

Rare/BSM higgs recent highlights and Summary

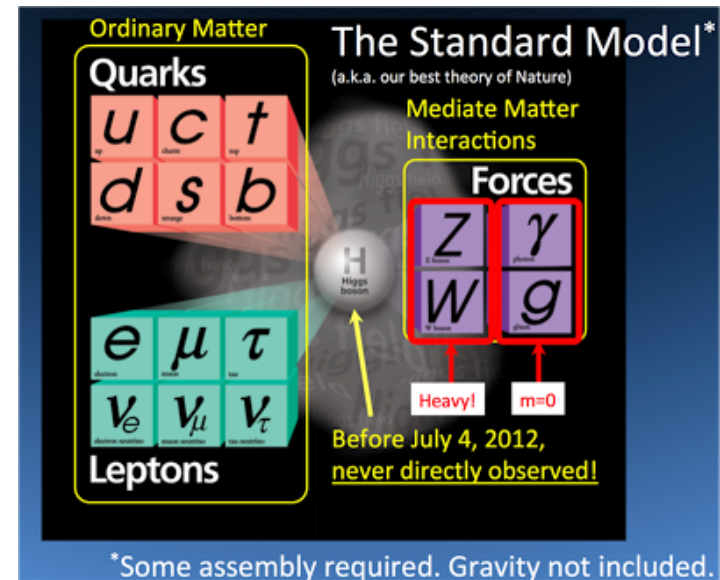
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Introduction

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- Standard Model (SM) of particle physics is very successful in describing and predicting experimental results
 - discovery of Higgs in 2012: an important piece to complete SM
- Higgs is really unique and special**
 - the only particle that talks to everybody
 - the only fundamental scalar particle
 - the only particle that is condensed in the universe
 - the source of all masses of elementary particles

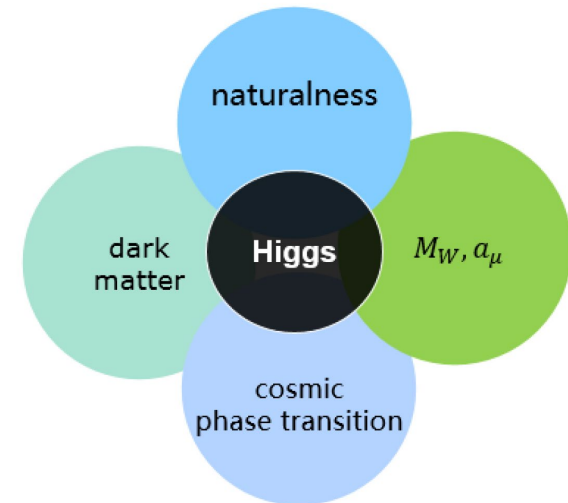


- Motivates a detailed study of Higgs properties
 - Including rare decays and its couplings to different generations of fermions

Higgs portal to BSM

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- Strong evidence that physics beyond SM (BSM) exist
 - Neutrino masses, matter–antimatter asymmetry, dark matter, gravity and hierarchy problem etc.
- Higgs boson plays a central role for probing BSM physics
 - Dark matter candidates from rare and exotic Higgs decays
 - Axion-Like Particles in Higgs exotic decays
 - Supersymmetry
 - Higgs just one of many scalar bosons, superpartners
 - Composite Higgs
 - Higgs spins cancel among constituents
 - top partner, vector-like quarks etc.
 - Extra dimension
 - Higgs spinning in extra dimensions
 - new forces from particles running in extra dimension, KK particles



This talk will present a few selected results on Higgs rare and exotic decays, extended Higgs sector, DM with higgs

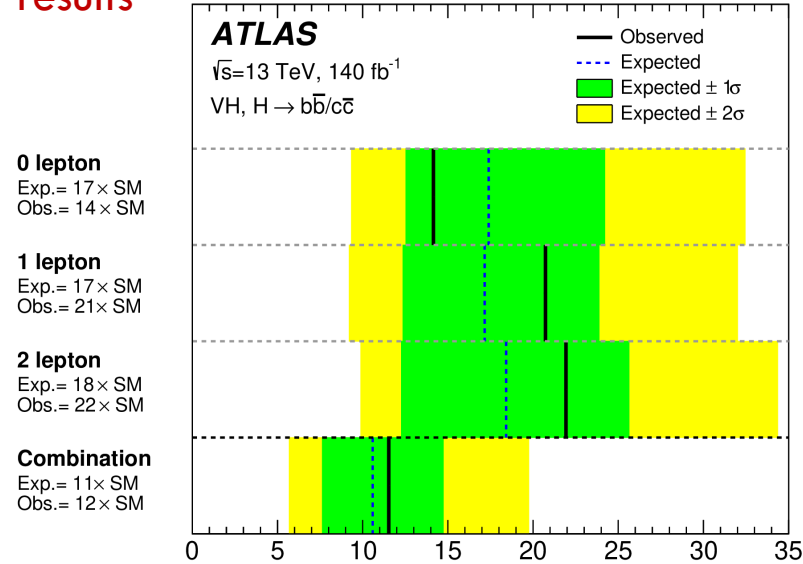
ATLAS $VH \rightarrow cc$

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ATLAS $VH \rightarrow cc$

New results

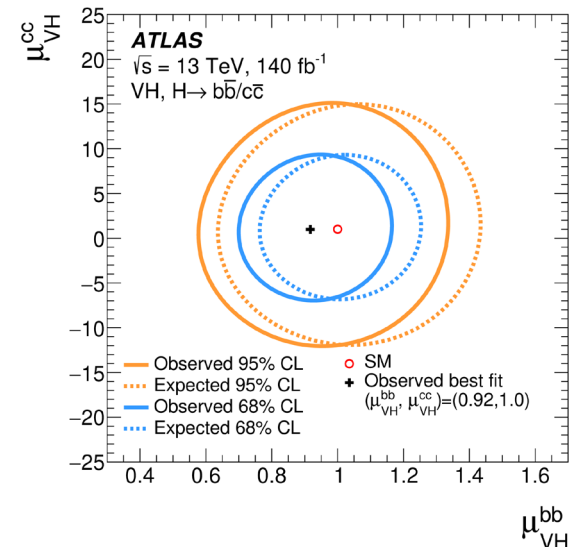
- Based on a re-analysis of the $VH \rightarrow bb/cc$
 - $V=Z/W$, split into 0, 1 and 2 muons electrons taus
 - Split also between resolved and boosted cases
- Rapid progress in c-tagging techniques
 - Graph NNs, transformer networks
 - Major driver of sensitivity increases



[arXiv:2410.19611](https://arxiv.org/abs/2410.19611)

95% CL limit on $\mu_{VH(cc)}$

- $\mu_{VH \rightarrow cc} < 11.5$ @ 95% CL (10.6 exp.)
 - Best limit to date
 - Factor 2.5 improvement over previous limit
- $|k_c| < 4.2$ @ 95% CL
 - Factor 2 improvement over previous result

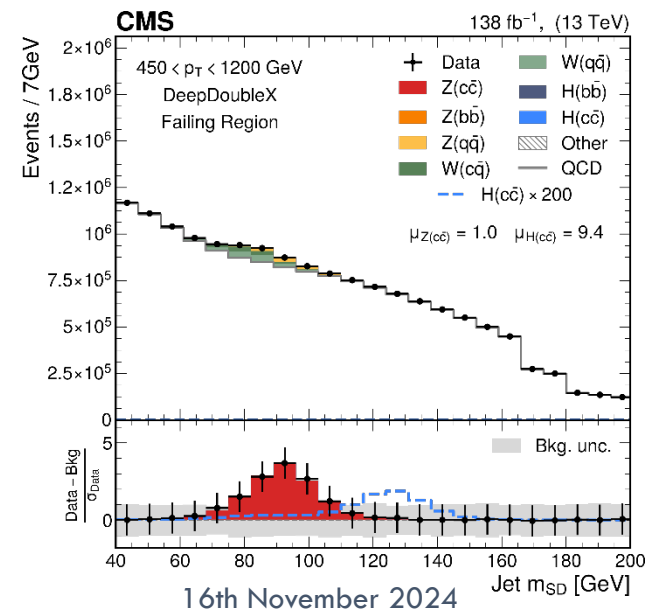
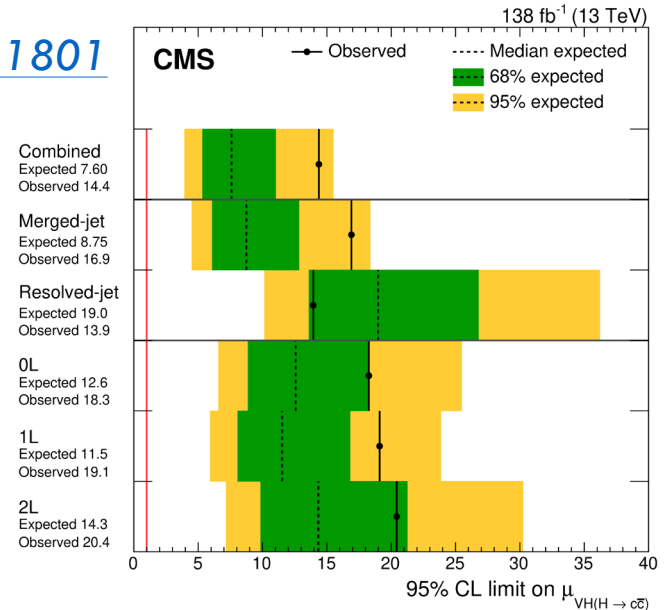


CMS $VH \rightarrow cc$

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- CMS $VH \rightarrow cc$ [Phys. Rev. Lett. 131 \(2023\) 061801](#)
 - Leptonic decays of W/Z boson
 - With both resolved and boosted jet analyses
 - Used GNN based c-tagging
- $\mu_{VH \rightarrow cc} < 14$ @ 95% CL (7.6 exp.)
 - Best sensitivity
- $|k_c| < 3.4$ @ 95% CL
 - Most stringent constraint to date
- Boosted $H \rightarrow cc$ ($p_T^H > 300$ GeV)
 - Boosted fat jets identified with DNN c-tagging
 - First observation of $Z \rightarrow cc$ in hadronic collisions

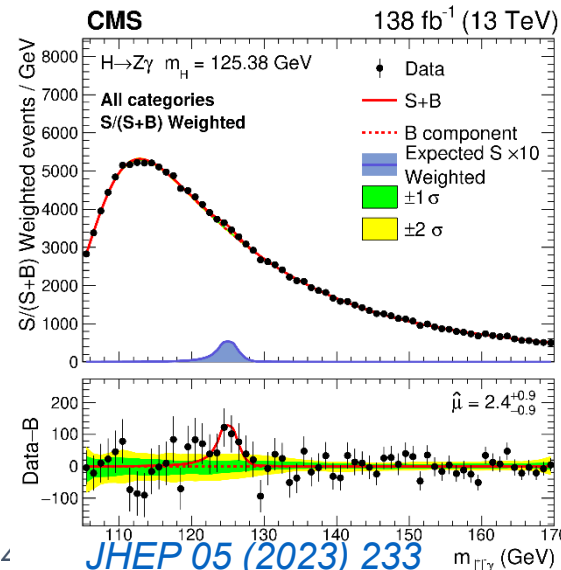
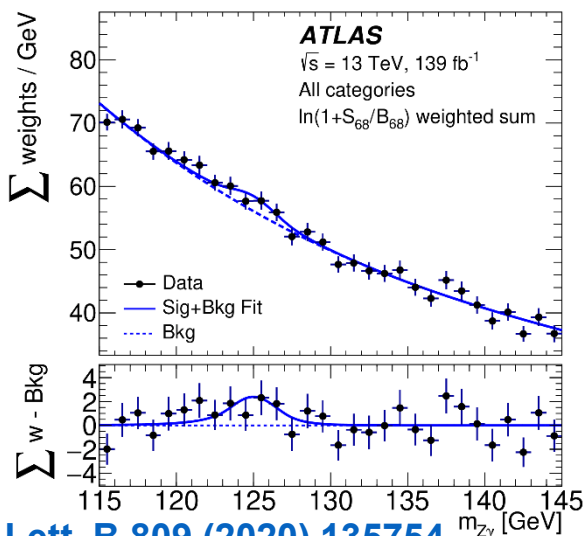
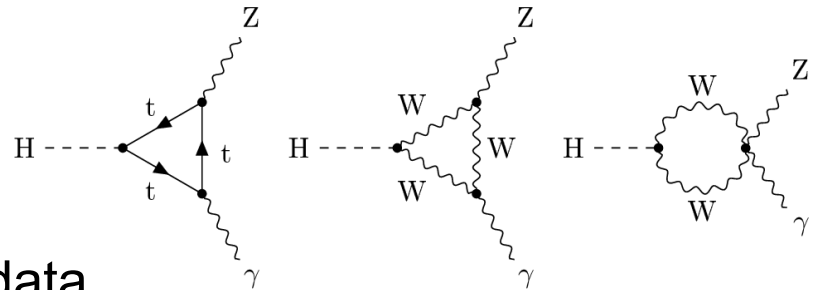
[Phys. Rev. Lett. 131 \(2023\) 041801](#)



$H \rightarrow Z\gamma$ (ATLAS+CMS)

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- Small branching ratio predicted by the SM with loop processes
 - $Br(H \rightarrow Z\gamma) = 1.6 \times 10^{-3}$
 - Sensitive to BSM effects
- ATLAS and CMS results with full Run2 data
 - Events selected with two leptons and one photon
 - Optimized event categorization for 4 main production mode
 - Simultaneous fit to $m_{ll\gamma}$ spectra over all categories



ATLAS: Obs.(exp.)
 significance: 2.2 (1.2) σ

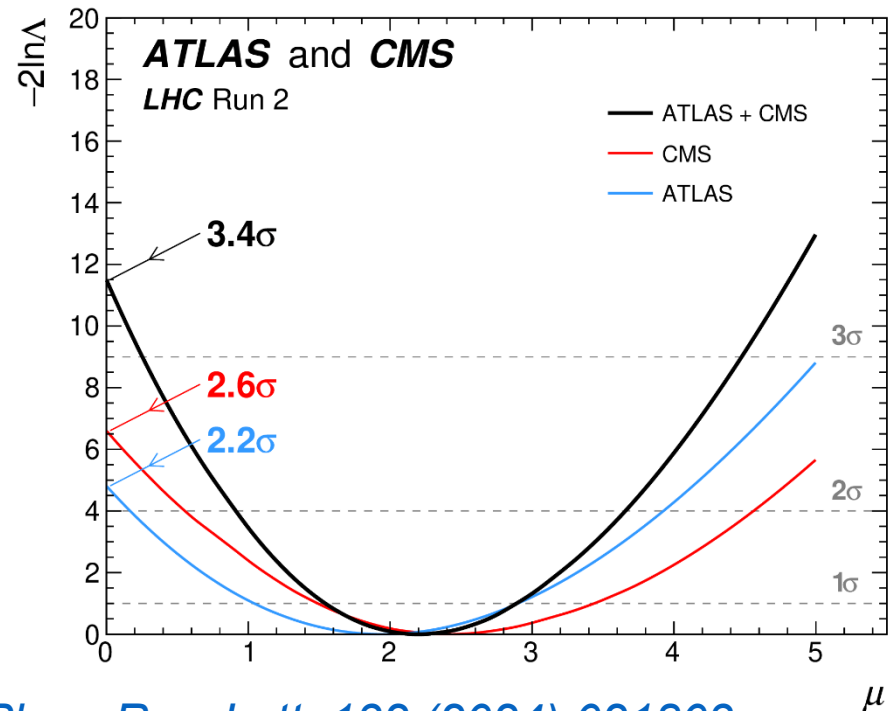
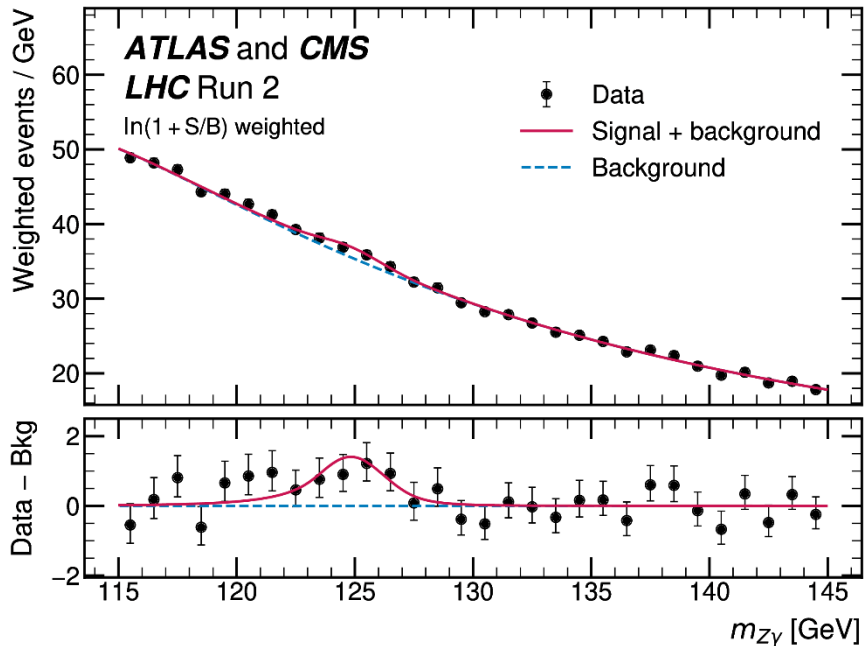
CMS: Obs.(exp.)
 significance: 2.7 (1.2) σ

Results dominant by
 statistical uncertainty

$H \rightarrow Z\gamma$ (ATLAS+CMS)

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- Statistical combination of ATLAS and CMS results



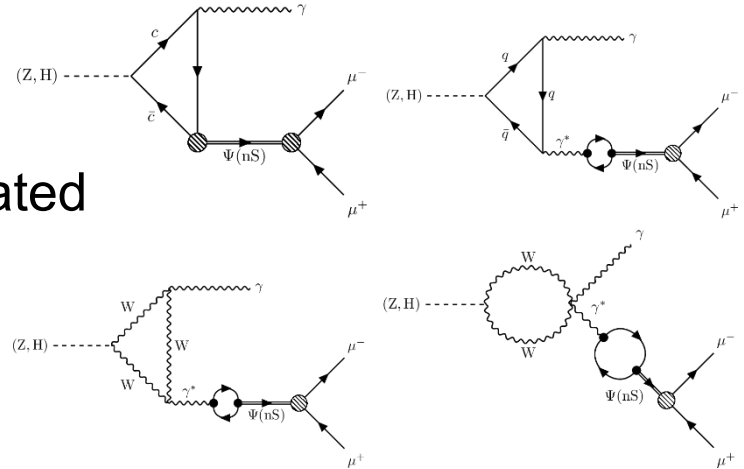
[Phys. Rev. Lett. 132 \(2024\) 021803](#)

- Best fit signal strength at 2.2 ± 0.7 times the SM prediction
- The observed (expected) $H \rightarrow Z\gamma$ significance is 3.4 (1.6) σ
 - First evidence of the $H \rightarrow Z\gamma$ decay

$H \rightarrow meson + \gamma$ in CMS

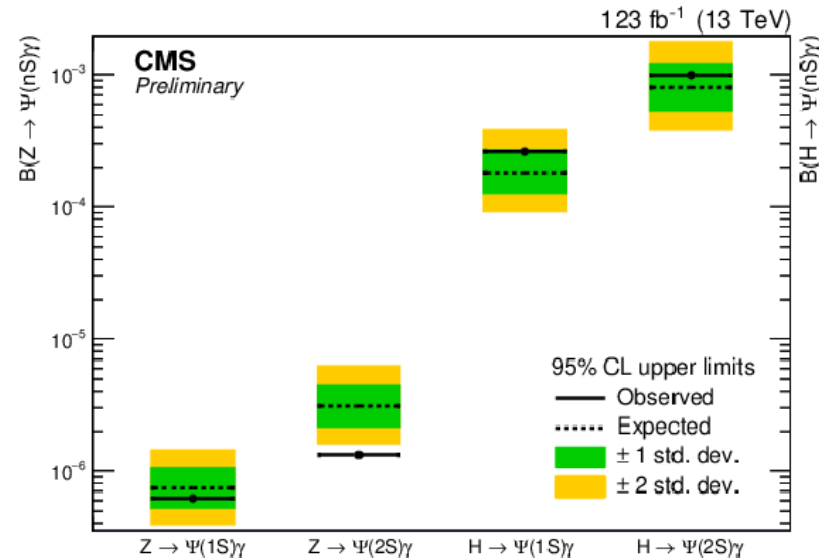
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- $H \rightarrow meson(J/\psi \text{ or } \psi') + \gamma$ allows to access the c-quark Yukawa coupling
 - Also probes new physics in the loops
- Final states with two muons and one isolated photon
 - Exploring also the Z boson decays
- Fit to $m_{\mu\mu\gamma}$ with different higgs production



Process	\mathcal{B}
$H \rightarrow \Psi(1S)\gamma$	$3.01^{+0.15}_{-0.15} \times 10^{-6}$
$Z \rightarrow \Psi(1S)\gamma$	$8.96^{+1.51}_{-1.38} \times 10^{-8}$
$H \rightarrow \Psi(2S)\gamma$	$1.03^{+0.06}_{-0.06} \times 10^{-6}$
$Z \rightarrow \Psi(2S)\gamma$	$4.83^{+1.02}_{-0.91} \times 10^{-8}$
$\Psi(1S) \rightarrow \mu^+\mu^-$	$5.961^{+0.033}_{-0.033} \times 10^{-2}$
$\Psi(2S) \rightarrow \mu^+\mu^-$	$8.0^{+0.6}_{-0.6} \times 10^{-3}$

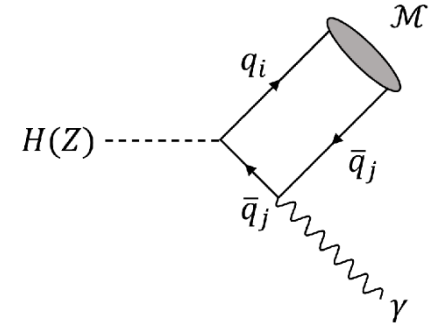
- No excess observed**
- Constraints on k_c/k_γ @ 95% CL
 - Observed: [-157, 199]
 - Expected: [-121, 161]



$H \rightarrow D^* \gamma$ in ATLAS

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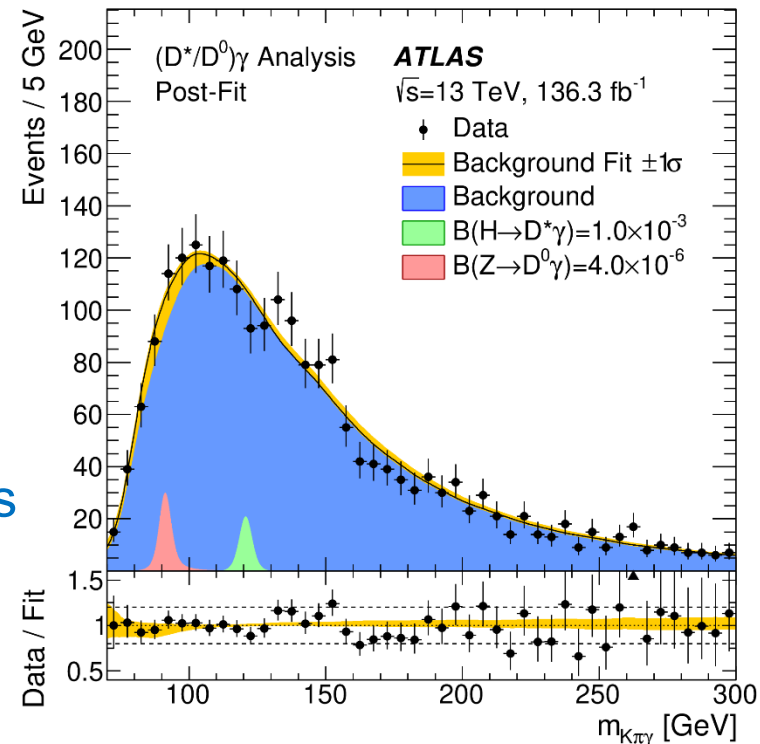
- $H \rightarrow D^* \gamma$ measurement probes H_{uc} couplings
 - Forbidden at tree-level within the SM
 - Sensitive to BSM effects
- Signal is selected with di-tracks and isolated photon
- Major background is multi-jet and photon+jet events
 - Estimated by data-driven method
- **No excess observed**



Channel	Mass range [GeV]	Observed (Expected) background	H signal $\mathcal{B} = 10^{-3}$	Z signal $\mathcal{B} = 10^{-6}$
$H \rightarrow D^* \gamma$	116–126	203 (214.8 ± 5.5)	25.4 ± 2.0	–
$Z \rightarrow D^0 \gamma$	86–96	215 (206 ± 14)	–	10.3 ± 0.7
$Z \rightarrow K_s^0 \gamma$	86–96	21 (19.5 ± 2.0)	–	4.2 ± 0.4

- First limits on $H \rightarrow D^* \gamma$ branching fractions at the LHC

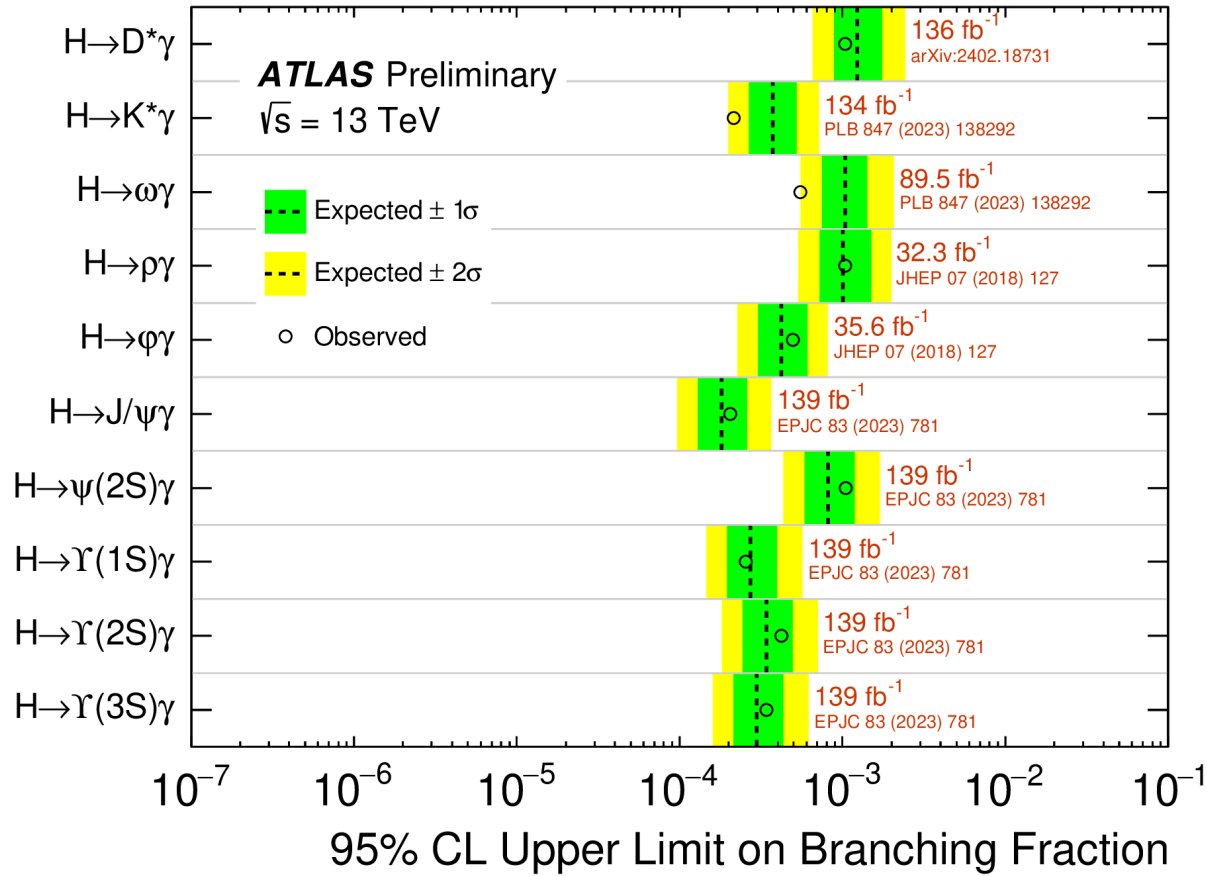
[Phys. Lett. B 855 \(2024\) 138762](#)



Summary of $H \rightarrow \text{meson} + \gamma$ in ATLAS

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- Summary of the 95% confidence-level upper limits on Higgs boson branching fractions for decays to a meson and a photon.



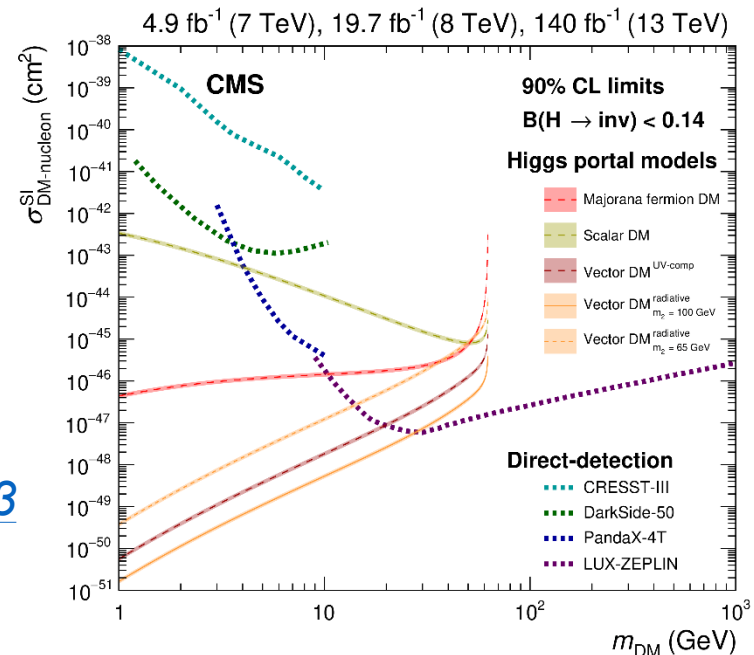
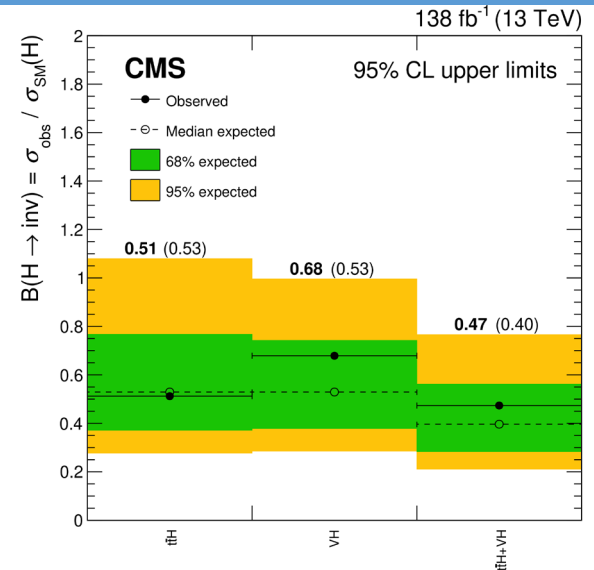
ATL-PHYS-PUB-2023-004

CMS $H \rightarrow \text{invisible}$

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- Tiny branching fraction in SM $\sim 0.1\%$
- Higgs portal model predicts larger values
 - The Higgs mediates interactions between SM and DM particles
- CMS results of the Higgs invisible decays
 - **Explored ttH and VH modes with fully hadronic final states**
- Run 1 + Run 2 combined upper limit on the branching fraction
 - 15 % at 95 % CL
- Interpreted to probe different DM models

[Eur. Phys. J. C 83 \(2023\) 933](#)



$H \rightarrow Za \rightarrow ll\gamma\gamma$

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- First search for axion like particles in $H \rightarrow Za \rightarrow ll\gamma\gamma$

- The light boson as a mediator in axion models

- solution to the strong CP violation problem

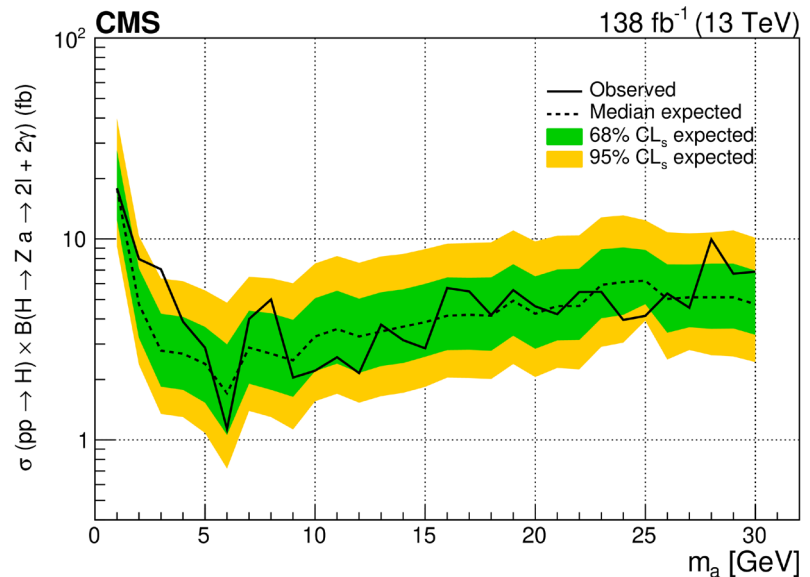
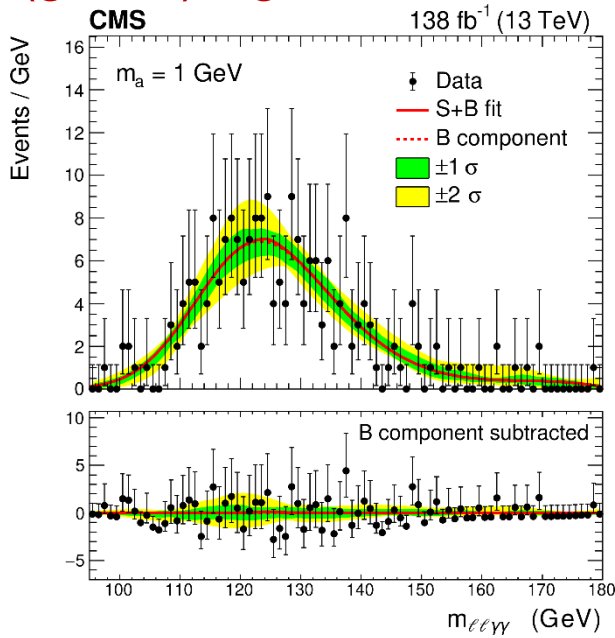
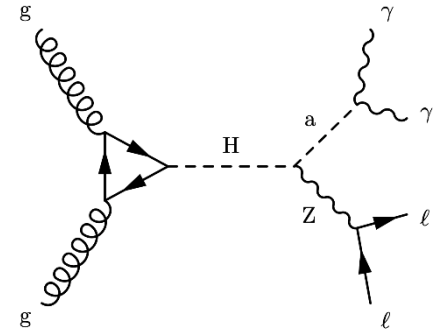
- Mass range of search: $1 < m_a < 30$ GeV.

- Dominant background: SM Drell yan

- Optimized event categories based on BDT scores

- Designed new photon ID for closed-photons [Phys. Lett. B 852 \(2024\) 138582](#)

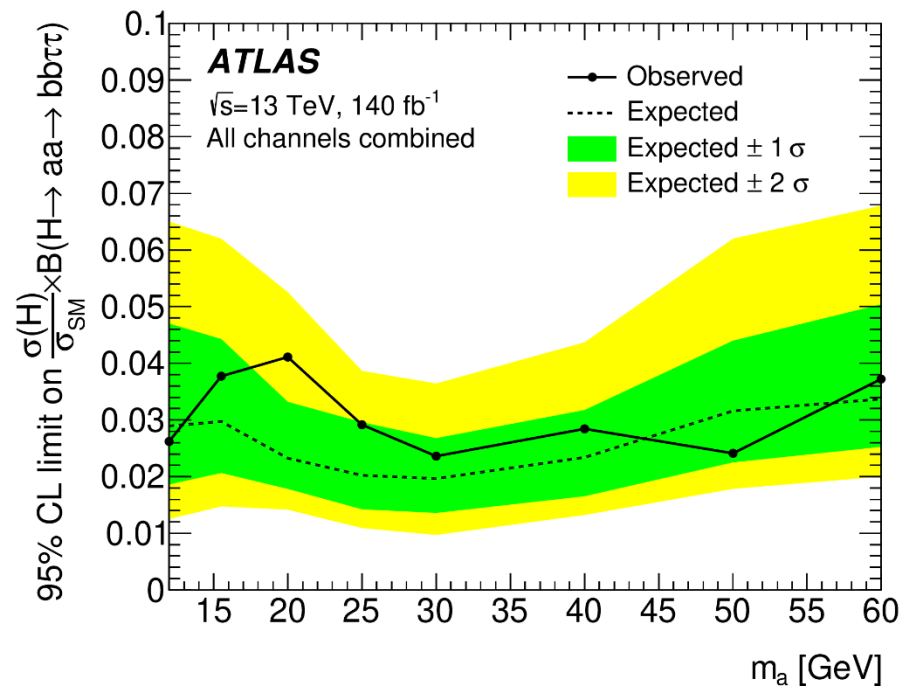
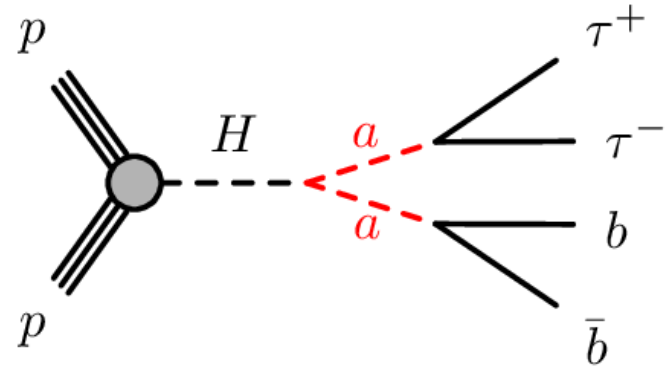
- Local (global) significance of 2.6 (1.3) σ @ $m_a = 3$ GeV



$H \rightarrow aa \rightarrow b\bar{b}\tau\bar{\tau}$

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- First search in ATLAS for decays of the Higgs boson into a pair of pseudoscalar particles decaying into $b\bar{b}\tau\tau$
- Novel ML algorithm to identify low mass merged “double b-quark” jets
 - Improves the sensitivity at low mass
- No significant excess above the SM background expectation is observed

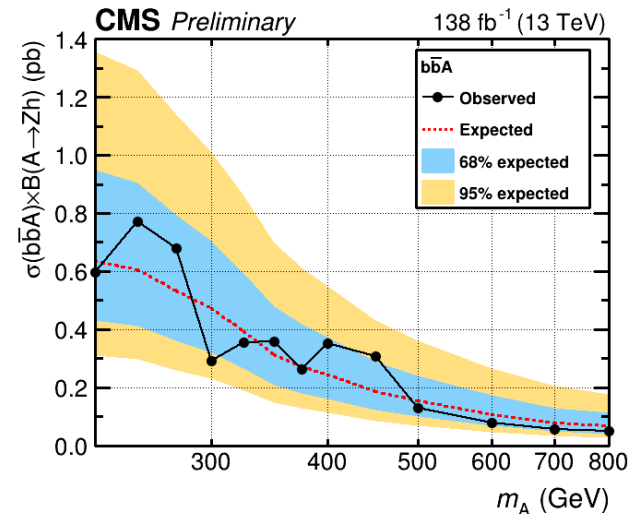
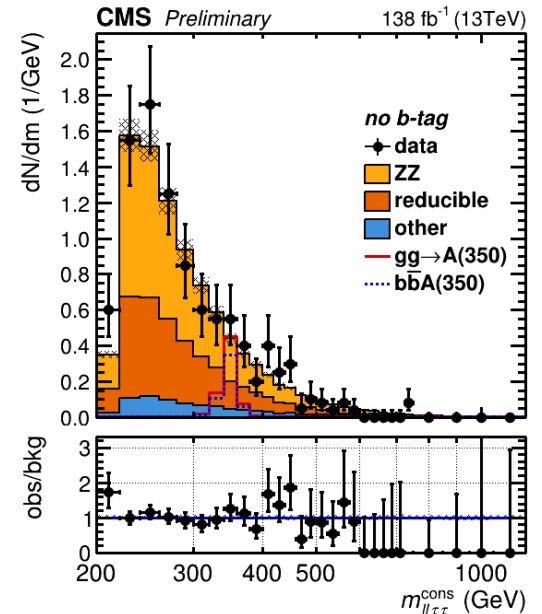
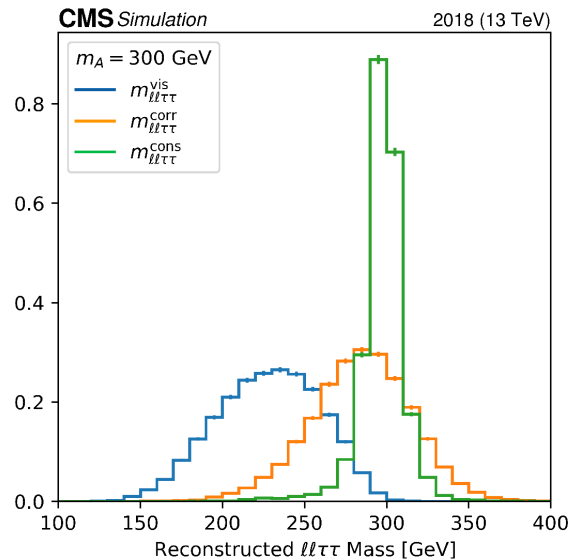
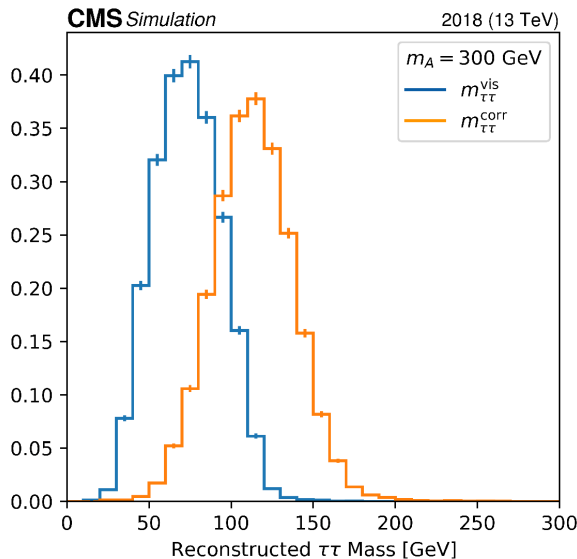


[Phys. Rev. D 110 \(2024\) 052013](#)

Extended Higgs A in 2HDM

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- Search for $A \rightarrow Zh$ ($h \rightarrow \tau\tau$)
- Dedicated mass estimator corrects for missing momentum from neutrinos while constraining h mass to 125 GeV
 - Good mass resolution of 5-7%
- Also probes bbA production mode
- No excess observed**

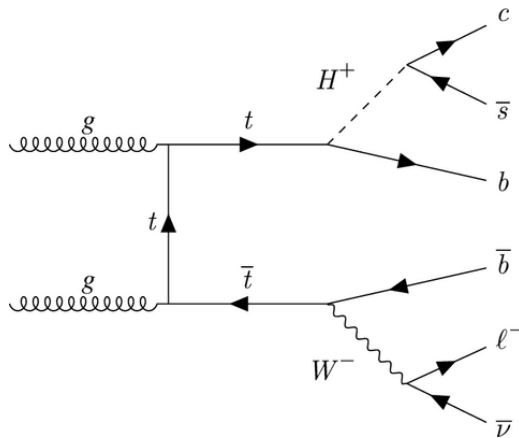


CMS-PAS-HIG-22-004

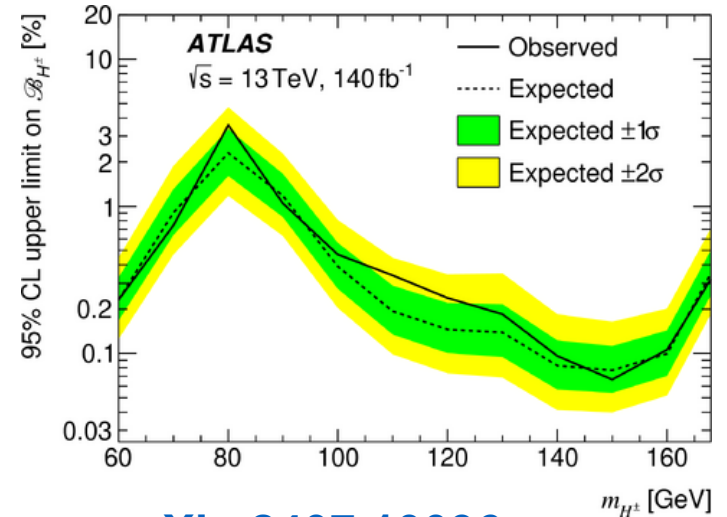
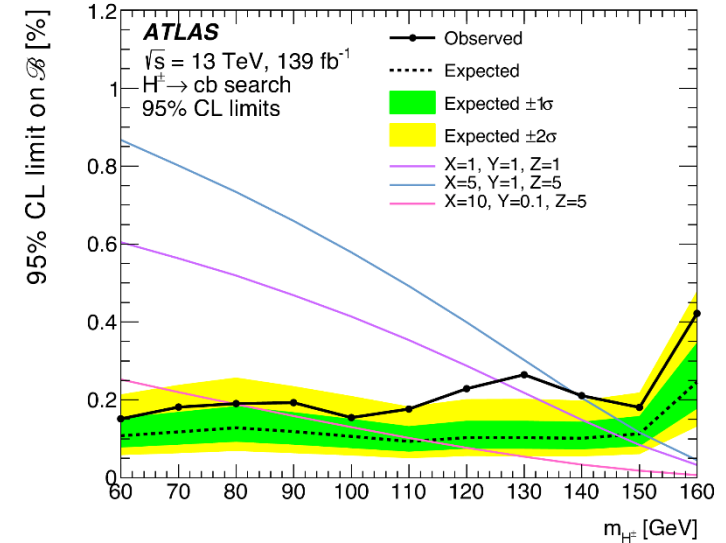
Extended Higgs H^\pm in 2HDM

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- Previous ATLAS $H^\pm \rightarrow cb$ analysis
 - Excess observed around 130GeV with global significance 2.5σ
- Recent ATLAS $t \rightarrow H^\pm b$ search with $H^\pm \rightarrow cs$
 - Simultaneous tagging of b and c jets
 - No excess observed



JHEP 09 (2023) 004



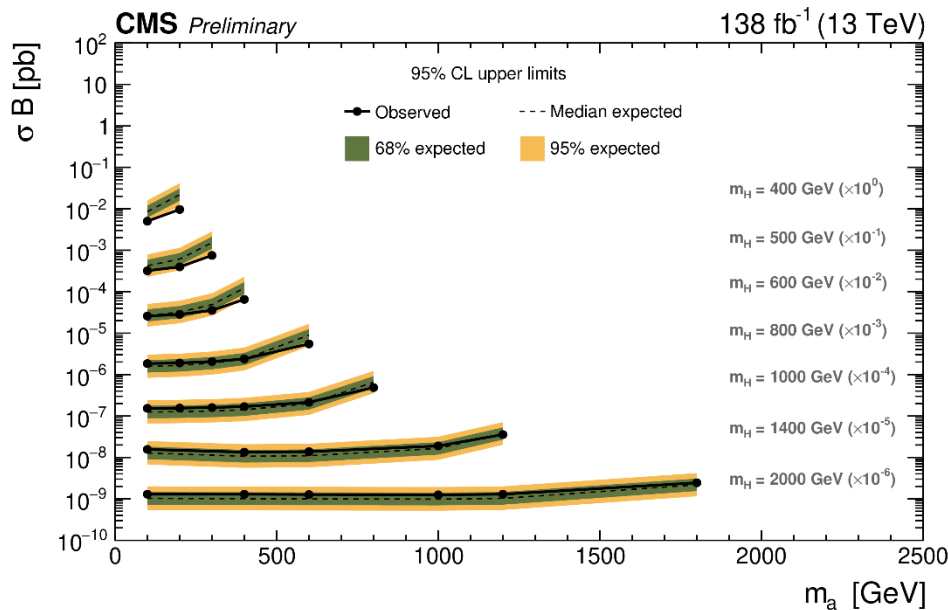
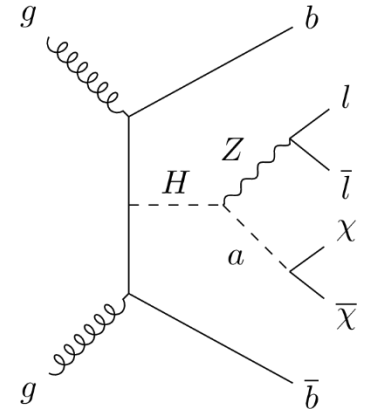
arXiv:2407.10096

Extended Higgs H in 2HDM

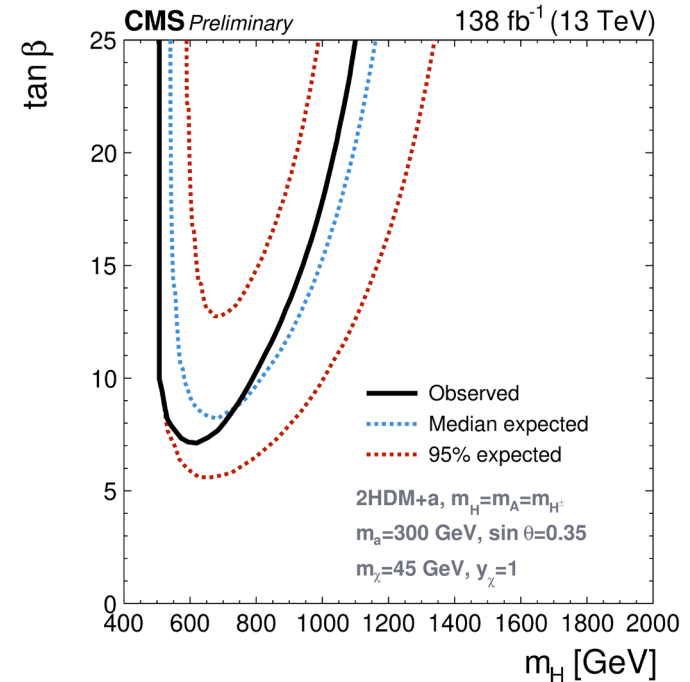
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- Heavy higgs to dark matter with b-quarks and lepton pairs
 - First time at the LHC
- Dark Matter candidate χ appearing as a large momentum imbalance in the CMS detector
- Sophisticated ML techniques use to distinguish signal and backgrounds
- No excess observed

CMS-PAS-SUS-23-018



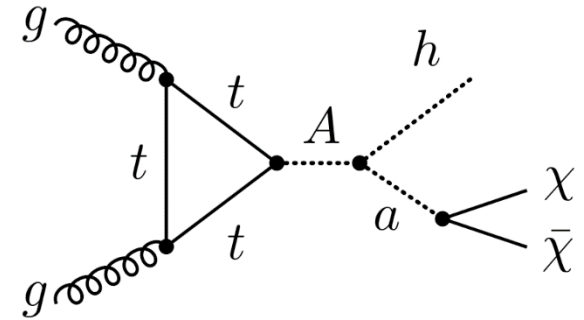
CLHCP2024



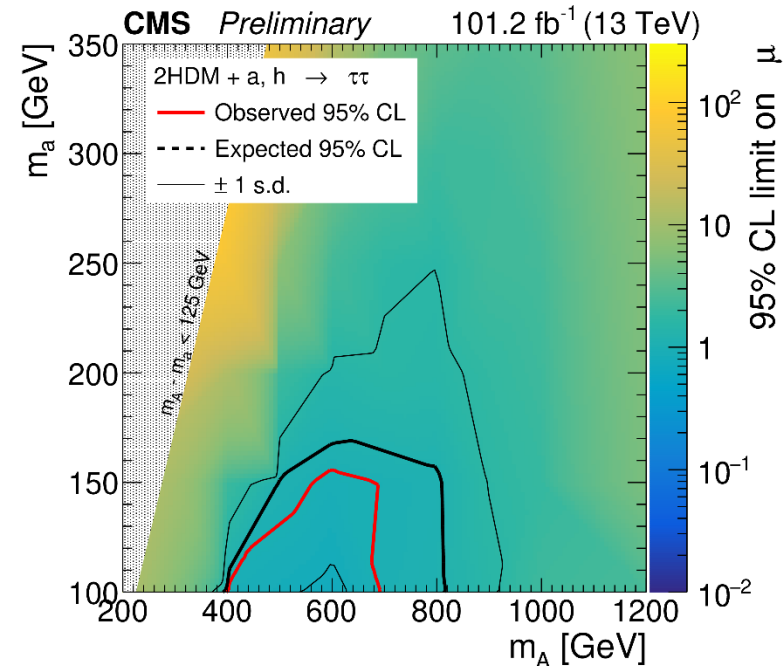
Higgs+DM in 2HDM+a

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- 2HDM+a: extension of the Standard Model that includes two Higgs doublets and an additional pseudoscalar particle (a)
- Search for dark matter produced with a Higgs boson decaying to $\tau\tau$
- No excess observed**
- Results interpreted within the framework of 2HDM+a and the baryonic-Z' models.
 - heavy pseudoscalar masses between 400 and 700 GeV are excluded for a light pseudoscalar mass of 100 GeV
 - Z' masses up to 1050 GeV are excluded for a dark matter mass of 1 GeV



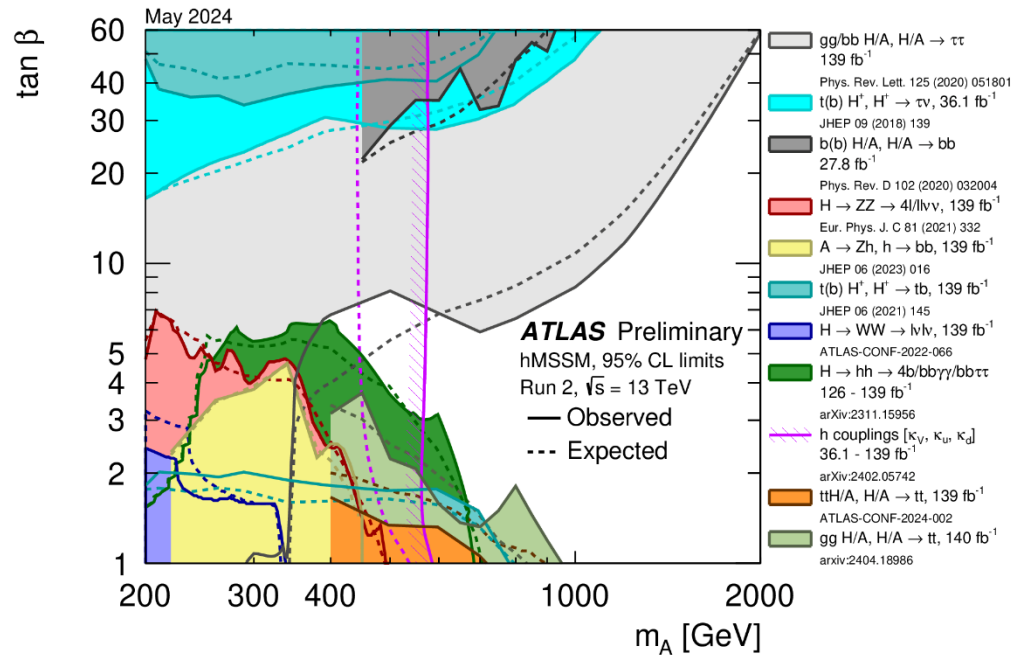
CMS-PAS-SUS-23-012



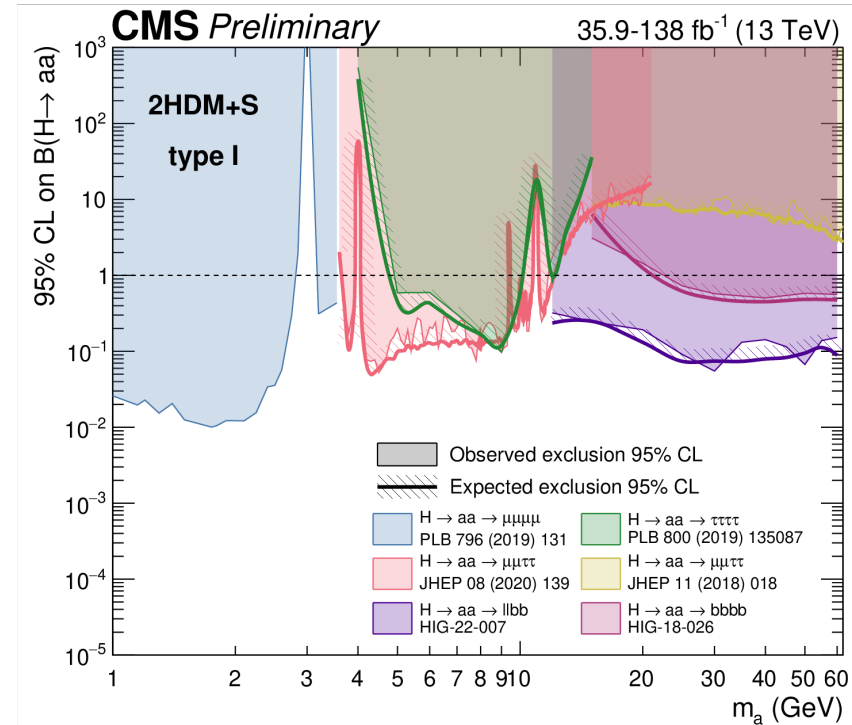
Summary plot with BSM Higgs in ATLAS and CMS

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The interpretations of various searches for additional Higgs bosons beyond the Standard Model, as well as the Higgs boson coupling combination, in the hMSSM and the 2HDM



hMSSM exclusion in ATLAS



2HDM+Singlet searches in CMS

Conclusion

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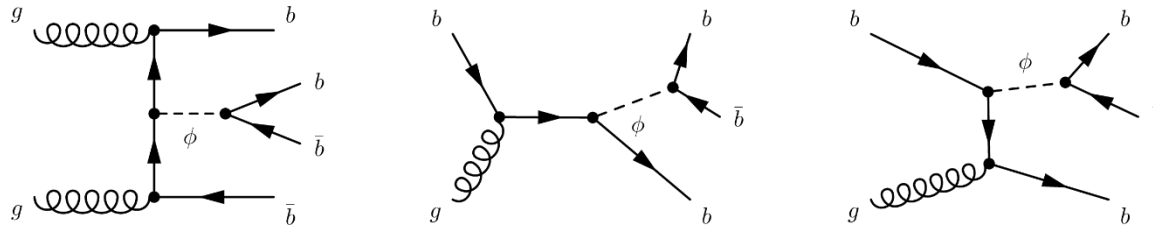
- ⊙ Rare and BSM Higgs studies are one of the most promising corners to look for new physics!
- ⊙ Many new results delivered by ATLAS and CMS experiments
 - ⊙ Improved constraints on the c-quark Yukawa couplings
 - ⊙ First evidence of the $H \rightarrow Z\gamma$ decay
 - ⊙ New results with Higgs to meson+photon to probe light quark Higgs couplings
 - ⊙ New search channels in BSM Higgs
 - ⊙ Better constraints on BSM models
- ⊙ No significant excess observed so far
- ⊙ Greater sensitivity and new physics discovery potential in the future
 - ⊙ More statistics coming in Run3
 - ⊙ More advanced techniques in analysis (tagging, classification..)

backup

Two Higgs doublet model (2HDM): H^\pm , A , H , h

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- Search for bosons of an extended Higgs sector in b quark final states
 - Exploring the invariant mass distribution of the two b -jets with the highest p_T



- Two different signatures explored to maximize sensitivity over a wide mass range
 - Semi leptonic (SL)
 - Fully hadronic (FH)
- No clear excess observed

CMS-PAS-SUS-24-001

