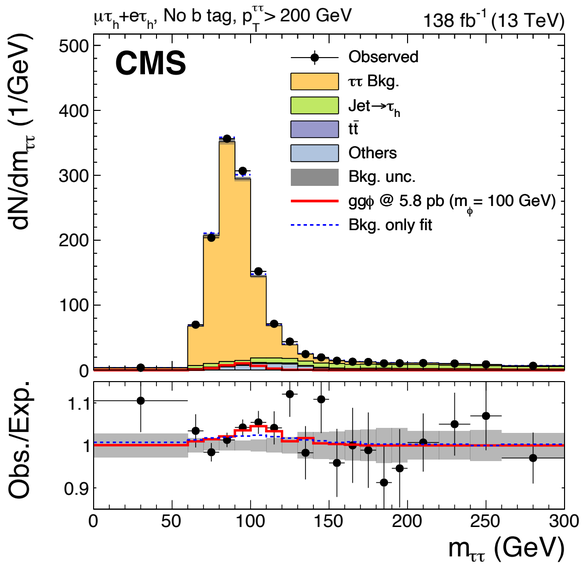
4 ττ final states ($\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, $e\mu$)
b-tag/no b-tag category



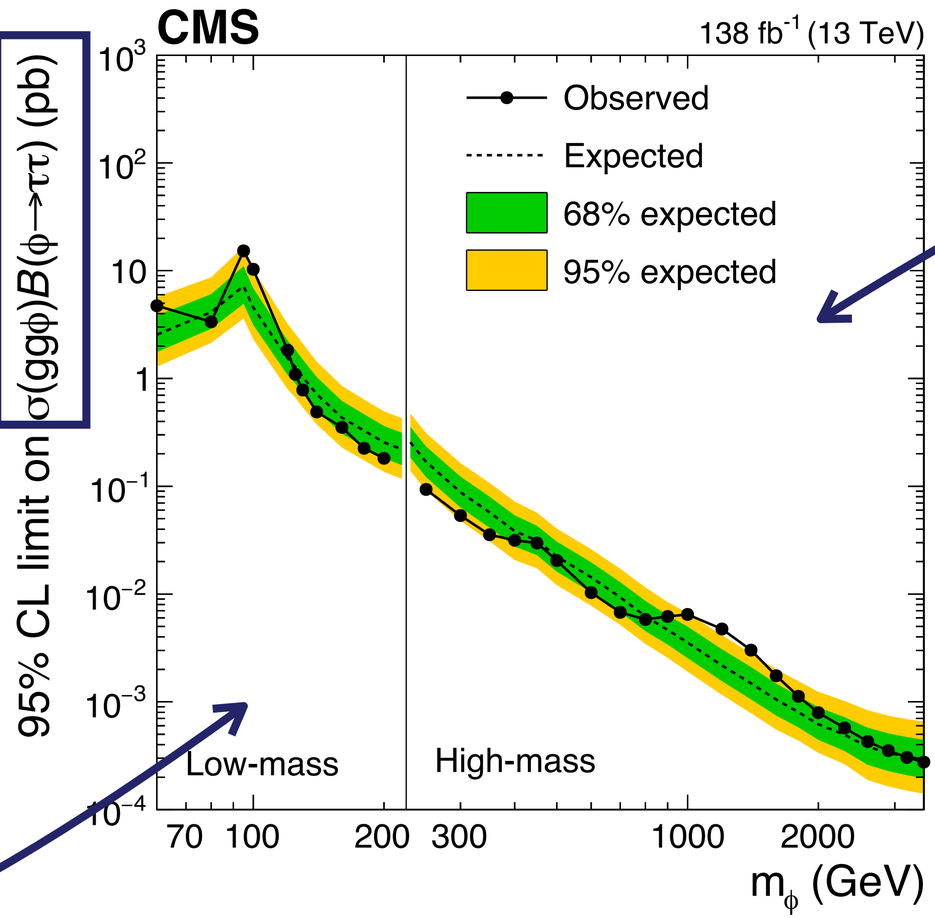




Fit $m_{\tau\tau}$
in various Higgs $p_T$ categories




**Low-mass analysis**

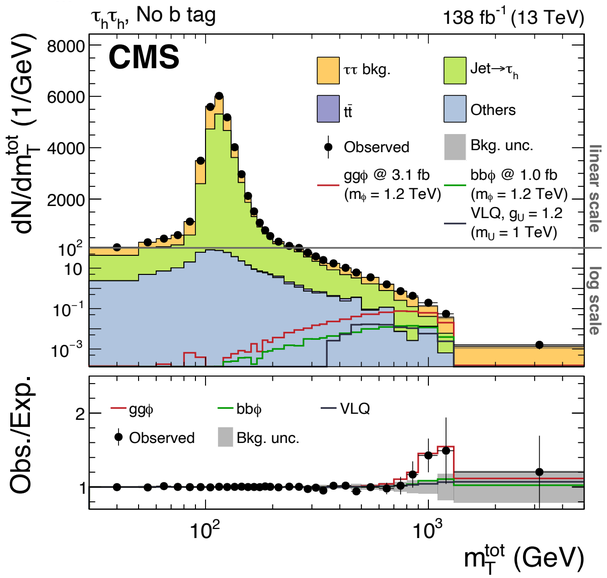
$m_\phi < 250$ GeV




Model-independent limits
on $\sigma(gg\phi)$ and $\sigma(bb\phi)$

**High-mass analysis**

$m_\phi > 250$ GeV

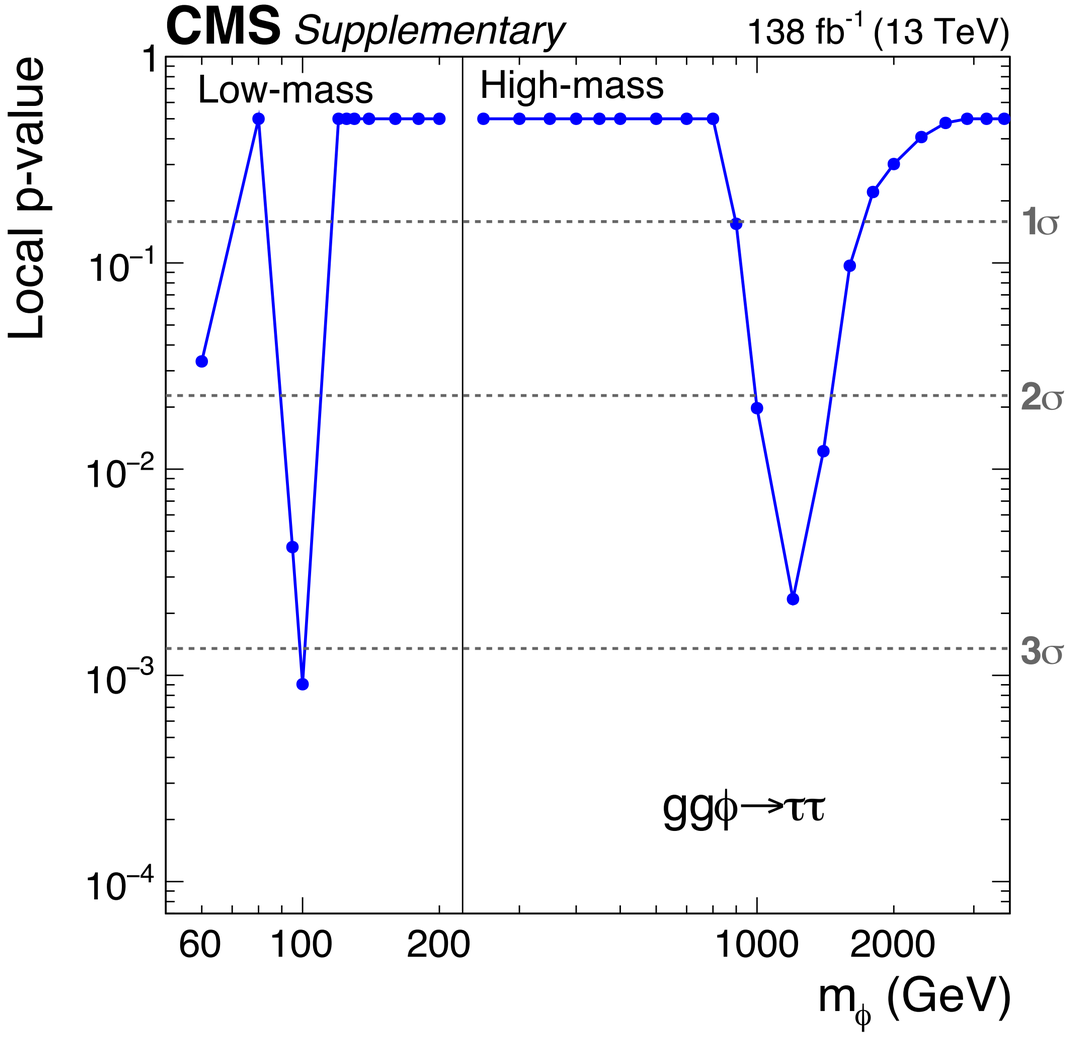



Fit transverse mass variable
Few $m_T$ categories

# Light/Heavy resonance: A/H→$\tau\tau$

JHEP 07 (2023) 073

$gg\phi$ signal while $\sigma(bb\phi)$ is profiled.




As written in the paper :

"Two excesses for $gg\phi$ production with local *p*-values equivalent to about 3 standard deviations at $m_\phi$ = 0.1 and 1.2 TeV. Within the resolution of the reconstructed invariant mass of the $\tau\tau$ system, the excess at 100 GeV coincides with a similar excess observed in a previous search for low-mass resonances by the CMS Collaboration in the $\gamma\gamma$ final state at a mass of ≈95 GeV "

- Cannot be combined with other final states w/o a signal hypothesis
- ATLAS result (PRL (2020) 051801) starts at 200 GeV

# Heavy resonance: X → ZZ

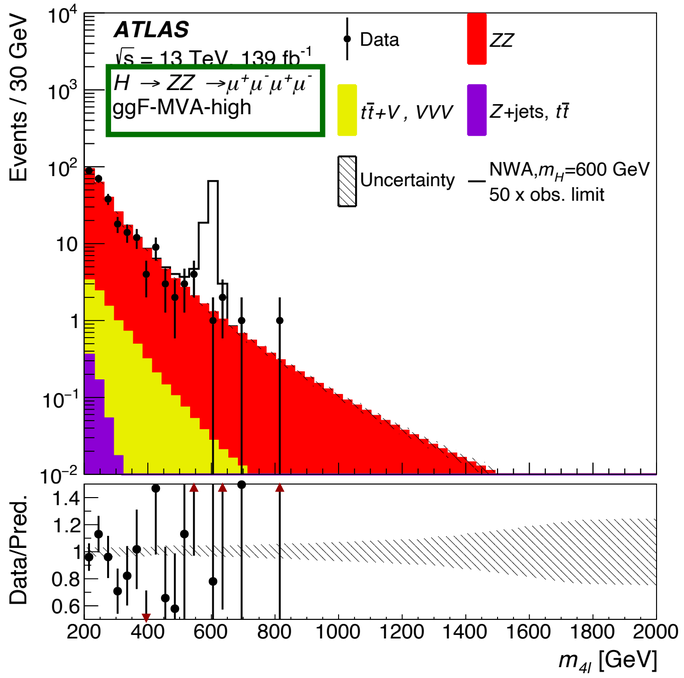
Eur. Phys. J. C 81 (2021) 332

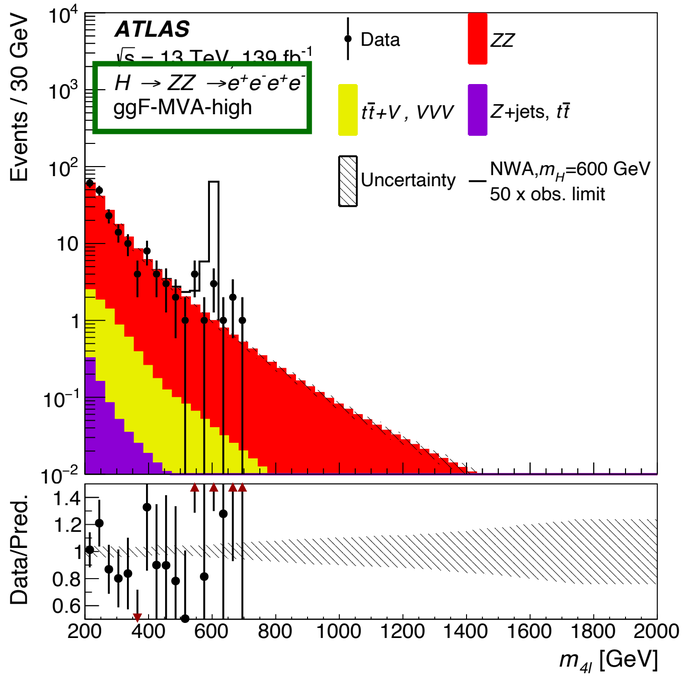
Two final states : $4\ell$, $\ell\nu\ell\nu$

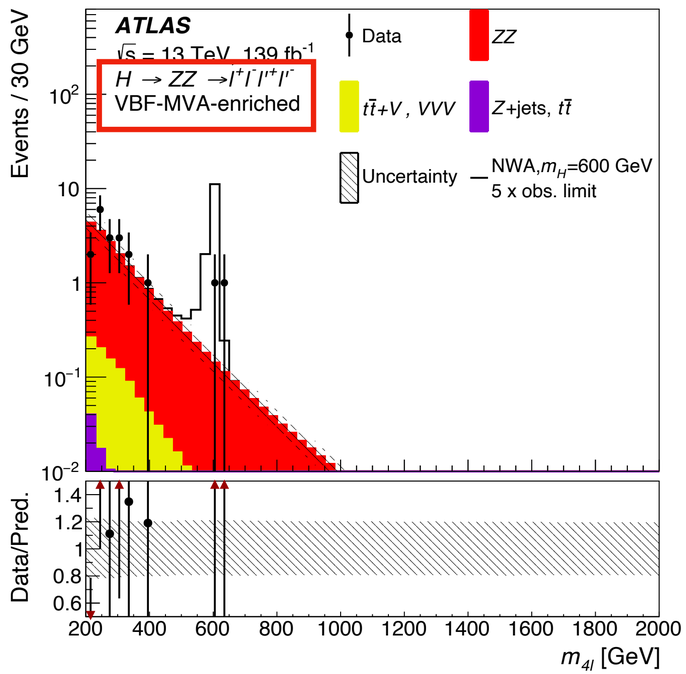
Only “Narrow Width Approximation” hypothesis tested

Two production mechanisms : ggF production or VBF production

Events categorised in ggF-enriched or VBF-enriched categories



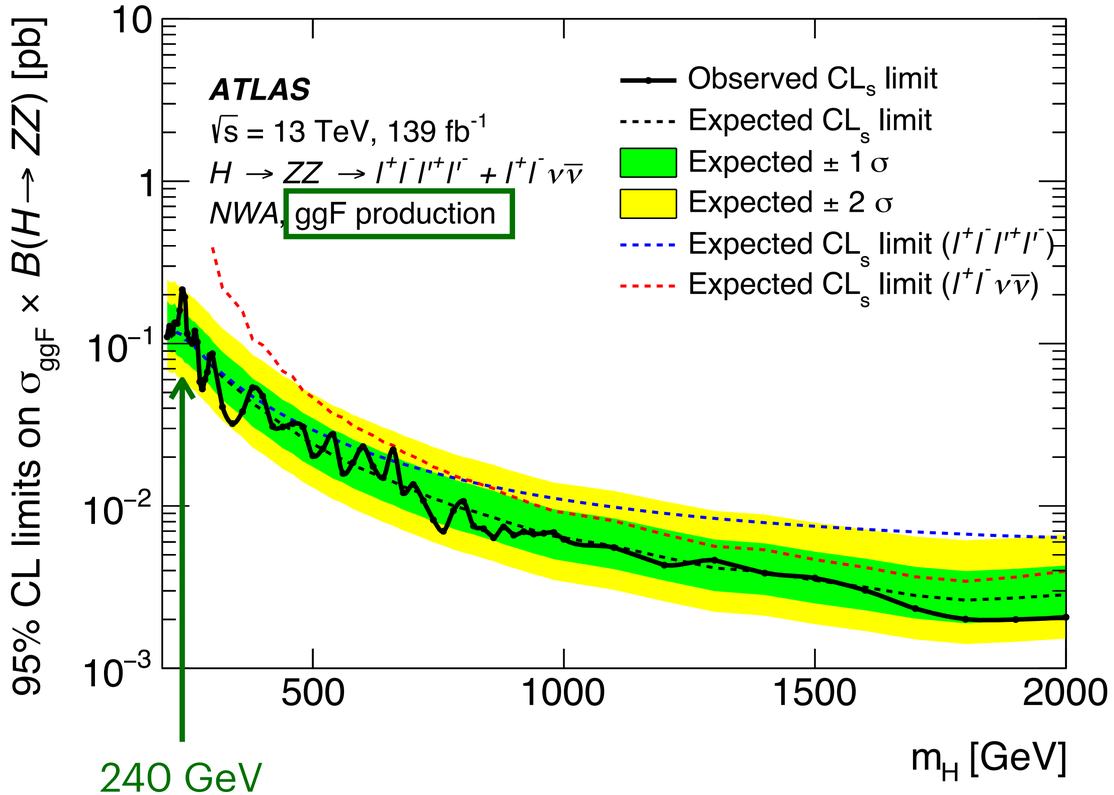



# Heavy resonance: X → ZZ

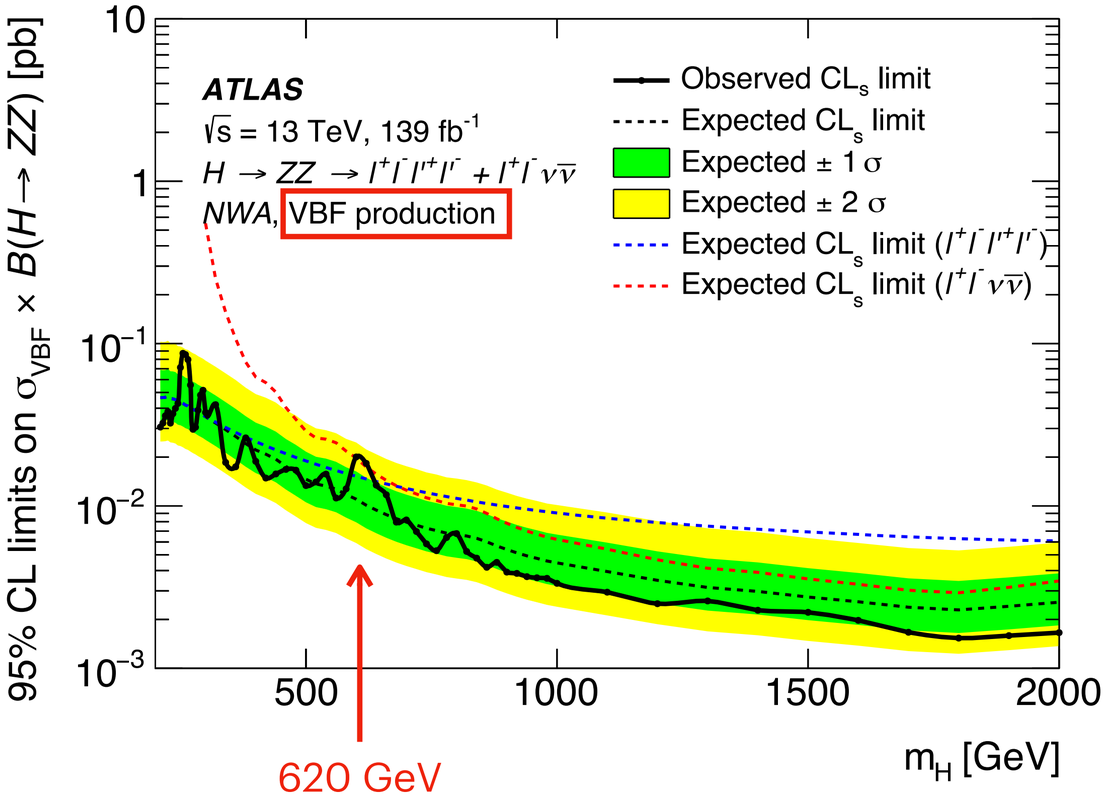
Eur. Phys. J. C 81 (2021) 332

As written in the paper :

"For the ggF production, the maximum deviation is for a signal mass hypothesis around 240 GeV, with a local (global) significance of 2.0$\sigma$ (0.5$\sigma$). For the VBF production, the maximum deviation is for a signal mass hypothesis around 620 GeV, with a local (global) significance of 2.4$\sigma$ (0.9$\sigma$)"




240 GeV
Driven by 4e and 4mu final states




620 GeV
Driven by 2 events

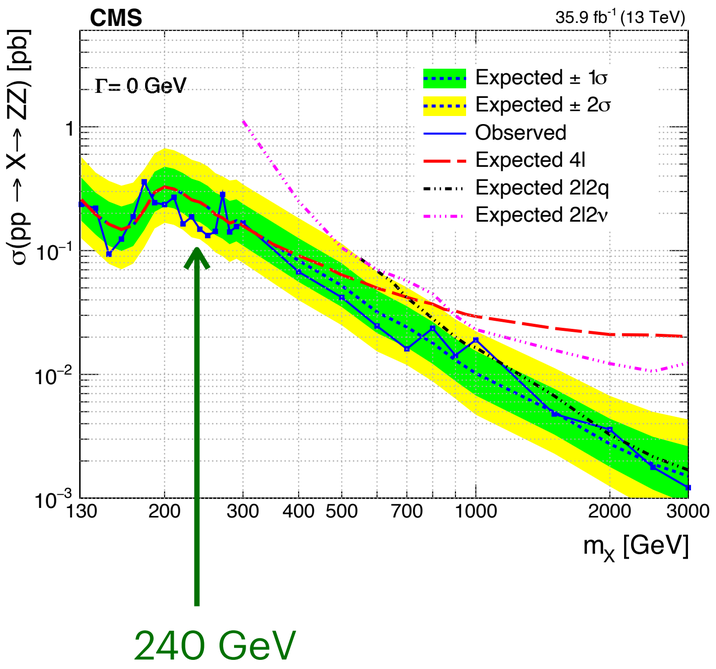
# Heavy resonance: other ZZ analyses

JHEP 06 (2018) 127

No excesses in CMS (2016-only/36 fb$^{-1}$) result

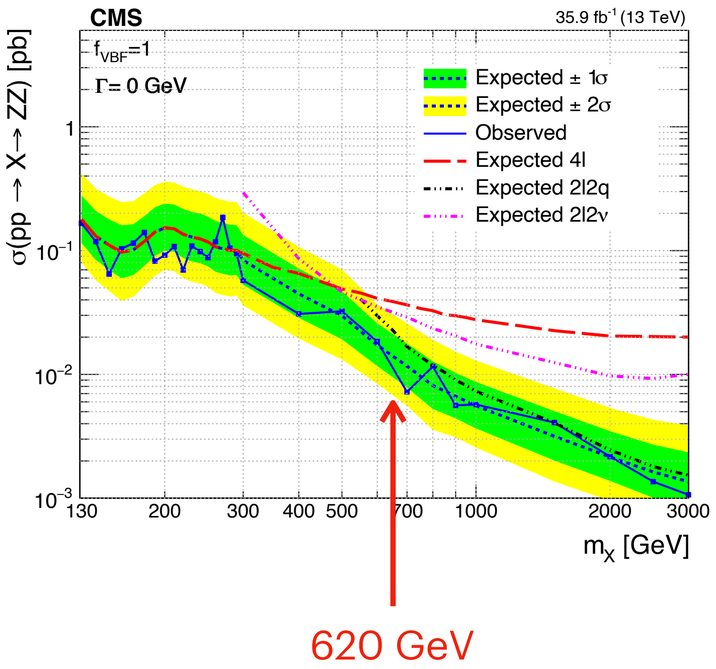
Three final states : $4\ell$, $\ell\nu\ell\nu$, $2\ell 2q$

VBF fraction free parameter
mainly ggF production




240 GeV

VBF fraction fixed to 1
no ggF production




620 GeV

- CMS full Run2 results not yet out
- Necessity to cover the 3 final states ($2\ell 2q$ could have competitive sensitivity of $4\ell$)

Deficits where ATLAS has excesses, observed ULs tighter

# Heavy resonance: X→WW

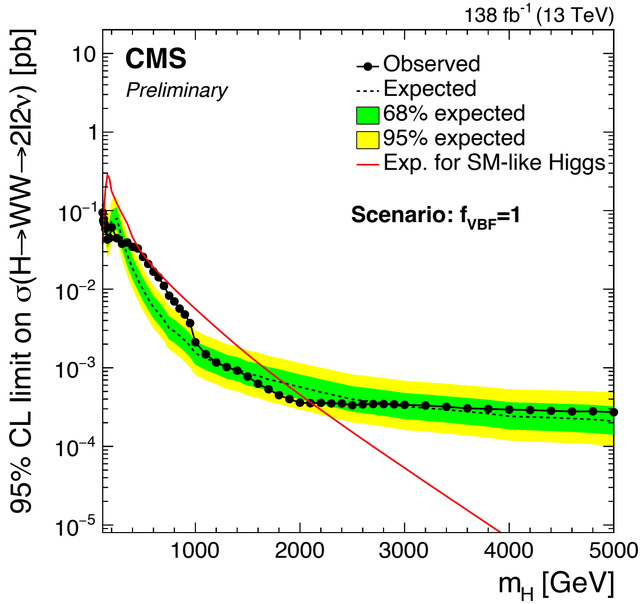
CMS-PAS-HIG-20-016

ATLAS-CONF-2022-066

CMS has a broad deviation in WW → $\ell\nu\ell\nu$, mostly in VBF

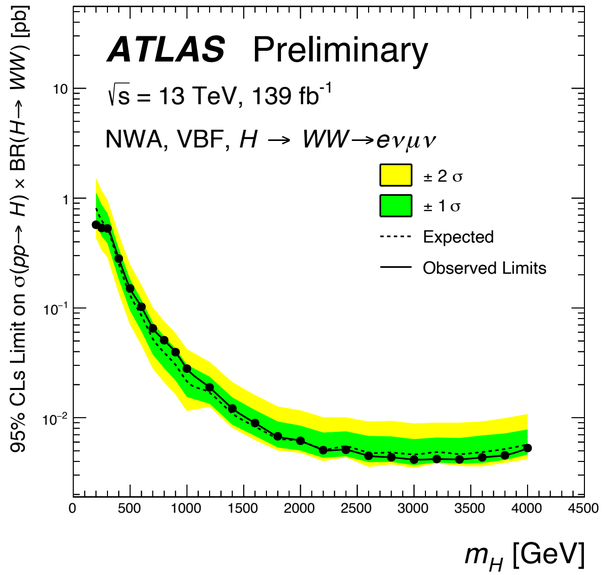
As written in the paper :

"The highest local(global) significance, 3.80$\sigma$(2.60$\sigma$), is found for the $f_{VBF}$=1 scenario and corresponds to a signal hypothesis with a mass of 650 GeV"




VBF fraction fixed to 1
no ggF production

ATLAS has an $e\nu\mu\nu$ result with no excess

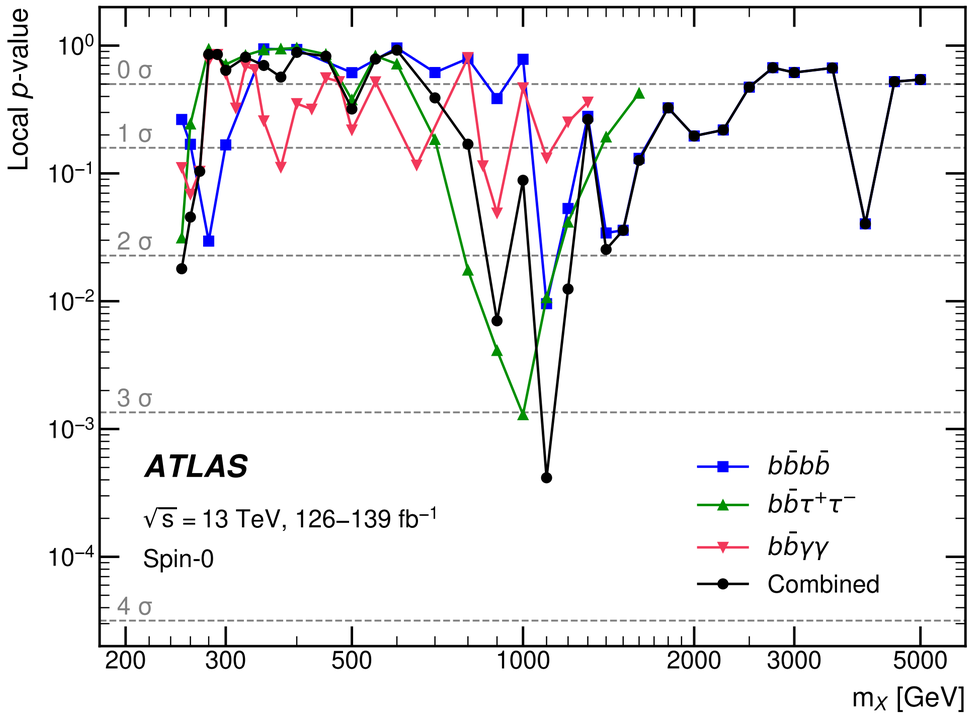


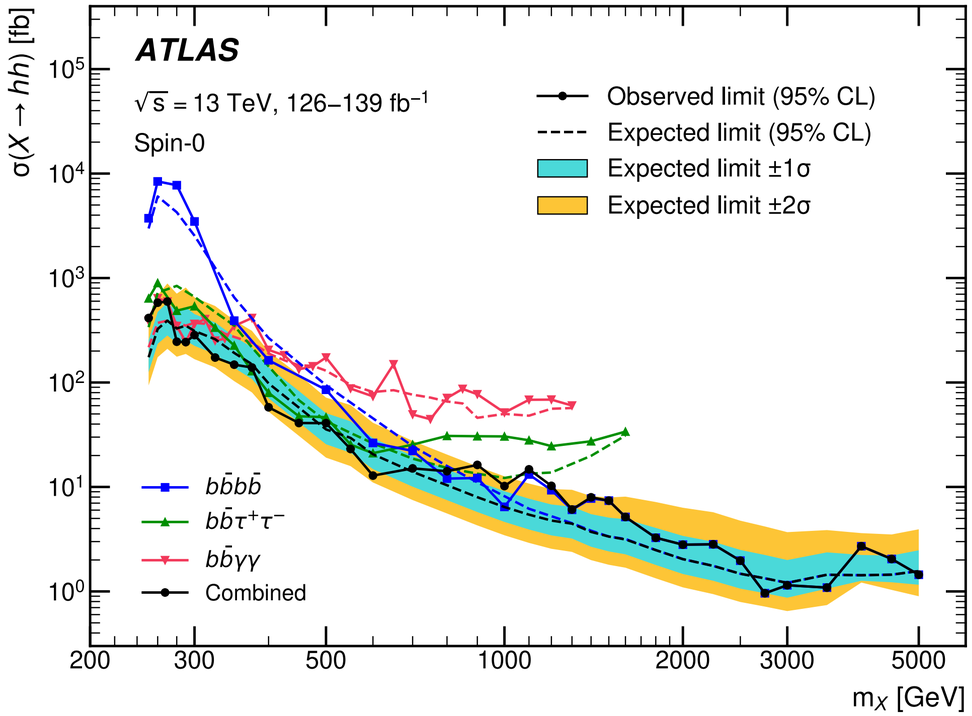

VBF production only

# Heavy resonance: combination of HH

arXiv:2311.1595

X→$H_{125}H_{125}$ combination of three final states: *bbbb*, *bbττ*, *bbγγ*



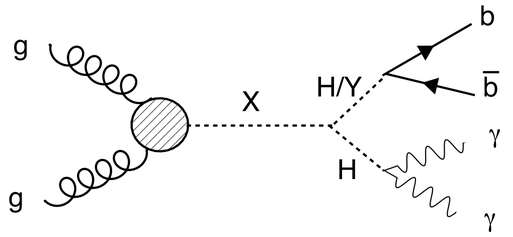

As written in the paper :

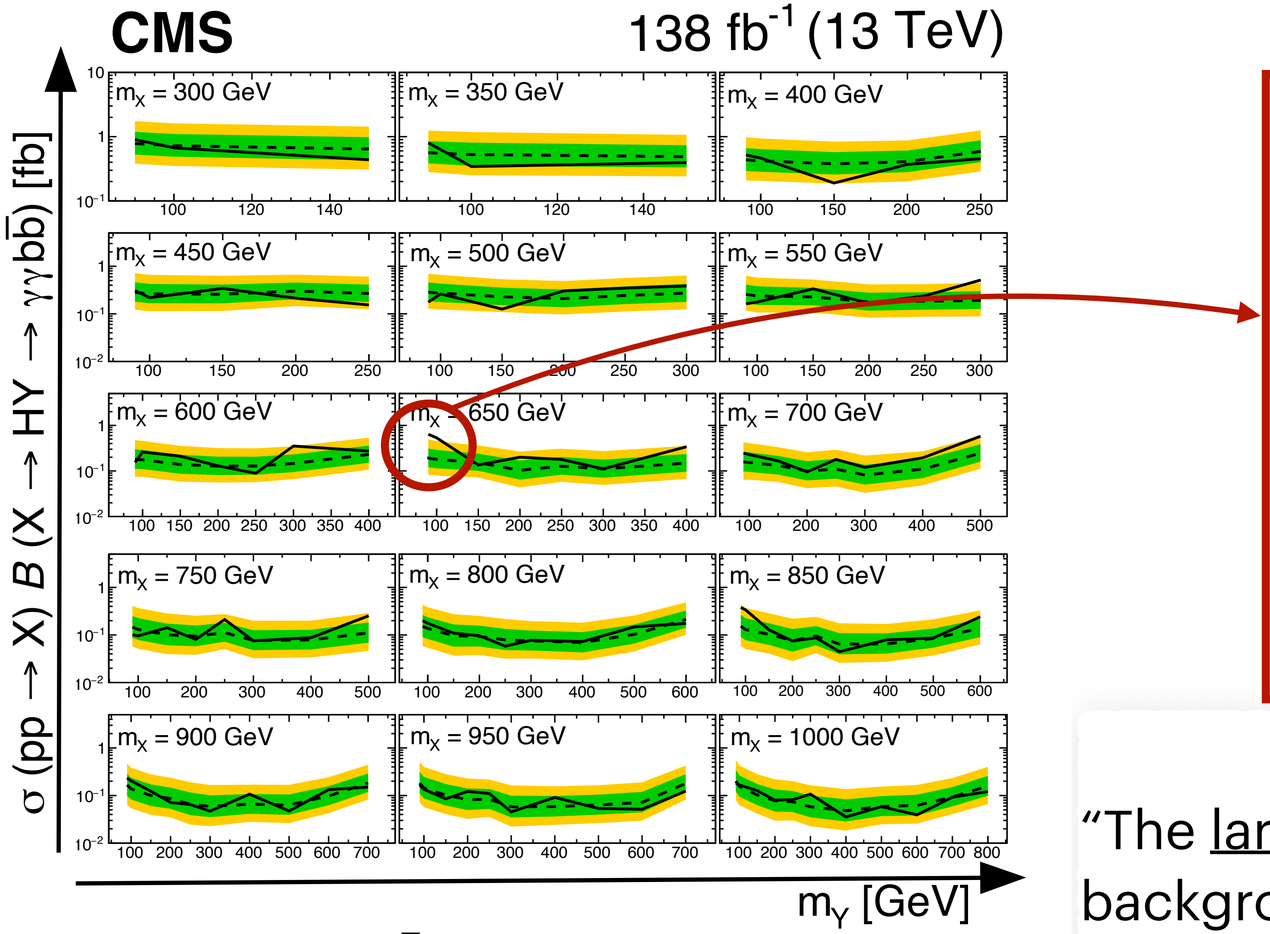
"The largest deviation is observed at 1.1 TeV and corresponds to a local(global) significance of 3.3σ(2.1σ)"

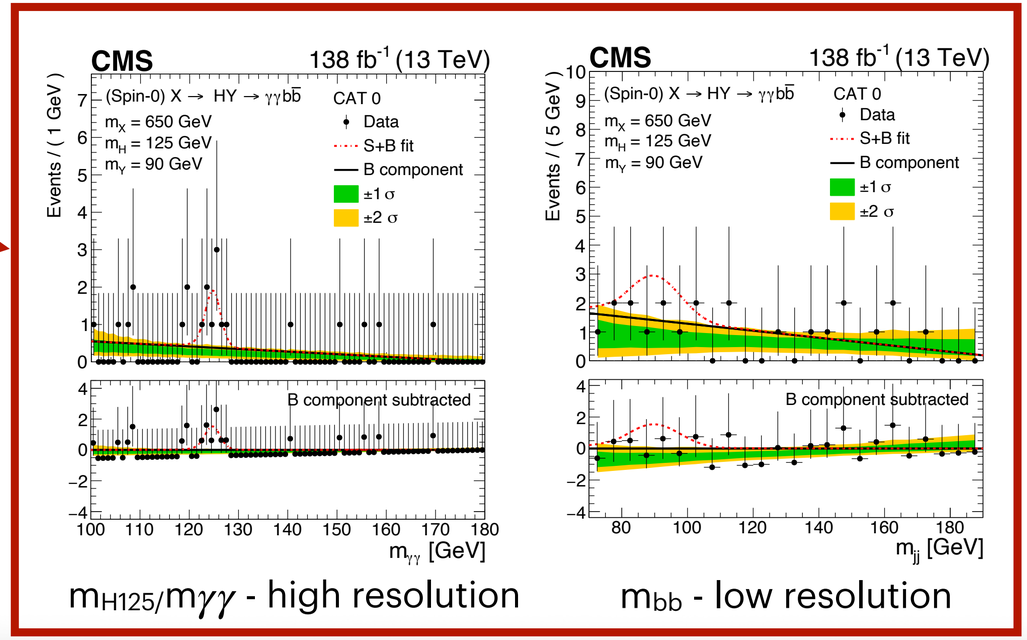
# Heavy resonance: X→Y(bb)$H_{125}(\gamma\gamma)$

arXiv:2310.01643

Appealing search for a next-to-minimal supersymmetric SM interpretation




As written in the paper :

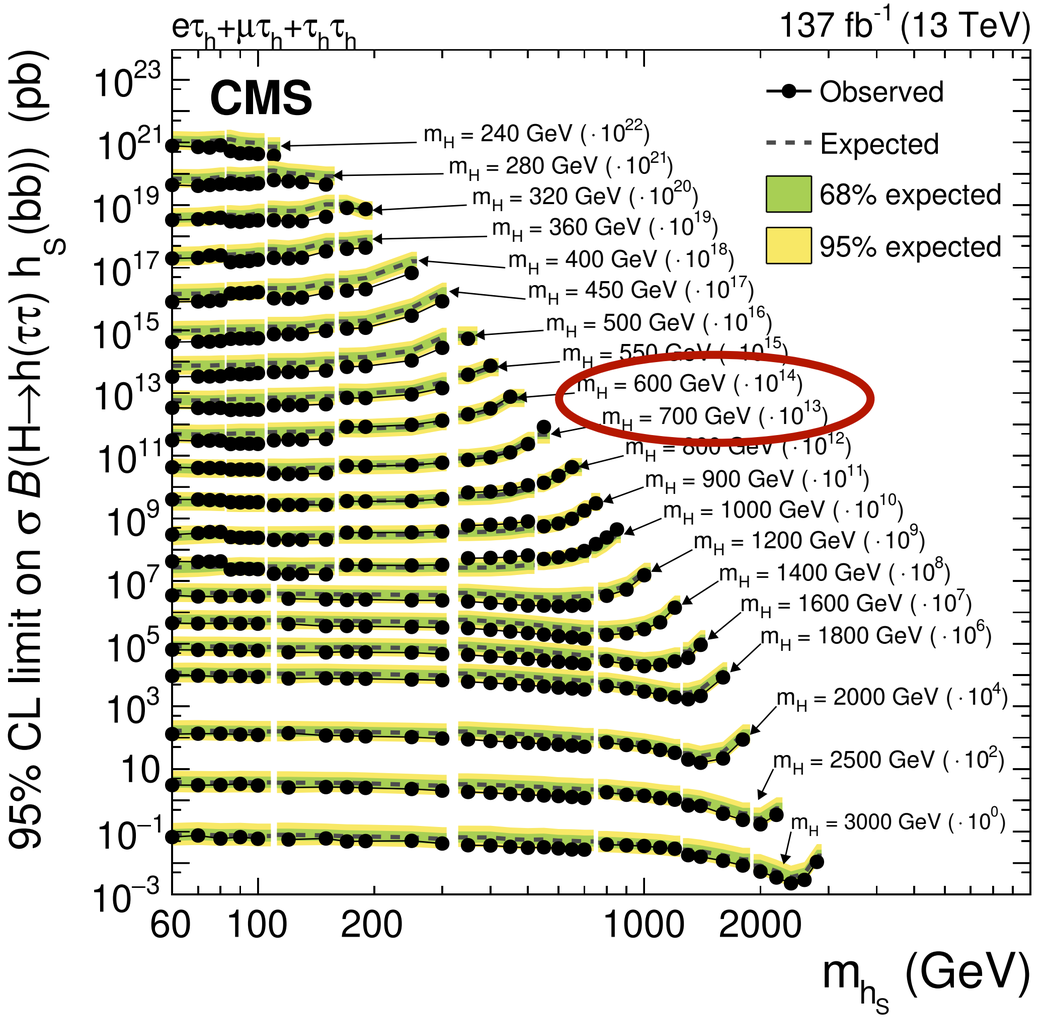
"The largest excess of the observation over the estimated background occurs for $m_X$ = 650 GeV and $m_Y$= 90 GeV with a local(global) significance of 3.8$\sigma$(2.8$\sigma$)."

# Heavy resonance: X→Y(bb)$H_{125}(\tau\tau)$

JHEP11(2021)057

CMS have a similar search: X→Y(bb)$H_{125}(\tau\tau)$
No excess observed
Missing $m_X$ = 650 GeV

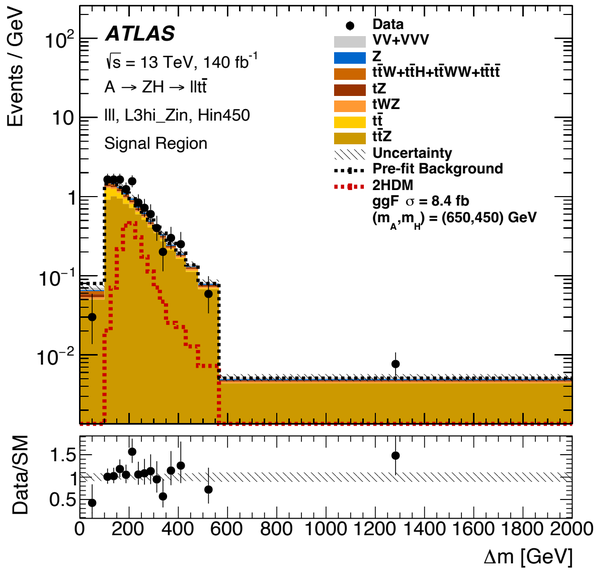
ATLAS does not have a corresponding search

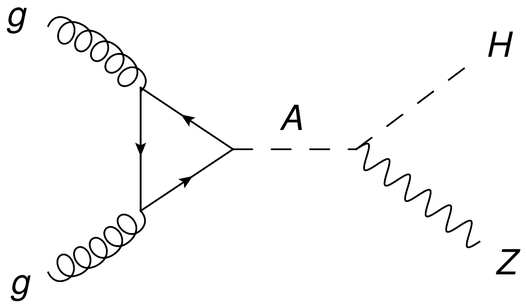


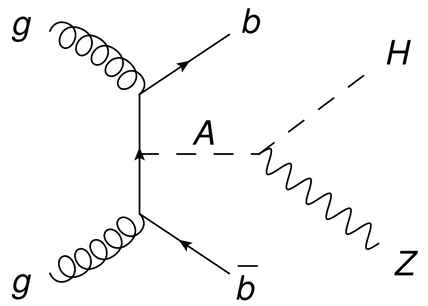

Full range of possibilities need to be explored

# Heavy resonance: X→ZA

arXiv:2311.0403

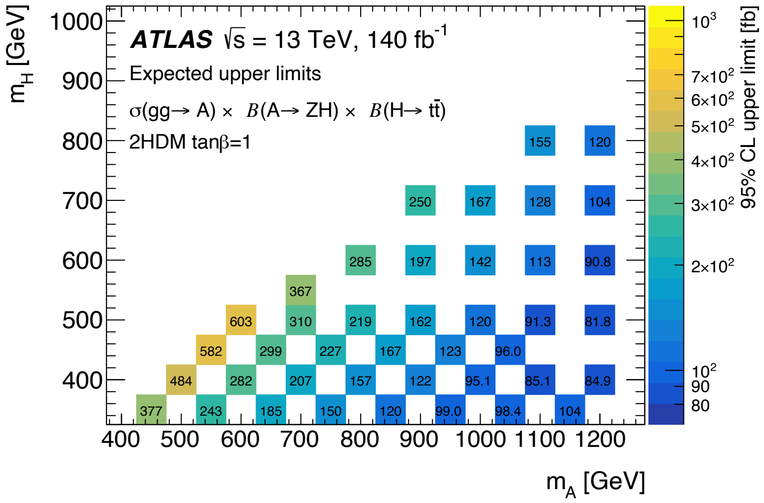


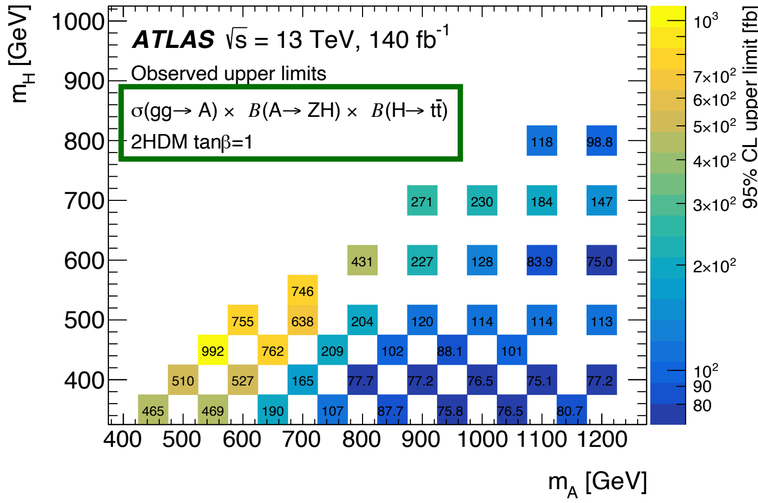




As written in the paper :

"The observed exclusion limit for the *lltt* channel is smaller than the expected exclusion limit in the region around ($m_A$,$m_H$) = (650,450) GeV "



# Conclusions

At the LHC, an active program is underway to search for additional particles as part of an extended Higgs sector.

The selected collection of results presented today did not reveal any large excess but rather depicted a mixed scenario of deviations and and other results that dismiss them.

A complete and coherent picture across experiments has not yet emerged.
ATLAS misses some searches of CMS, and CMS misses some searches of ATLAS.

Many Run2 analyses are still ongoing with a target for completion this year.
Additionally we can count on the LHC Run3 being in full swing, with the HL-LHC just around the corner!