LHCでのBSMヒッグス物理

佐藤構二

宇宙史研究センター構成員会議

2024年7月2日

BSM Higgs Search Motivation

- Many BSM theories predict additional Higgs Bosons.
- BSM can enhance rare decay modes of $H(125)$ boson.
- 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)

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

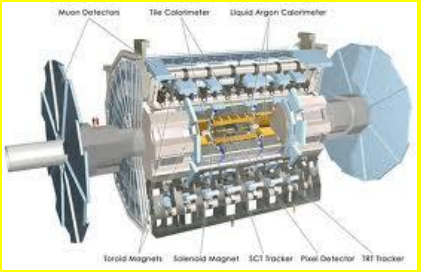
- Many other models are searched for at LHC.

- 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)

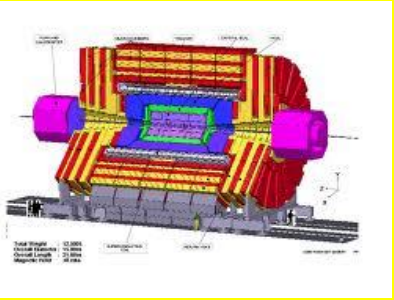
Particle physics experiment at the highest energy
$p - p$ collisions at $E_{CM} \leq$14 TeV
Broad physics program at ATLAS and CMS, including BSM Higgs Searches.

ATLAS



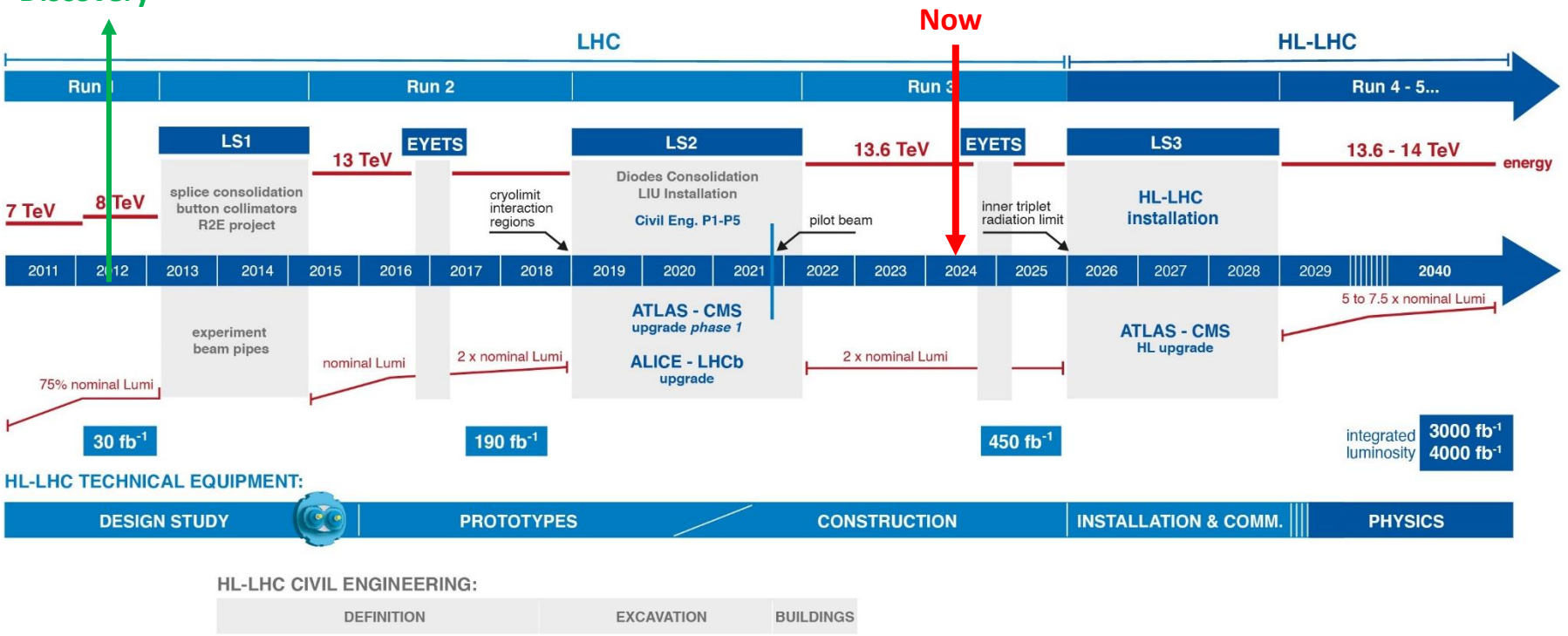
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

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.

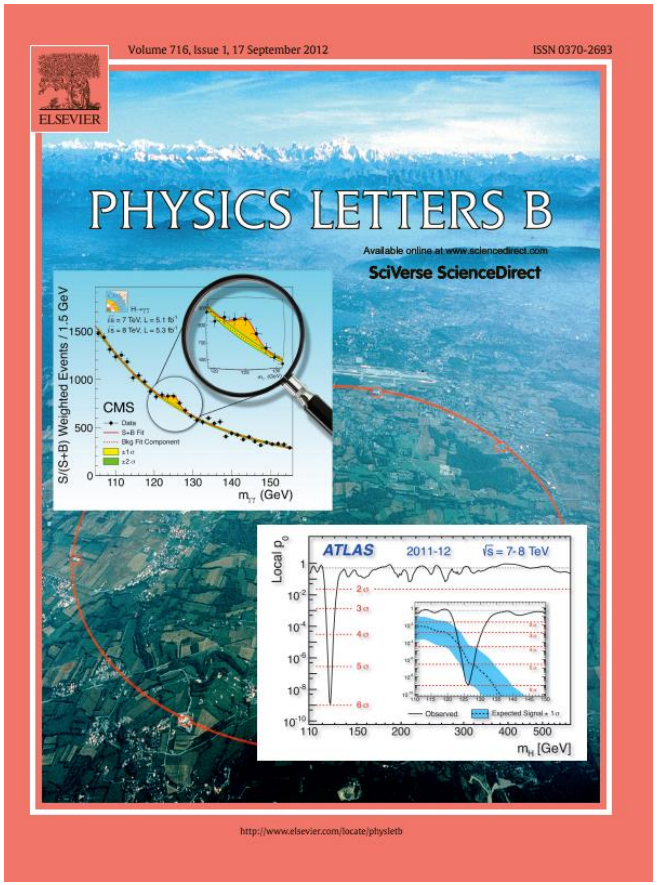
	year	E_{CM}(TeV)	integ lumi [fb^{-1}]
Run 1	2011	7	5
	2012	8	21
Run 2	**2015-2018**	**13**	**139**
Run 3	**2022-2025**	**13.6**	**250**
HL-LHC	2029-2038	14	3000

Searches in 2HDM/MSSM Regime

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

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

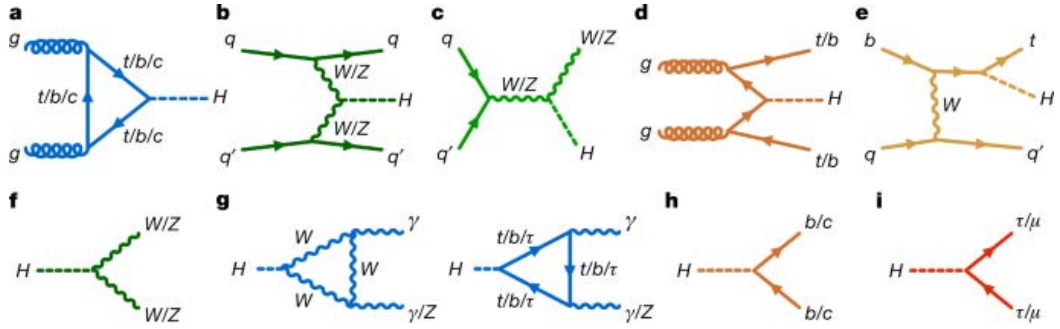
Higgs Discovery in 2012



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

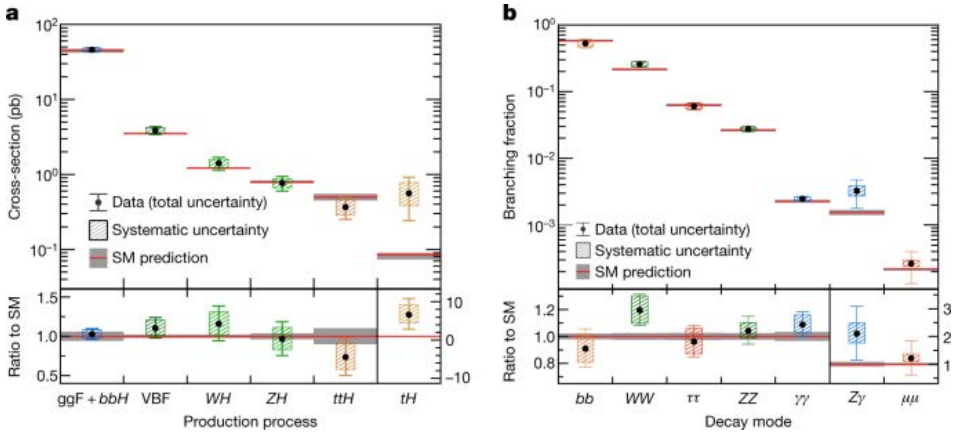
$H(125)$ Measurements

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



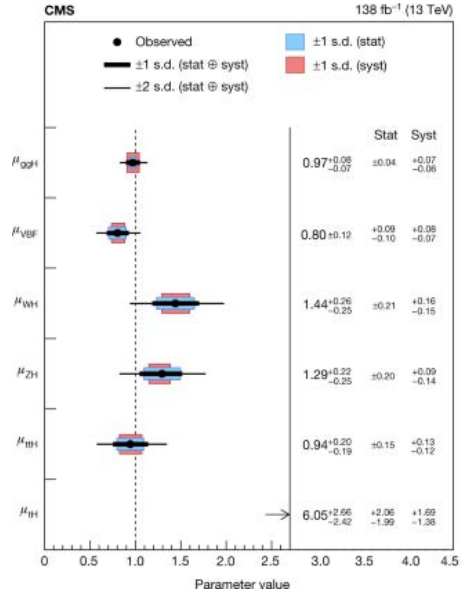
[*Nature* **607**, 52–59 (2022)](#)

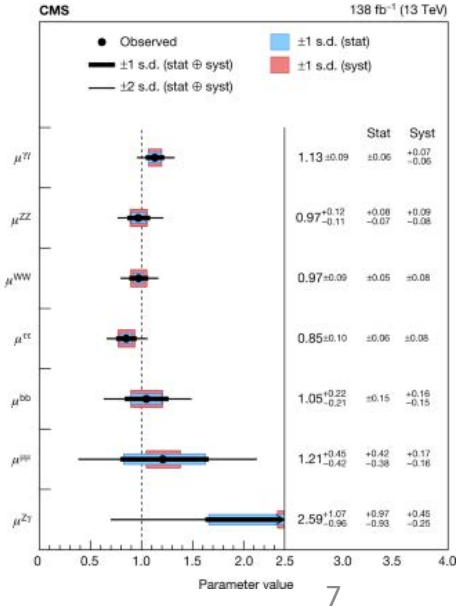
ATLAS EXPERIMENT



[*Nature* **607**, 60–68 (2022)](#)

CMS



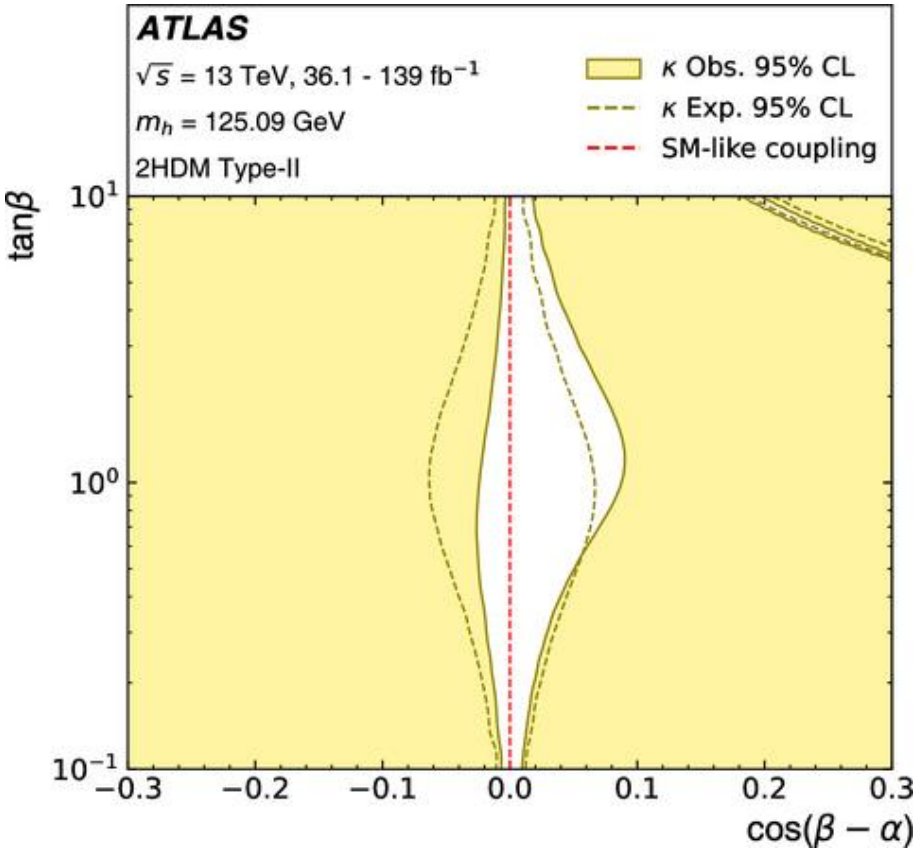


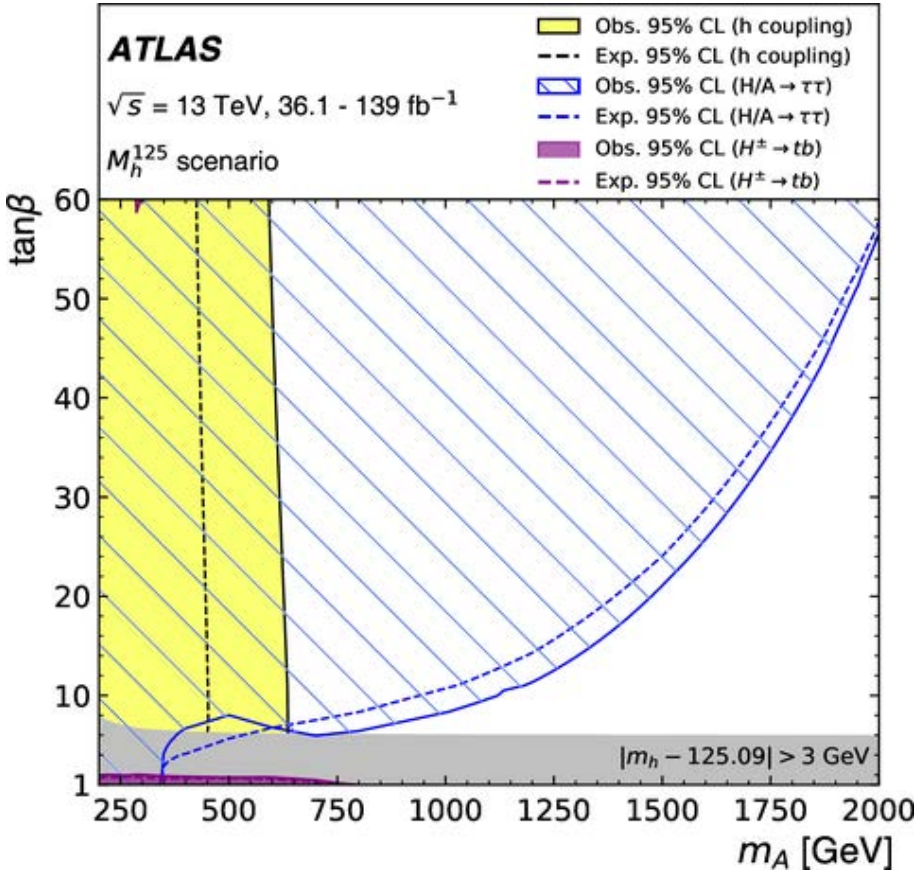
These results can be used to constrain BSM Higgs scenarios.

Interpretation of $H(125)$ Measurements

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

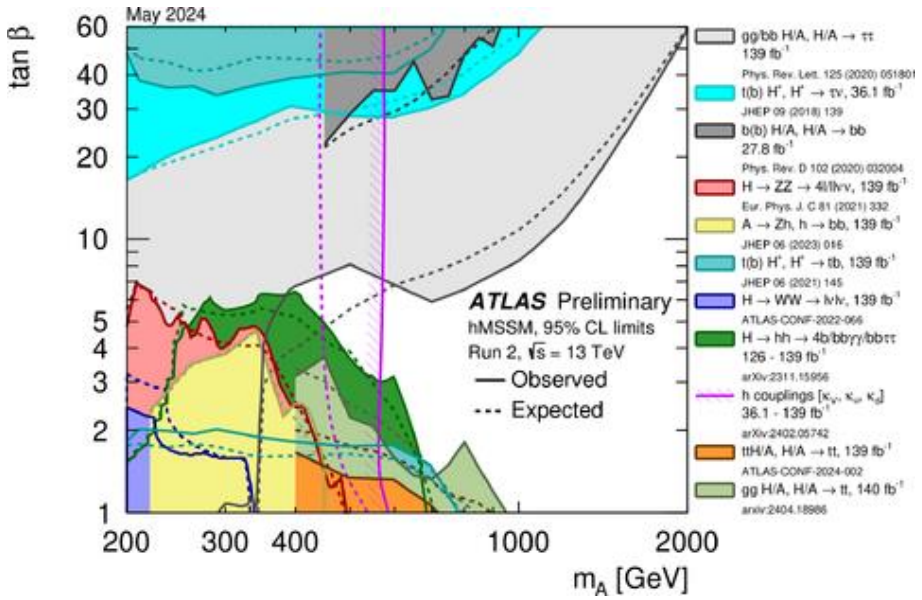
arXiv:2402.05742



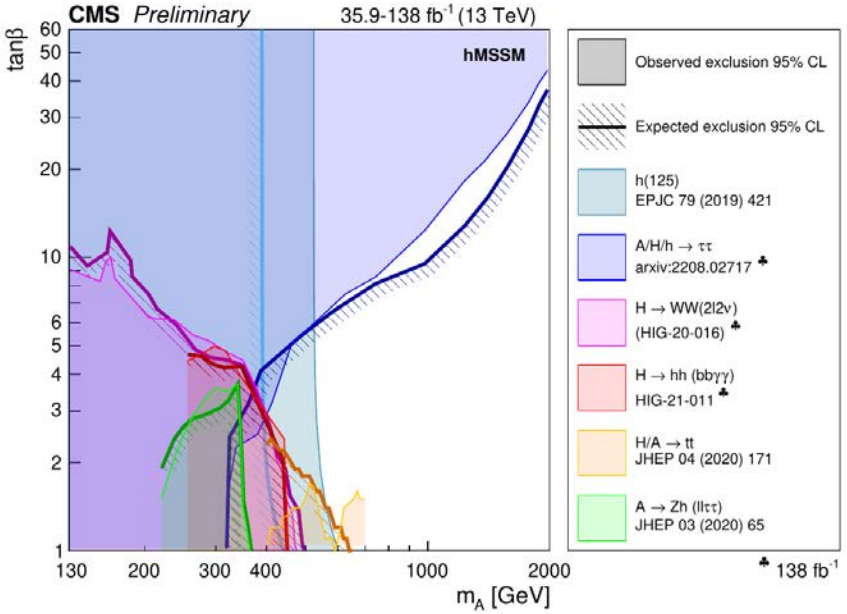


MSSM Higgs Status

- 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/

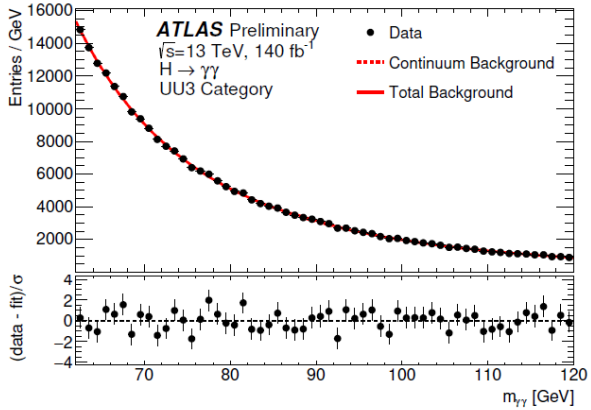


https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG#NEW_Summary_of_MSSM_Higgs_Boson

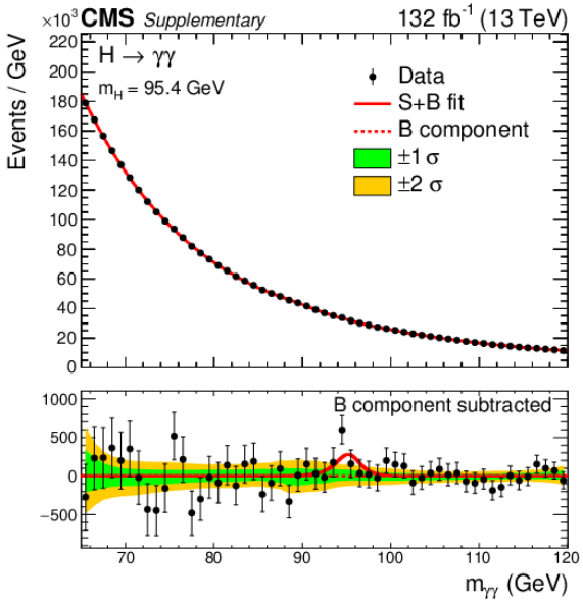
Low mass $H \to \gamma\gamma$

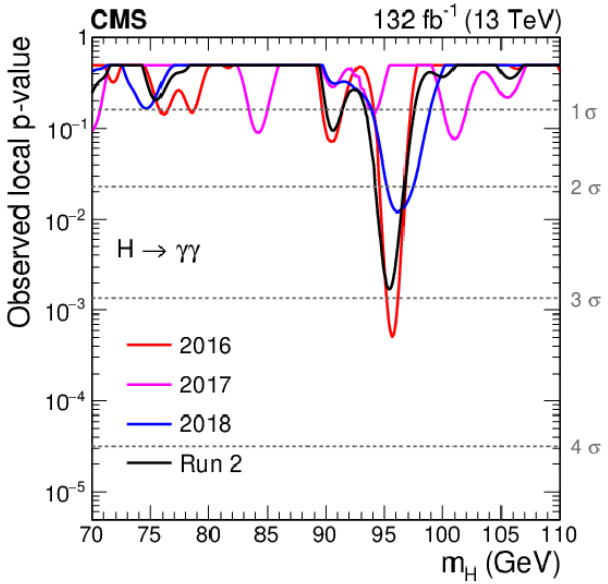
- Many theories can give rise to additional low mass Higgs bosons.
- CMS observes an excess around $95.4\ \mathrm{GeV}$ with local (global) significance of 2.9σ (1.3σ).
- ATLAS local significance of 1.7σ at $95.4\ \mathrm{GeV}$.

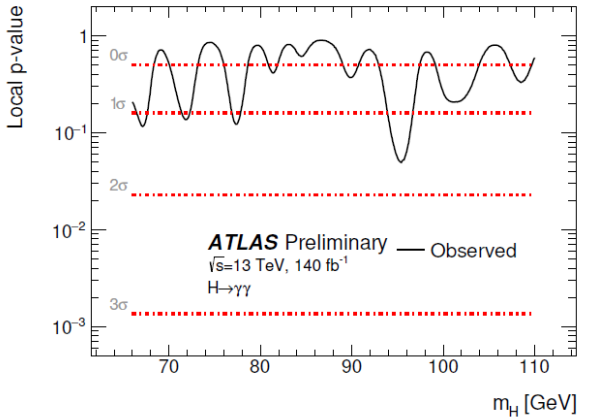
ATLAS-CONF-2023-035



arXiv:2405.18149



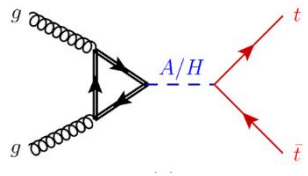


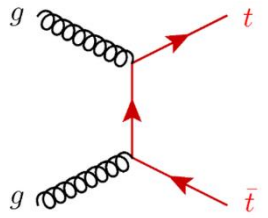


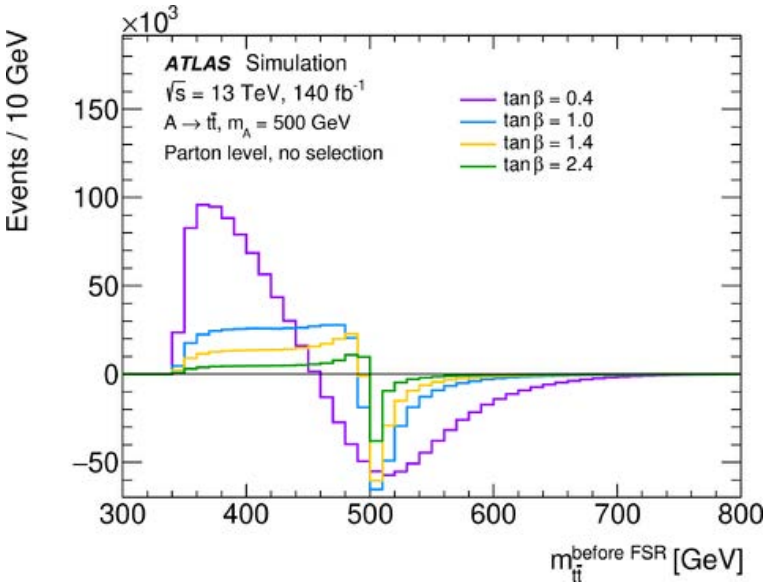
BSM $H/A \to t\bar{t}$

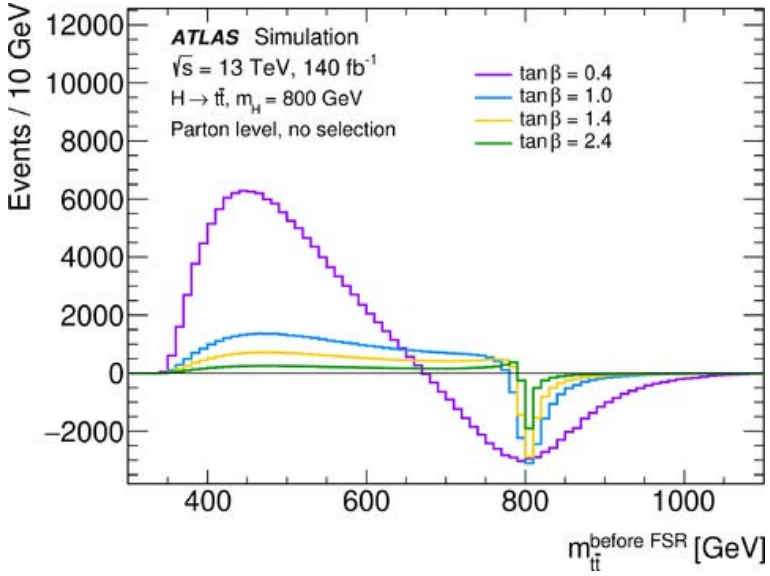
arXiv:2404.18986

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





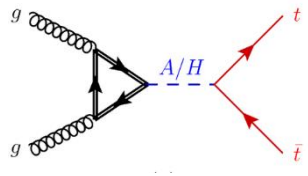


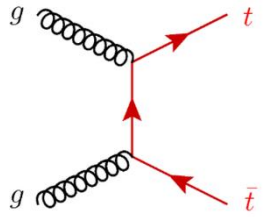


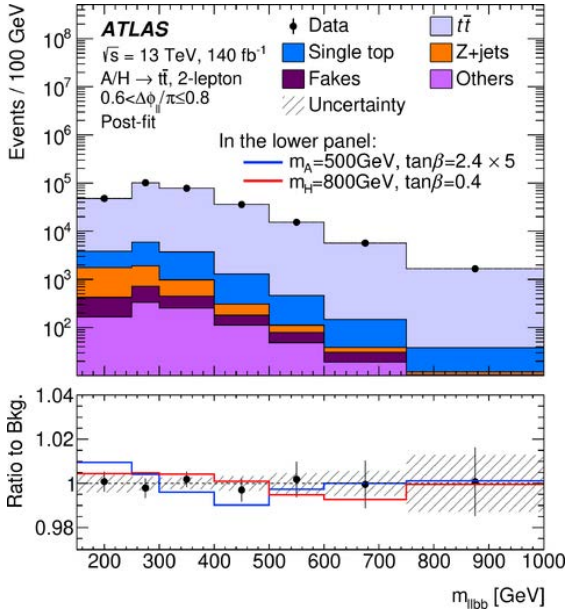
BSM $H/A \to t\bar{t}$ (cont'd)

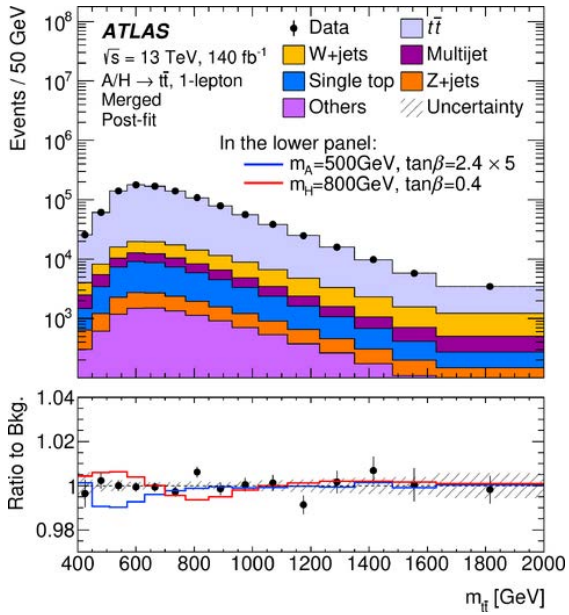
arXiv:2404.18986

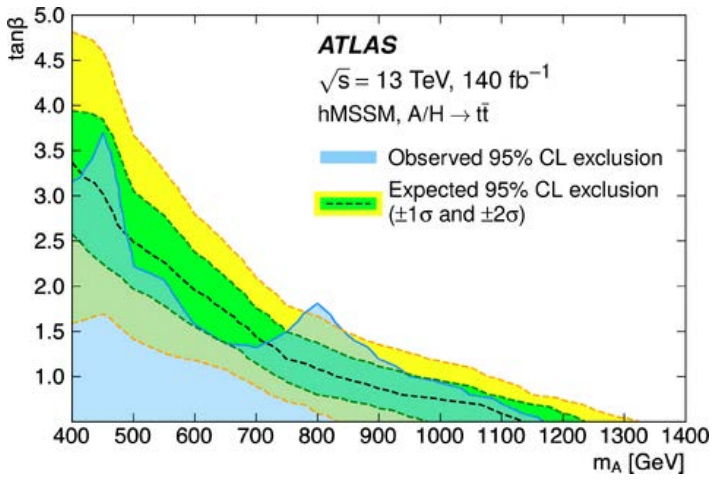
- Analyzed 1 and 2 lepton final states.
- Data were consistent with SM background.
- Most significant deviation was at $800\ \mathrm{GeV}$ with a local significance of $2.3\ \sigma$.





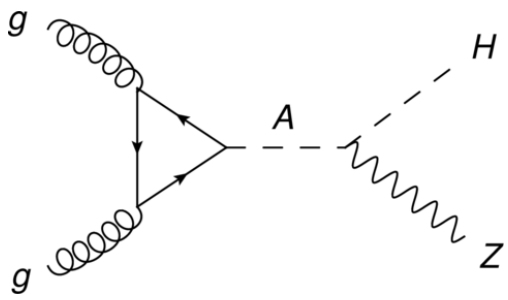






$A \to ZH \to \ell\ell t\bar{t}$

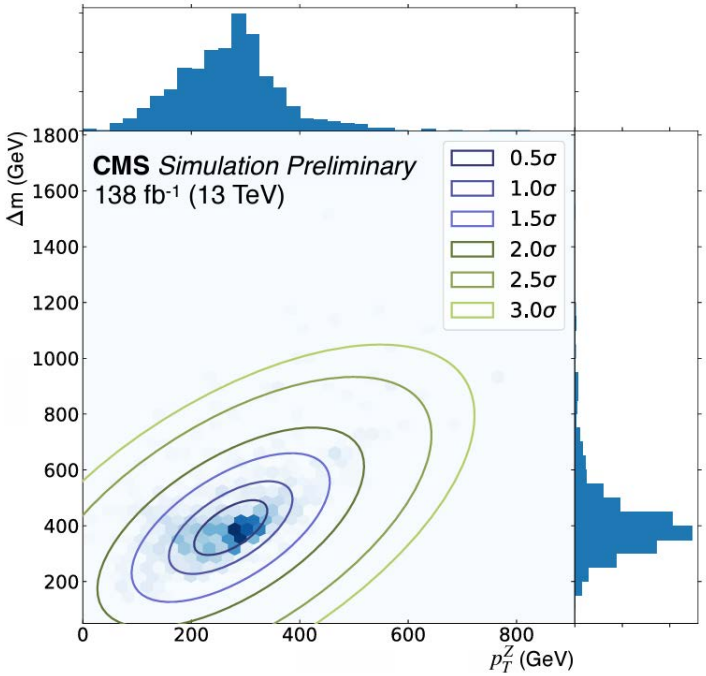
CMS-PAS-B2G-23-006



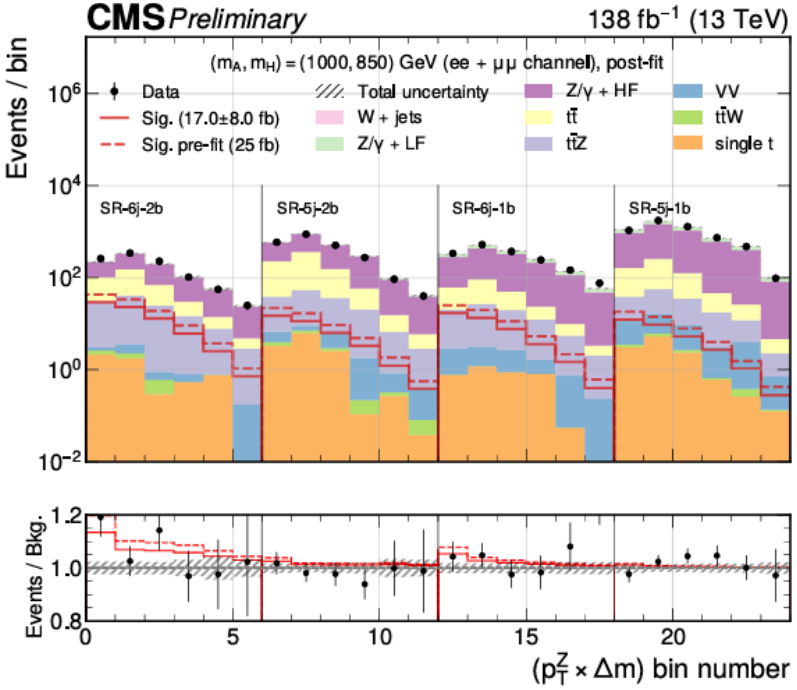
- Region with $400\ \text{GeV} < m_H \ll m_A$ is unexplored.
- This region is favored by some electroweak baryogenesis scenarios.
- Analyze events with $\ell^+\ell^- + \text{nj}(1, \geq 2b)$
- Elliptical bins $(\Delta m, p_z)$ define final discriminant
- No significant deviation from SM background.

Involves two BSM Higgs bosons

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



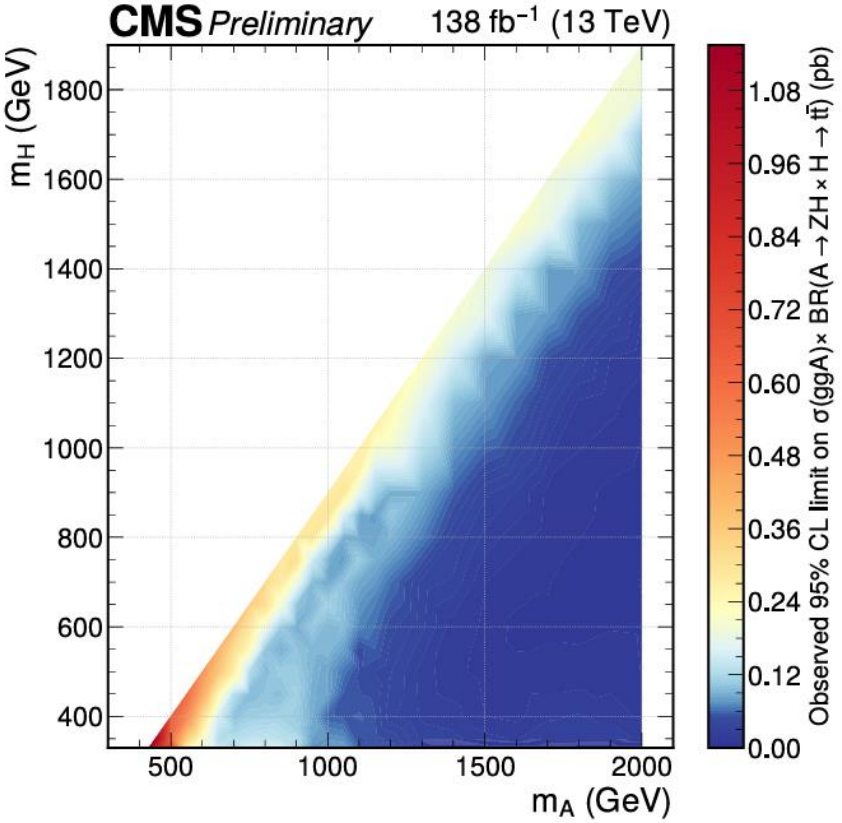
Data distribution for signal hypothesis of $m_A = 1000\ \text{GeV}, m_H = 850\ \text{GeV}$

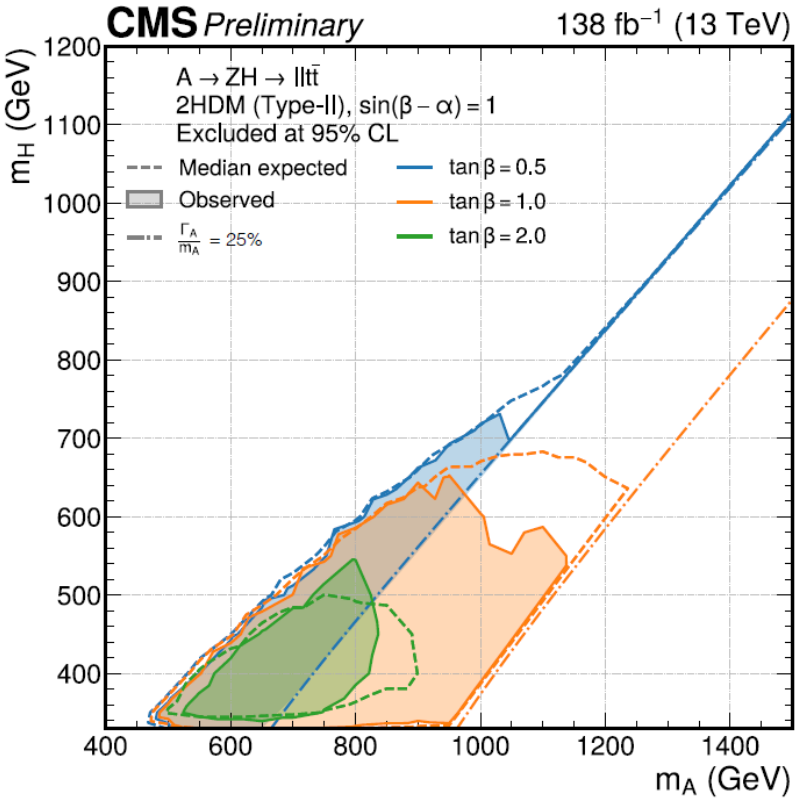


CMS-PAS-B2G-23-006

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

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



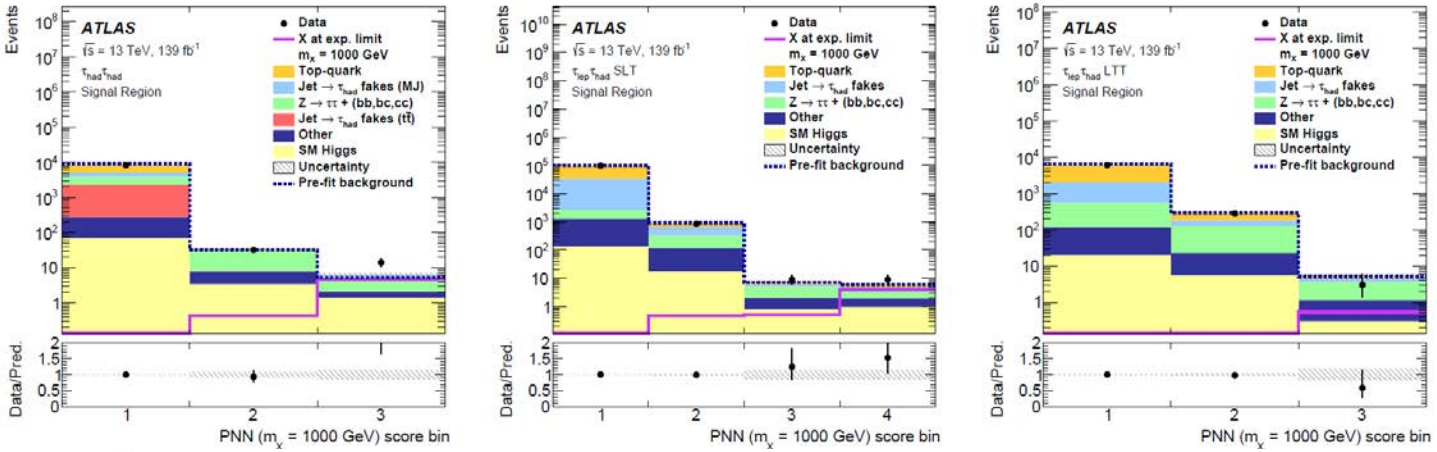


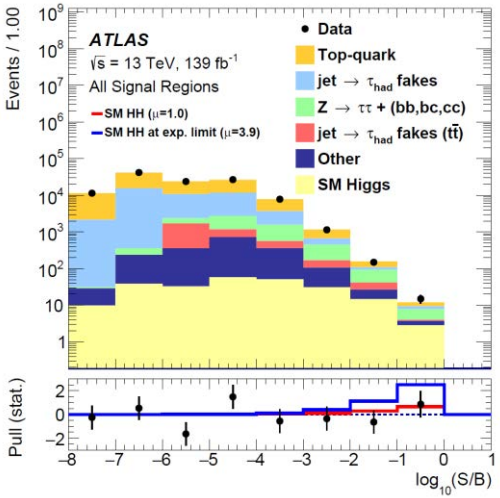
ATLAS has a comparable results for $A \to ZH \to \ell\ell t\bar{t}, \nu\nu t\bar{t}$ JHEP 02 (2024) 197

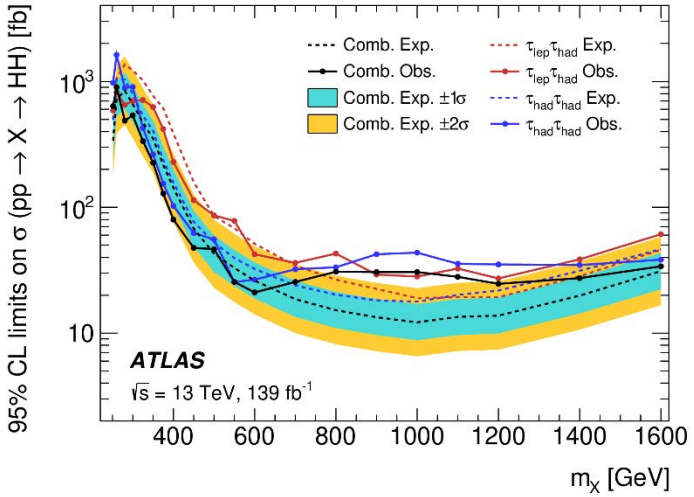
$H \to h_{125}h_{125} \to bb\tau\tau$

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 $m_{hh}, m_{\tau\tau}, m_{bb}$



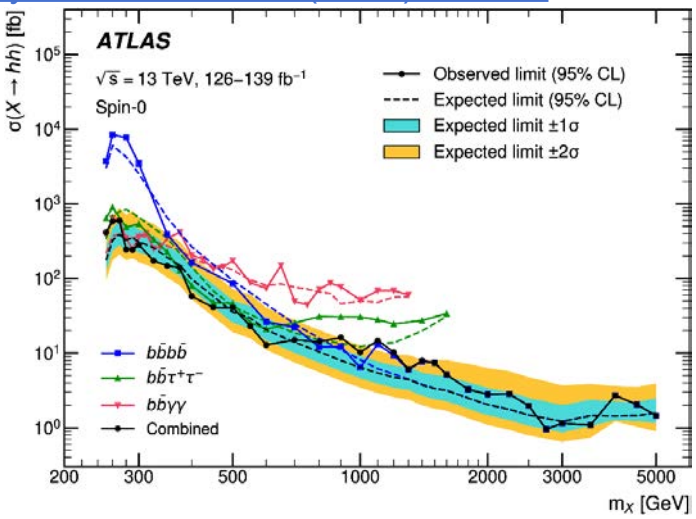


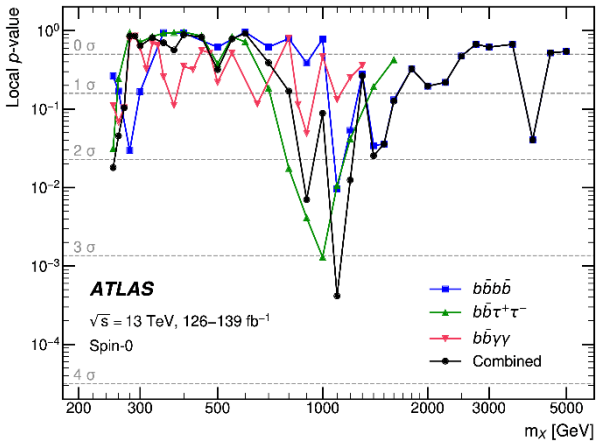


Largest deviation at 1 TeV with local (global) significance of 3.1σ (2.0σ).

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

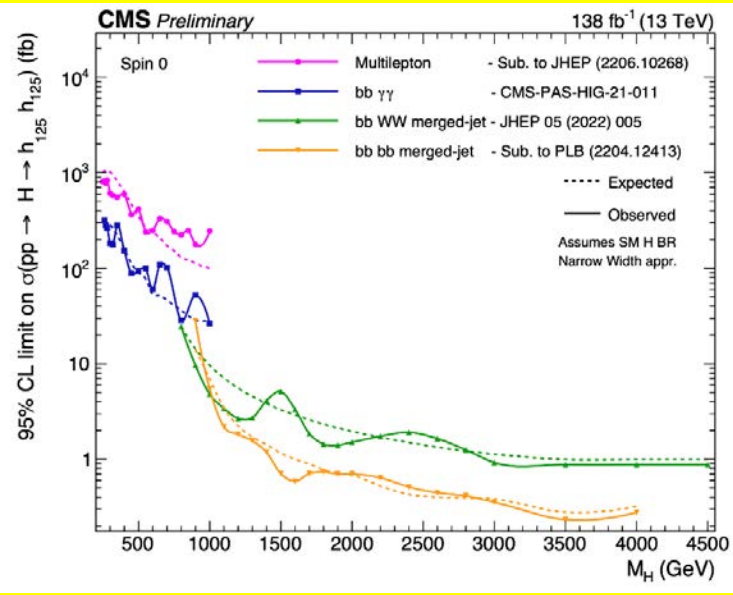
Phys. Rev. Lett. 132 (2024) 231801

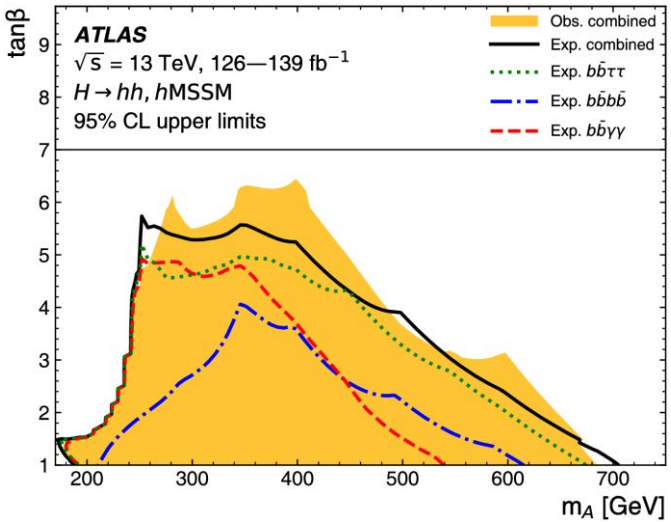




Largest 1.1 TeV, with a local (global) significance of 3.3σ (2.1σ).

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

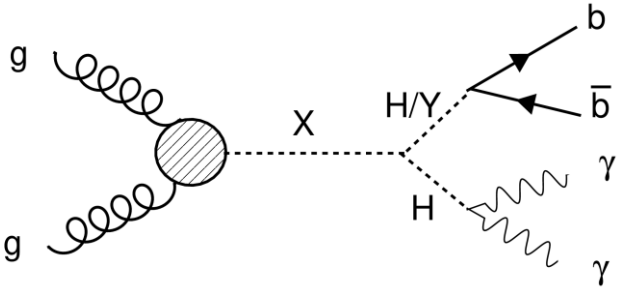


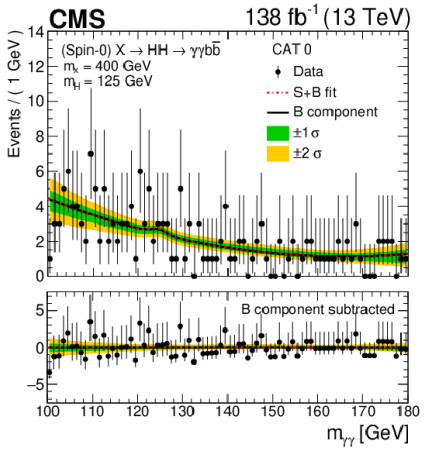


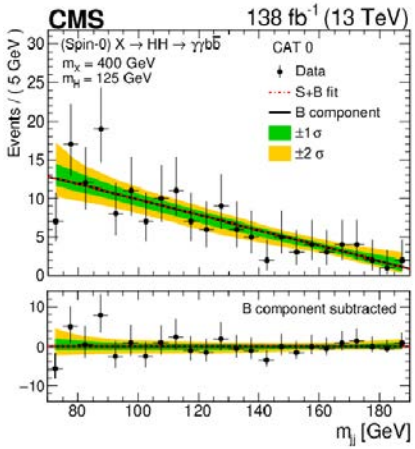
JHEP 05 (2024) 316

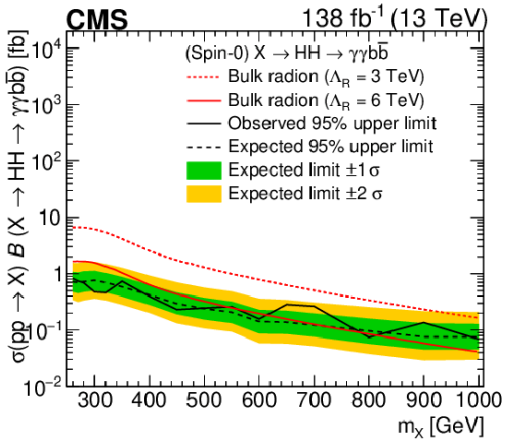
$X \to HH/HY \to bb\gamma\gamma$

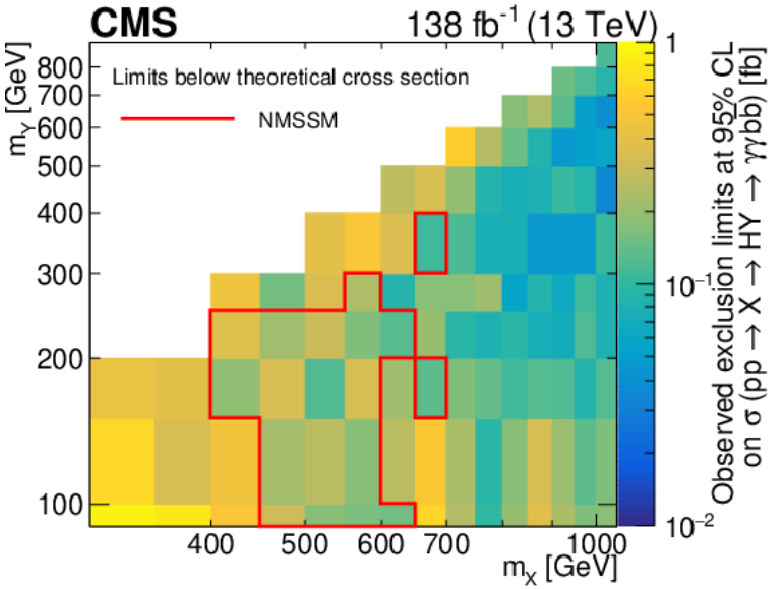
- MSSM motivated search.
- X: heavy spin-0 particle.
  - Spin-2 was also searched for.
- Y: spin-0 particle. Can be another $H(125)$.
- BDT was trained to divide signal regions.











Involves two BSM Higgs bosons.
Interpretation with NMSSM.

Searches in 2HDM+Singlet/NMSSM

– 7 Higgs Bosons

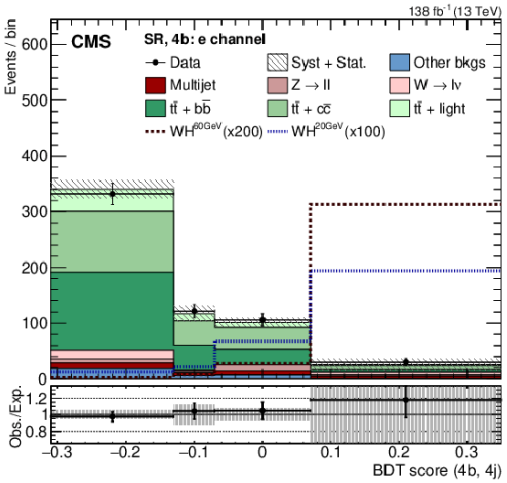
$$h_1, h_2, h_3, H^+, H^-, a_1, a_2$$

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

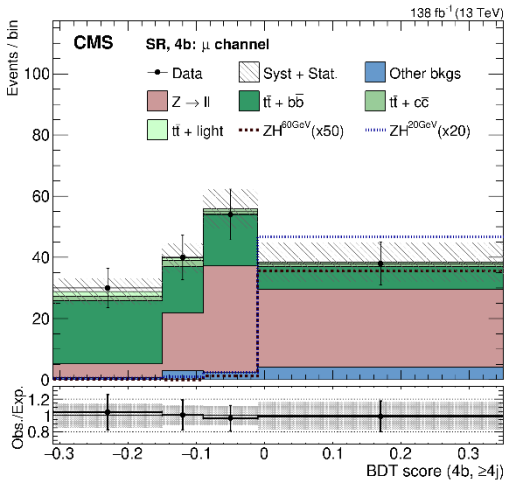
arXiv:2403.10341

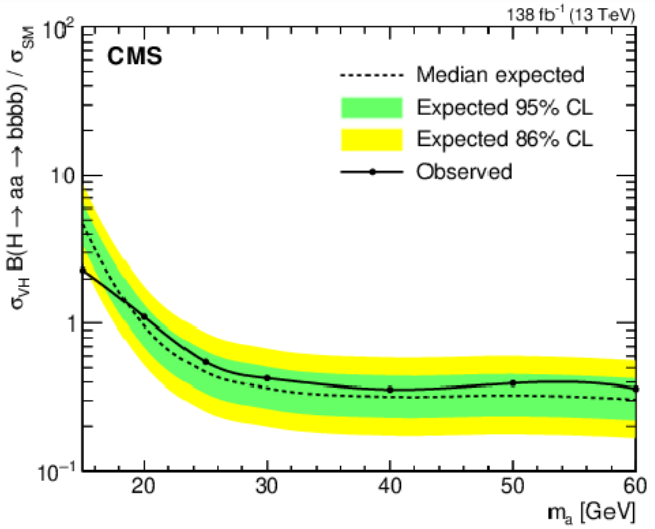
- $a \to b\bar{b}$ is usually the dominant decay mode above $b\bar{b}$ threshold.
- $Z \to \ell\ell$ and $W \to \ell\nu$ channels.
- 3 or 4 b-tagged jets.
- BDT discriminants trained for ZH and WH channels for signal separation.

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



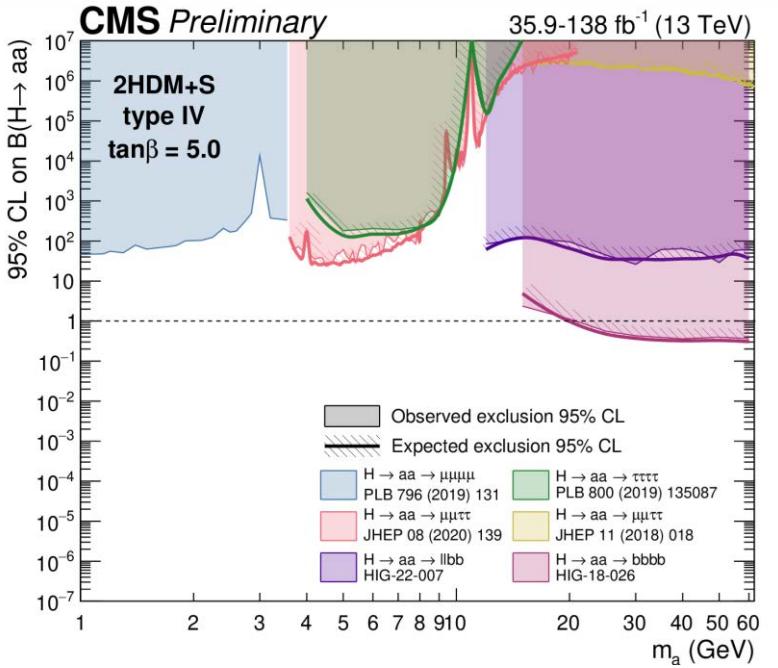
$ZH \to \mu\nu + 4b$ chan.



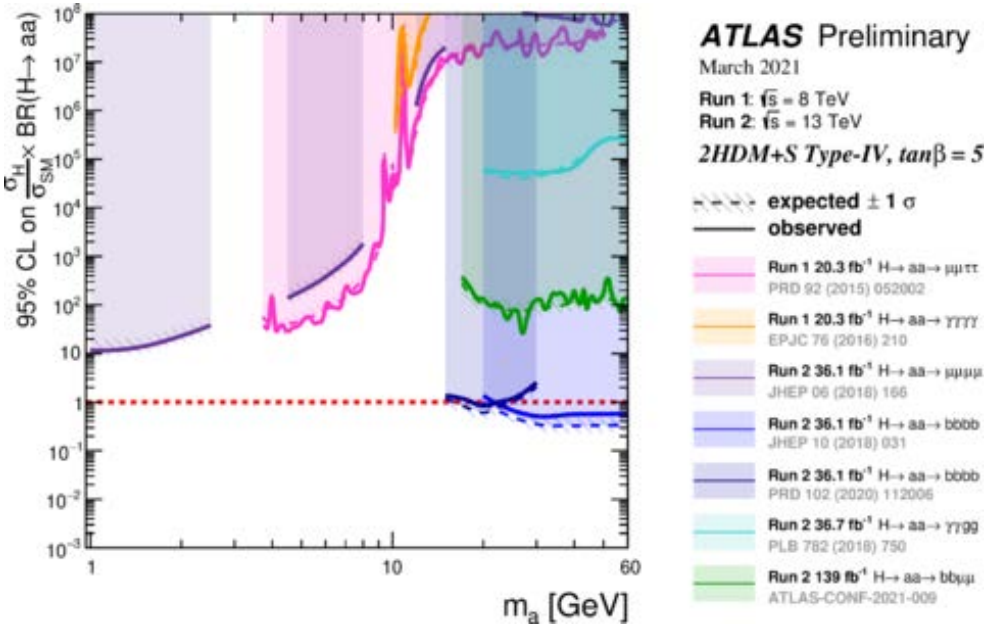


$H \to aa$ Search Summary Plots

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

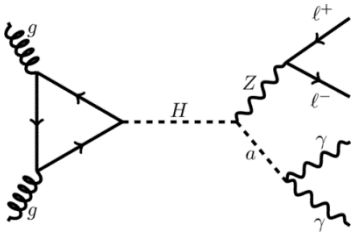


ATL-PHYS-PUB-2021-008



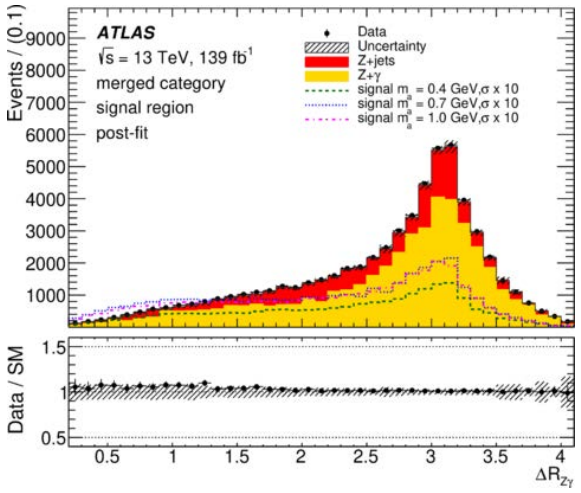
$H \to Za, a \to \gamma\gamma$

Phys. Lett. B 848 (2024) 138536

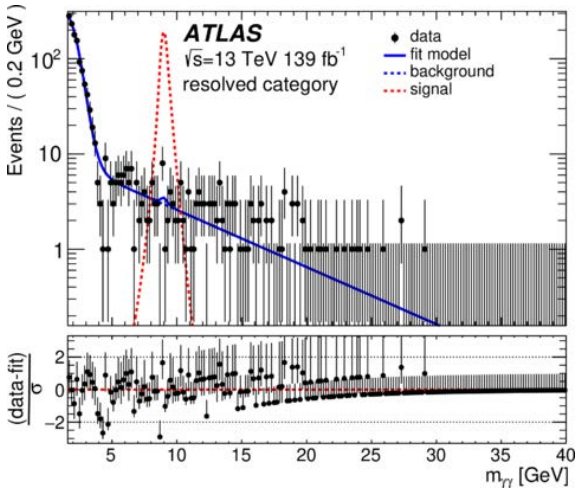


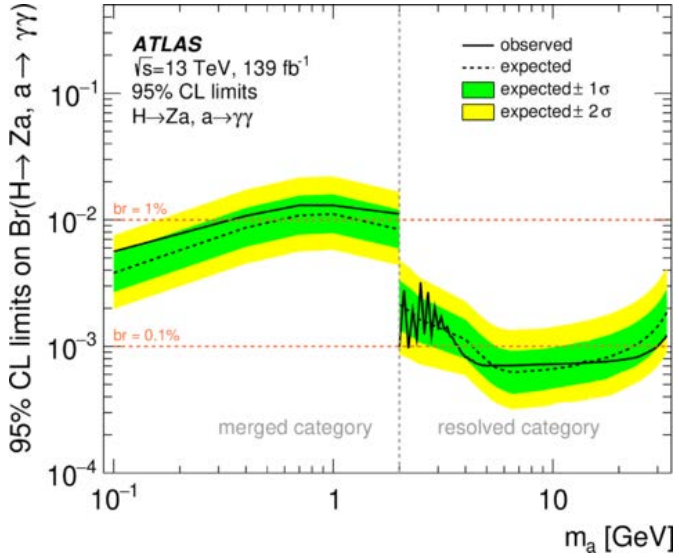
- $H \to Za$ decay is unexplored.
- $H \to Za$ decay is also motivated by axion models.
- Analysis split into resolved and merged categories based on angular separation of γ's.
- Main backgrounds from $Z + jets$ (π^0 decays) and $Z + \gamma$.
  - Composition is 25:75 in merged, 90:10 in resolved.

Merged



Resolved





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

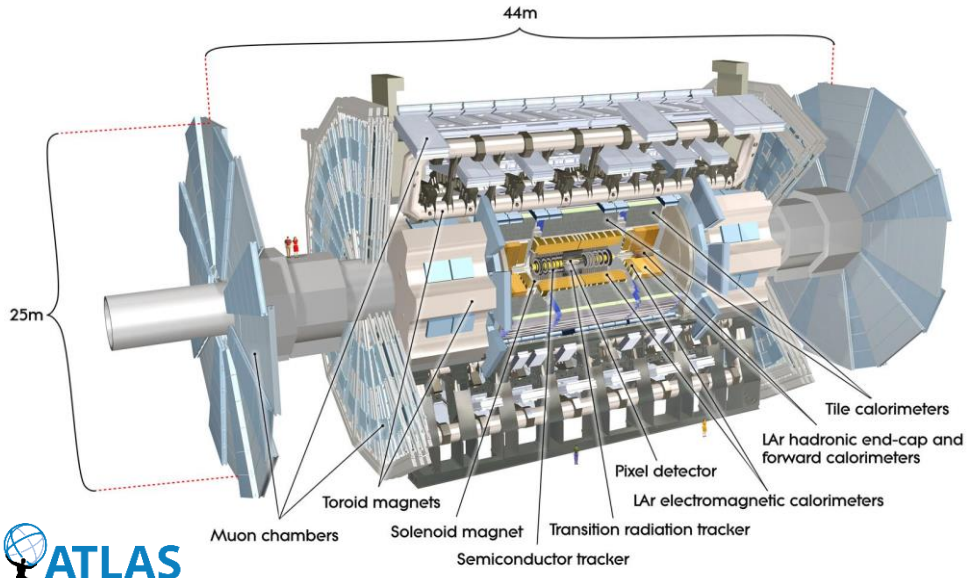
Summary

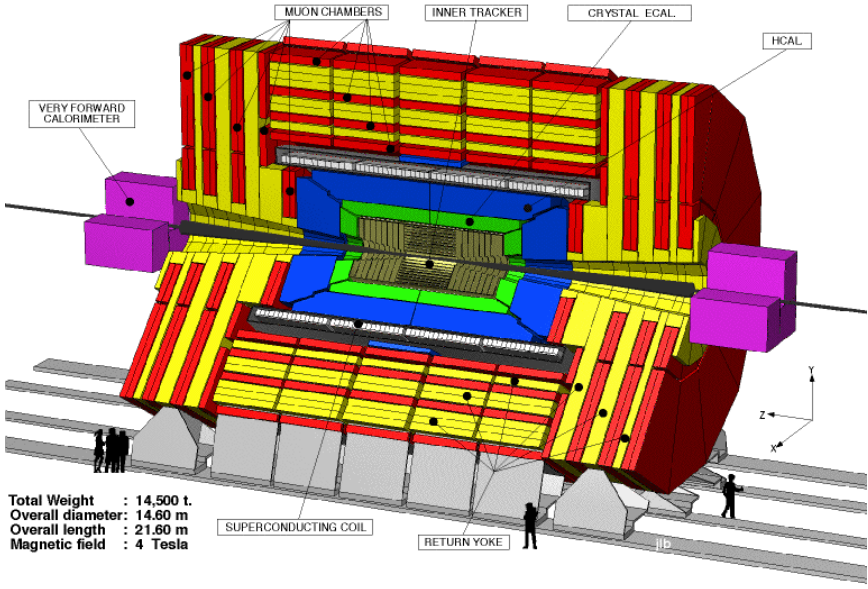
- LHC is under Run3 operation in 2022-2025.
  - ATLAS/CMS recorded $\sim 100\ \mathrm{fb}^{-1}$ of $13.6\ \mathrm{TeV}\ p-p$ collision data in Run 3.
  - Plan to have $250\ \mathrm{fb}^{-1}$ at end of 2025.
  - Collaborations ramping up Run 3 analyses.
- Full Run 2 data ($\sim 140\ \mathrm{fb}^{-1}$ 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.

Backup

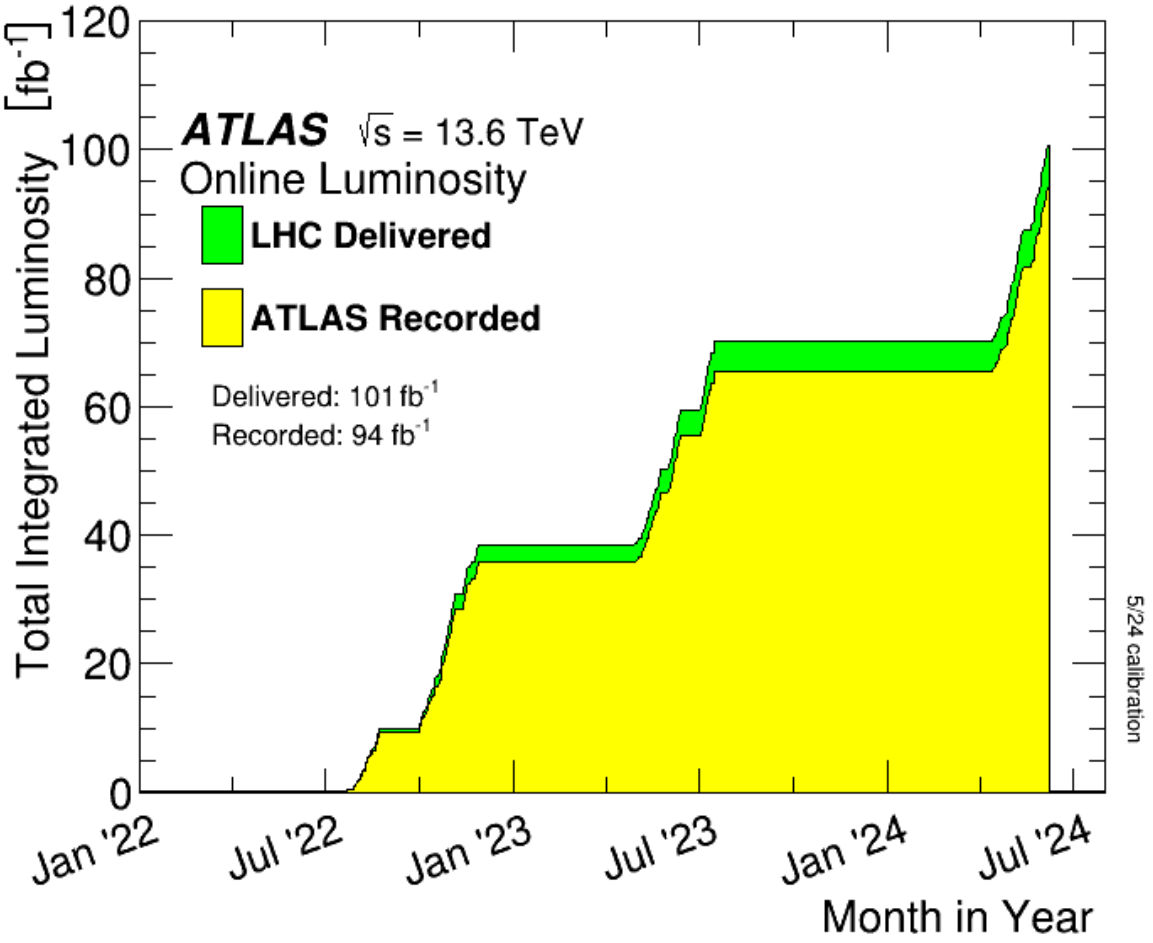
ATLAS and CMS at LHC

- Multi-purpose detectors observing $p - p$ collisions at World Highest Energy of $\sqrt{s} \leq 14\ \mathrm{TeV}$
  - Standard Model phenomena: Higgs bosons, top quarks, Electroweak, B Physics, …
  - Searches for BSM physics: BSM Higgs, Supersymmetry, …





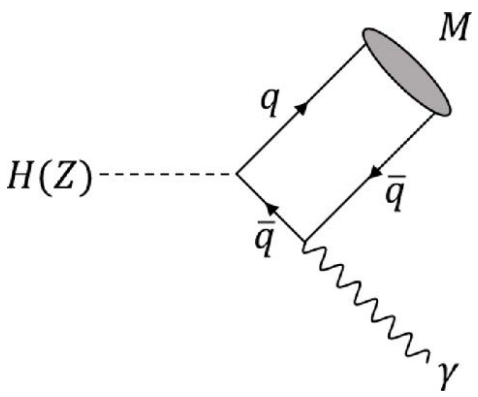
Luminosity Delivered in Run 3

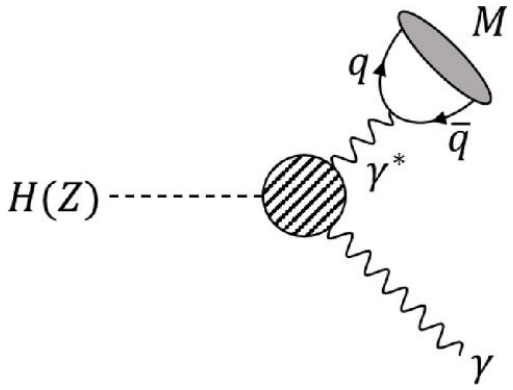


Searches for rare $H(125)$ decays

Rare Decays $H(125) \rightarrow \gamma + Meson$ Search Motivation

- SM predicts very small branching fractions.
- $H \rightarrow \gamma(q\bar{q})$ occur through direct Yukawa coupling and through $H \rightarrow \gamma\gamma^* \rightarrow \gamma(q\bar{q})$.
  - Yukawa coupling to 1st and 2nd generation is unknown.
- BSM processes can enhance the branching fractions.
- Processes like $H \rightarrow K^*\gamma$ can be sensitive to flavor violating Yukawa couplings.

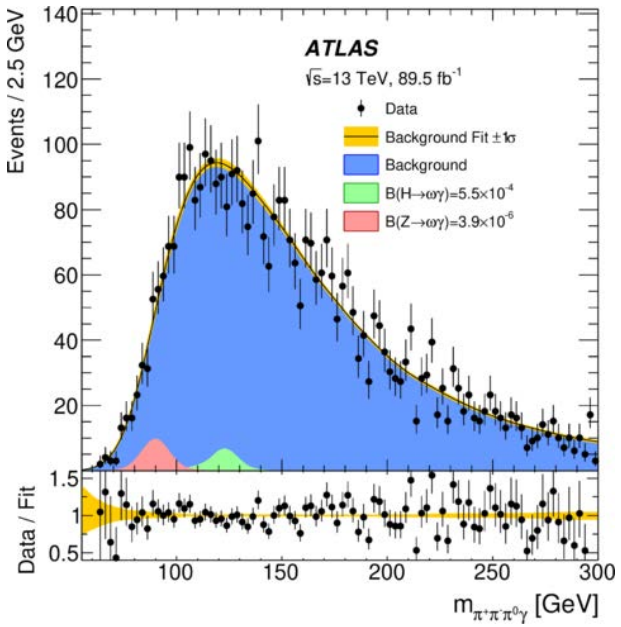


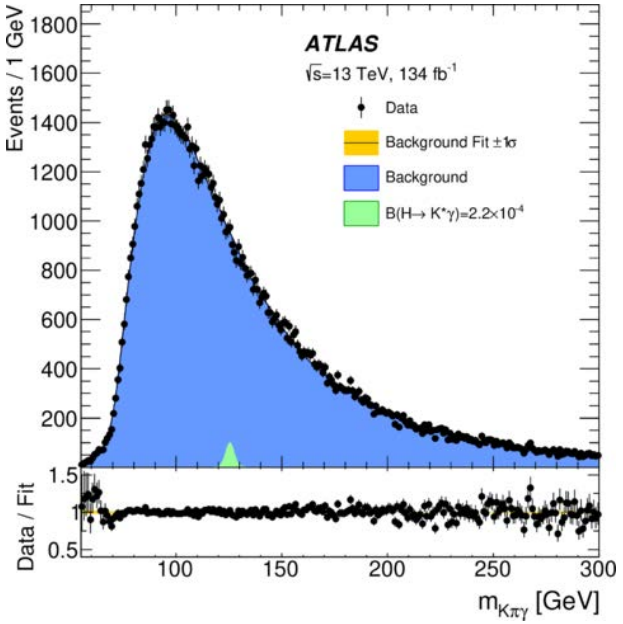


Phys. Lett. B 847 (2023) 138292

Rare Decays $H(125) \to \gamma\omega/\gamma K^*$

- Trigger on $\gamma + \text{tracks}$. Utilize modified version of τ trigger for γK^*.
- Meson reconstructions:
  - $\omega \to \pi^+\pi^-\pi^0$: $279 < m(\pi^+\pi^-\pi^0) < 648$ MeV. π^0 reconstructed as Calorimeter cluster.
  - $K^* \to K^+\pi^-$: $790 < m(\pi^+\pi^-\pi^0) < 990$ MeV.
-



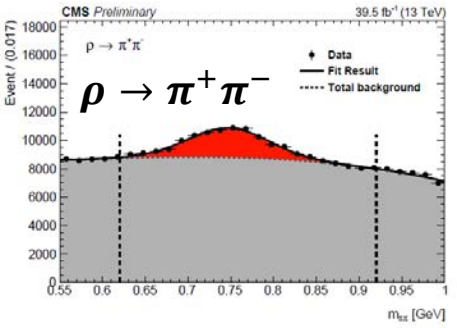


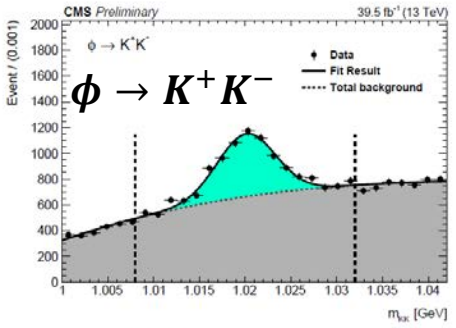
	Observed Upper Limit
$Br(H \to \omega\gamma)$	5.5×10^{-4}
$Br(H \to K^*\gamma)$	2.2×10^{-4}

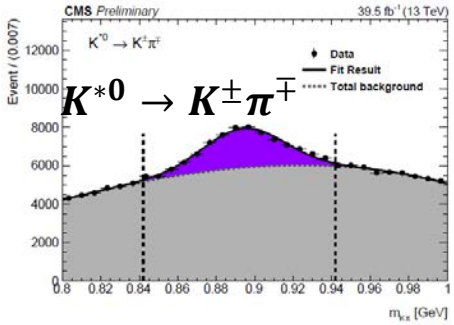
Rare Decays $H(125) \to \gamma\rho, \gamma\phi, \gamma K^{*0}$

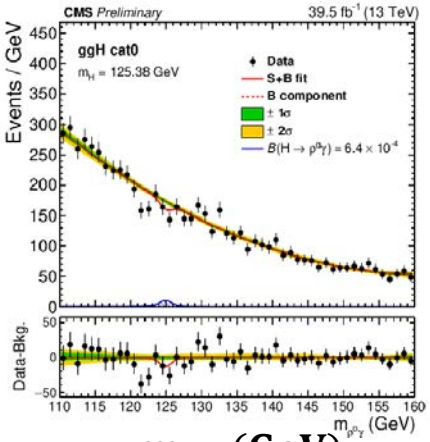
- Mesons are reconstructed as a track pair.

CMS-PAS-HIG-23-005

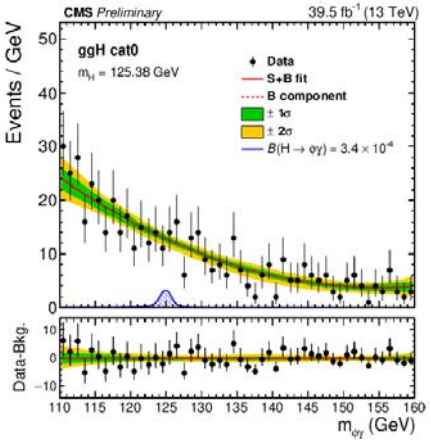




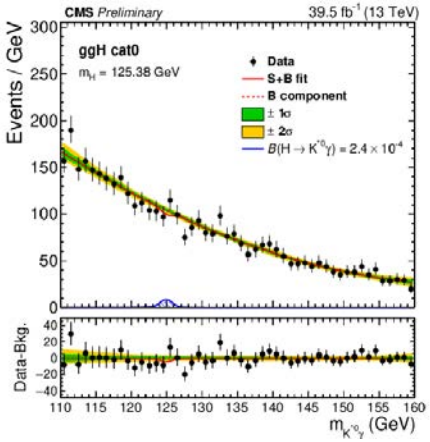




$m_{\rho\gamma}$ (GeV)



$m_{\phi\gamma}$ (GeV)



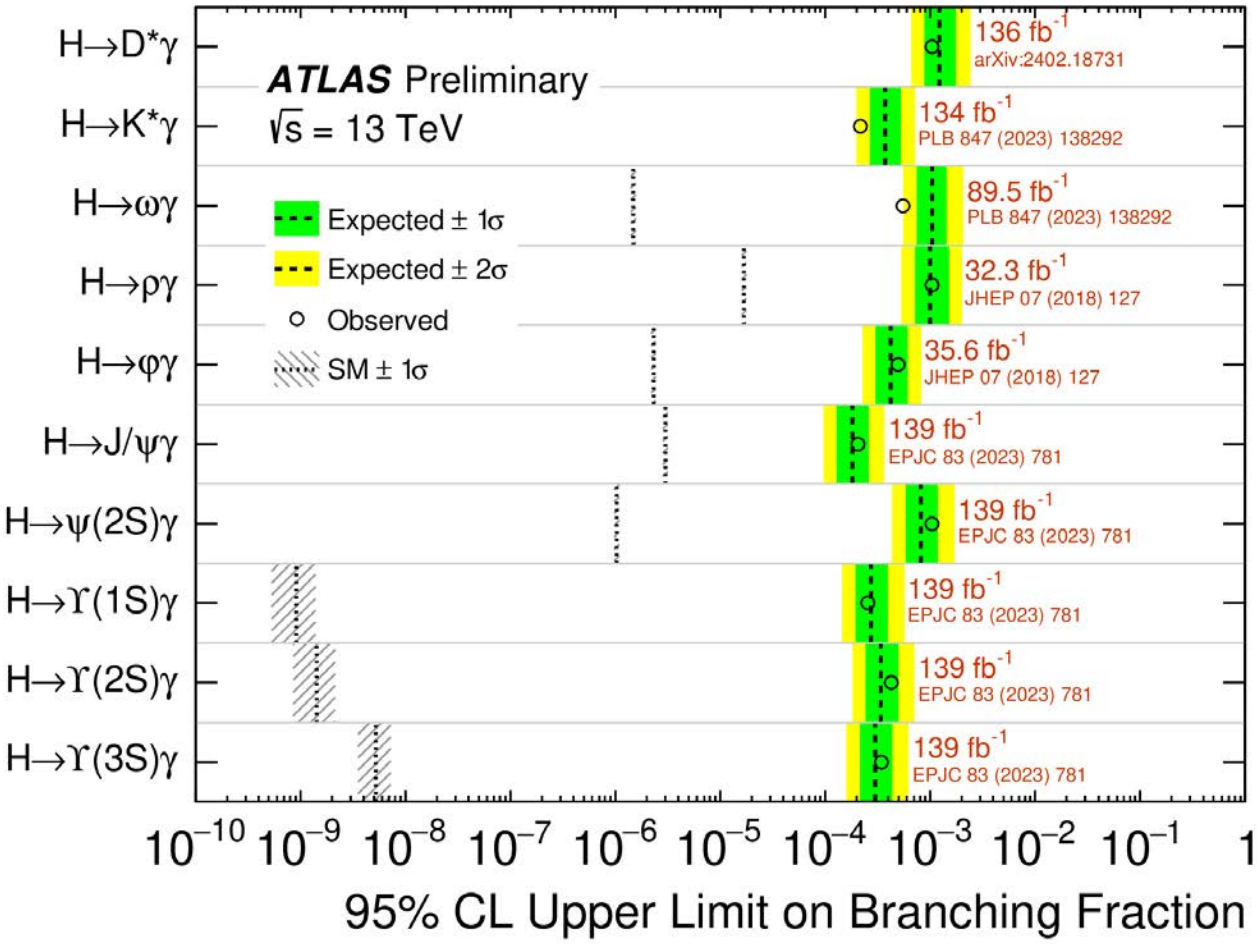
$m_{K^{*0}\gamma}$ (GeV)

Obtained most stringent 95% CL experimental upper limits to date:

$$\mathrm{Br}(H \to \gamma\rho^0) \leq 3.74 \times 10^{-4}$$
$$\mathrm{Br}(H \to \gamma\phi) \leq 2.97 \times 10^{-4}$$
$$\mathrm{Br}(H \to K^{*0}\phi) \leq 1.71 \times 10^{-4}$$

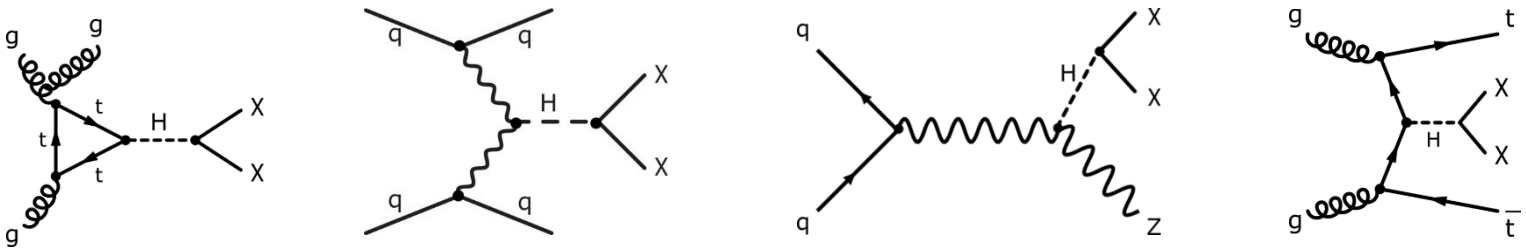
Rare Decays $H(125) \rightarrow \gamma + Meson$

ATL-PHYS-PUB-2023-004



$H(125) \rightarrow invisible$

- Massive DM can couple to Higgs boson.
- Some theories predict that H can act as a portal between DM and SM sector.
- Both ATLAS and CMS searched for invisible Higgs decays in different production modes.



$H(125) \rightarrow invisible$

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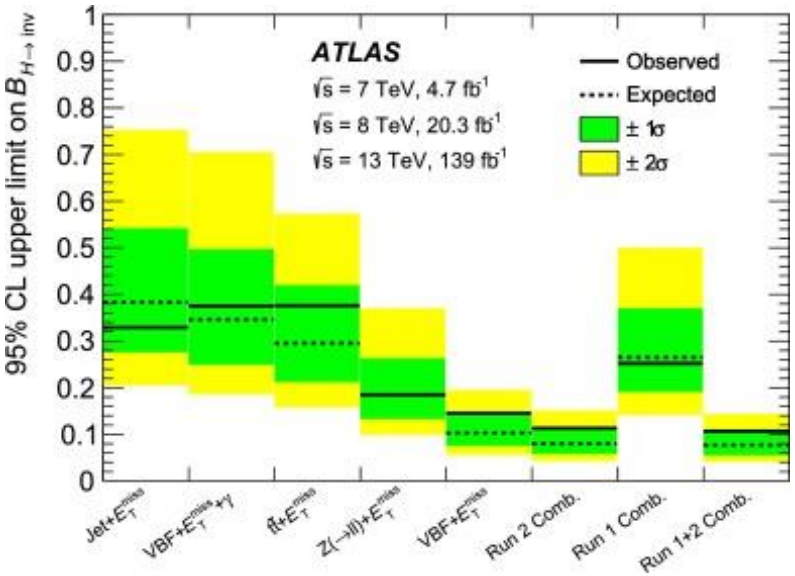
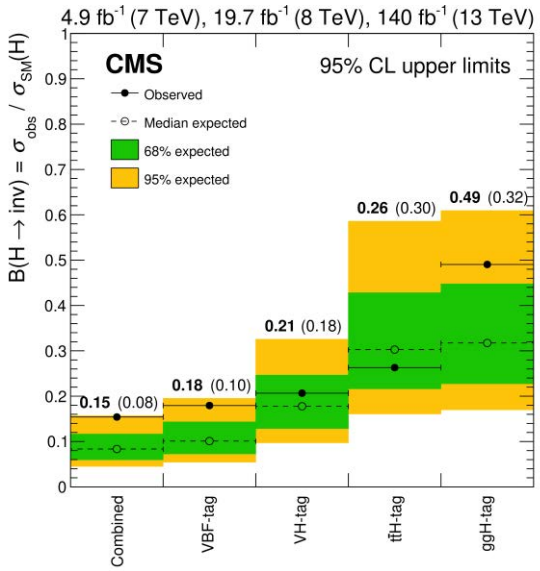
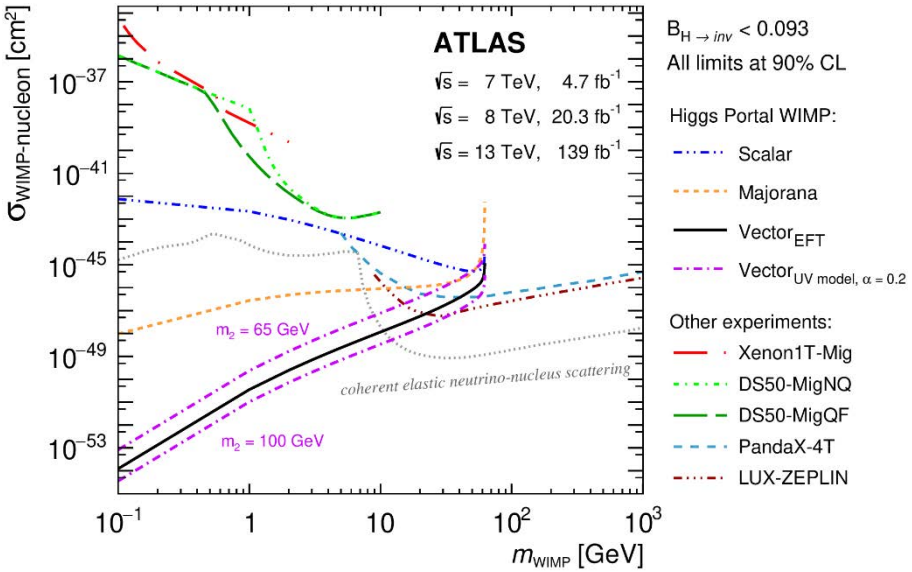
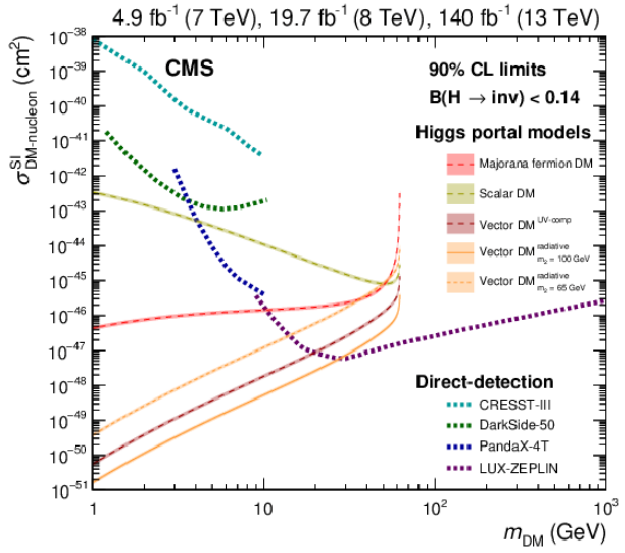


Eur. Phys. J. C 83 (2023) 933







DM plots

Phys. Lett. B 842 (2023) 137963

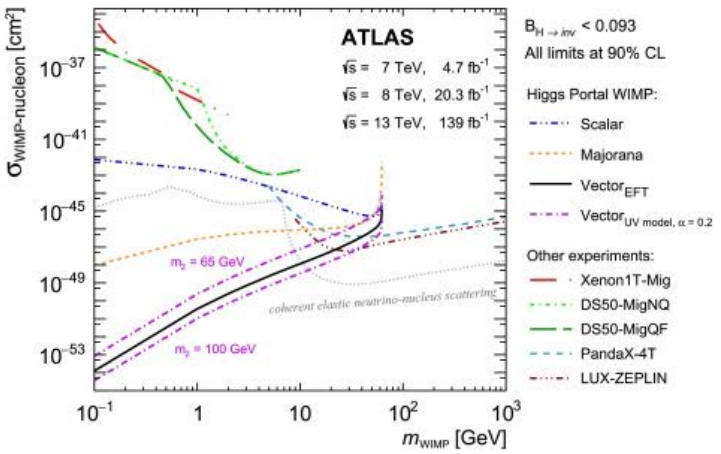


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Fig. 4. Upper limit at the 90% CL on the spin-independent WIMP-nucleon scattering cross-section as a function of the WIMP mass for direct detection experiments and the interpretation of the $H \rightarrow$ invisible combination result in the context of Higgs portal models considering scalar, Majorana and vector WIMP hypotheses. For the vector case, results from UV-complete models are shown (pink curves) for two representative values for the mass of the predicted Dark Higgs particle (m_2) and a mixing angle α=0.2. The uncertainties from the nuclear form factor are smaller than the line thickness. Direct detection results are taken from Refs. [65], [66], [67], [68]. The neutrino floor for coherent elastic neutrino-nucleus scattering (dotted gray line) is taken from Refs. [69], [70], which assume that germanium is the target over the whole WIMP mass range. The regions above the limit contours are excluded in the range shown in the plot.

2.3 Objection on EFT, first UV model arXiv:2107.01252 [hep-ph]

In the EFT approach used in LHC Run–1 [23], the mass of the VDM was entered arbitrarly, which leads to a non-renormalisable Lagrangian and violation of unitarity [25]. For this reason, it is safer to consider a better framework, i.e. a simple UV completion with a dark Higgs sector that gives mass to the vector DM via spontaneous electroweak symmetry breaking (EWSB). The simplest renormalisable Lagrangian for the Higgs portal VDM in such a UV model is given by Ref.[25]:

$$\mathcal{L}_{VDM} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + D_\mu\Phi^\dagger D^\mu\Phi - \lambda_\Phi(\Phi^\dagger\Phi - \frac{\nu_\Phi^2}{2})^2 - \lambda_{\Phi H}(\Phi^\dagger\Phi - \frac{\nu_\Phi^2}{2})(H^\dagger H - \frac{\nu_H^2}{2}), \quad (6)$$

where Φ is the dark Higgs field which generates a nonzero mass for the VDM through spontaneous $U(1)'$ breaking; $D_\mu\Phi = (\partial_u + ig_X Q_\Phi V_\mu)\Phi$ and g_X is the coupling constant.

From the Lagrangian, one can derive the invisible branching fraction of the Higgs decay [25]:

$$\Gamma_{\text{inv}}^{\text{H}} = \frac{g_X^2}{32\pi}\frac{m_H^3}{m_V^2}(1 - 4\frac{m_V^2}{m_H^2} + 12\frac{m_V^4}{m_H^4})(1 - 4\frac{m_V^2}{m_H^2})^{1/2}, \quad (7)$$

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

- Analyses in ATLAS combination Phys. Rev. Lett. 132 (2024) 231801
  - $bb\gamma\gamma$ resolved only Phys. Rev. D 106 (2022) 052001
  - $bb\tau\tau$ resolved only JHEP 07 (2023) 040
  - $bbbb$ Phys. Rev. D 105 (2022) 092002

$X \to YH$

- Atlas
  - $X \to SH \to bb\gamma\gamma$ 2404.12915
  - $X \to SH \to leptons + \gamma\gamma$ 2405.20926
- CMS
  - $X \to YH \to bbbb$ Phys. Lett. B 842 (2023) 137392
  - $X \to YH \to bb\tau\tau$ JHEP 11 (2021) 057
  - $X \to YH \to bb\gamma\gamma$ JHEP 05 (2024) 316

ATLAS 2HDM+S Searches

- Full Run2 2HDM+S results from ATLAS:
- $H \to aa \to 4\gamma$ 2312.03306
- $H \to aa \to bb\mu\mu$ Phys. Rev. D 105 (2022) 012006
- $t\bar{t}a, a \to \mu\mu$ Phys. Rev. D 108 (2023) 092007
- $H \to Za, a \to \gamma\gamma$ Phys. Lett. B 848 (2024) 138536
- $H \to Za, a \to hadrons$ Phys. Rev. Lett. 125 (2020) 221802