ATLAS/CMS BSM Higgs Physics

(including exotic Higgs and exotic Higgs decays)

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on behalf of ATLAS and CMS Collaborations

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July 9, 2024
Quy Nhon, Vietnam

Rencontres du Vietnam

August 11 – 17, 2013 • ICISE • Quy Nhon, Vietnam

BSM Higgs Physics Motivation

- BSM can enhance rare decay modes of $H(125)$ boson.
  - "Rare (SM) Higgs boson decays and rare Higgs production modes at CMS" this afternoon.
- Many BSM theories predict additional Higgs Bosons.
- Two Higgs Doublet Model (2HDM, e.g. MSSM)
  - 5 Higgs Bosons

$$h, H, A, H^+, H^-$$

  - Widely used as a benchmark for BSM Higgs searches.
- 2HDM+Singlet (e.g. NMSSM)
  - 7 Higgs Bosons
  - 5 of 2HDM, with 2 additional neutral bosons (1 CP-even and 1 CP-odd)

$$h_1, h_2, h_3, H^+, H^-, a_1, a_2$$

- I will present a small subset of newest and moderately new results among many BSM Higgs results from ATLAS and CMS.

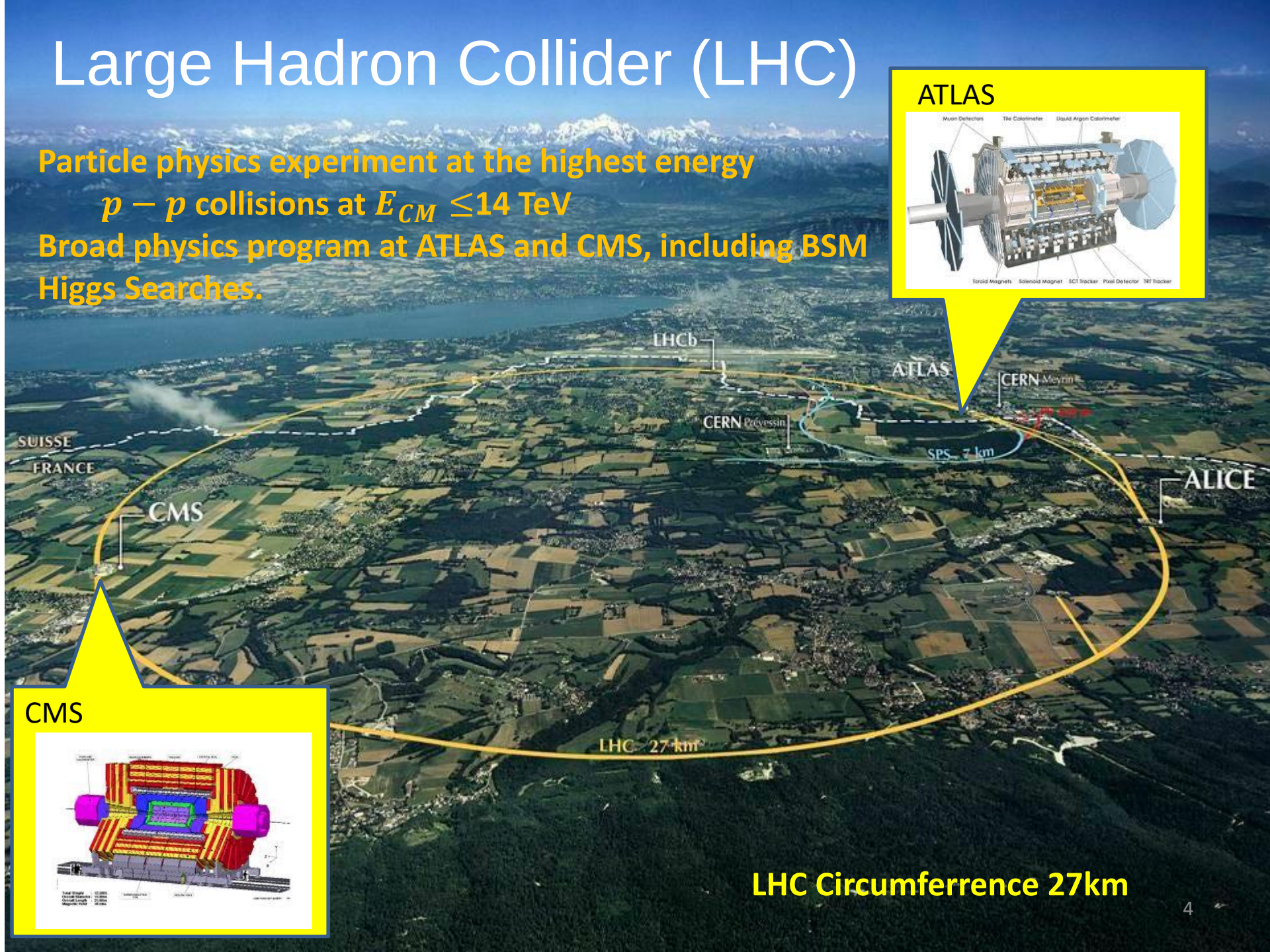
Large Hadron Collider (LHC)

Particle physics experiment at the highest energy

$p - p$ collisions at $E_{CM} \leq$14 TeV

Broad physics program at ATLAS and CMS, including BSM Higgs Searches.

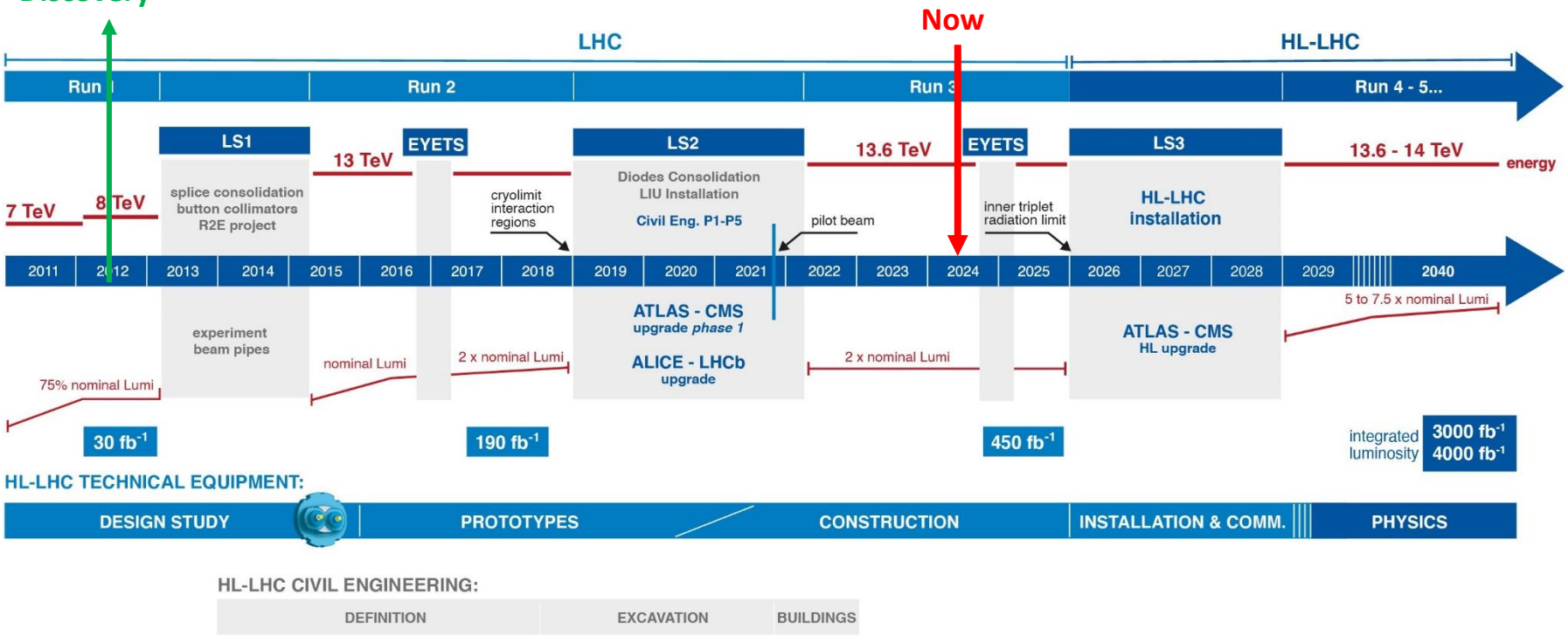
ATLAS



CMS

LHC Circumferrence 27km

LHC Long Term Schedule



- Each Exp. Collected $\sim 100\ \mathrm{fb}^{-1}$ in Run 3.
- Many analyses still working on Run 2 dataset.
- Analysis groups starting to work on Run 3 data.

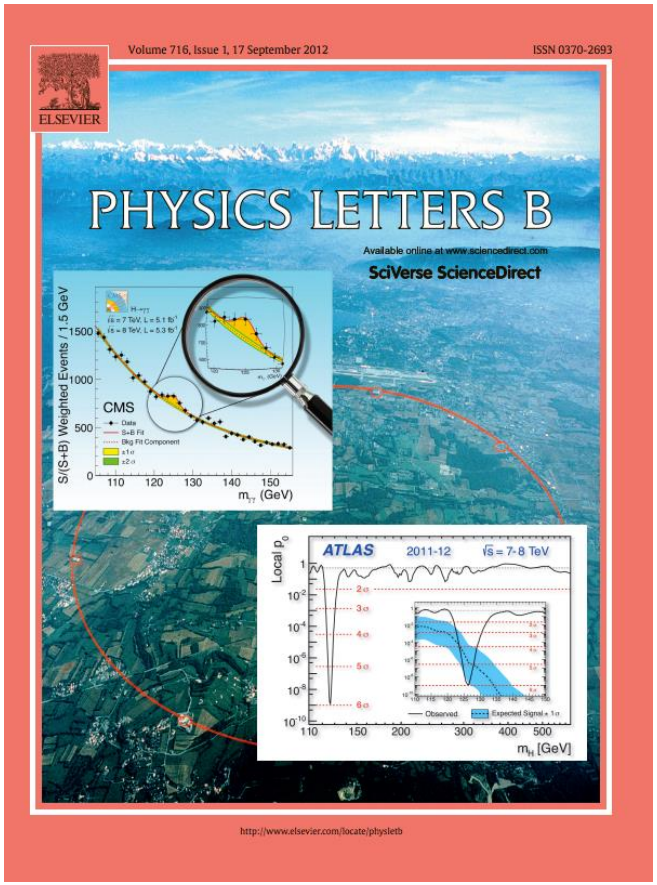
	year	$E_{CM}(\mathrm{TeV})$	integ lumi [fb^{-1}]
Run 1	2011	7	5
	2012	8	21
Run 2	**2015-2018**	**13**	**139**
Run 3	**2022-2025**	**13.6**	**250**
HL-LHC	2029-2038	14	3000

Searches in 2HDM/MSSM Regime

- 2HDM and MSSM are widely used as a theoretical benchmark for BSM Higgs searches.
- 5 Higgs bosons

$$h, H, A, H^{+}, H^{-}$$

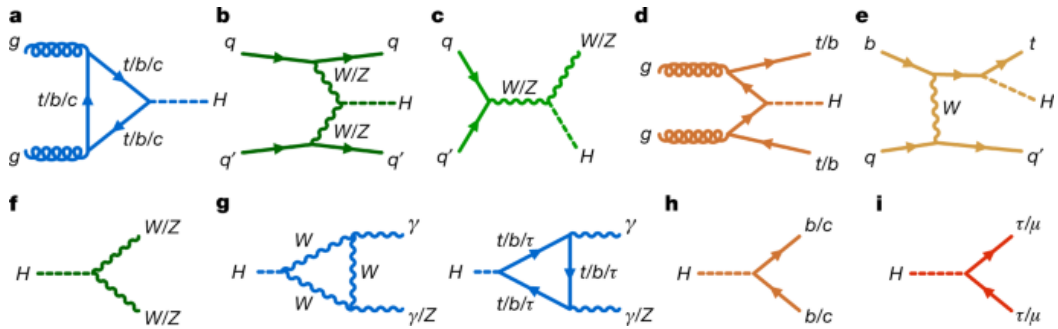
Higgs Discovery in 2012



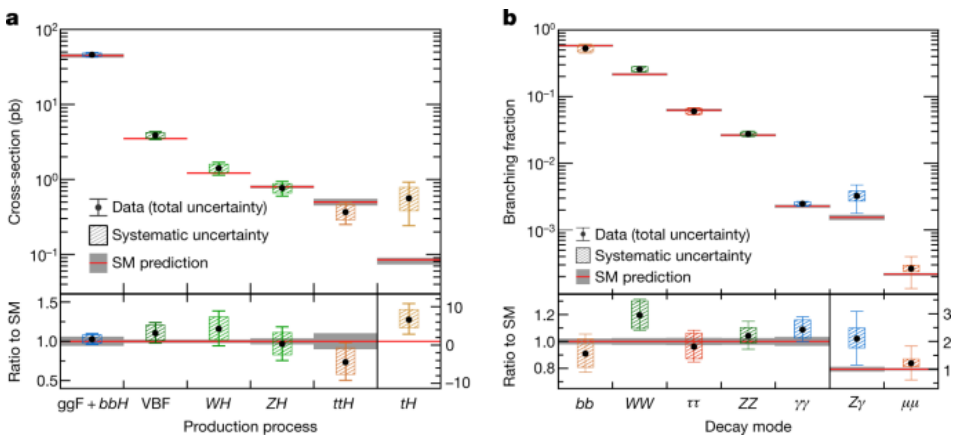
- ATLAS and CMS reported discovery of Higgs boson on July 4, 2012.
- Englert and Higgs won the Nobel prize in 2013.

$H(125)$ Measurements

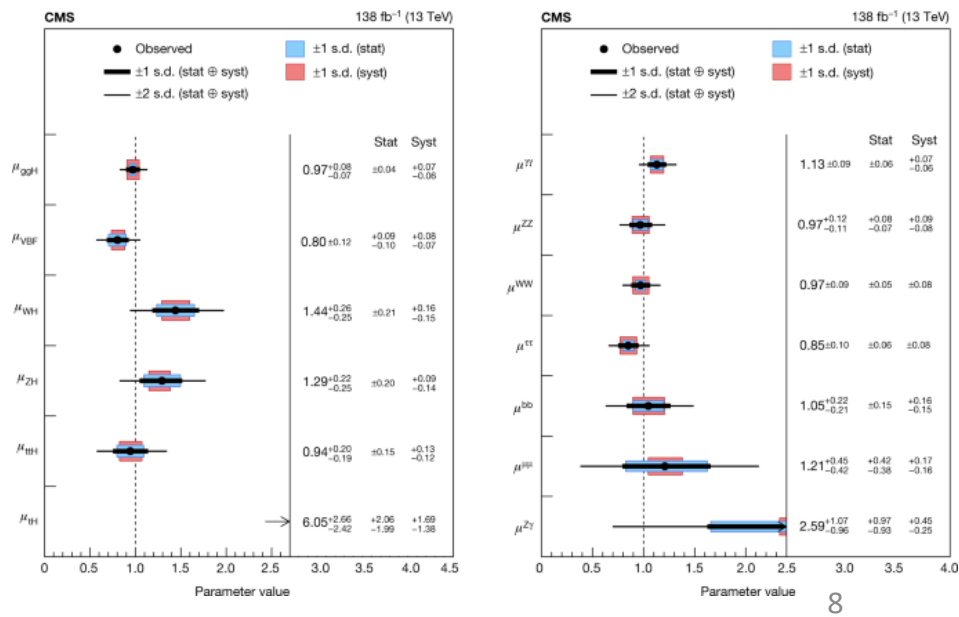
- Both collaborations have measured H(125) properties.
- Results are consistent with SM.



Nature **607**, 52–59 (2022)



Nature **607**, 60–68 (2022)

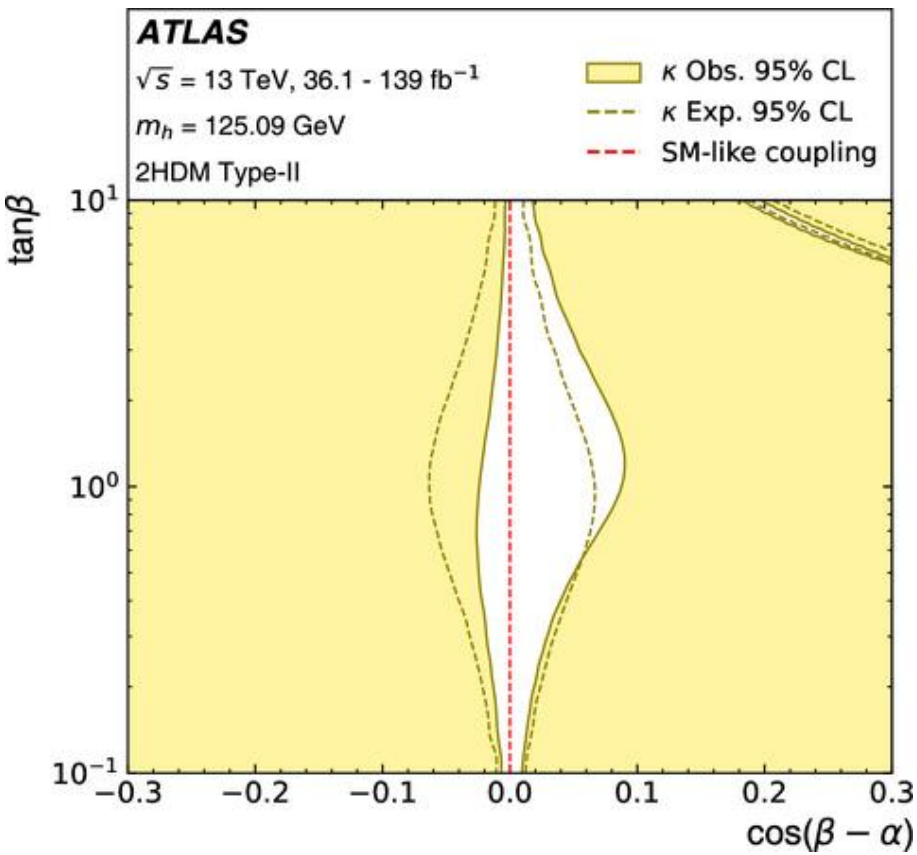


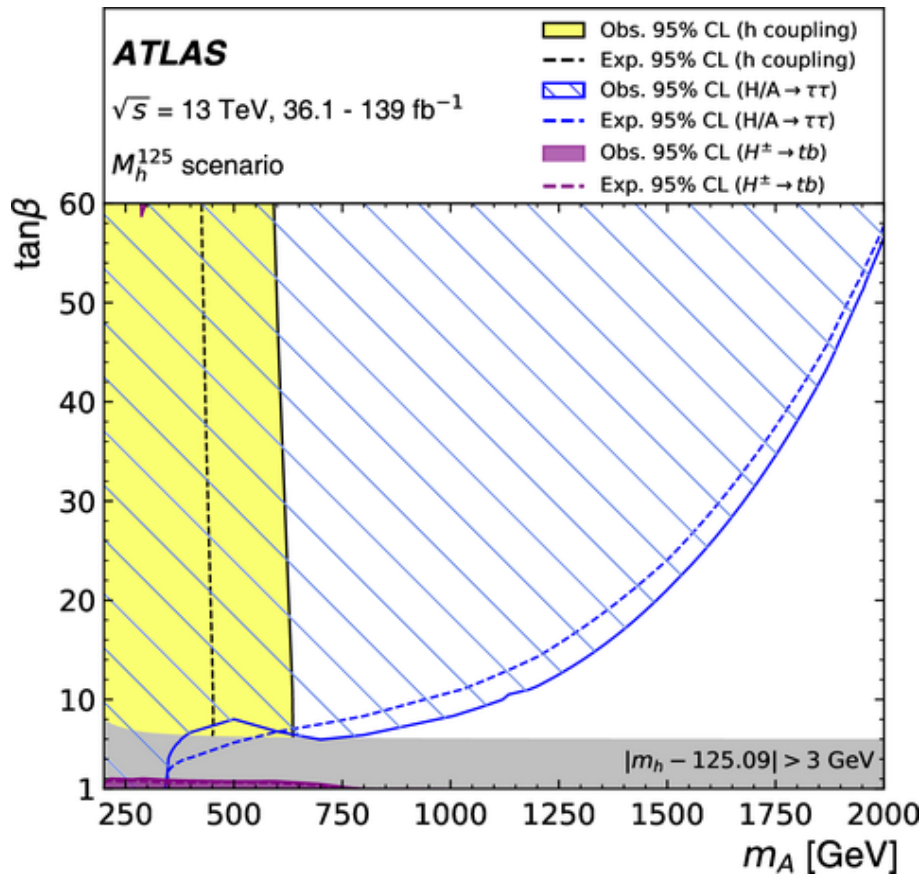
These results can be used to constrain BSM Higgs scenarios.

Interpretation of $H(125)$ Measurements

- Production and decay rates of $H(125)$ are interpreted in 2HDM and MSSM scenarios.

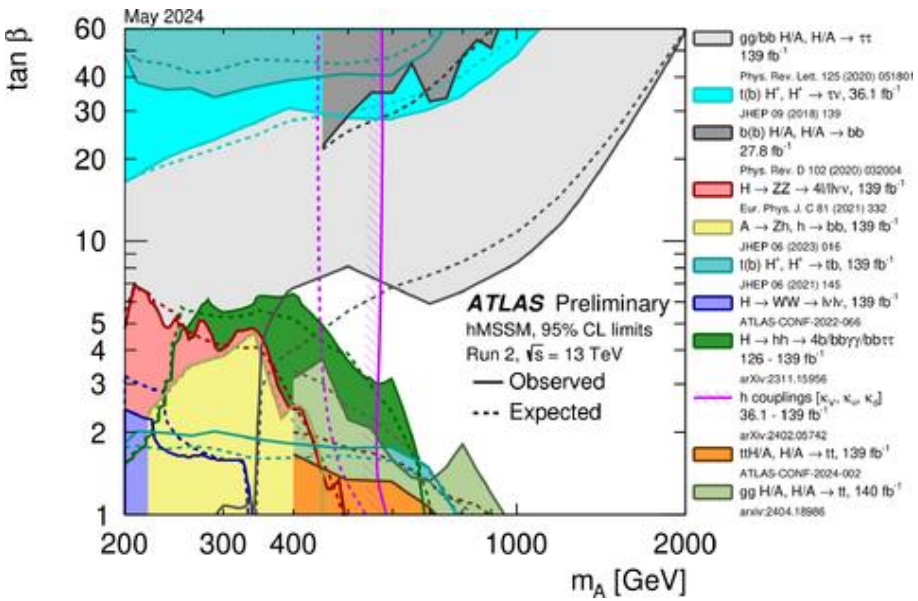
arXiv:2402.05742



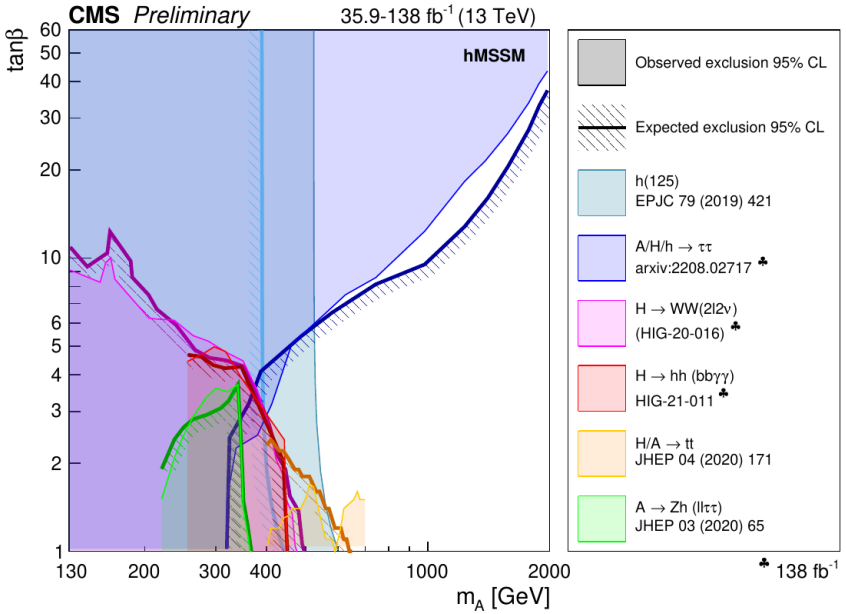


MSSM Higgs Status

- Current status of hMSSM.
- Some more full Run2 results to be released.



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2024-008/



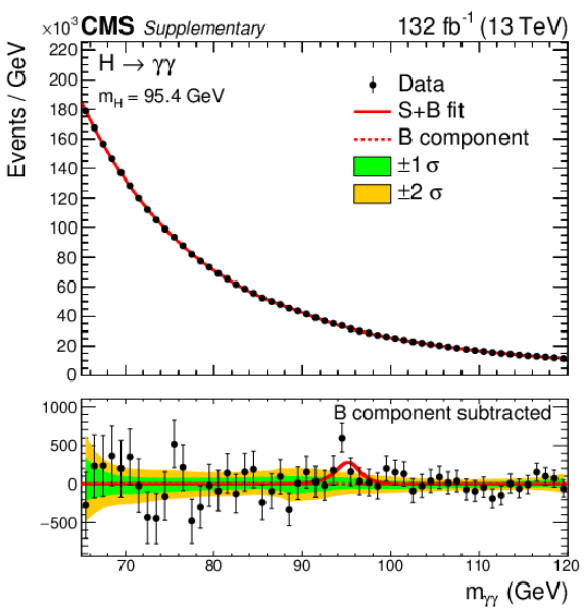
https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG#NEW_Summary_of_MSSM_Higgs_Boson

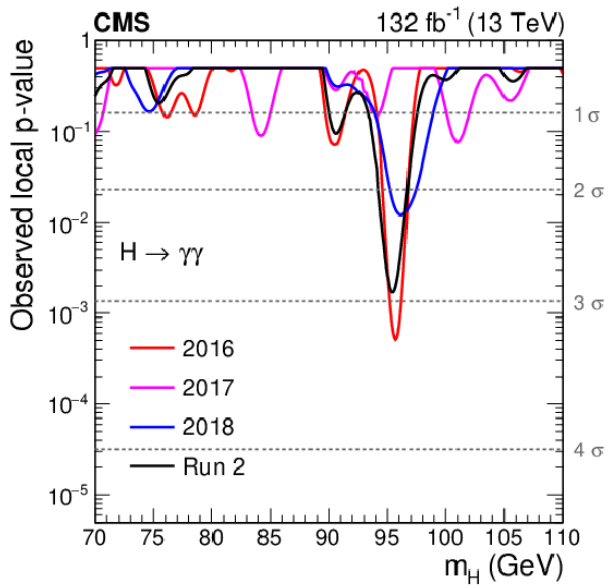
Low mass $H \to \gamma\gamma$

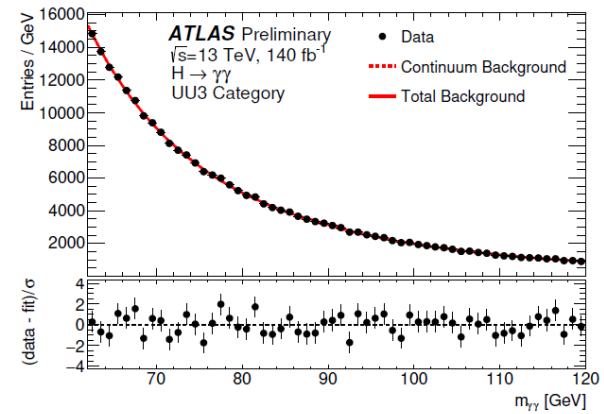
- Many theories can give rise to additional low mass Higgs bosons.
- CMS observes an excess around $95.4\ \mathrm{GeV}$ with local (global) significane of 2.9σ (1.3σ).
- ATLAS local significance of 1.7σ at $95.4\ \mathrm{GeV}$.

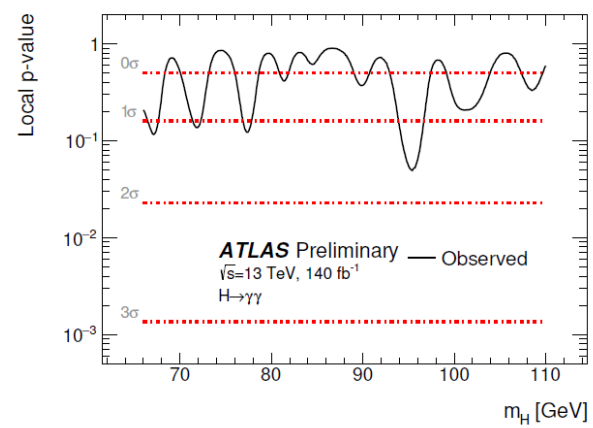
ATLAS-CONF-2023-035

arXiv:2405.18149





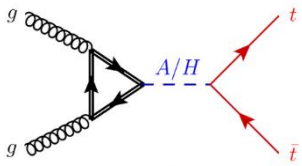


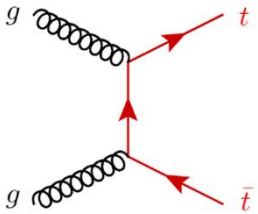


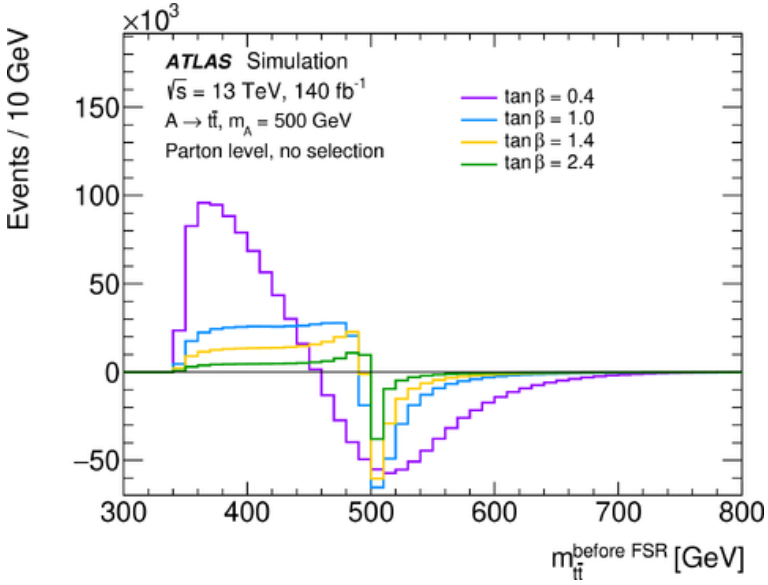
BSM $H/A \to t\bar{t}$

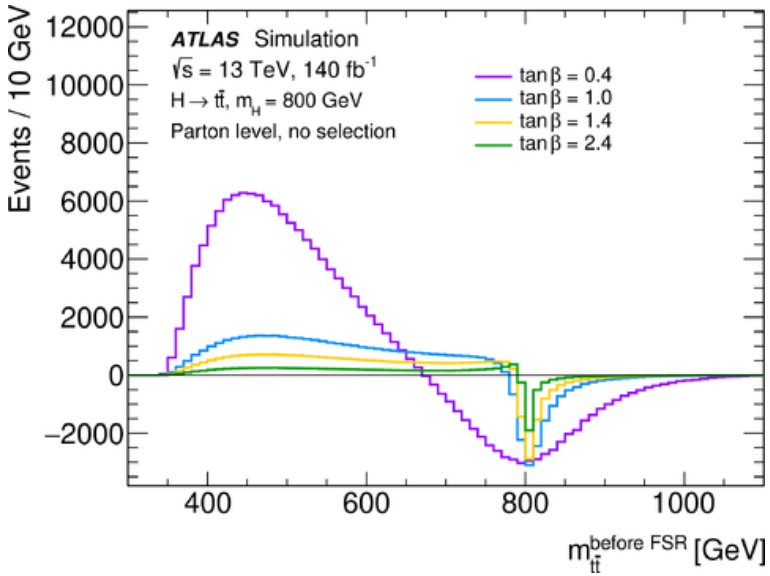
arXiv:2404.18986

- Promising search for heavy H/A in 2HDM (e.g. MSSM) at low $\tan\beta$.
- Consider the intereference with SM $t\bar{t}$ background.





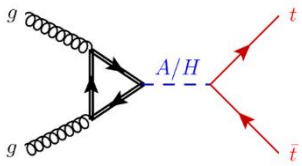


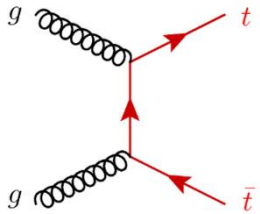


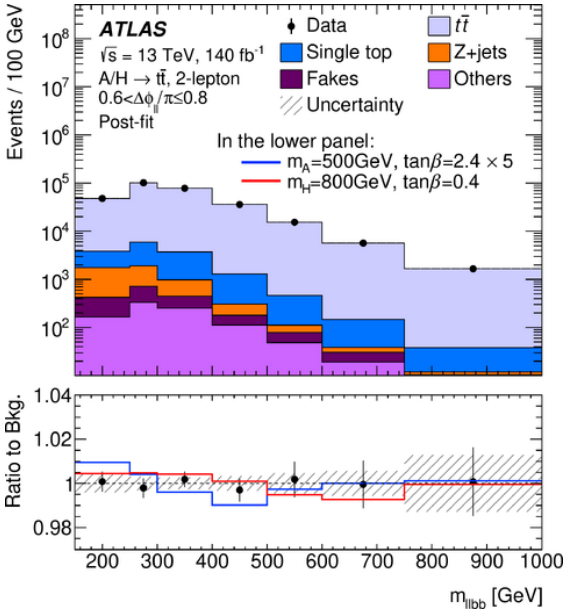
BSM $H/A \to t\bar{t}$ (cont'd)

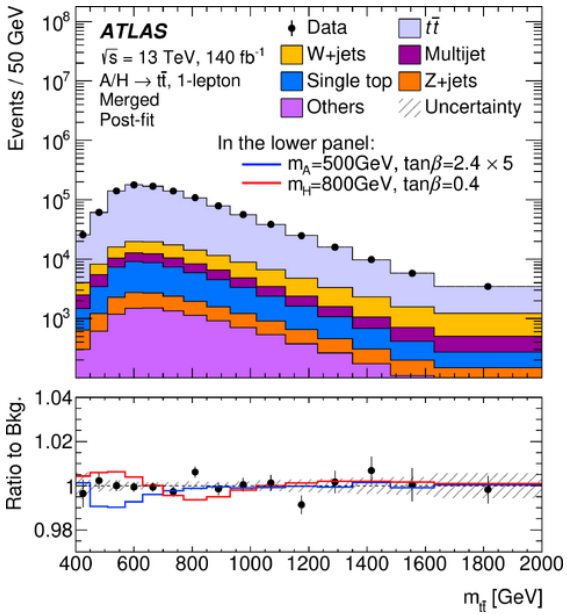
arXiv:2404.18986

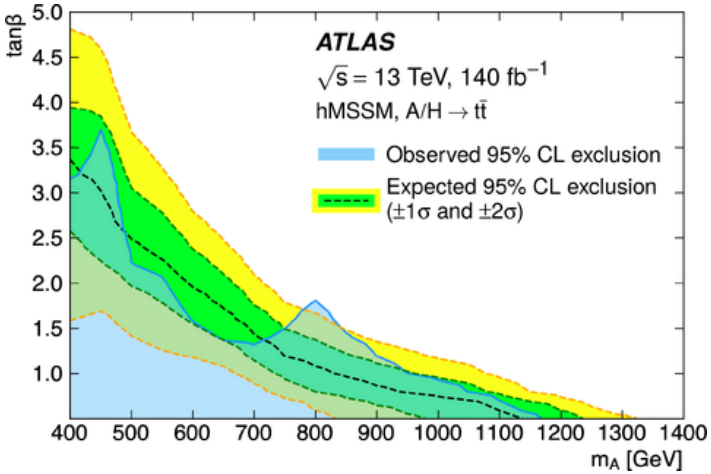
- Analyzed 1 and 2 lepton final states.
- Data were consistent with SM background.
- Most significant deviation was at 800 GeV with a local significance of 2.3 σ.





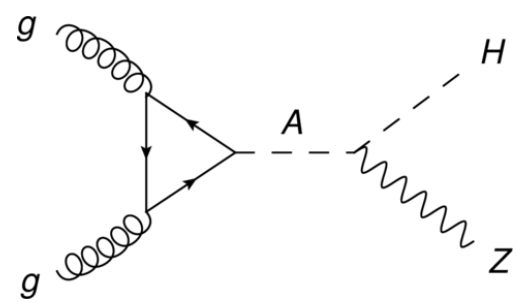






CMS-PAS-B2G-23-006

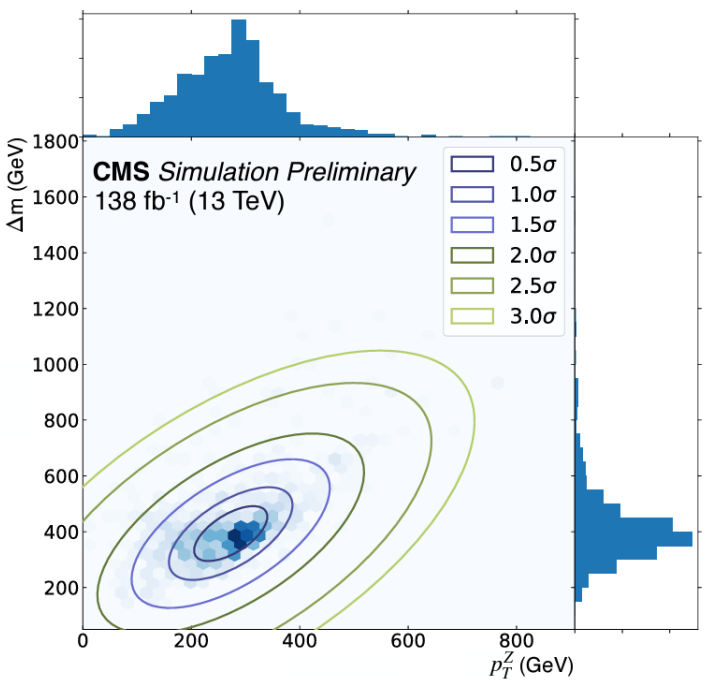
$A \to ZH \to \ell\ell t\bar{t}$



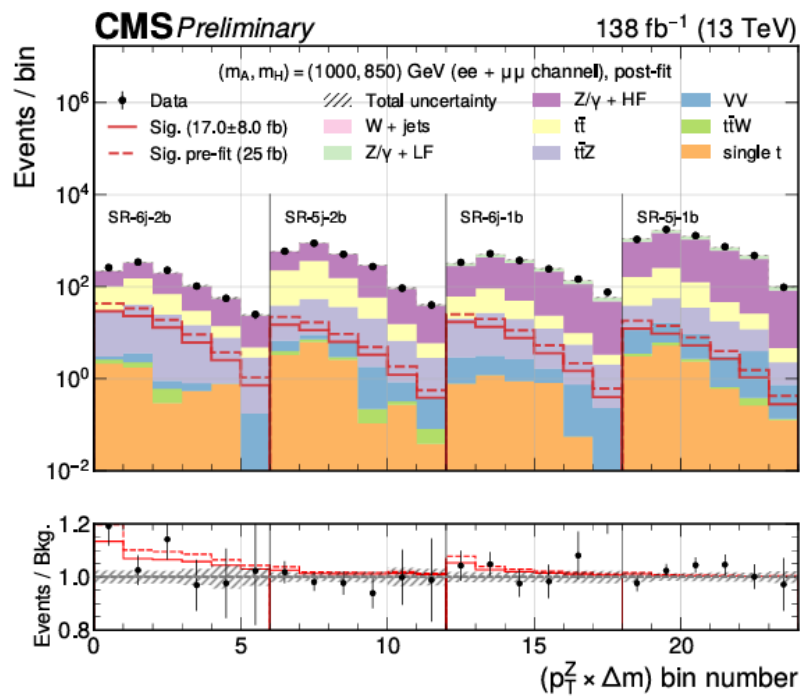
- Region with $400\ \mathrm{GeV} < m_H \ll m_A$ is unexplored.
- This region is favored by some electroweak baryogenesis scenarios.
- Analyze events with $\ell^+\ell^- + \mathrm{nj}(1, \geq 2b)$
- Elliptical bins $(\Delta m, p_z)$ define final discriminant
- No significant deviation from SM background.

Involves two BSM Higgs bosons

Expected $(\Delta m, p_z)$ distribution for signal for $m_A = 1000\ \mathrm{GeV}, m_H = 600\ \mathrm{GeV}$



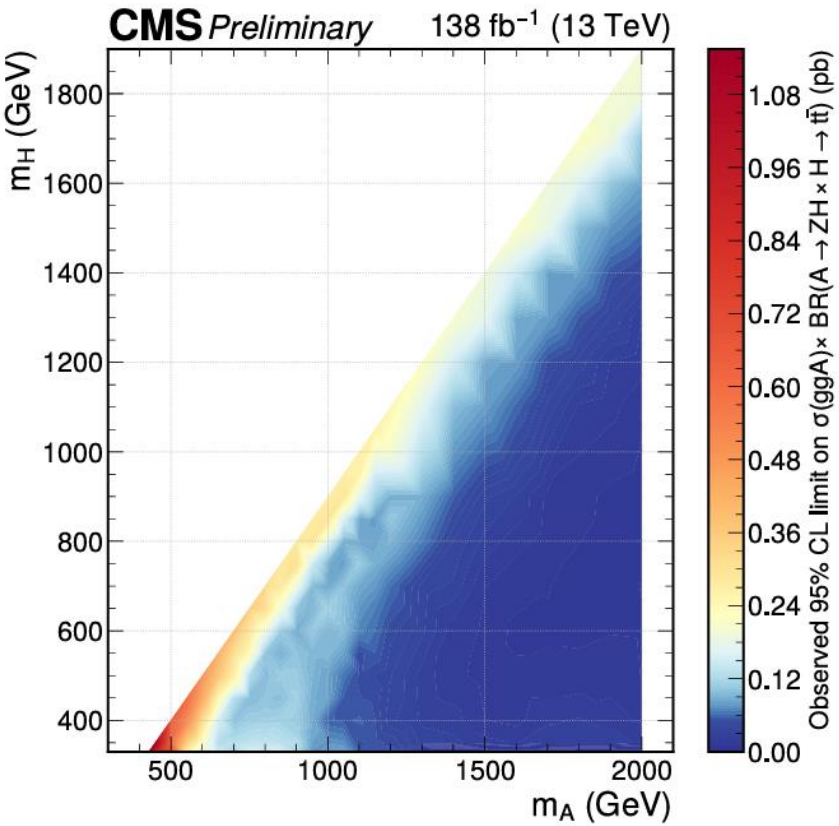
Data distribution for signal hypothesis of $m_A = 1000\ \mathrm{GeV}, m_H = 850\ \mathrm{GeV}$

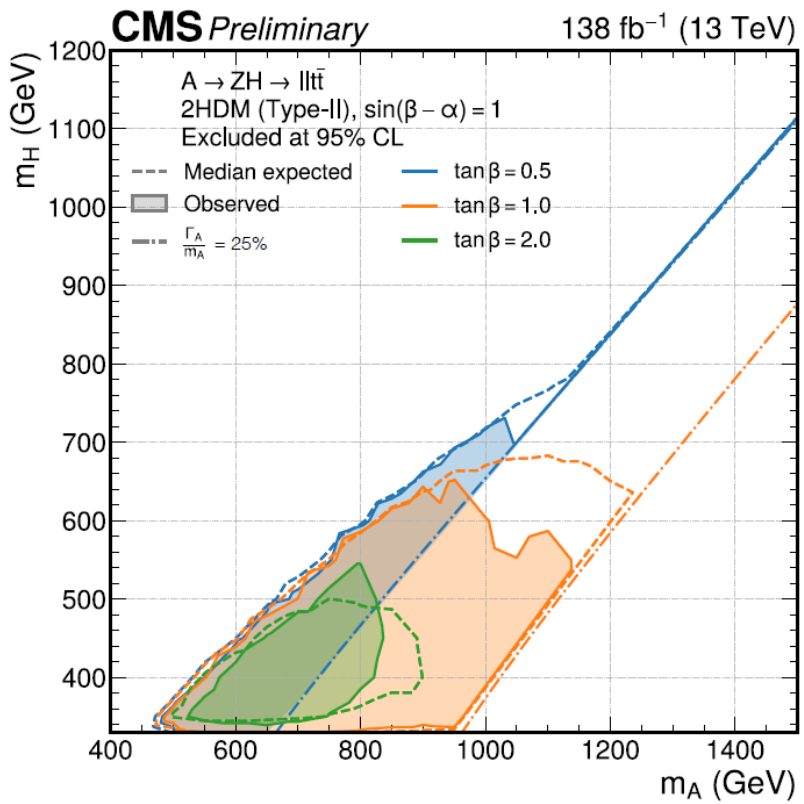


CMS-PAS-B2G-23-006

$A \to ZH \to \ell\ell t\bar{t}$ (cont'd)

Exclusion limits for Type II 2HDM are set at low $\tan\beta$ values.



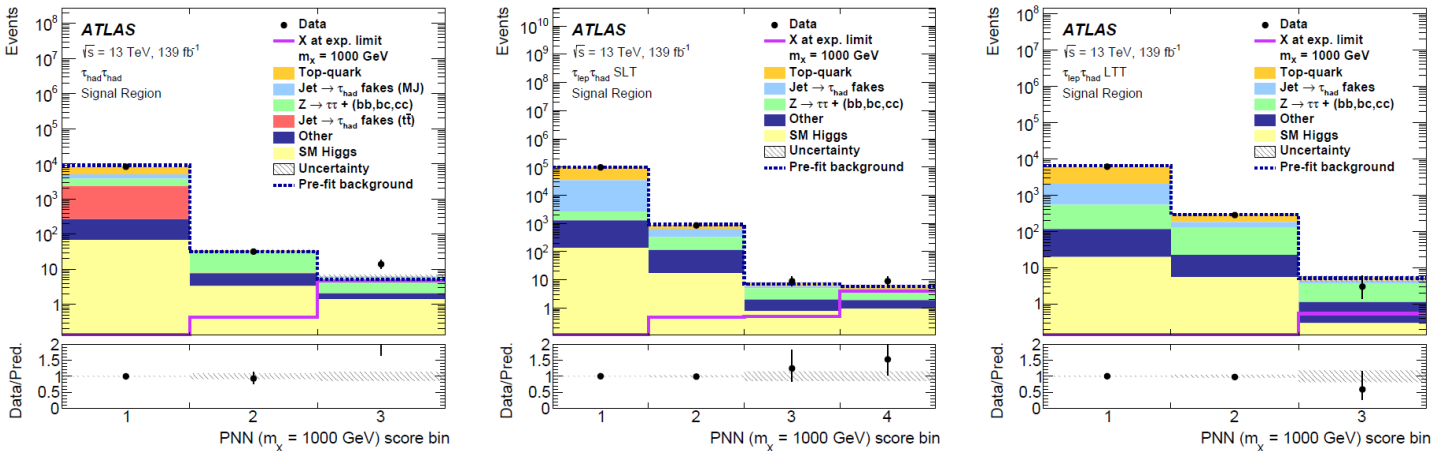


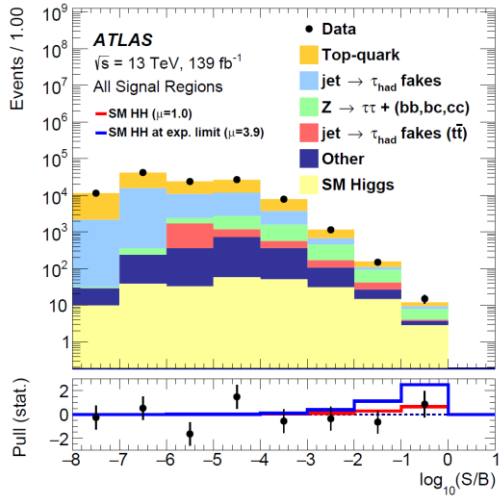
ATLAS has a comparable results for $A \to ZH \to \ell\ell t\bar{t}, \nu\nu t\bar{t}$ JHEP 02 (2024) 197

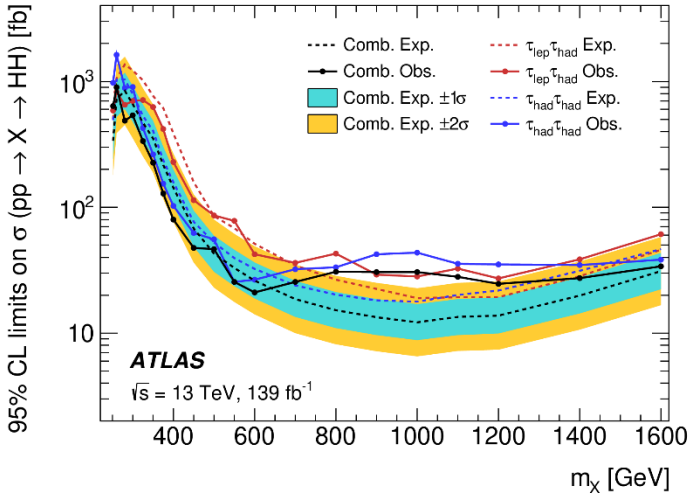
$H \to h_{125}h_{125} \to bb\tau\tau$

JHEP 07 (2023) 040

- $\tau_{had}\tau_{had}$(single and double $\tau_{had-vis}$ triggers), $\tau_{lep}\tau_{had}$(single lepton and lepton+$\tau_{had-vis}$ triggers). Require two b-jets.
- PNN trained with inputs including $m_{hh}, m_{\tau\tau}, m_{bb}$



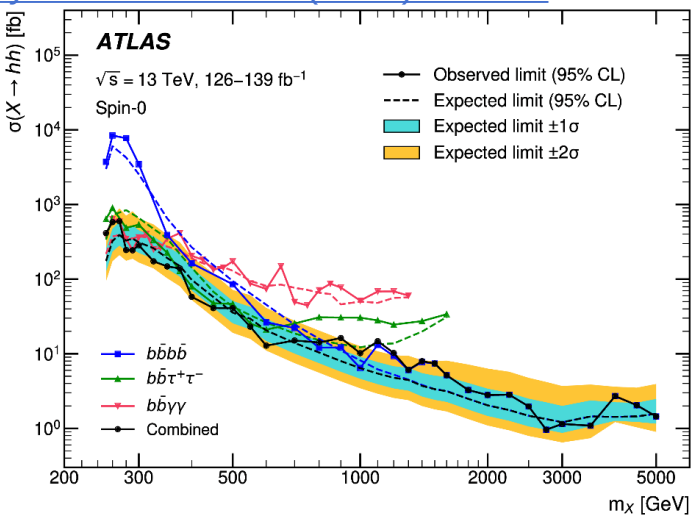


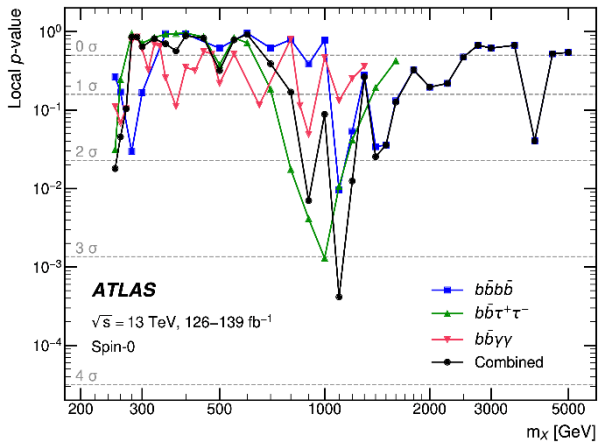


Largest deviation at 1 TeV with local (global) significance of 3.1σ (2.0σ).

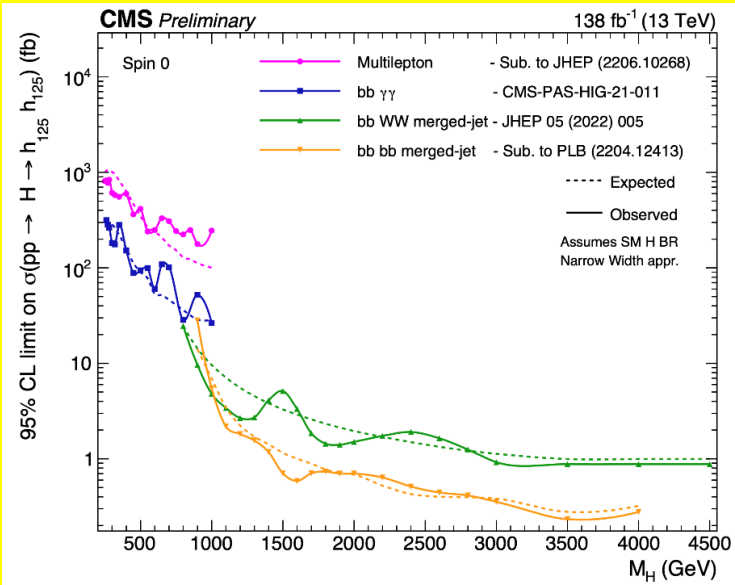
$H \to h_{125} h_{125}$

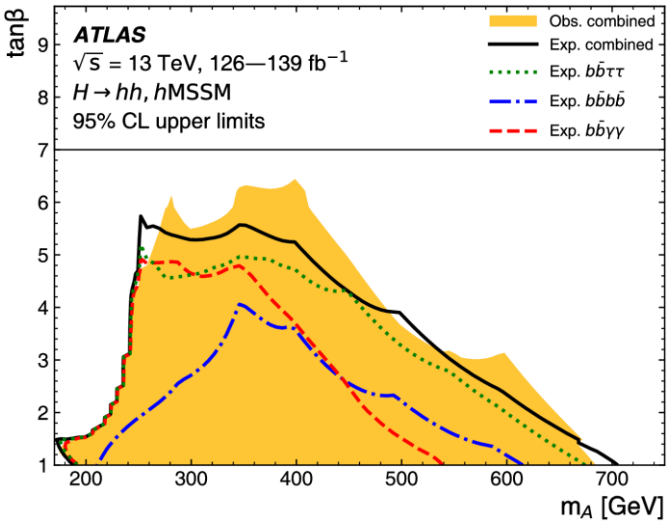
Phys. Rev. Lett. 132 (2024) 231801





https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG

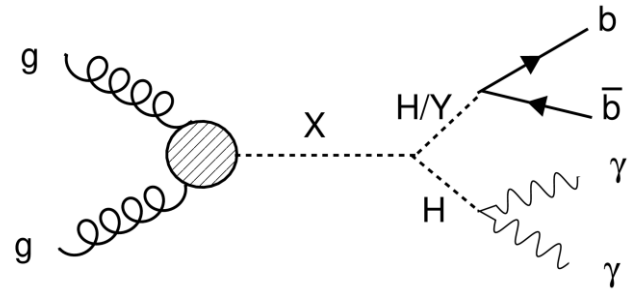


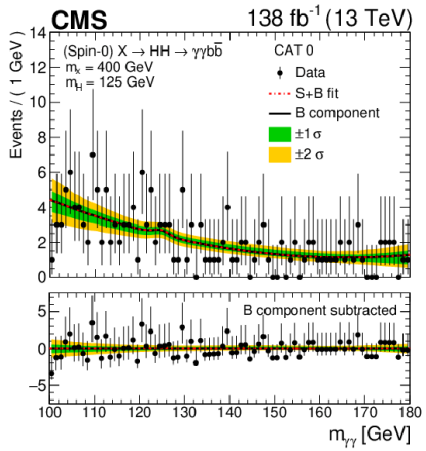


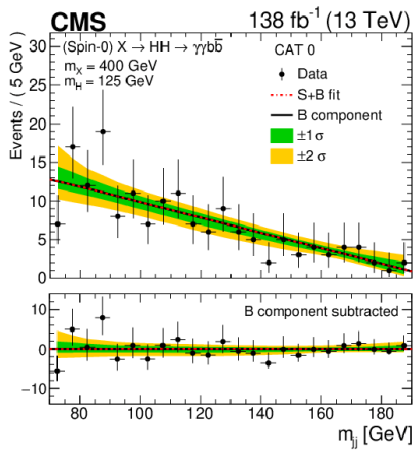
Largest 1.1 TeV, with a local (global) significance of 3.3σ (2.1σ).

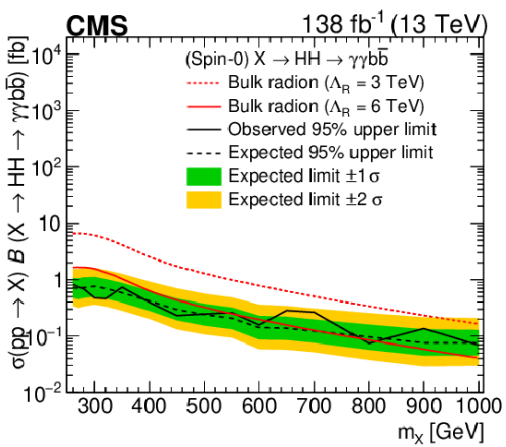
$X \to HH/HY \to bb\gamma\gamma$

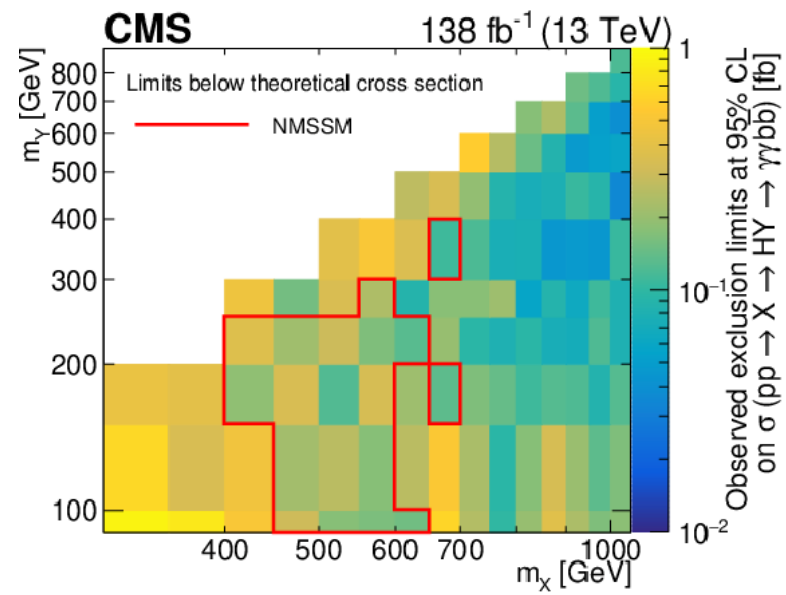
- MSSM motivated search.
- X: heavy spin-0 particle.
  - Spin-2 was also searched for.
- Y: spin-0 particle. Can be another $H(125)$.
- BDT was trained to divide signal regions.











Involves two BSM Higgs bosons.
Interpretation with NMSSM.

Searches in 2HDM+Singlet/NMSSM

– 7 Higgs Bosons

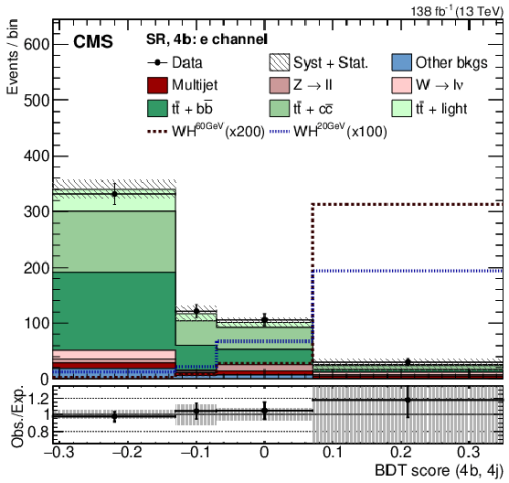
$$h_1, h_2, h_3, H^+, H^-, a_1, a_2$$

$VH, H \to aa \to b\bar{b}\ b\bar{b}$

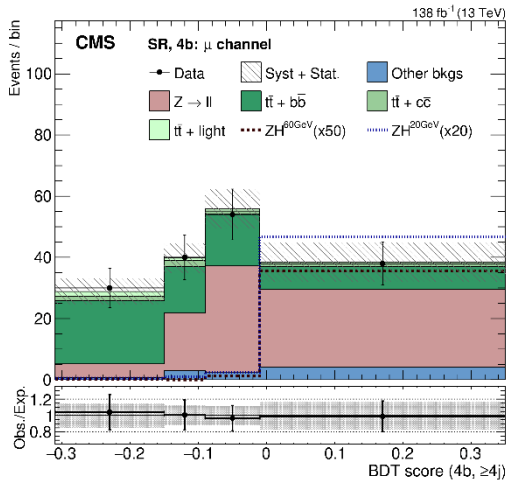
arXiv:2403.10341

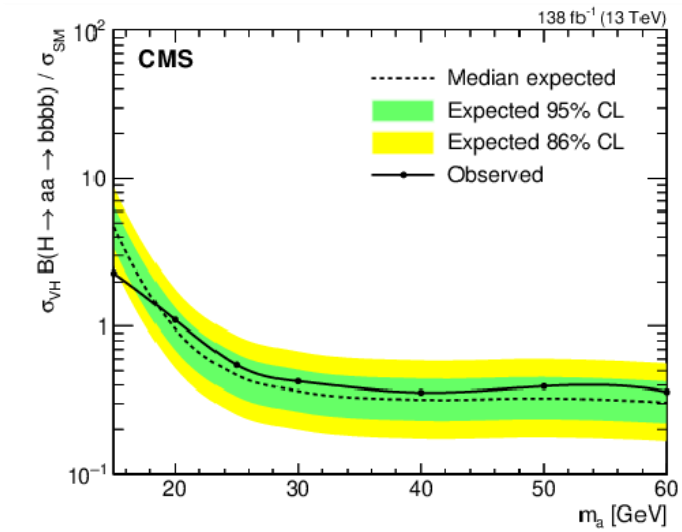
- $a \to b\bar{b}$ is usually the dominant decay mode above $b\bar{b}$ threshold.
- $Z \to \ell\ell$ and $W \to \ell\nu$ channels.
- 3 or 4 b-tagged jets.
- BDT discriminants trained for ZH and WH channels for signal separation.

$WH \to e\nu + 4b$ chan.



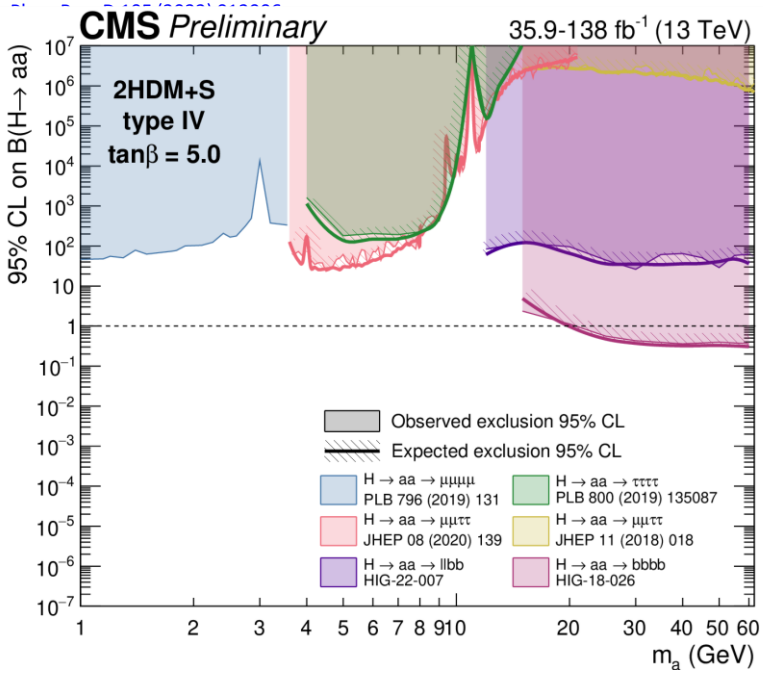
$ZH \to \mu\nu + 4b$ chan.





$H \to aa$ Search Summary Plots

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Summary2HDMSRun2



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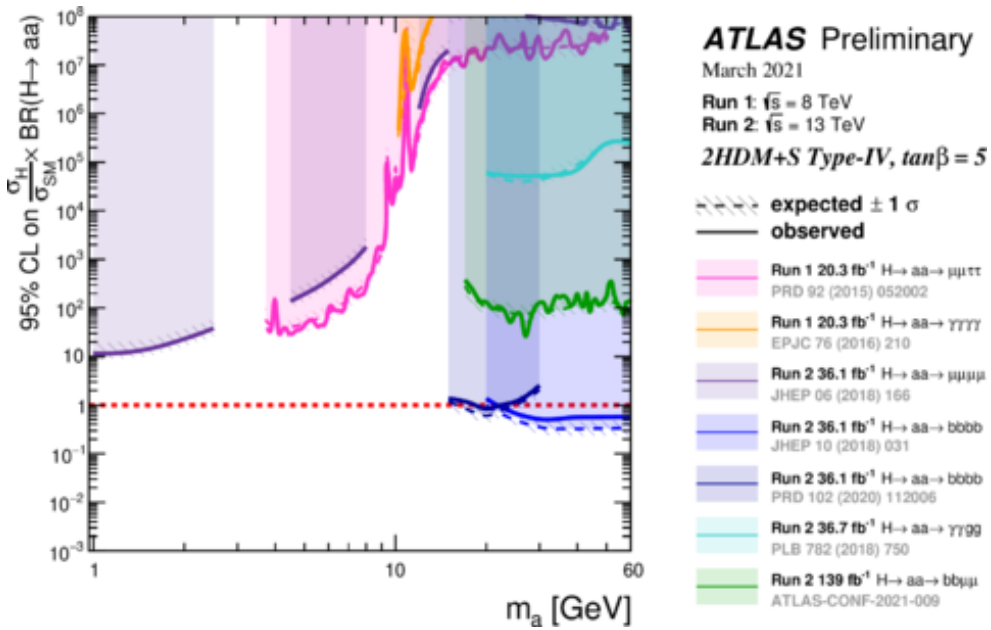
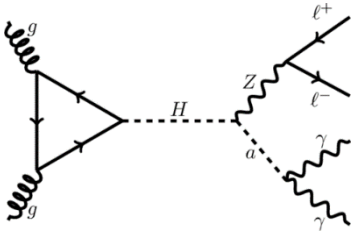


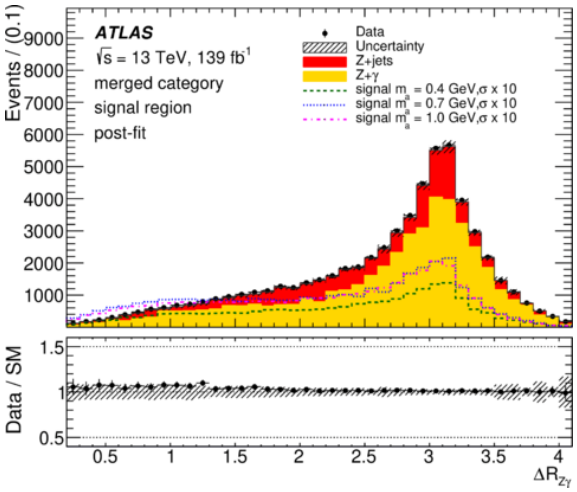
$H \to Za, a \to \gamma\gamma$

Phys. Lett. B 848 (2024) 138536

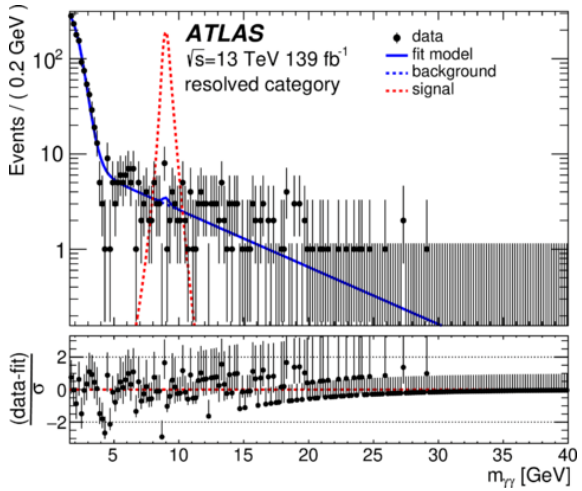


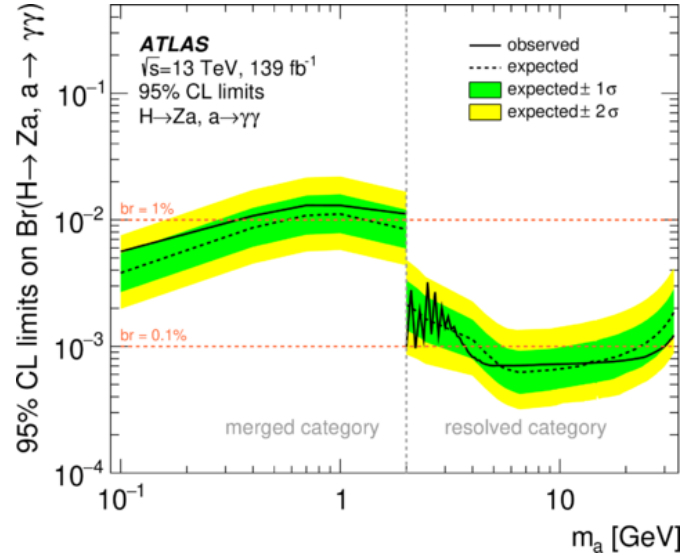
- $H \to Za$ decay is unexplored.
- $H \to Za$ decay is also motivated by axion models.
- Analysis split into resolved and merged categories based on angular separation of γ's.
- Main backgrounds from $Z + jets$ (π^0 decays) and $Z + \gamma$.
  - Composition is 25:75 in merged, 90:10 in resolved.

Merged



Resolved





CMS has a comparable results in this search: Phys. Lett. B 852 (2024) 138582.

Summary

- LHC is under Run3 operation in 2022-2025.
  - ATLAS/CMS recorded $\sim 100\ \mathrm{fb}^{-1}$ of $13.6\ \mathrm{TeV}\ p-p$ collision data in Run 3.
  - Plan to have $250\ \mathrm{fb}^{-1}$ at end of 2025.
  - Collaborations ramping up Run 3 analyses.
- Full Run 2 data ($\sim 140\ \mathrm{fb}^{-1}$ at $13\ \mathrm{TeV}$) analysis are going on.
  - Some more full Run2 results to be released for 2HDM, MSSM scenarios.
  - Complicated signatures and heavier masses are searched for.
  - Advanced theoretical scenarios are explored.
- Run 3 dataset will enable searches and measurements at higher precision.