BSM Higgs Searches

(Incl. exotic Higgs Decays)

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QCD@LHC 2024 | University of Freiburg

7 October 2024

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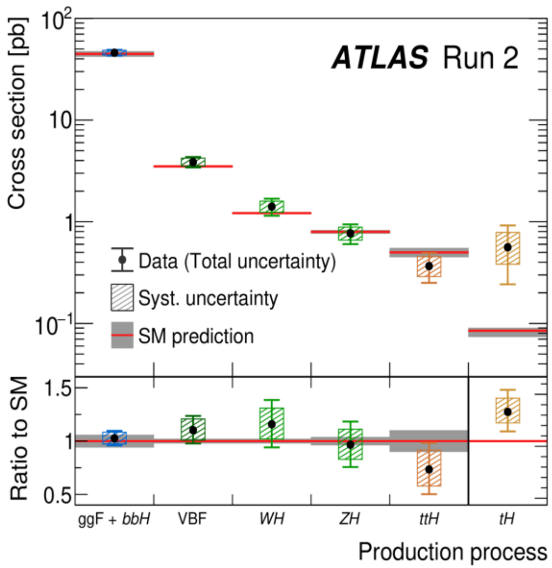
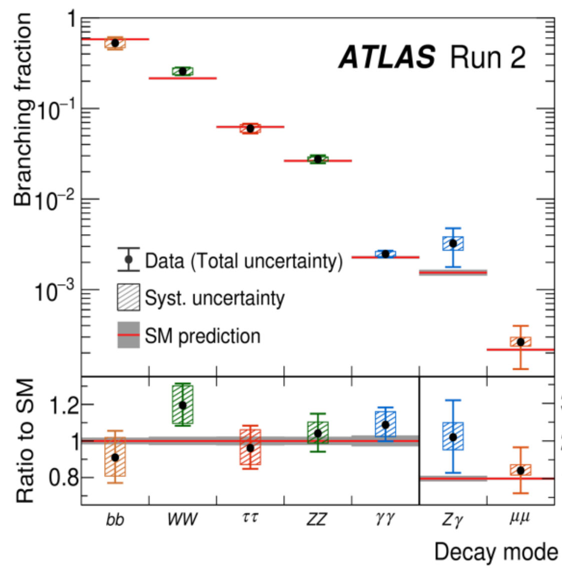
Current state of the art

Multitude of measurements so far have confirmed that the properties of h_{125} are compatible with the SM predictions.

However, several puzzles remain unanswered…

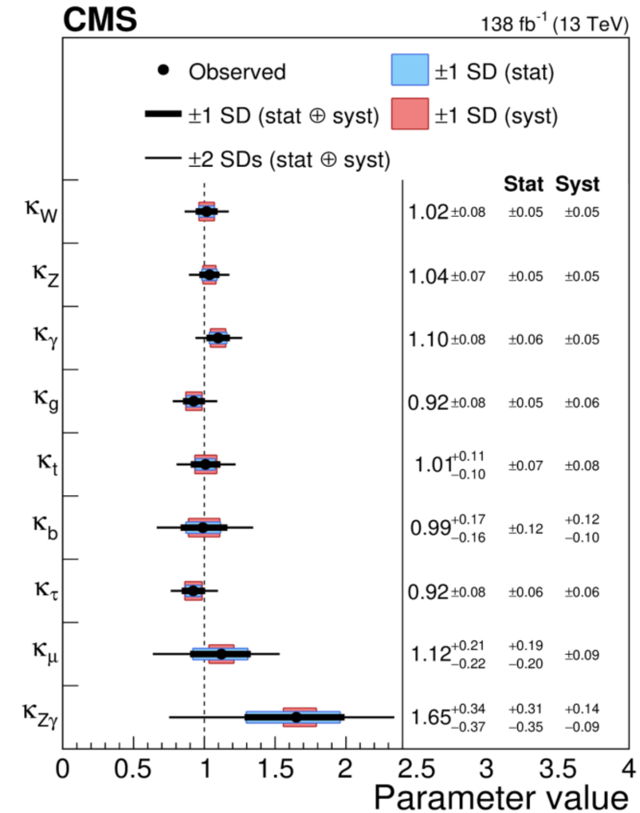
Nature 607 52 (2022)





Main production and decay processes were observed and measured with ~10% precision

Nature 607 (2022) 60-68



Coupling modifiers are probed at a uncertainty level of ~10-40%

Higgs and major open questions of SM

The matter-antimatter asymmetry problem

- Are there anomalies in Higgs boson self-coupling which would implies stronger early-Universe phase transition?
- Are there CP violating Higgs decays?
- Are there multiple Higgs sectors?

Hierarchy/Fine tuning problem

- Is the Higgs boson an elementary/composite particle?
- Are there anomalies in the interaction of Higgs boson with *W* and *Z*?
- Any new particles close to the Higgs mass?

What is the origin of the large difference in fermion mass?

- Are there modified Higgs boson couplings to known particles?
- Is $h_{125} \rightarrow \mu^{+}\tau^{-}$ *possible*?

What is dark matter?

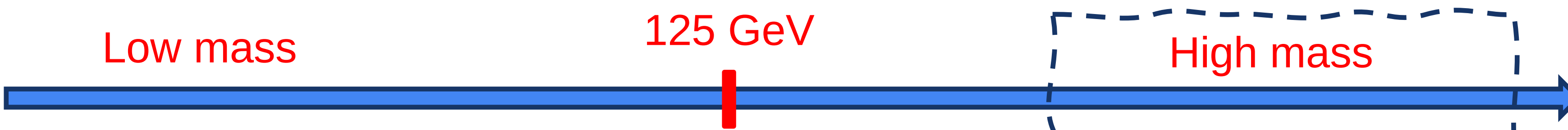
- Can the Higgs boson provide a portal to dark matter or a dark sector?
- Is the Higgs boson lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs boson ?

Precision measurement of Higg boson's properties or direct searches for BSM Higgs and rare decay modes of h_{125} boson could help us to answer these questions.

Theoretical frameworks

- Most BSM scenarios presume the existence of SUSY with extended Higgs sector, e.g:
  - Two Higgs Doublet Model (2HDM) and its variation
    - e.g: MSSM, hMSSM
    - 5 Higgs Bosons: h, H, A, H^{+}, H^{-}
    - 7 free parameters: 5 Higgs masses, α, $tan\ \beta$
    - Widely used as a benchmark for BSM Higgs searches.
  - 2HDM+Singlet and its variation
    - e.g: Complex singlet + SUSY conditions → NMSSM
    - 7 Higgs Bosons: five of 2HDM, with 2 additional neutral bosons (1 CP-even and 1 CP-odd)
    - One of the scalars could be a dark matter candidate.

BSM Higgs boson searches landscapes

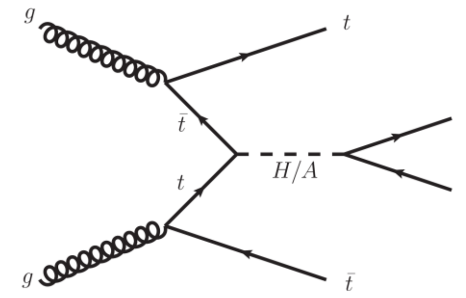


$pp \to a$
$h_{125} \to aa$, $h_{125} \to a_1 a_2$
$h_{125} \to Za$

h_{125} rare decays
h_{125} exotic decays
$h_{125} \to invisible$

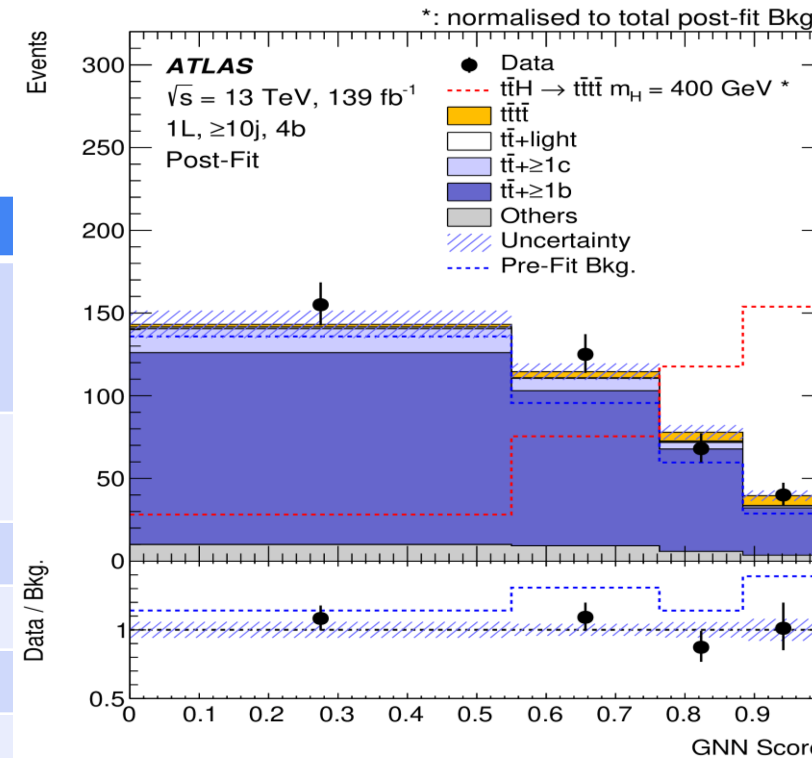
$pp \to t\bar{t}H/A$,
$pp \to H/A$
$H \to h_{125}h_{125}$
$H \to Sh_{125}$, $H \to SS$
$H^{+} \to$tb /$\boldsymbol{\tau}^{+}\boldsymbol{\nu}$
$A \to ZH$, $A \to Zh_{125}$

$t\bar{t}H/A \rightarrow t\bar{t}\ t\bar{t}$



- In type-II 2HDM, $t\bar{t}H$ production mode is enhanced at low $tan\beta$
- Multivariate (MVA) techniques to separate the signal from the SM backgrounds
    - SM BDT + BSM mass-parameterised BDT/Graph Neural Network

	JHEP **07** (2023) 203		arXiv.2408.17164	
	Same sign dilepton	Multilepton	1-lepton	Opposite sign dilepton
Main event selection criteria	Single and dilepton triggers		Single lepton trigger	
	$\geq$ 6 jets		$\geq$ 7 jets	$\geq$ 5 jets
	$\geq$ 2 b-jets			
	Z mass veto			
Main bkg	$t\bar{t}t\bar{t}$, $t\bar{t}V$, $t\bar{t}$ +jets, *V*+jets			



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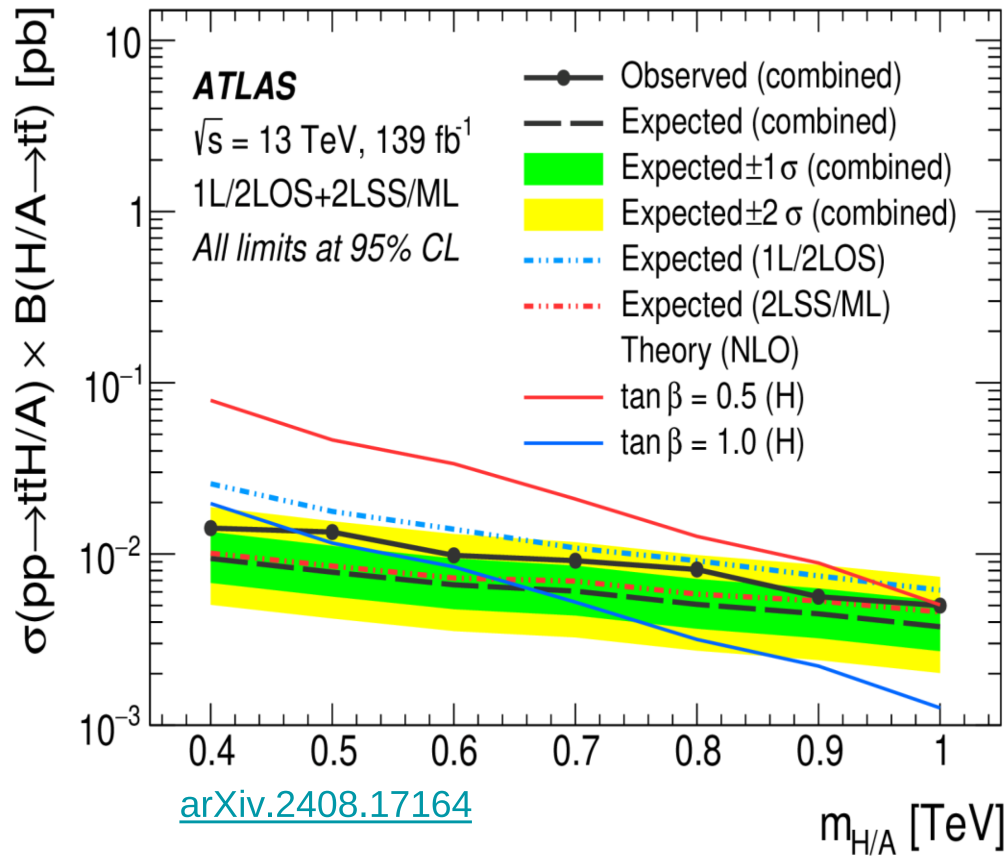
$t\bar{t}H/A \rightarrow t\bar{t}\ t\bar{t}$ (continued)

- Dominant uncertainty: modelling of the SM $t\bar{t}t\bar{t}$ and $t\bar{t}$+jets
- Simultaneous fit using the MVA output distribution in the CRs and SRs to extract the μ_s
- No significant excess of signal event is observed



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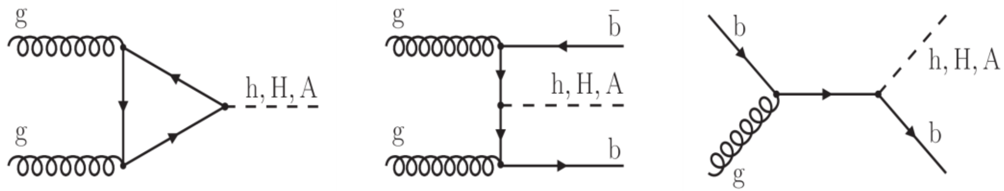
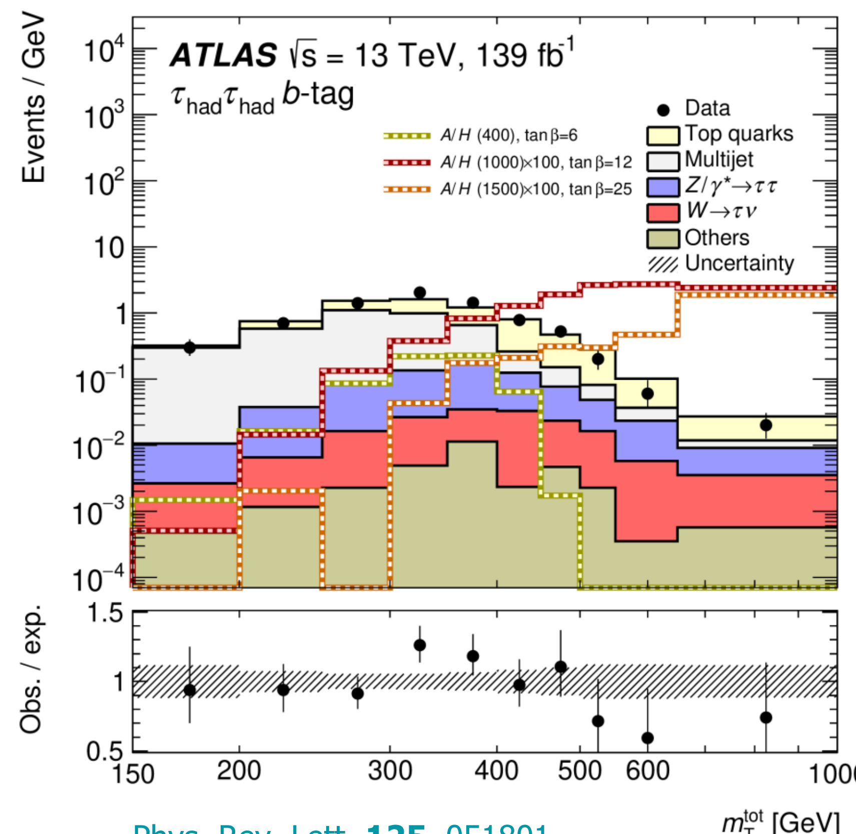
$H/A \rightarrow \tau^+\tau^-$

enhanced at high $tan\beta$

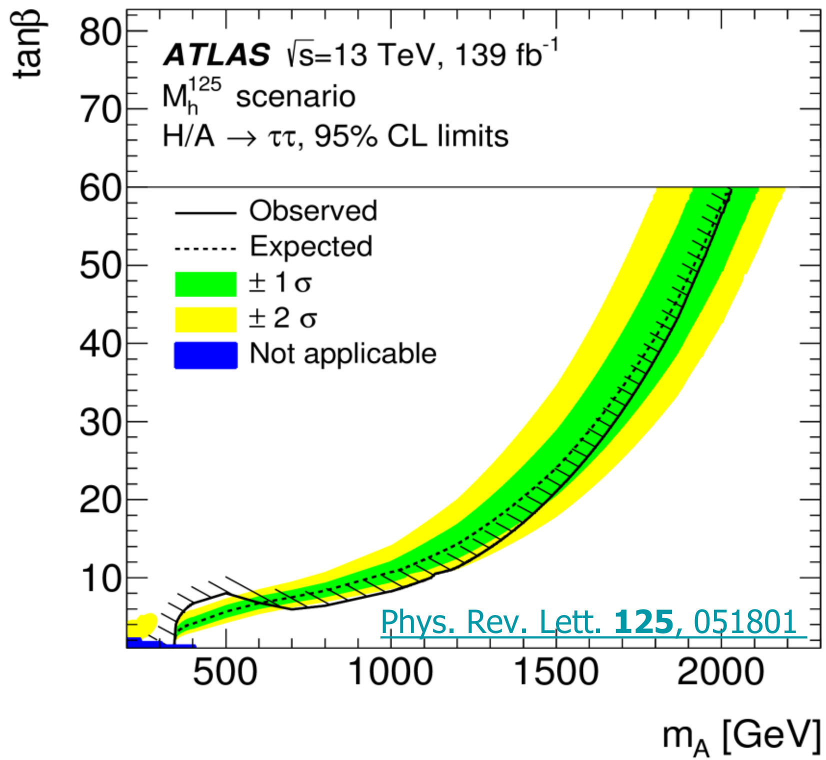


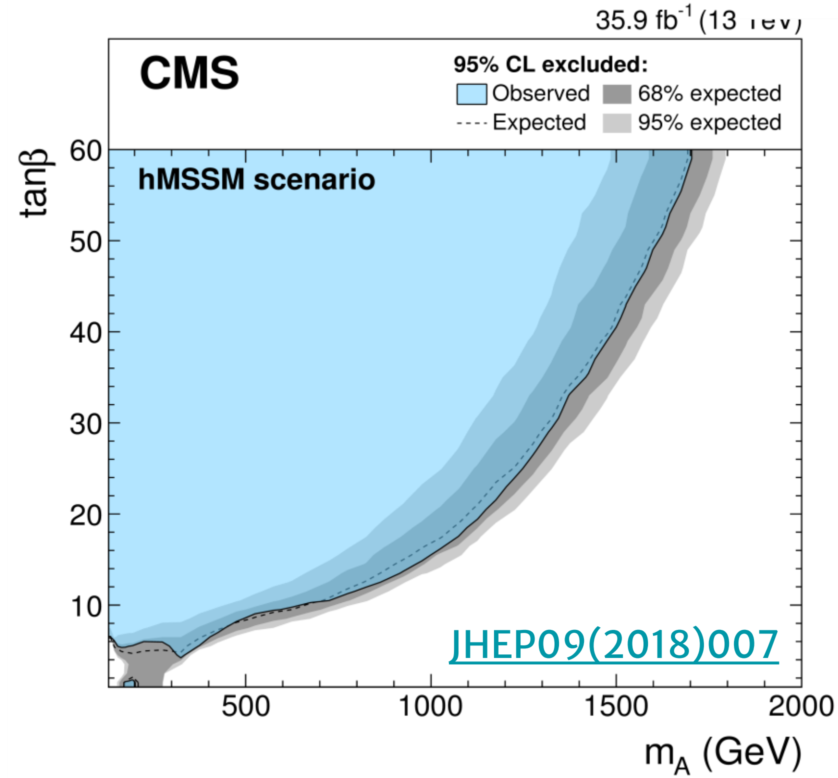
- ATLAS: $\boldsymbol{\tau_{had}\tau_{had}}$ and $\boldsymbol{\tau_{lep}\tau_{had}}$ channels, 139 fb^{-1} of data.
  - CMS: $\boldsymbol{\tau_{had}\tau_{had}}$, $\boldsymbol{\tau_{lep}\tau_{had}}$ and $e\mu$ channels, 35.9 fb^{-1} of data
- Two main categories:
  - b-tag : b associated signal
  - b-veto: ggF signal
- Main backgrounds:
  - multijet, W+jets and $t\bar{t}$ events, jet → $\boldsymbol{\tau_{had}}$ misidentication
- Total transverse mass, m_T^{tot} as final discriminant
- Main syst. uncert.: τ_{had} ID efficiency and mis-ID of τ_{had}



[Phys. Rev. Lett. **125**, 051801](https://doi.org/10.1103/PhysRevLett.125.051801)

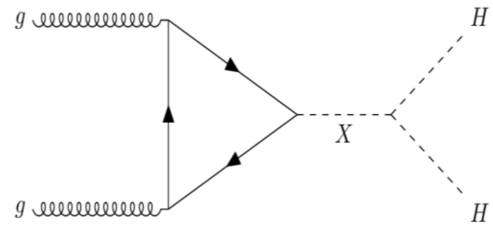
$H/A \rightarrow \tau^+\tau^-$ (continued)

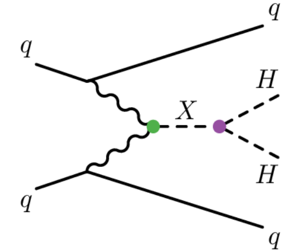




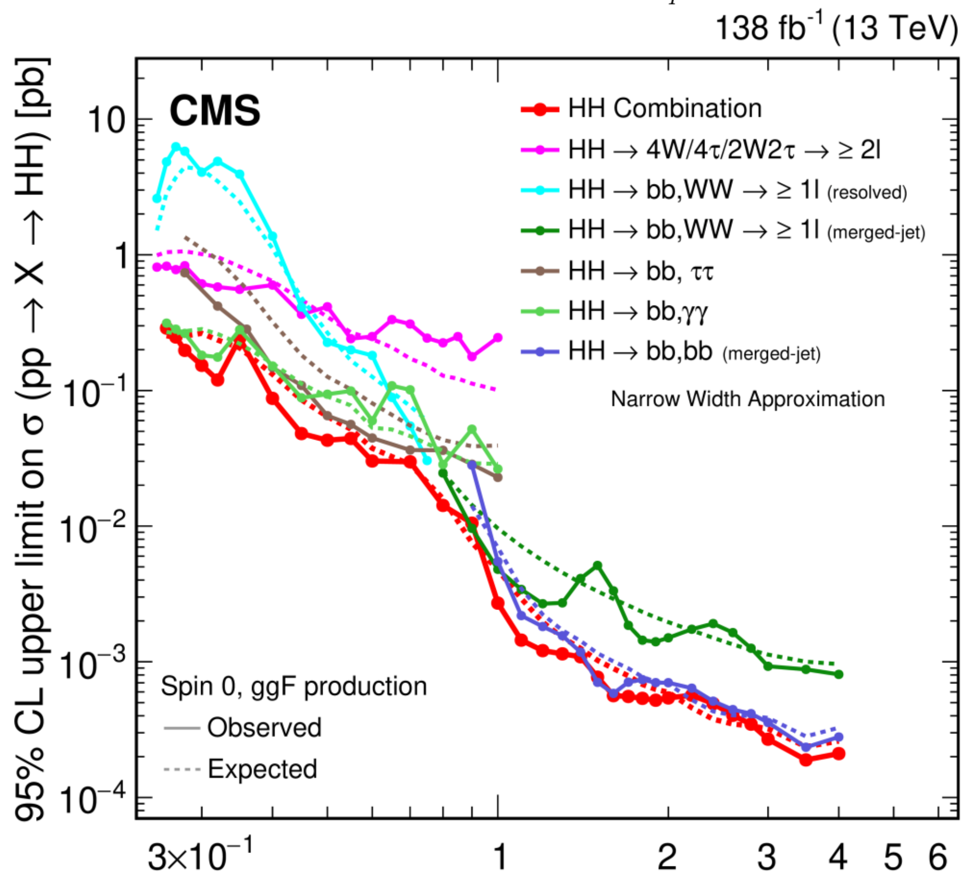
- slight excess around m_A = 400 GeV,
  - contributed by the b-tag category of the $\tau_{had}\tau_{had}$ channel and the b-veto category of the $\tau_{lep}\tau_{had}$, local significance = 2.2σ (ggF), 2.7σ (b-associated production)
  - global significance = 1.9 σ

Resonant $X \to H_{125}H_{125}$





- CMS: combination of $HH \to b\bar{b}b\bar{b}$ / $\gamma\gamma b\bar{b}$ / $b\bar{b}\tau^+\tau^-$/WW*WW* / $b\bar{b}$ WW*
- Boosted/resolved (or both) topologies
- only consider ggF
- ensure orthogonality, e.g:
  - between 4b and $bb\tau^+\tau^-$ by vetoing events in $bb\tau^+\tau^-$ with >1 large-R b-tagged jet.
  - between $bb\tau^+\tau^-$ and bbWW, by vetoing events in bbWW with ≥ 1 τ^+_{had}
  - e.t.c

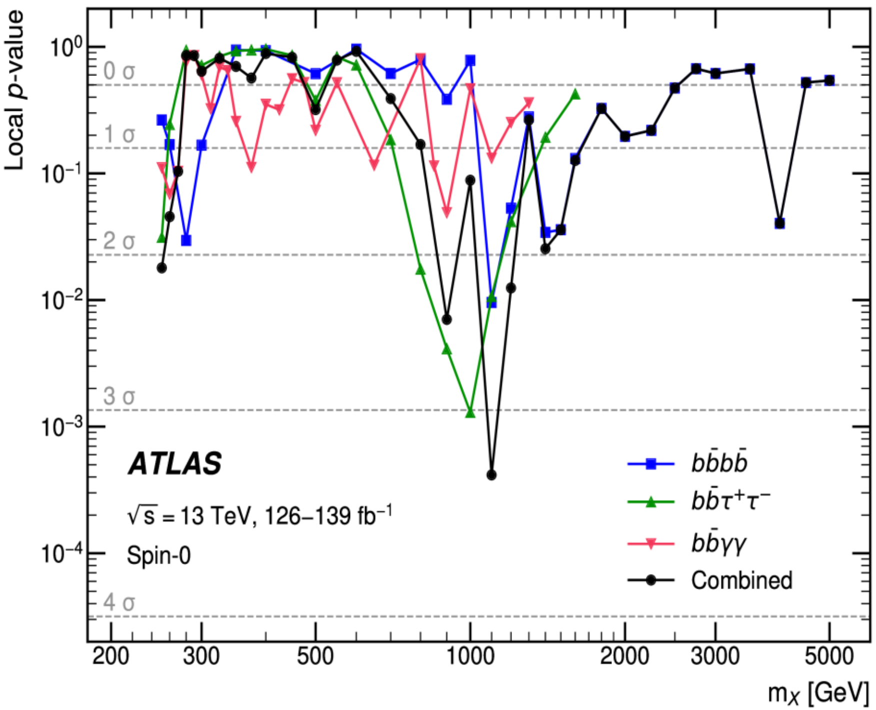


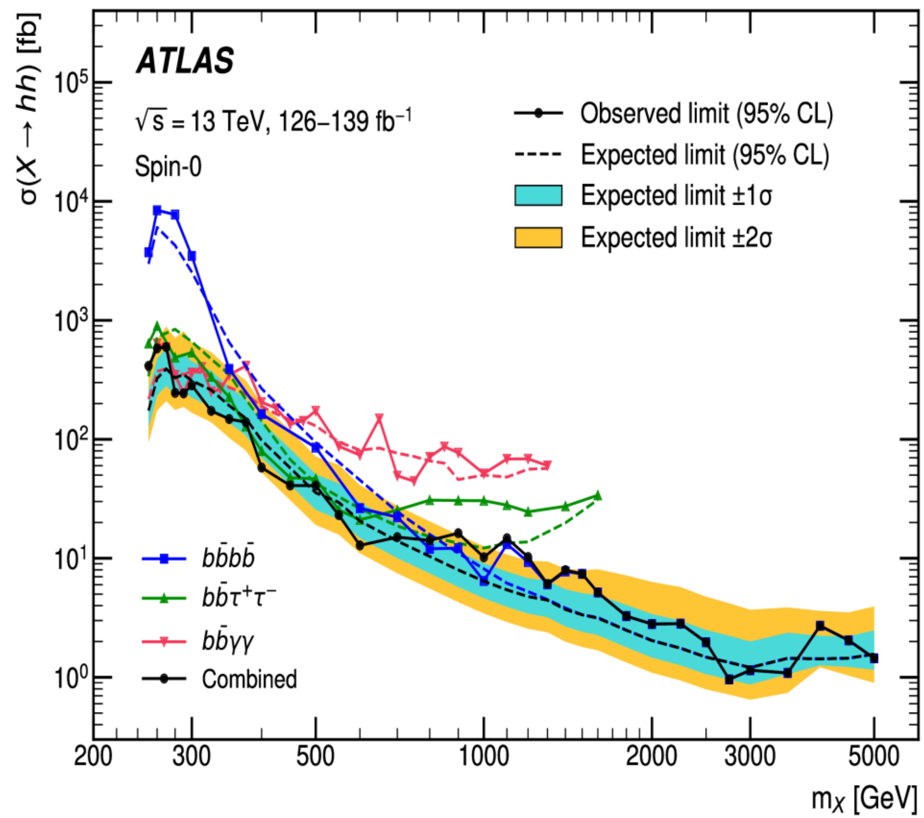
arXiv:2403.16926

Resonant $X \to hh$(continued)

- ATLAS: combination of $X \to HH \to b\bar{b}b\bar{b}$ / $\gamma\gamma b\bar{b}$ / $b\bar{b}\tau^+\tau^-$ channels
- Largest excess at m_x = 1.1TeV, with a local(global) significance of 3.3σ(2.1σ).

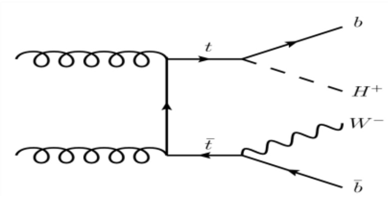
Phys. Rev. Lett. **132**, 231801



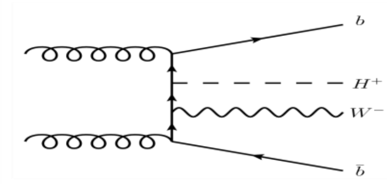


$H^+ \to \tau^+\nu$

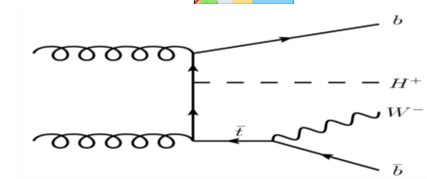
- Analyses channels:
  - $\tau^+_{had} + jets$, $\tau^+_{had} + \boldsymbol{e}/\mu$, no $\tau^+_{had} + lepton$ (CMS)
- Main bkg:
  - multijet, V+jets and $t\bar{t}$ events, jet $\to \boldsymbol{\tau_{had}}$ misidentication
- Main syst. uncert.:
  - jet energy scale, ID efficiency and mis-ID of τ_{had}
- BDT score (m_T) distribution is used as the final discriminant and in the fit in ATLAS (CMS).



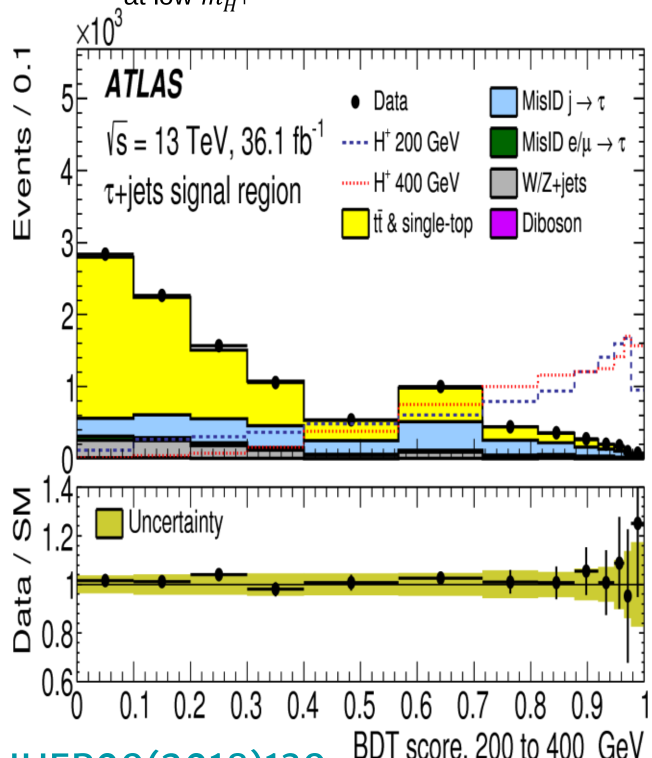
double-resonant top-quark production that dominates at low m_{H^+}



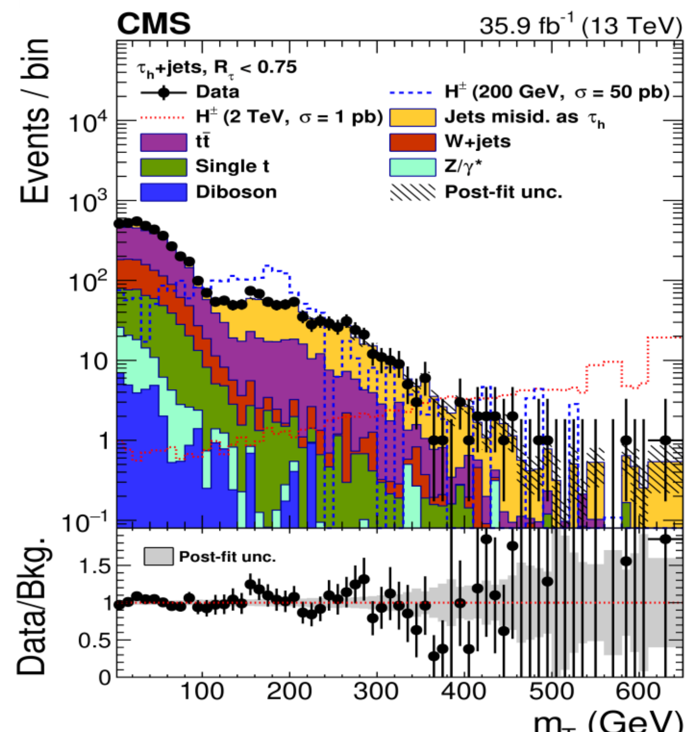
non-resonant top-quark production $m_{H^+} \approx m_{top}$



single-resonant top-quark production that dominates at large m_{H^+}



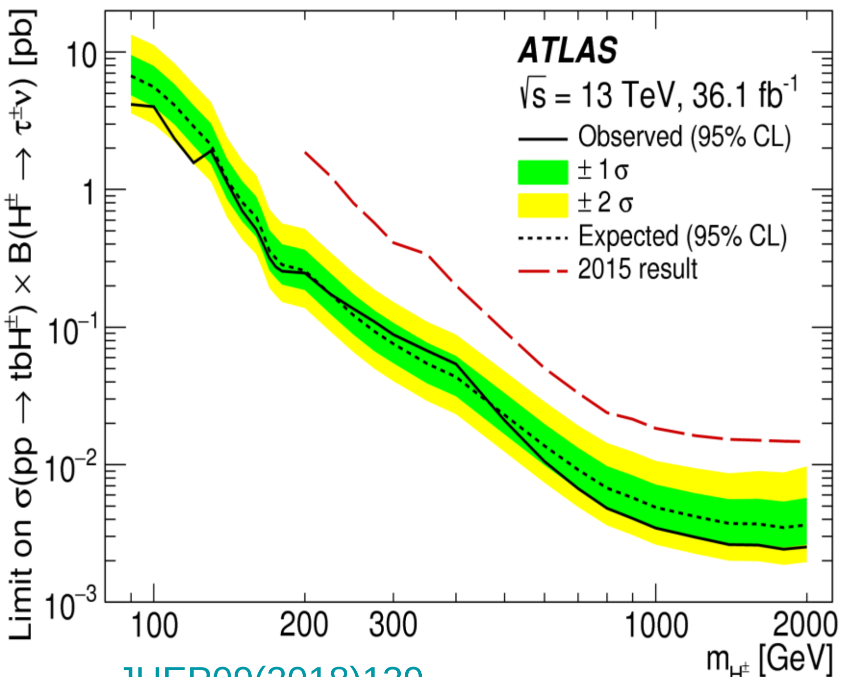
JHEP09(2018)139



JHEP07(2019)142

$H^+ \rightarrow \tau^+\nu$ (continued)

- Conducted over a wide mass range of 80–2000 GeV
- The results agree with the background expectation of the Standard Model



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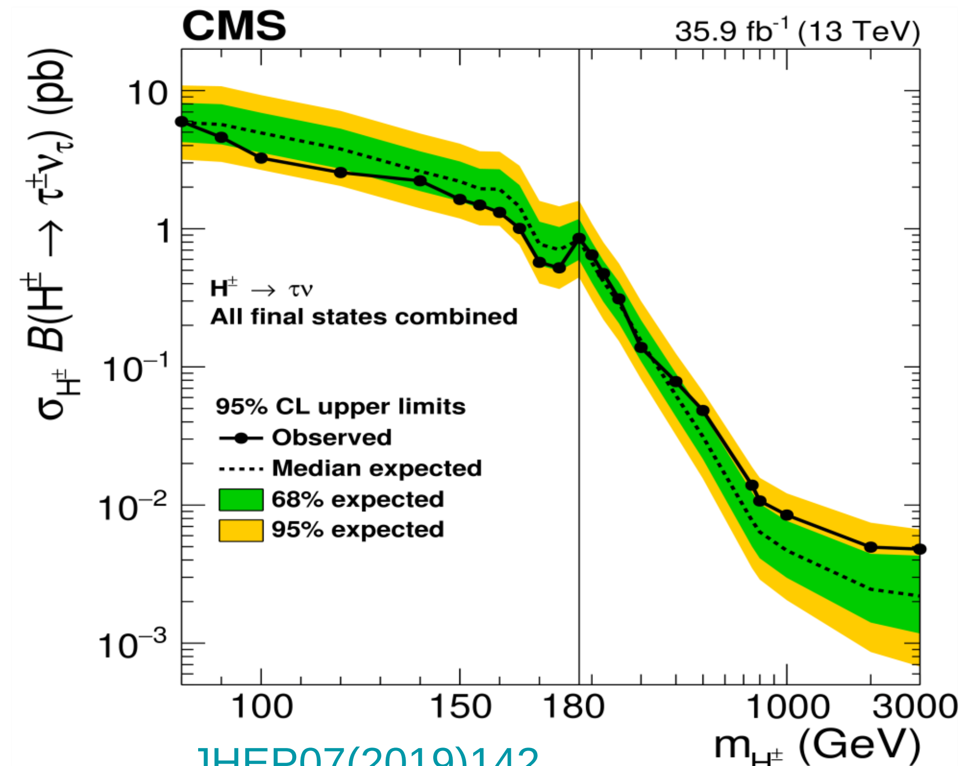
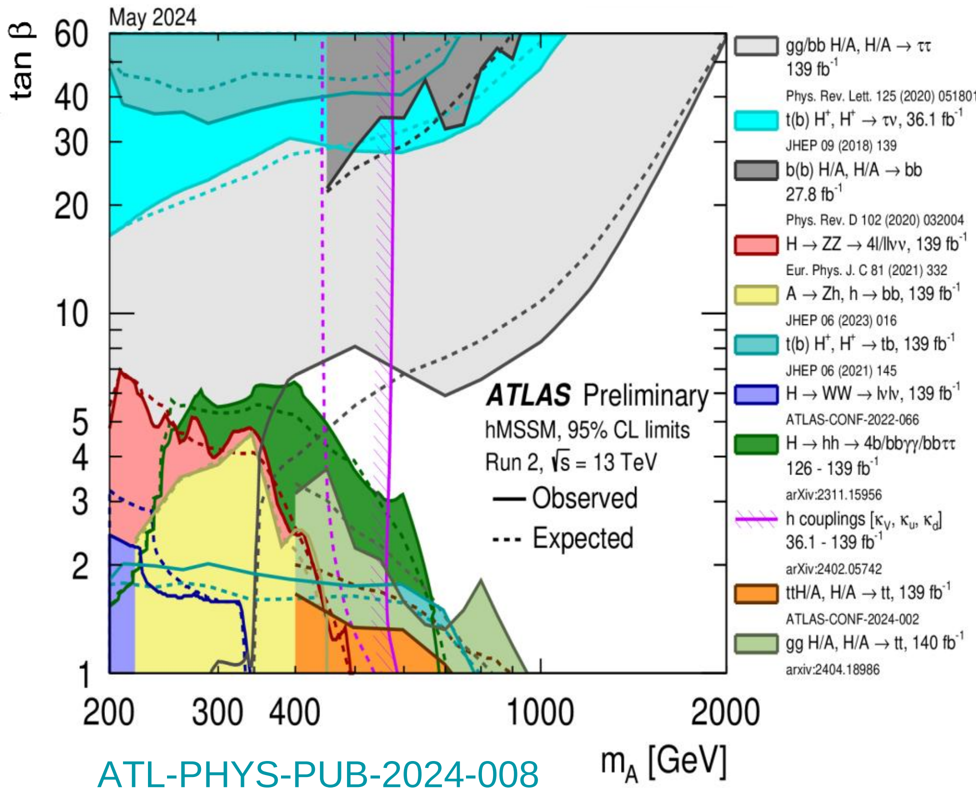


JHEP07(2019)142

Current State of MSSM Higgs Searches

Many full Run-2 results have been (or to be) released.



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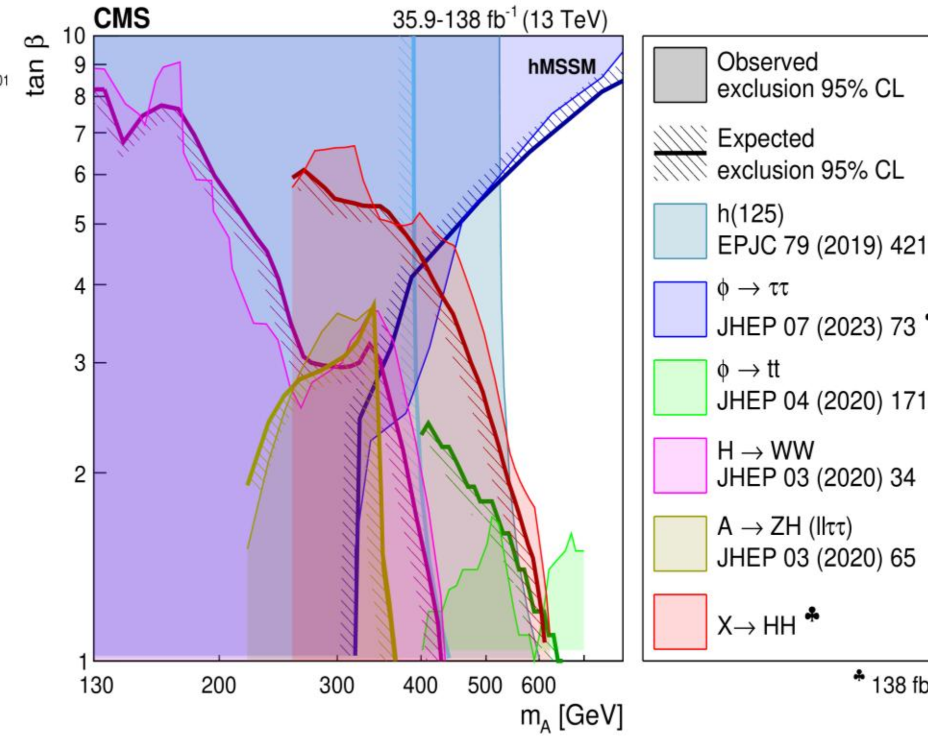
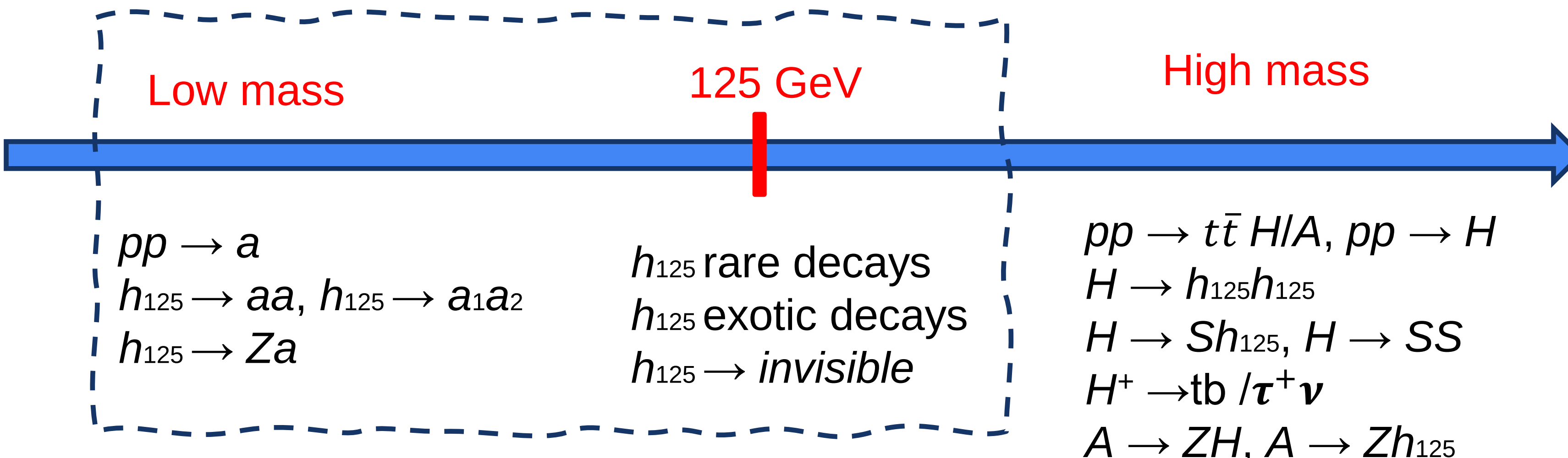


arXiv:2403.16926

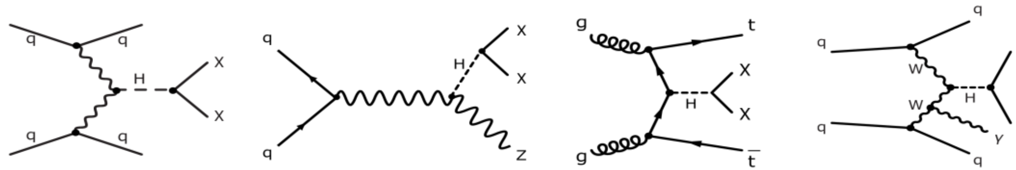
Searches for additional scalars and exotic decays of the H_{125}

- The Higgs boson has a particularly narrow width (4.1 MeV)
  - branching fraction to BSM particles via exotic decays could be sizeable
- Most recent combination from ATLAS (CMS):
  - B($H \to$ undetected) < 12% (16%)

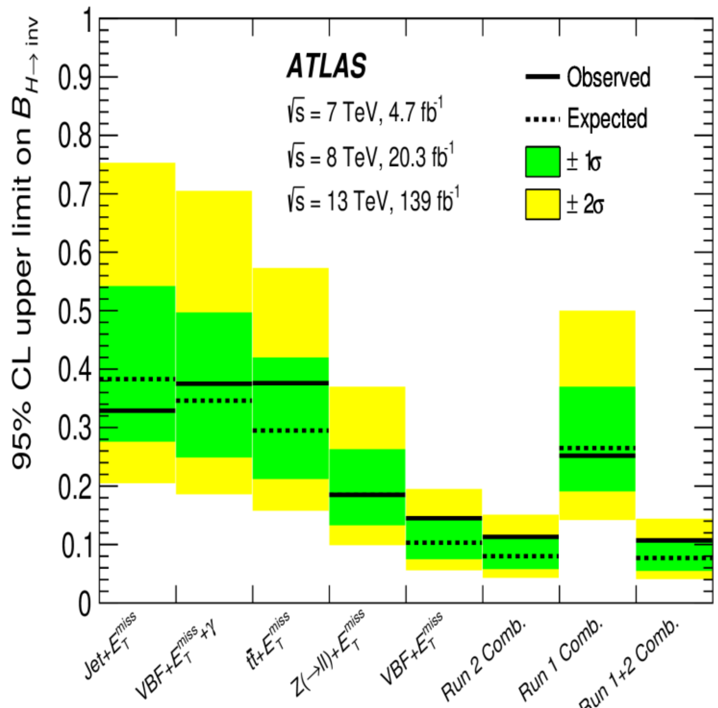


Next few pages

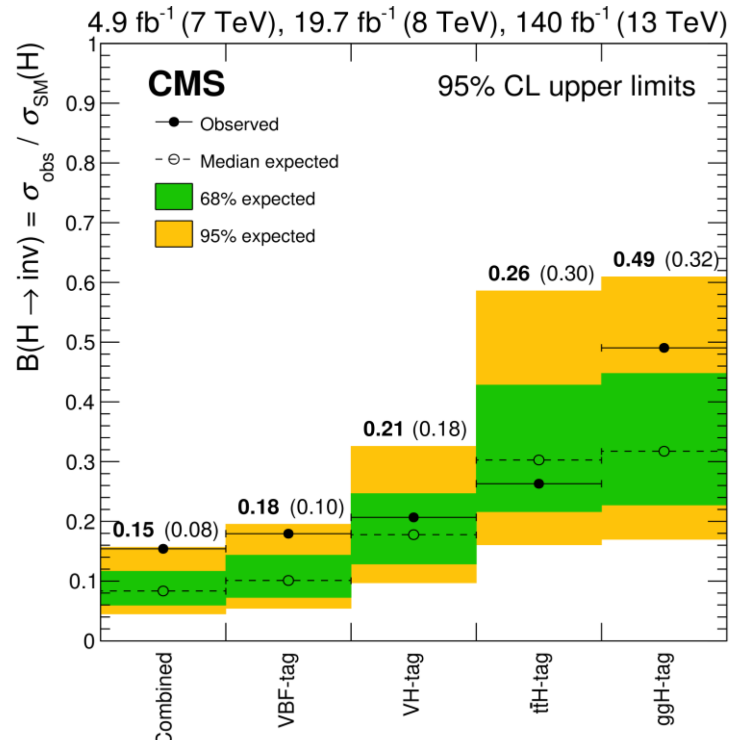
$H_{125} \to inv$



- Many BSM theories predict that H can act as a portal between dark and SM sectors
- Measuring the B($H \to$ invisible), can lead to constraints on the dark sector
- Both ATLAS and CMS searched for invisible Higgs decays in different production modes
- Observed (expected) upper limit at 95% CL. of the B(H→invisible) :
  - ATLAS: 0.107 (0.077); CMS: 0.15 (0.08)



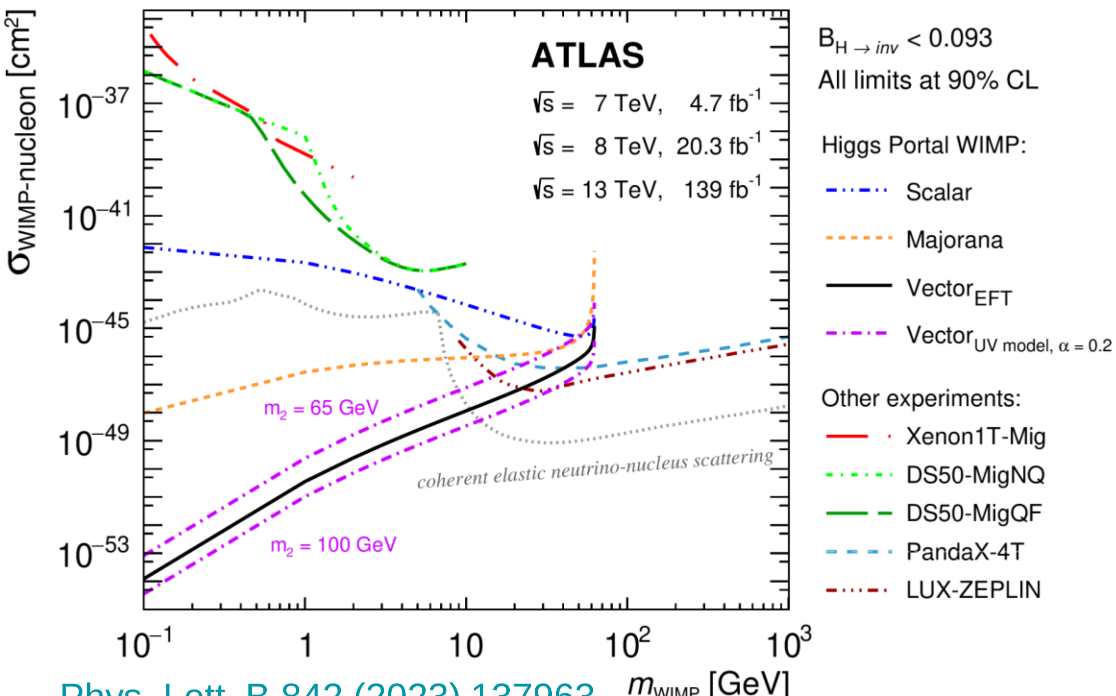
[Phys. Lett. B 842 (2023) 137963]



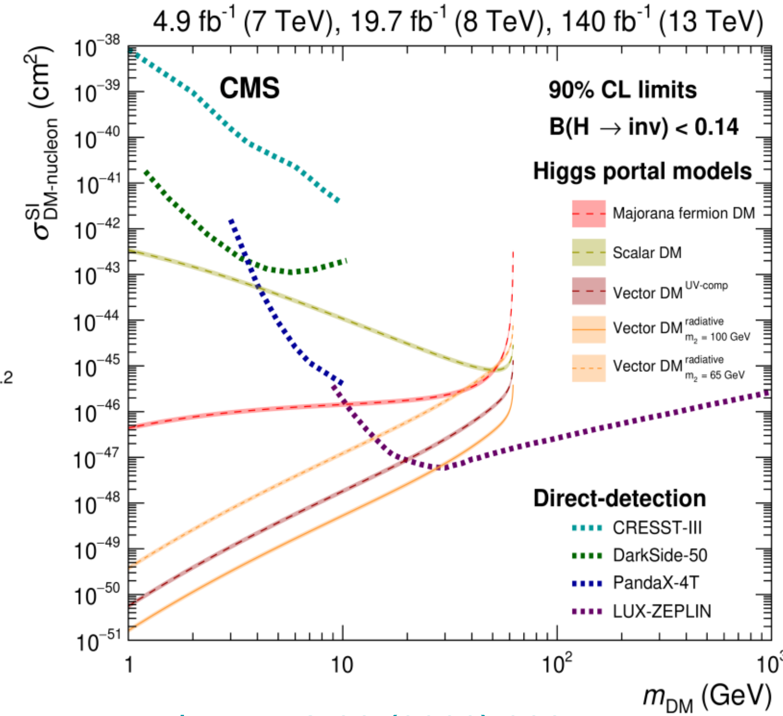
[Eur. Phys. J. C 83 (2023) 933]

$H_{125} \to inv$ (continued)

- Model-dependent Higgs portal interpretation where limits are set on the WIMP–nucleon scattering cross-section
  - highlighting the complementarity of DM searches at the LHC and direct-detection experiments



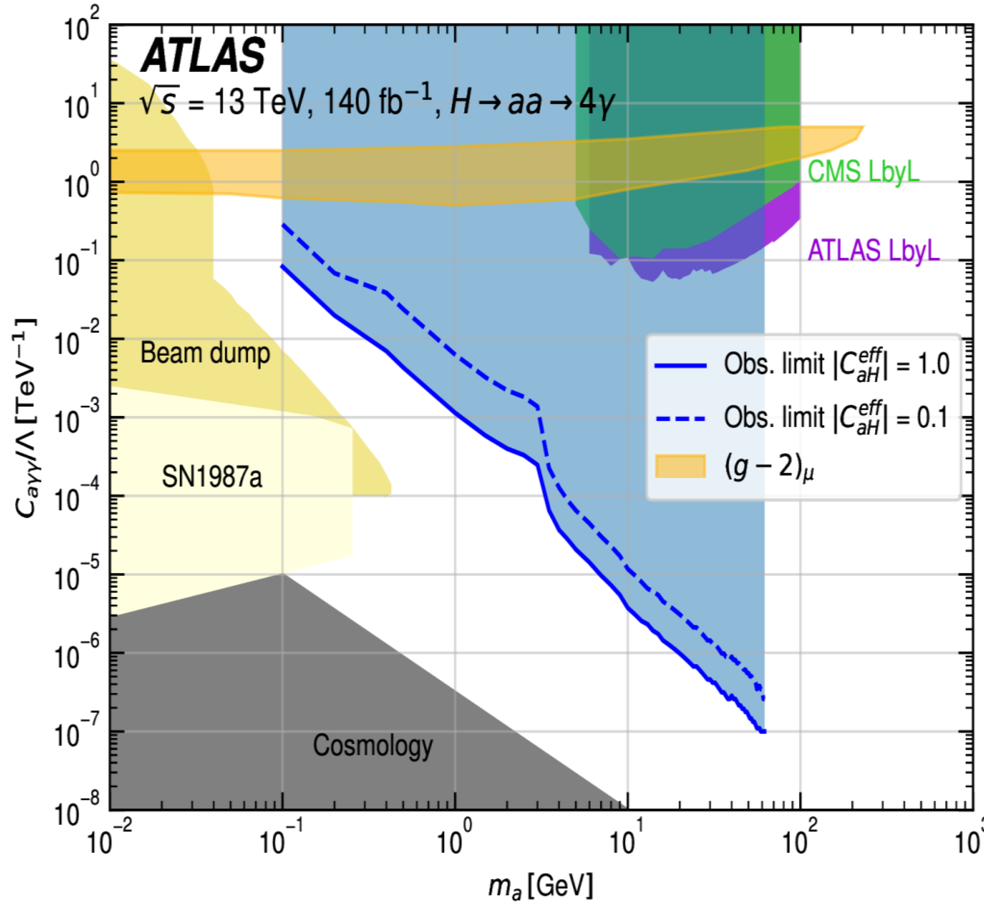
[Phys. Lett. B 842 (2023) 137963]



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

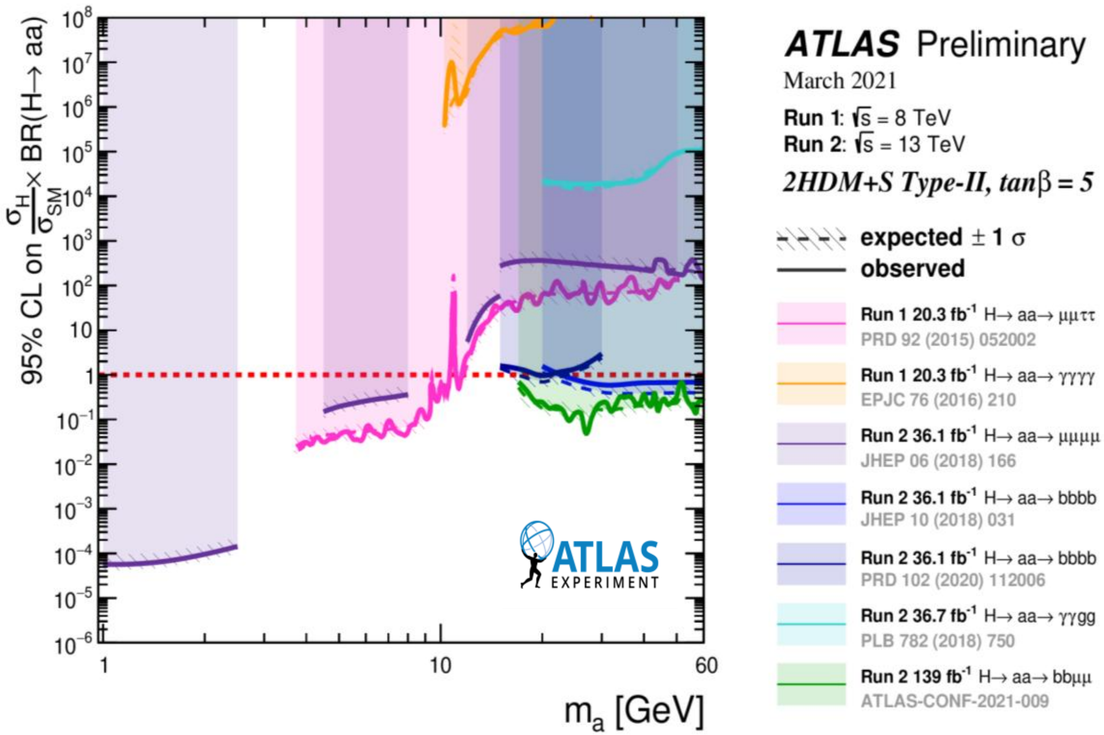
$H_{125} \to aa \to \gamma\gamma\gamma\gamma$

- a are axion-like particle (ALP)
- Sensitivity to models JHEP 12 (2017) 044 that could explain the $\mu(g-2)$ discrepancy.
- Both prompt and (for the 1st time) long-lived $a \to \gamma\gamma$ decays
  - via displaced vertex within the tracking system
- Final discriminant is the ALP mass m_a^{reco}
- No significant excess over the SM backgrounds is observed in the data.

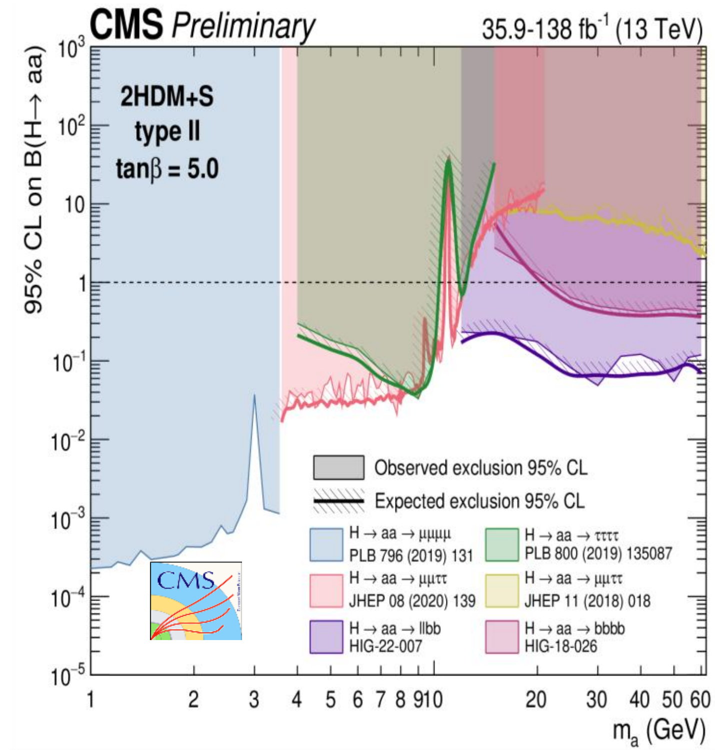


Eur. Phys. J. C 84 (2024) 742

Current Status of 2HDM+S with $H_{125} \to aa$



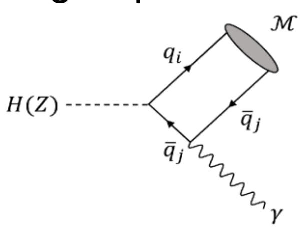
[ATLAS Summary Plots]

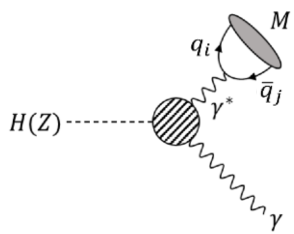


[CMS Summary Plots]

Rare Decays $H_{125} \to meson + \gamma$

- No evidence yet for Yukawa couplings to the 1st and 2nd generations of fermions.
  - distinct experimental signature offers an alternative way to probe the quark Yukawa couplings
- Processes like $H \to K^{*}\gamma$ and $H \to D^{*}\gamma$ can probe flavour-violating Yukawa couplings to light quarks





** i and j refer to the flavour of the quark, and $i \neq j$

- The observed data are compatible with the expected backgrounds.

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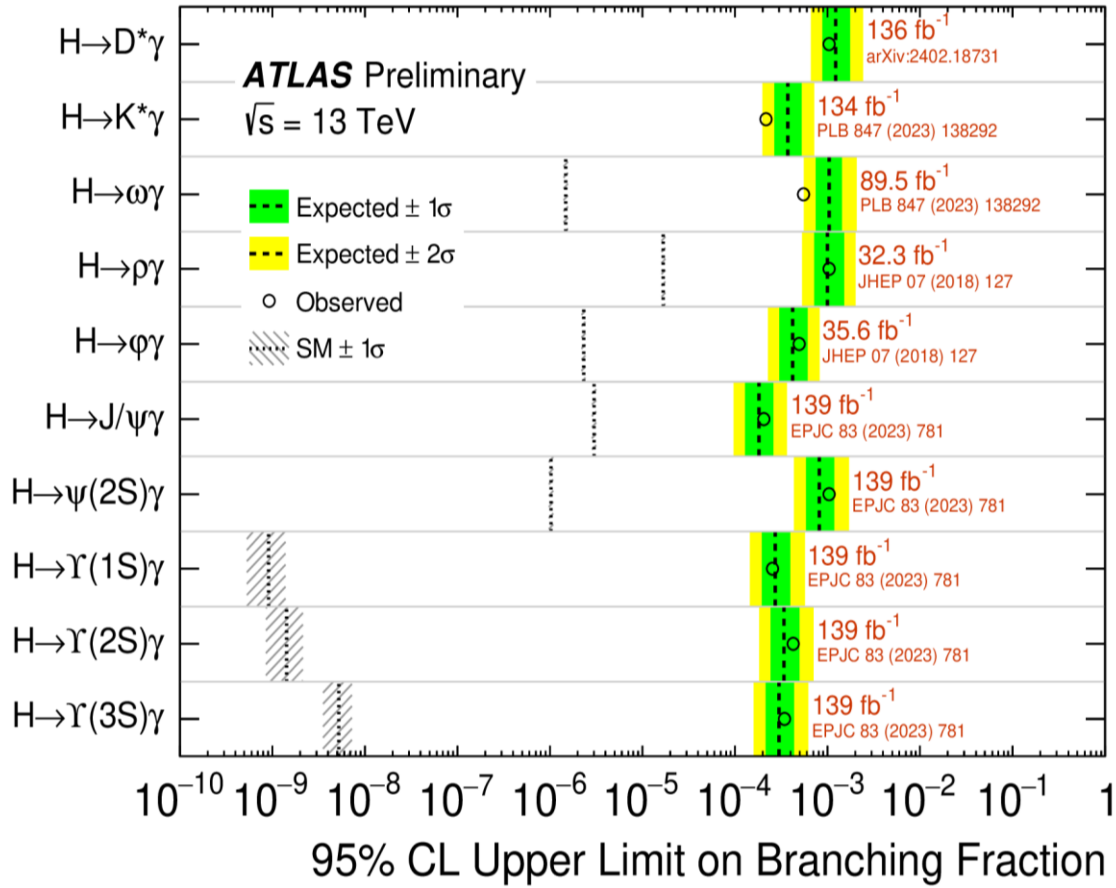

Summary of the 95% confidence-level upper limits on Higgs boson branching fractions for decays to a meson and a photon, including the SM expected branching fractions. SM Higgs boson production is assumed.

List of BSM Higgs Searches (with small excess)

- None of these small excess are significant enough to establish new physics yet.
- Awareness of these results is useful, as they can motivate future searches with the Run 3 dataset and help to set priorities

Decay channel	Production mode	Mass [GeV]	Significance local	Significance global	L [fb^{-1}]
$H \to \tau\tau$	b-associated	400	2.7σ	n.a.	139
$H \to \tau\tau$	ggF	400	2.2σ	n.a.	139
$H \to \mu\mu$	b-associated	480	2.3σ	0.6σ	36
$H \to t\bar{t}$	ggF	800	2.3σ	n.a.	140
$H \to t\bar{t}/t\bar{q}$	qq and qg	900	2.8σ	n.a.	139
$H \to ZZ \to 4\ell/2\ell2\nu$	ggF	240	2.0σ	0.5σ	139
$H \to ZZ \to 4\ell/2\ell2\nu$	VBF	620	2.4σ	0.9σ	139
$H \to \gamma\gamma$	ggF	684	3.3σ	1.3σ	139
$H \to \gamma\gamma$	ggF	95.4	1.7σ	n.a.	140
$H \to Z(\ell\ell)\gamma$	ggF	420	2.3σ	n.a.	140
$H \to Z(q\bar{q})\gamma$	ggF	3640	2.5σ	n.a.	139
$A \to Zh_{125}(b\bar{b})$	ggF	500	2.1σ	1.1σ	139
$A \to Zh_{125}(b\bar{b})$	b-associated	500	1.6σ	n.a.	139
$A \to ZH \to \ell\ell b\bar{b}$	ggF	610 (A), 290 (H)	3.1σ	1.3σ	139
$A \to ZH \to \ell\ell b\bar{b}$	b-associated	440 (A), 220 (H)	3.1σ	1.3σ	139
$A \to ZH \to \ell\ell WW$	ggF	440 (A), 310 (H)	2.9σ	0.8σ	139
$A \to ZH \to \ell\ell t\bar{t}$	ggF	650 (A), 450 (H)	2.9σ	2.4σ	140
$A \to ZH \to Zh_{125}(b\bar{b})h_{125}(b\bar{b})$	VH	420 (A), 320 (H)	3.8σ	2.8σ	139
$H^+ \to cb$	$t\bar{t}$ decay	130	3.0σ	2.5σ	139
$H^+ \to Wa(\mu\mu)$	$t\bar{t}$ decay	120–160 (H^+), 27 (a)	2.4σ	n.a.	139
$H^+ \to WZ$	VBF	375	2.8σ	1.6σ	139
$H^{++} \to WW$	VBF	450	3.2σ	2.5σ	139
$H \to h_{125}h_{125} \to 4b$	ggF	1100	2.3σ	0.4σ	126–139
$H \to h_{125}h_{125} \to 4b$	VBF	550	1.5σ	n.a.	126
$H \to h_{125}h_{125} \to b\bar{b}\tau\tau$	ggF	1000	3.1σ	2.0σ	139
$H \to h_{125}h_{125}$ combination	ggF	1100	3.3σ	2.1σ	126–139
$X \to Sh_{125} \to b\bar{b}\gamma\gamma$	ggF	575 (X), 200 (S)	3.5σ	2.0σ	140
$h_{125} \to Z_dZ_d \to 4\ell$	ggF	28	2.5σ	n.a.	139
$h_{125} \to ZZ_d \to 4\ell$	ggF	39	2.0σ	n.a.	139
$h_{125} \to aa \to b\bar{b}\mu\mu$	ggF, VBF, VH	52	3.3σ	1.7σ	139
$h_{125} \to aa \to 4\gamma$	ggF	10–25	1.5σ	n.a.	140
$h_{125} \to e\tau$ and $h_{125} \to \mu\tau$	ggF, VBF, VH	125	2.1σ	n.a.	138

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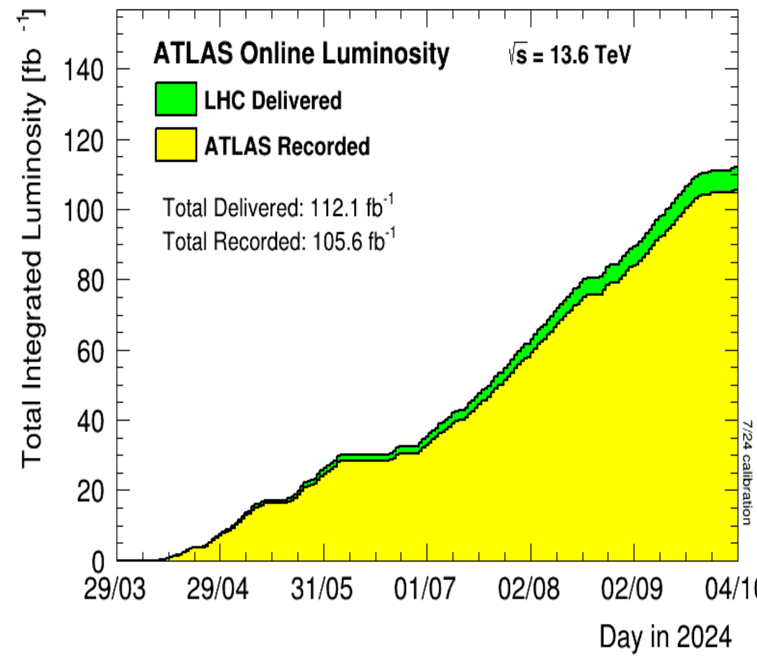
Uncovered signatures and outlook

- Many signatures remain uncovered and are topics for future investigations, e.g:
  - $H^+ \to Wh_{125}$, $H^+ \to W\gamma$, $H^+ \to \chi\chi^+$
  - $H \to WH^+$, $H \to SS$, $H \to \chi\chi$
  - rare multi-body decays of the h_{125} to axion-like particles, $h_{125} \to a\mu\mu/aa\mu\mu$
  - explore production modes other than *gg*F in exotic h_{125} decays

- Limitations of current searches:
  - data, data, more data
  - larger MC samples size (maintaining data:MC ~ 1:1)
    → need faster simulation
  - better MC modelling (see talks by Miha Impact of QCD and PDF uncertainties on BSM searches)
  - constraining systematic uncertainties using data

- Innovative ML and special techniques:
  - for better physics object reconstruction (e.g. τ_{had} and merged b-jets, displaced-jet) FTAG-2023-01, CERN-CMS-BTV-22-001-PAS
  - to estimate or reject the background and improve the analysis sensitivity
  - to collect data at a rate much higher than possible with standard triggers, e.g: **Trigger-level analysis** (ATLAS), **Scouting dataset** (CMS)
  - specialized triggers to enhance the efficiency for rare processes
  - online/offline flavour tagging



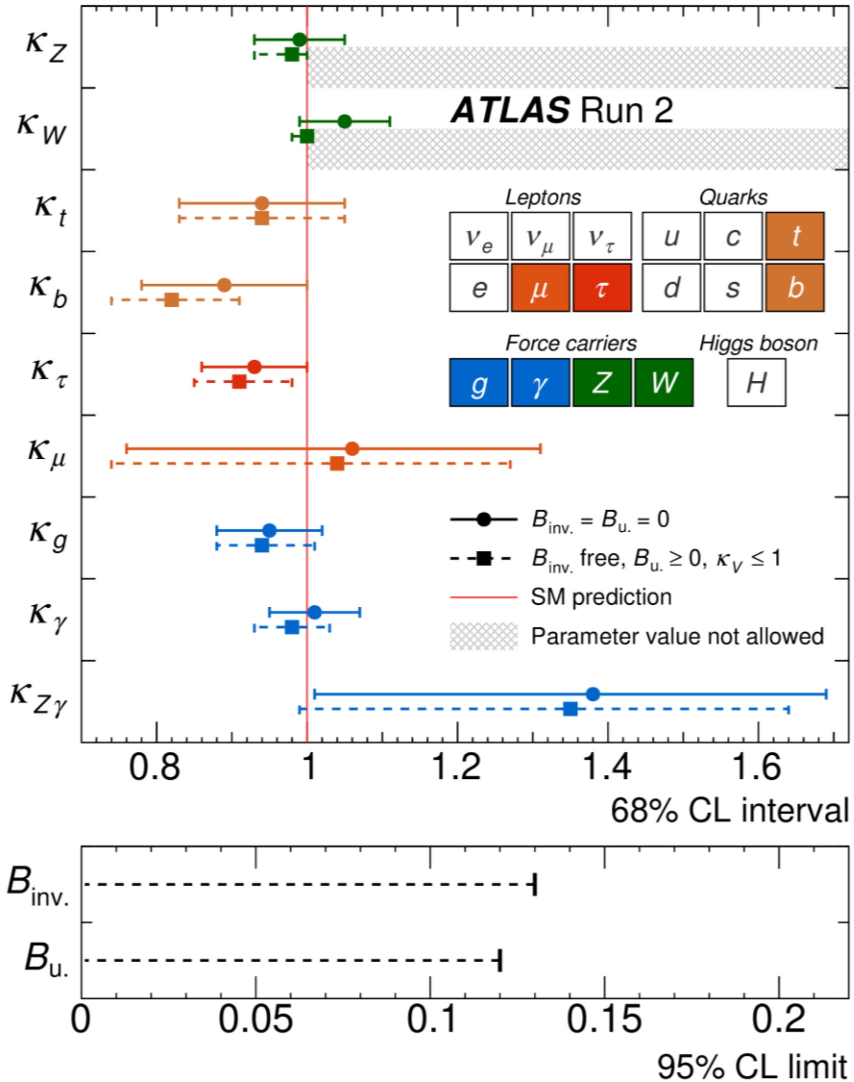
Summary

- **Very broad BSM Higgs boson physics program at ATLAS and CMS**
  - all yielded null results, thereby constraining the phase space of possible models.
  - sensitivity limited by the available data and the analysis tools used.

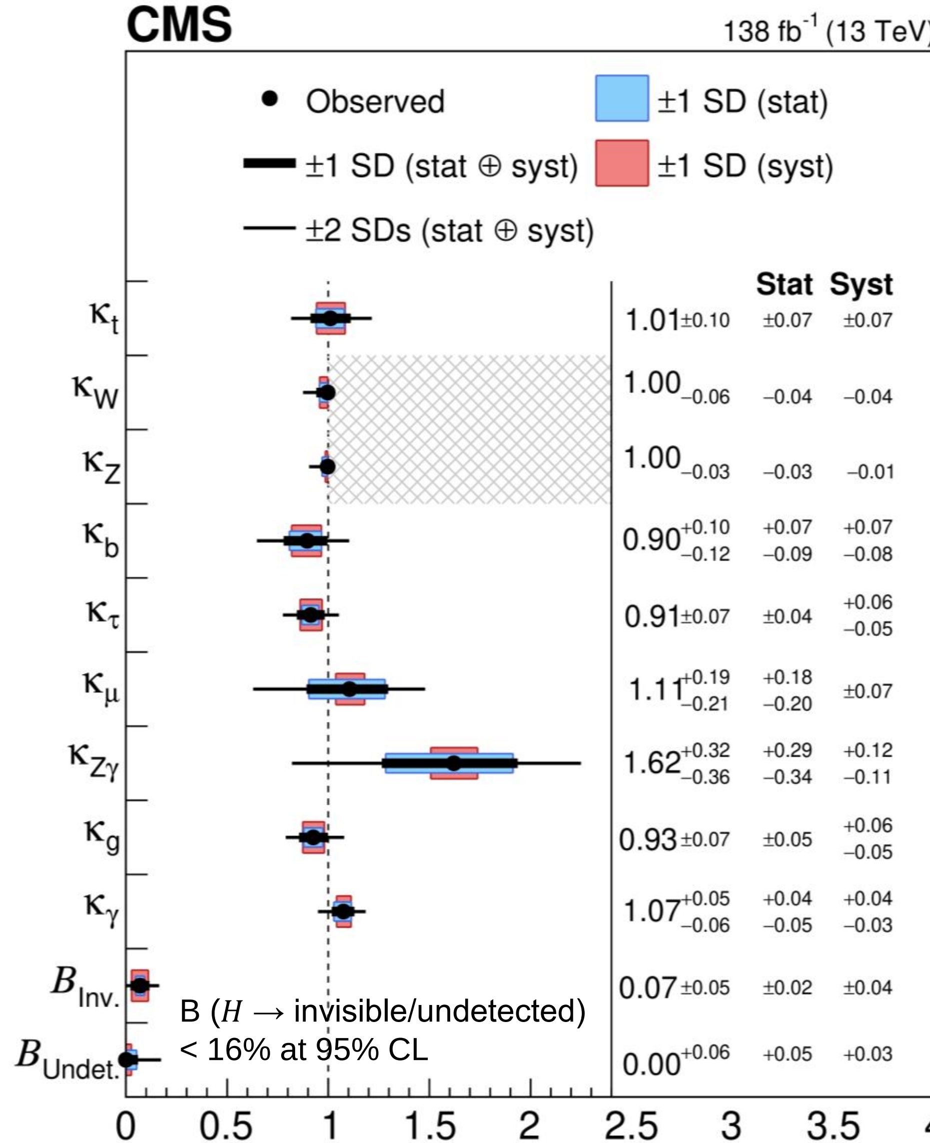
- More data and continued efforts are needed:
  - to extend the coverage,
  - to further study the presence of small excesses in a few searches, and
  - to work on uncovered signatures

- **Run 2 physics harvest close to the end, focus now on Run 3, there is much more to come!**

Additional Slides

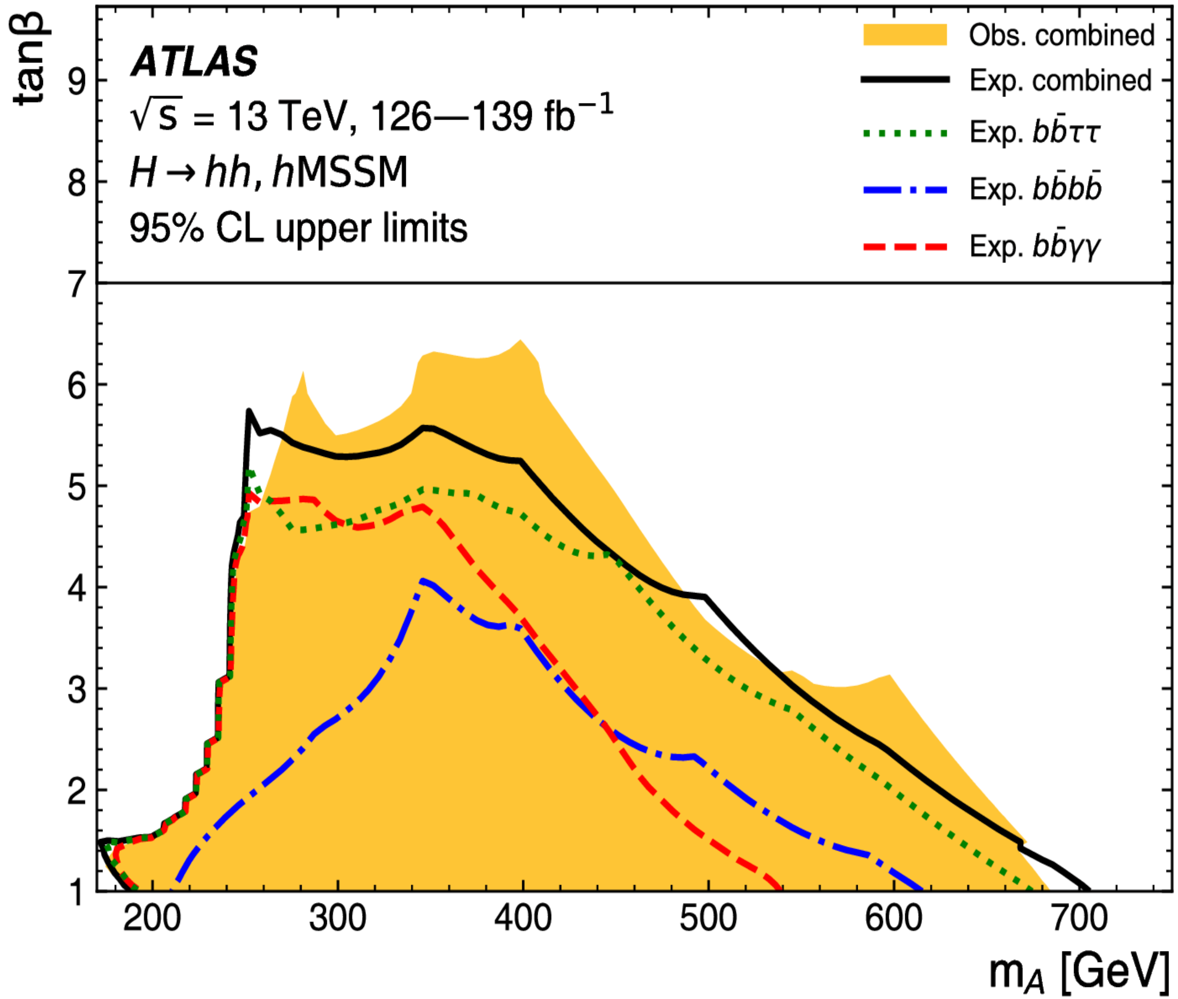


[Nature 607 52 (2022)]



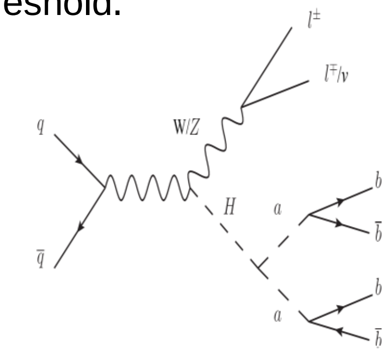
[Nature 607 (2022) 60-68]

Resonant $H \rightarrow hh$

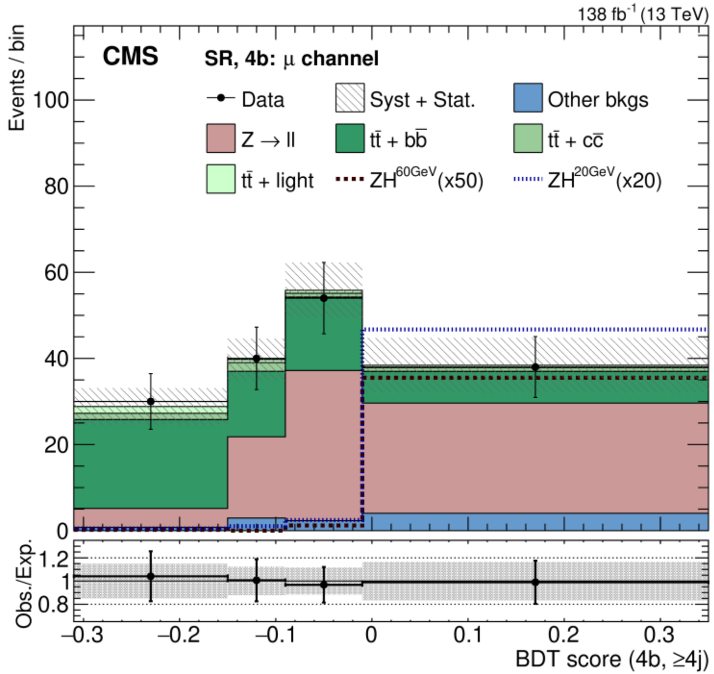


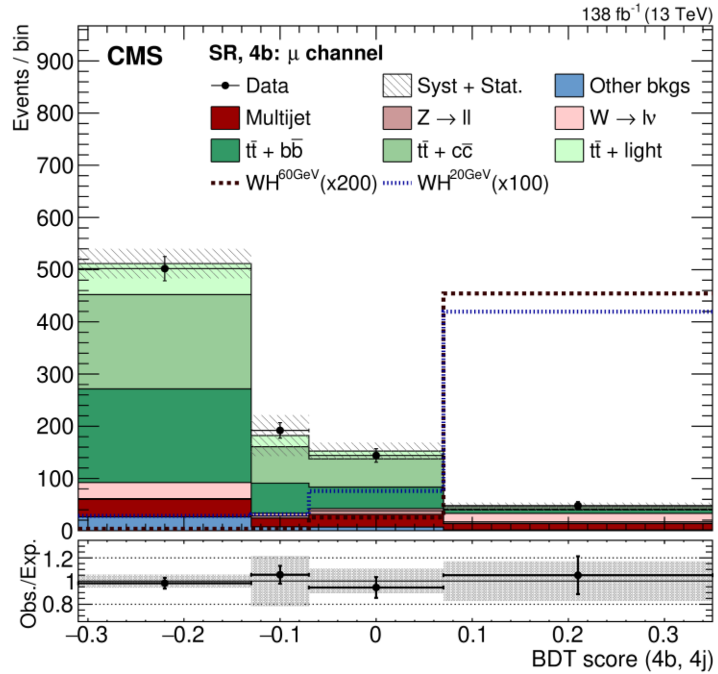
$H_{125} \to aa \to b\bar{b}b\bar{b}$

$a \to b\bar{b}$ is the dominant decay mode above $b\bar{b}$ threshold.



- $Z \to \ell\ell$ and $W \to \ell\nu$ channels with SR： 3 or 4 b-tagged jets.
- Main bkg: $t\bar{t}$+jets, V+jets
- Main syst. uncert.: B-tagging efficiency and mis-tagging of c- and LF-jets
- BDT discriminants trained separately for ZH and WH channels and the BDT score distribution is used in the fit.



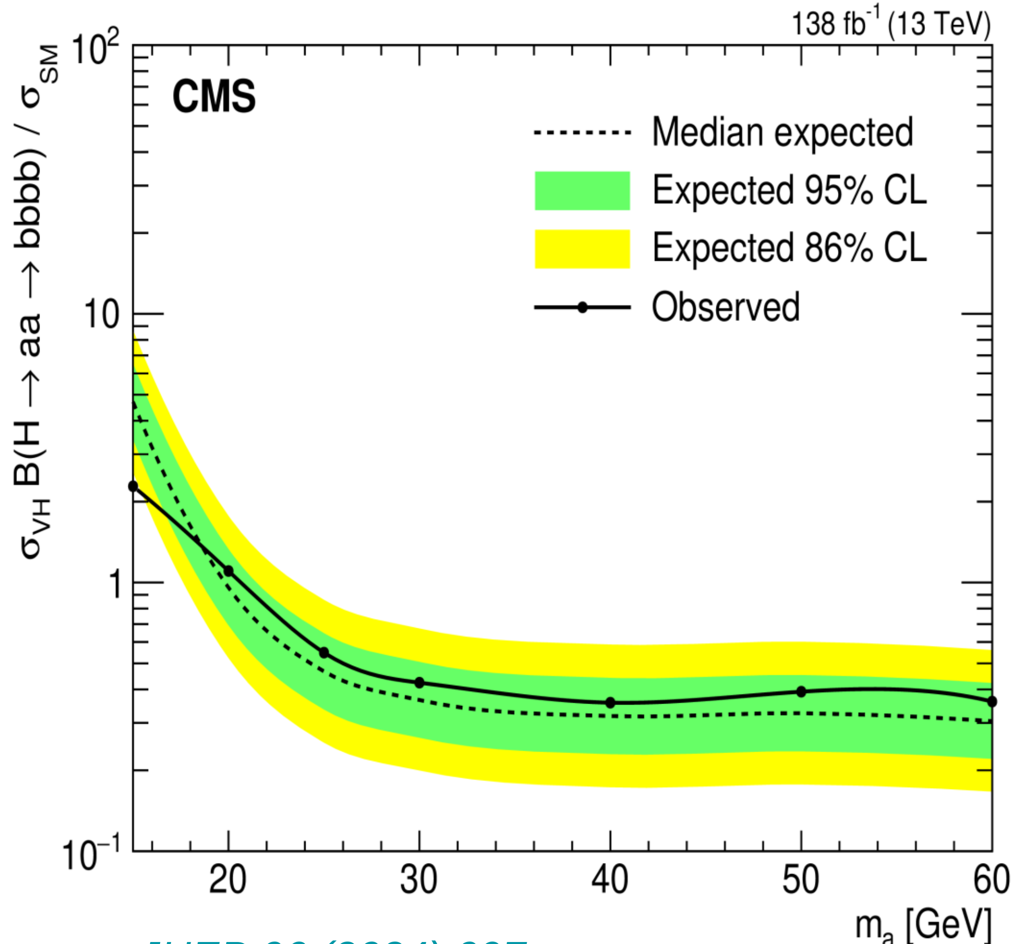


JHEP 06 (2024) 097

$H_{125} \rightarrow aa \rightarrow b\bar{b}b\bar{b}$ (continued)

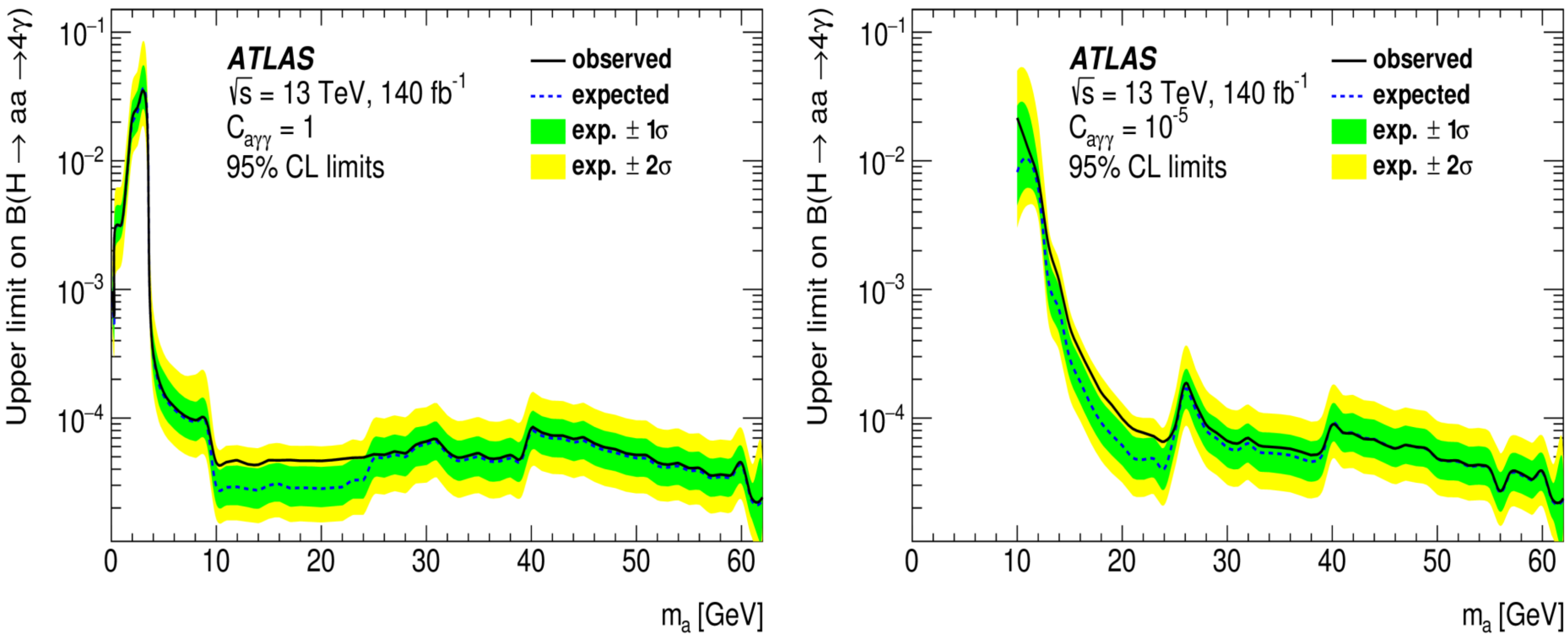
- Similarly, ATLAS result with $36 fb^{-1}$ Run2 data:
  - Both resolved JHEP **10** (2018) 031 and boosted regime Phys. Rev. D 102 (2020) 112006

- No evidence for the targeted decay mode is observed.



JHEP 06 (2024) 097

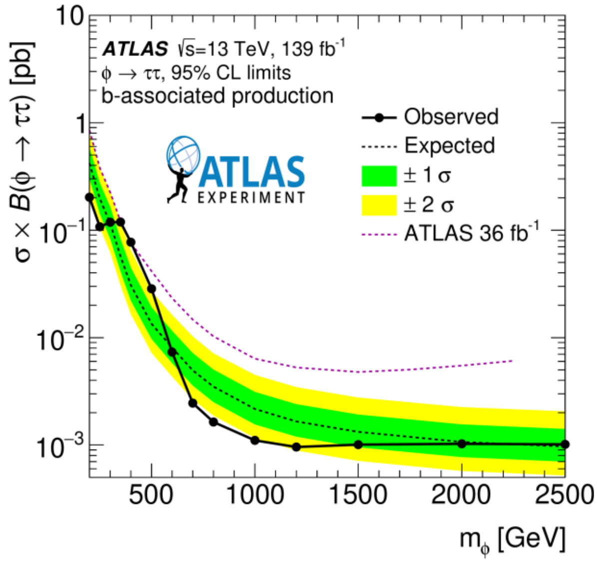
$H_{125} \to aa \to \gamma\gamma\gamma\gamma$ Eur. Phys. J. C 84 (2024) 742

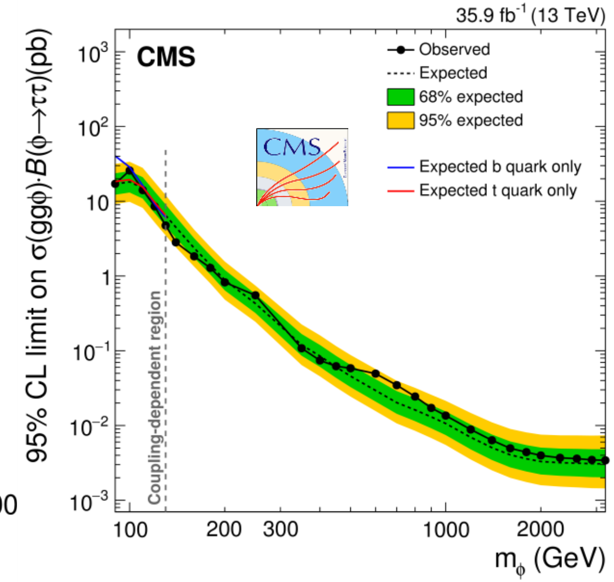


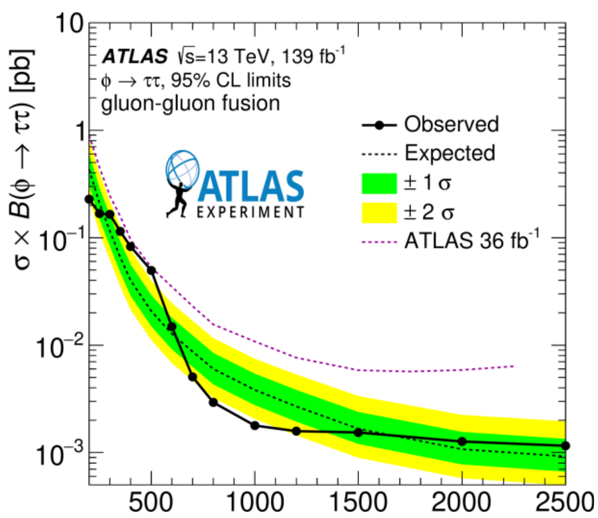
- Upper limits on B($H \to aa \to 4\gamma$) at 95% CL as a function of the axion mass and for different ALP-photon couplings, from $C_{a\gamma\gamma} = 1$ and $C_{a\gamma\gamma} = 10^{-5}$
- The limits on long-lived ALPs in anomalous Higgs boson decays are the first obtained by any experiment

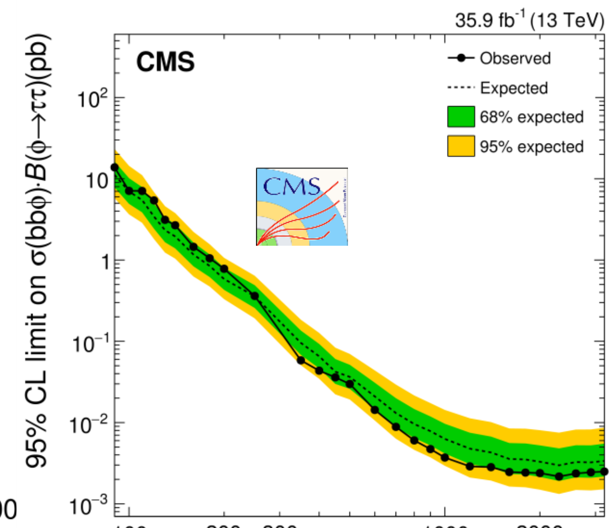
$H/A \to \tau^+\tau^-$

- No significant excess over expected SM bkgd.
- ATLAS: Small excess near m_A=400 GeV
  - local significances are $2.7\sigma(2.2\sigma)$ for b-associated production (ggF production)
  - global significance = 1.9 σ







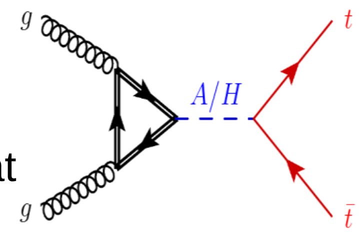


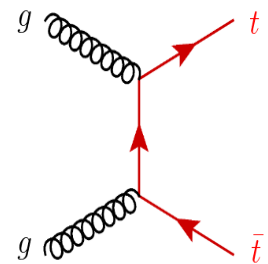
Phys. Rev. Lett. **125**, 051801

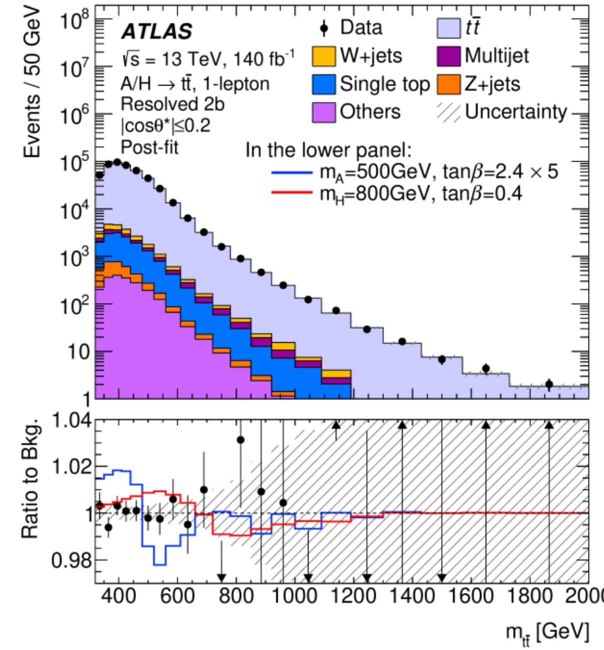
JHEP09(2018)007

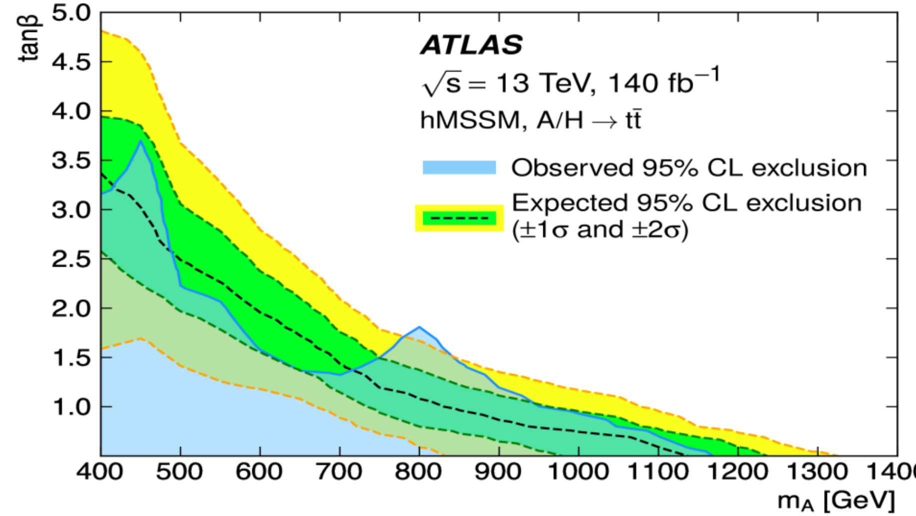
$H/A \to t\bar{t}$ [JHEP 08 (2024) 013]

- Promising search for heavy H/A in 2HDM at low tanβ
- Consider the interference between signal with the gg-induced $t\bar{t}$ production.
- Target two orthogonal 1- and 2-lepton channels.
- Main bkg:
  - $t\bar{t}$, V+jets, single-top
- Main syst. uncert.:
  - $t\bar{t}$ modelling, jet-energy and -mass scales and b-tagging
- Final discriminant is the reconstructed $t\bar{t}$ invariant mass binned in $|\cos(\theta^*)|$
- Data were consistent with SM background.
- Most significant deviation is at 800 GeV with a local significance of 2.3σ.



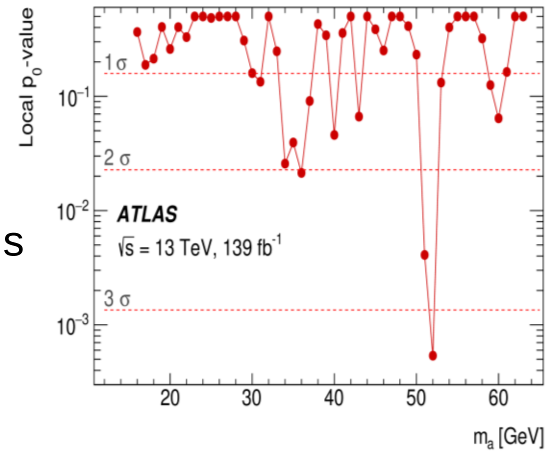


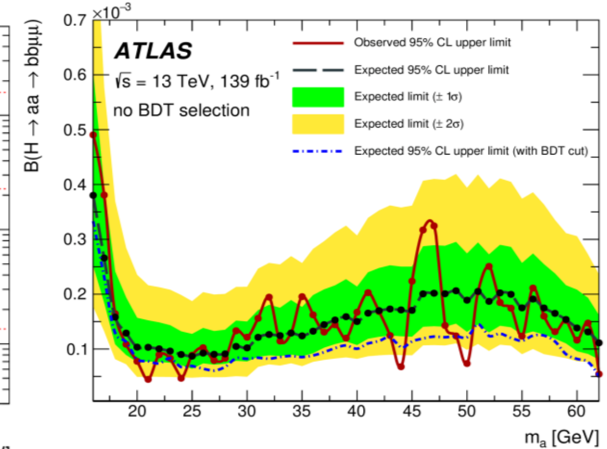




$H_{125} \rightarrow aa \rightarrow b\bar{b}\mu^+\mu^-$

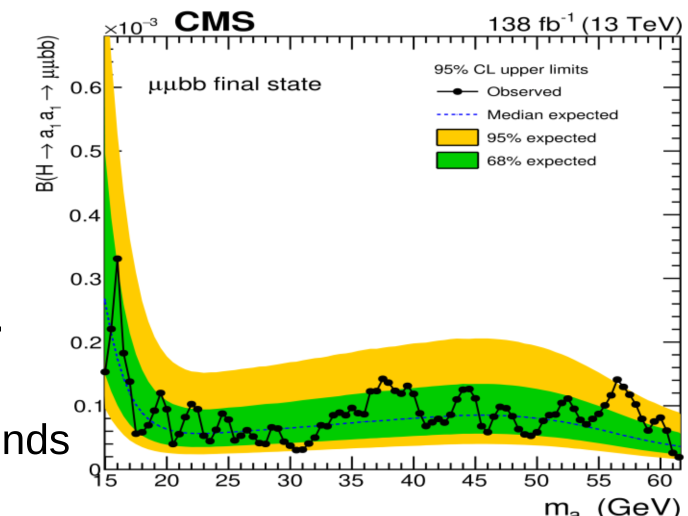
- Rare but clean $a \rightarrow \mu^+\mu^-$decay is balanced by the more probable $a \rightarrow b\bar{b}$ decay
- Sensitive to scenarios where there are enhanced lepton couplings JHEP **06** (2015) 25





Phys. Rev. D 105 (2022) 012006

- Main bkg:
  - DY di-muon+ jets, $t\bar{t}$
- BDT to enhance search sensitivity
- Main syst. uncert.:
  - B-tagging and BDT selection efficiency, MC stats.
- Final Discriminant: $m_{\mu\mu}$
- No significant excess in the data over the SM backgrounds is observed
  - a local (global) significance of 3.3σ (1.7σ)

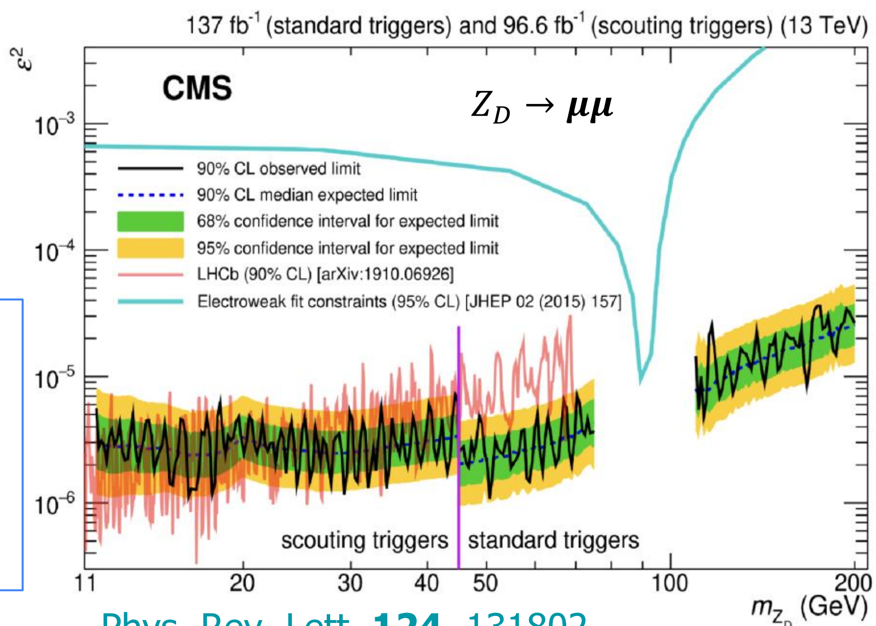


Eur. Phys. J. C 84 (2024) 493

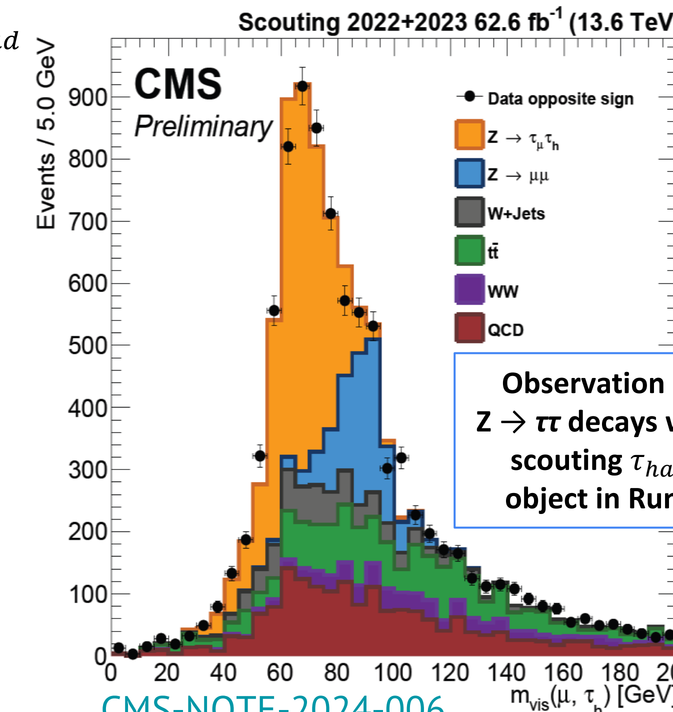
Data scouting and Data Parking [arXiv:2403.16134]

- Data **scouting** trades complete event information for higher event rates, while keeping the data bandwidth within limits.
- Data **parking** involves storing a large amount of raw detector data collected by algorithms with low trigger thresholds to be processed when sufficient computational power is available to handle such data.
- Opens possibilities for searches in new regions of phase space.
- **Scouting in Run 2** explored **simple objects**: low-mass dimuon**,** low energy di-jet
- **Scouting Run 3**: more elaborated objects, low-momentum τ_{had}

Scouting data sets stringent constraints on dark photon production in the 11–45 GeV mass range.



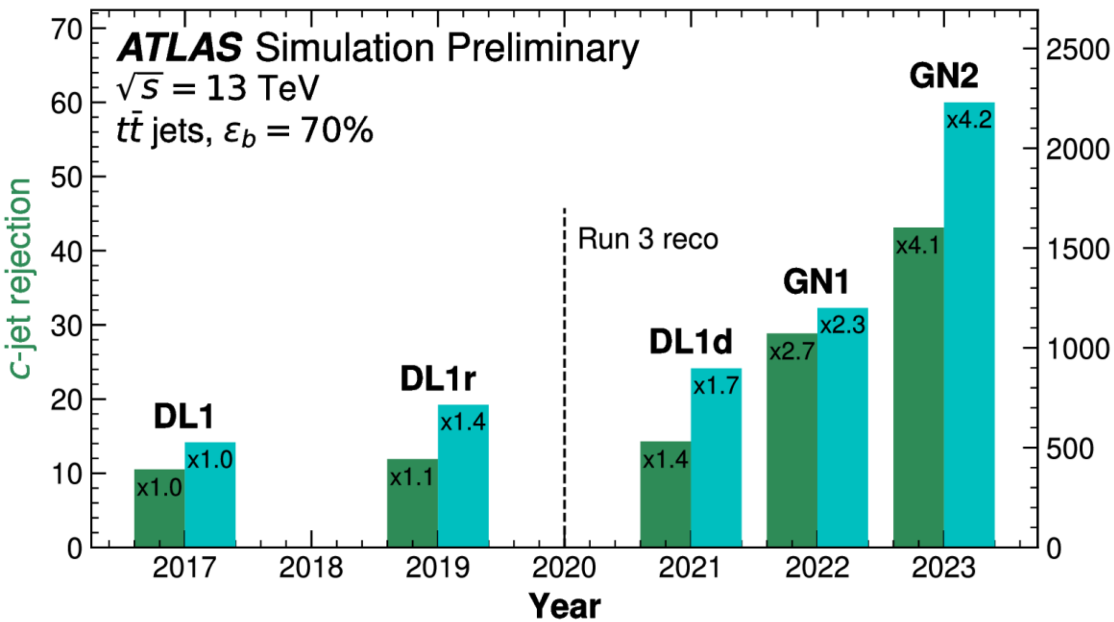
Phys. Rev. Lett. **124**, 131802



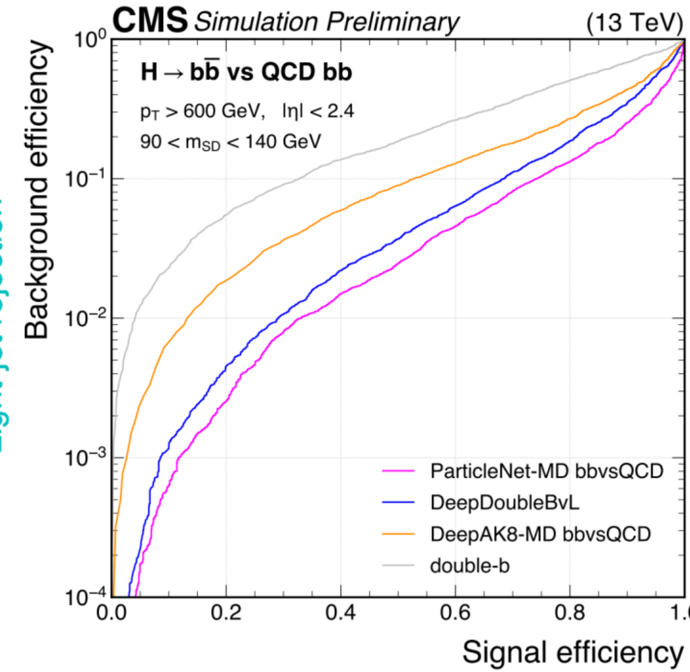
Observation of Z → $\tau\tau$ decays with scouting τ_{had} object in Run3

CMS-NOTE-2024-006

Advancement in flavour tagging

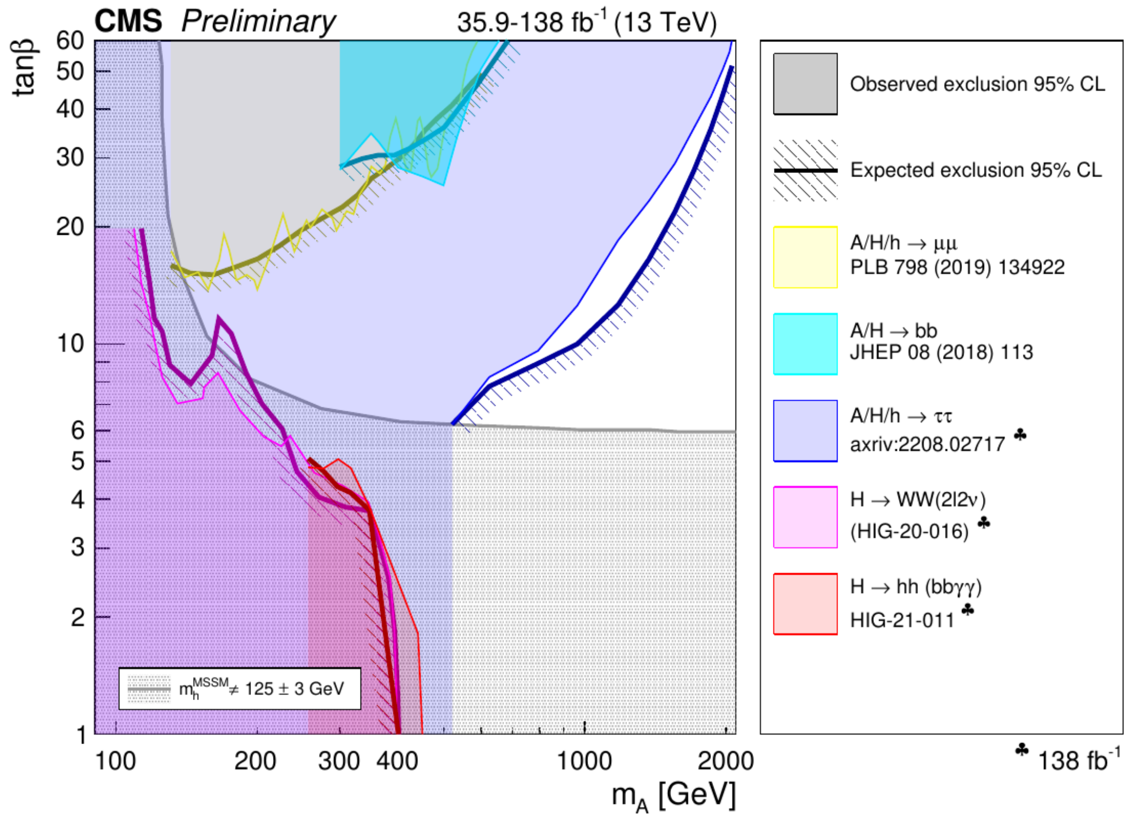


[Eur. Phys. J. C 83 (2023) 681](), [FTAG-2023-01]()



[CERN-CMS-BTV-22-001-PAS]()

- Rapid evolution in jet flavour tagging both in resolved and boosted topologies
  - BDTs → DNNs → GNN, transformer networks…
- Impressive gain in performance → increase analysis sensitivity



Observed and expected 95% CL upper limits for *mA* versus the MSSM parameter tan*β* in the h_{125} benchmark scenario, as proposed in arxiv:1808.07542