Exploring BSM through Higgs
Highlights of LHC BSM Higgs Results

Higgs Potential 2024

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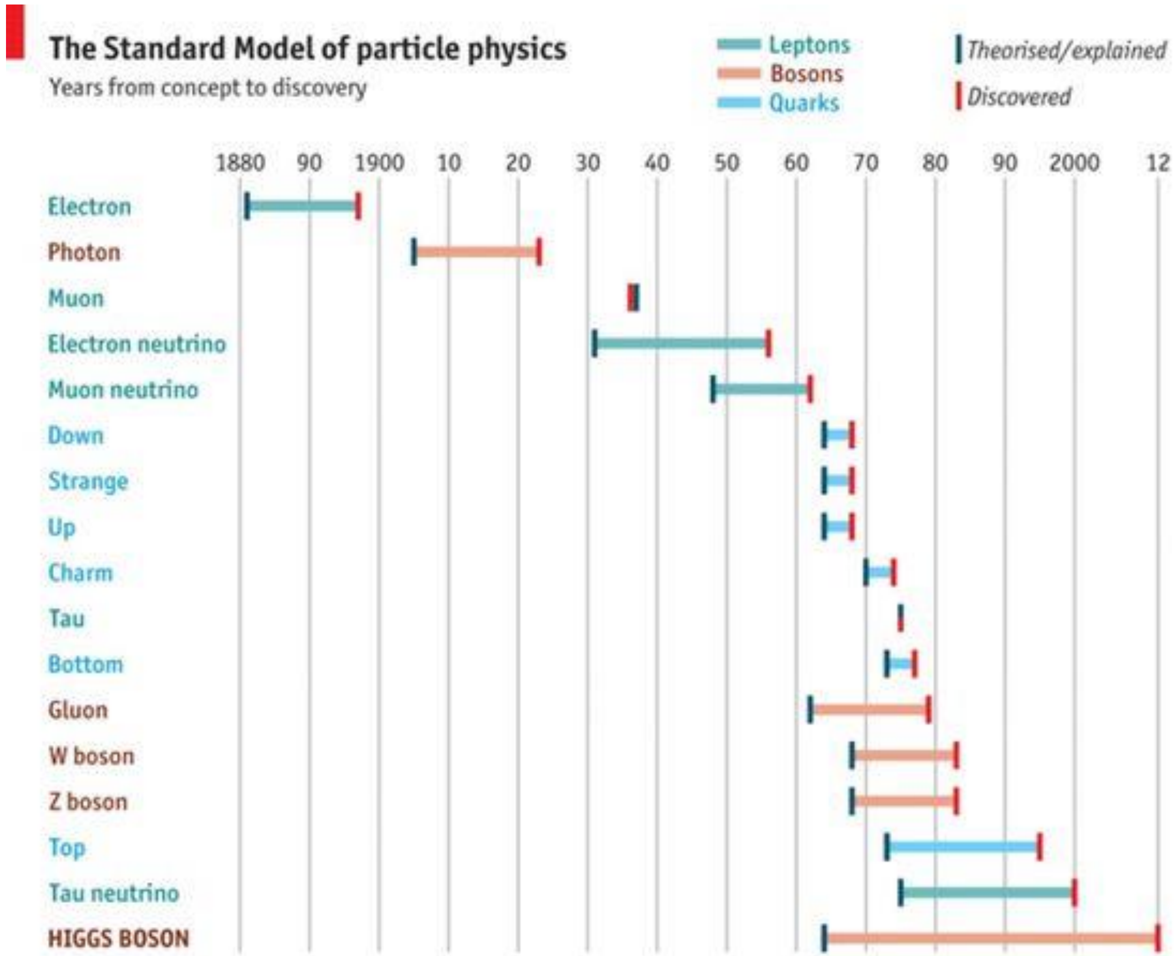
22 December 2024, USTC

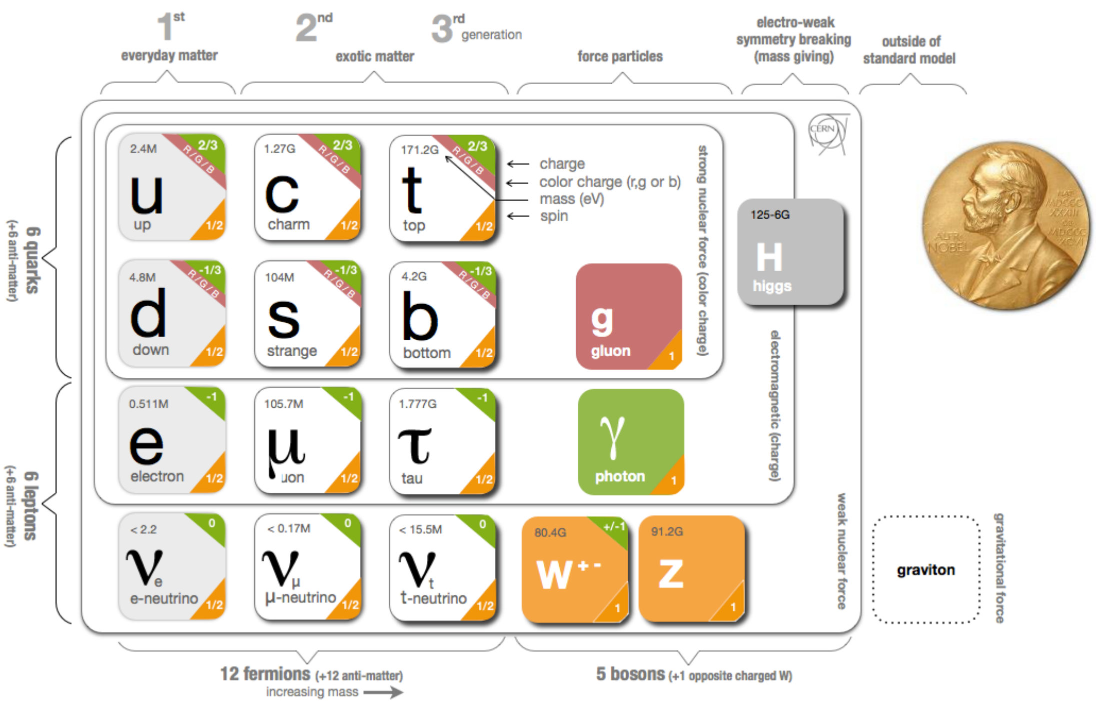
Theoretical and Experimental Particle Physics
have revealed much about the nature of our universe

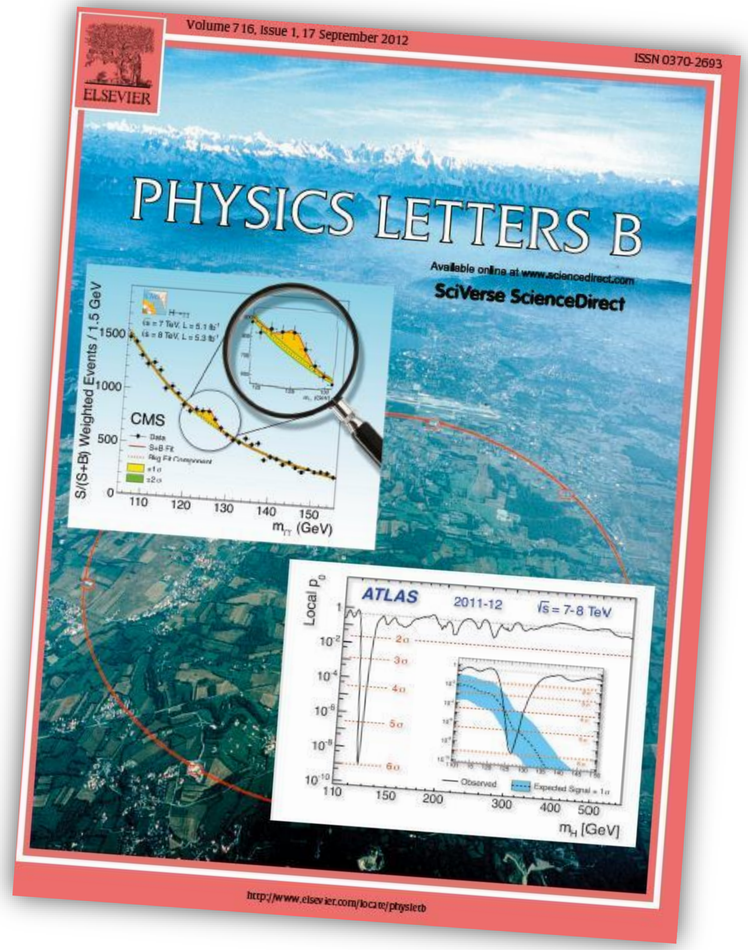


Source: economist

Higgs boson, with the existence predicted in 1964
Discovered on July 4th, 2012, by **ATLAS** and **CMS** experiments on **LHC**

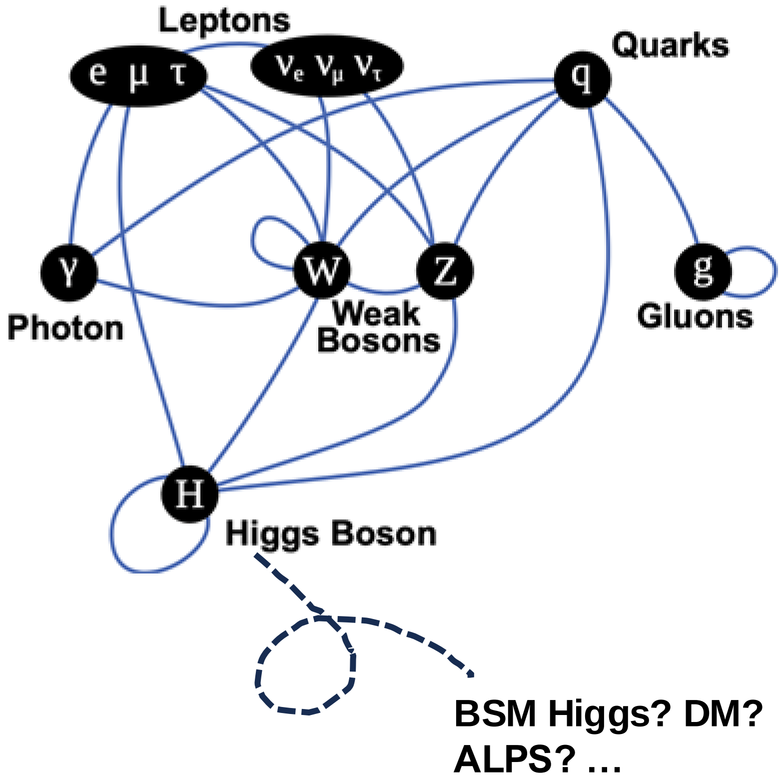
SM and Higgs boson discovery





- 2012, **Discovery of Higgs boson** → **Last piece of the elementary particle content in SM**
- Nobel Prize in Physics in 2013 → **Peter Higgs** and **François Englert**
- **So far, the SM is very successful,** that has been tested from the low to high energy experiments.

Could Higgs tell us more?



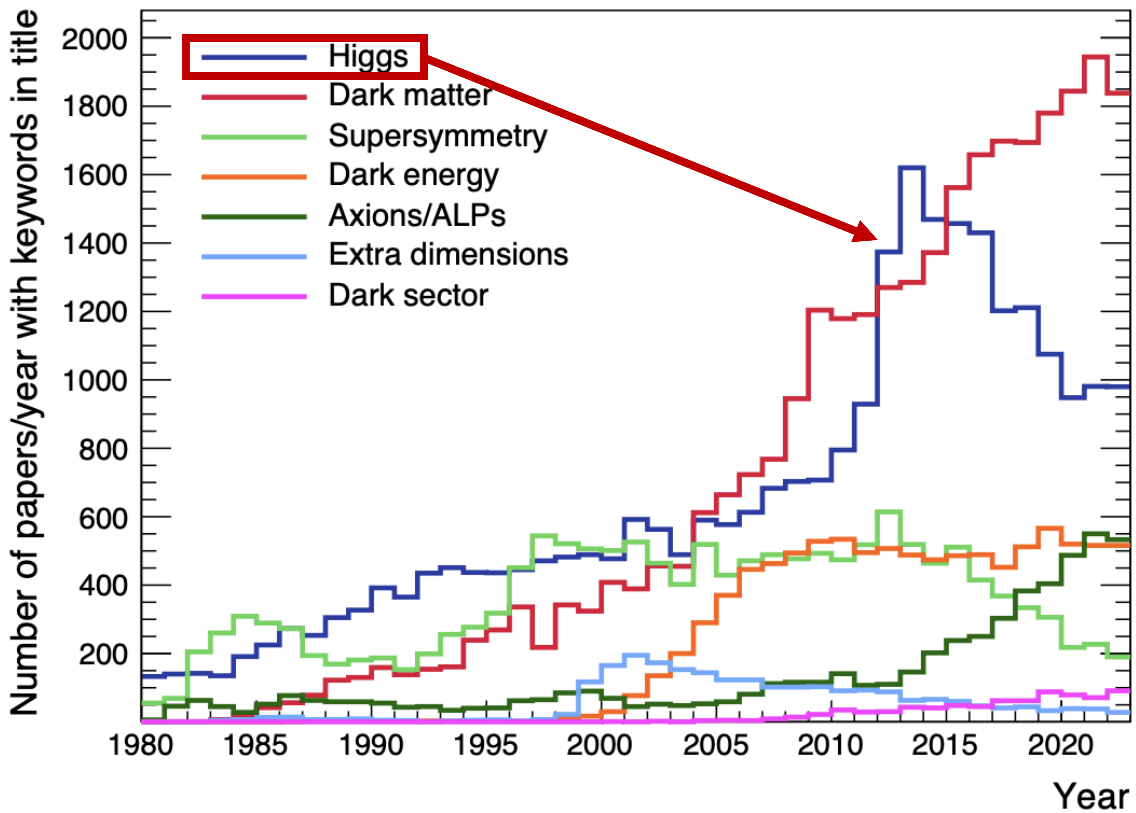
The discovery of Higgs boson completed the last piece of the SM particle content.

But **SM cannot explain**:

- What is the nature of dark matter and dark energy?
- How do neutrinos obtain their mass?
- How to include gravity in the SM ?
- …

Use Higgs as a tool to **probe new physics** to address those fundamental questions!

Connecting two pillars



INSPIRE keyword search in paper titles versus year
(credit: [Andreas Hoecker](#))

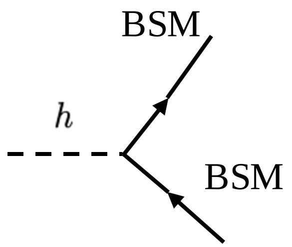
Higgs physics and **BSM searches** remain two pillars of HEP

Steady growth in Higgs and BSM research/publications

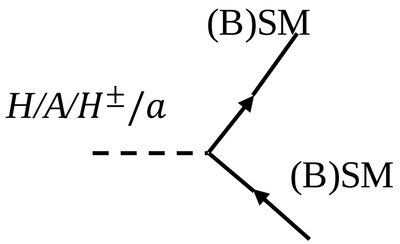
ATLAS and CMS has made **key contributions** in LHC Run 1 and Run 2**.**

Outline

I. Could Higgs decay to BSM?



II. Are there BSM Higgs bosons?

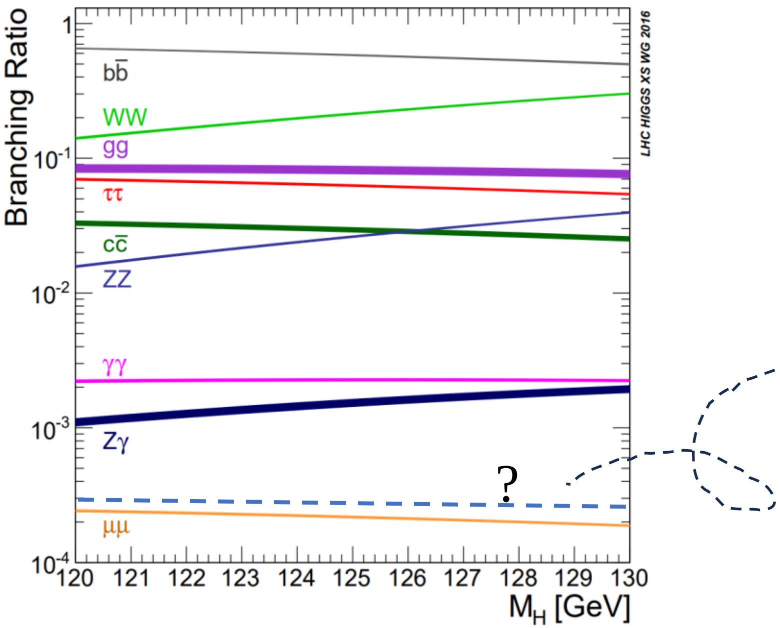


III. A joint exploration of Higgs exotic decays and the extended Higgs sector

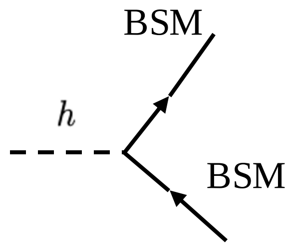
Caveats:

- A personal and incomplete selection of topics.
- More detailed discussions can be found in the many corresponding talks at this conference.
- Check out the ATLAS and CMS public page for a more comprehensive overview.

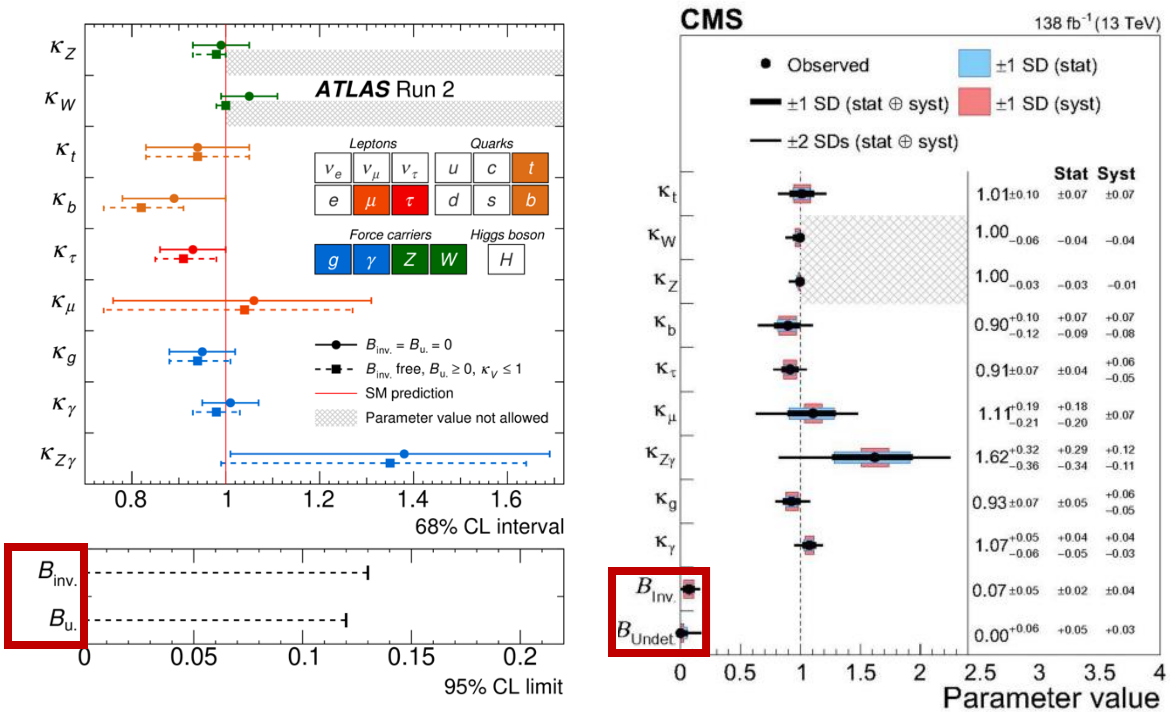
Part I: If Higgs decays to BSM



SM Higgs decay branching ratio



a lot of room for BSM contributions

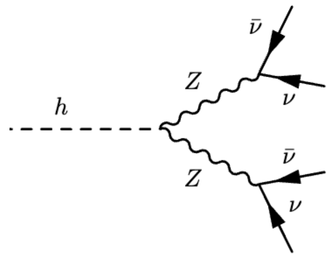


Higgs coupling global measurements (ATLAS and CMS)

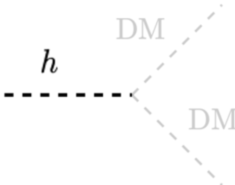
Constraints on new physics are still relatively loose (~10-20%) from the global Higgs coupling measurement: Nature, 2022, 607(7917): 52–59, Nature, 2022, 607(7917): 60–68

It is important to directly search for the Higgs BSM decay to dark matter, ALPs, pseudoscalars, etc

If Higgs is a portal to dark matter …

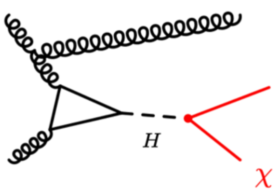


SM BR(H→inv) ~0.12%

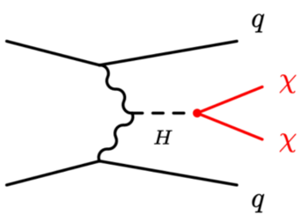


If H decays directly to DM,
BR(H→inv) can be larger

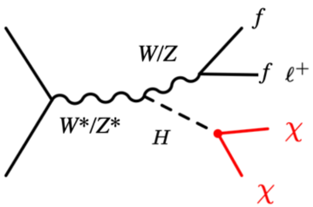
ggF (~ 49 pb)



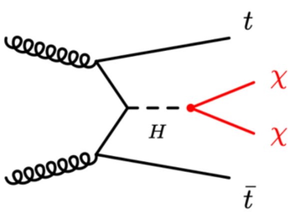
VBF (~ 3.8 pb)



VH (~ 2.3 pb)



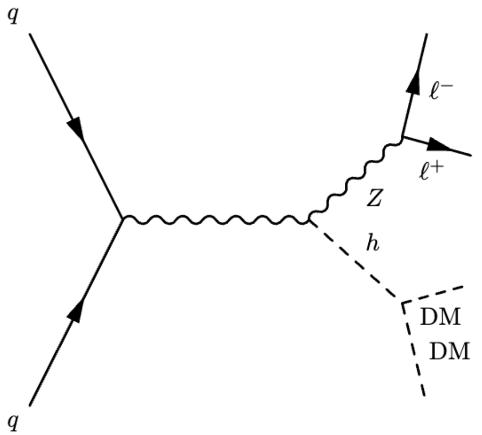
ttH (~ 0.5 pb)

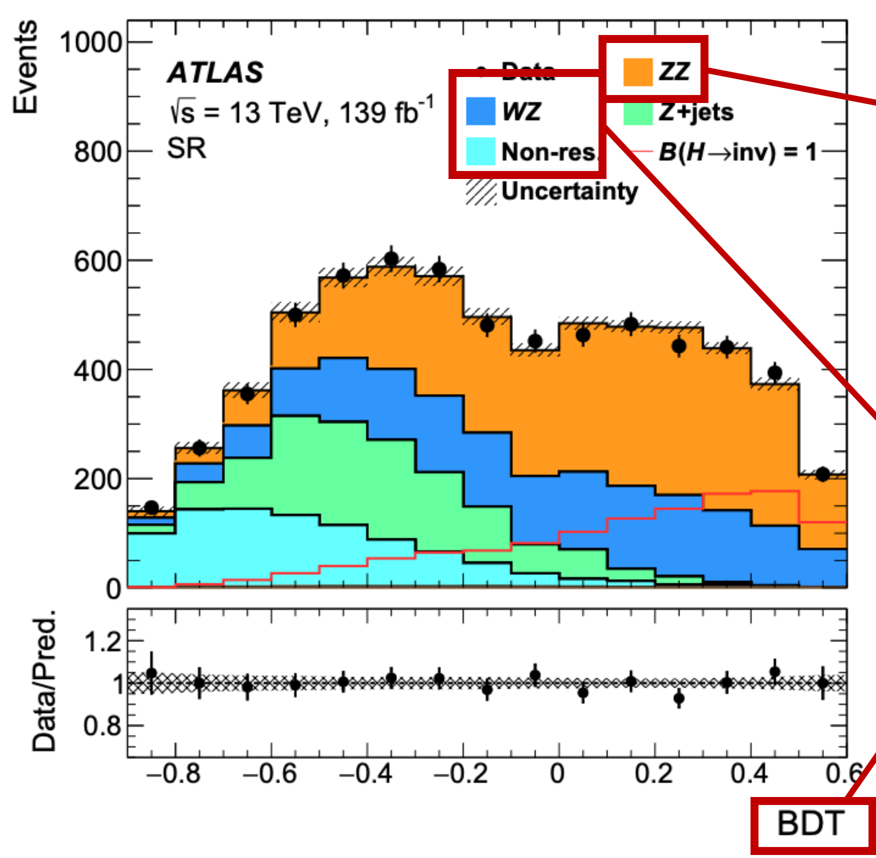


	ggF	VBF	VH	ttH
Selection	high p_T ISR jet	2 forward jets in opposite hemisphere	lepton or hadron decay from W/Z	leptonic, semi-leptonic, hadronic tt
Final state	mono-jet	**VBF + MET**, VBF + MET + ɣ	Z(ll) + MET, mono-largeR jet	tt + MET
Sensitivity	**Low**	**High**	**Intermediate**	**Intermediate**

Typical H→inv searching channels on LHC

Largely improved Hinv results in LHC run 2





State-of-the-art theoretical calculations on the major background

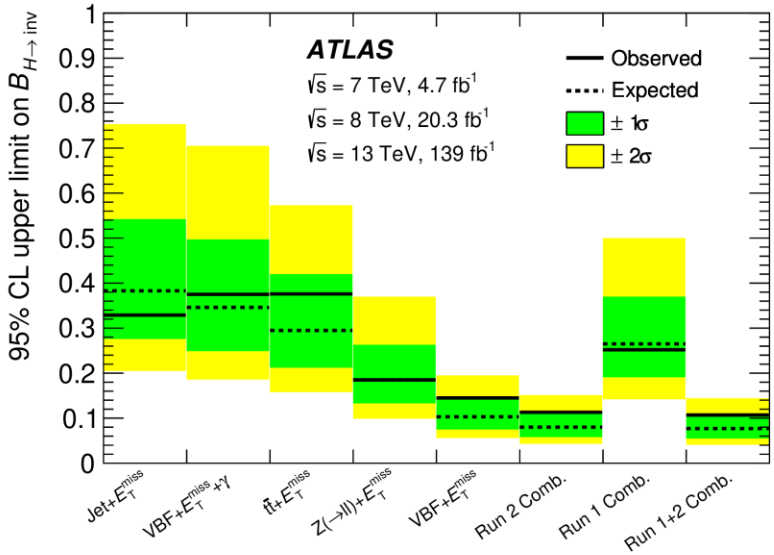
using data in CRs simultaneously to reduce background uncertainties

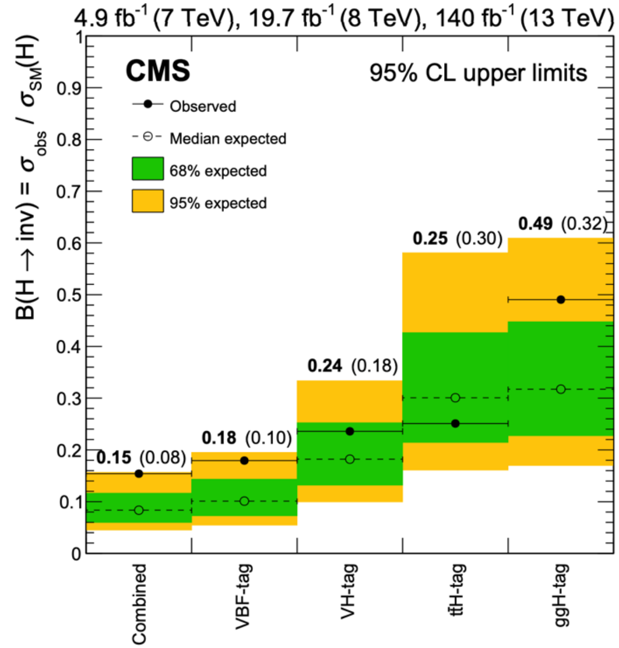
Benefit from ML observables

- Example: In the ATLAS full run 2 ZH(inv) search, **a remarkable ~45% improvement** compared to the projection
  - From **improved detector performance** and **better analysis strategies**

- ATLAS full run 2 Limit: BR(H→inv) < 19% (19%): PLB 829 (2022) 137066
  - Previous ATLAS results from 36.1 fb^{-1} dataset: BR(H→inv) < 67% (39%)
- CMS full run 2 result: BR(H→inv) < 29% (25%) EPJC 81 (2021) 13

The unprecedented limit





- The statistically combined LHC H→inv searches:
  - ATLAS: BR(H→inv) < 10.7% (7.7%) PLB 842 (2023) 137963
  - CMS: BR(H→inv) < 15% (8%) EPJC 83 (2023) 933

Uncertainty on BR (Hinv)	Absolute uncertainty	Relative contribution
Syst	0.035	91%
Stat	0.016	42%
Total	0.039	100%

The error decomposition of ATLAS results.

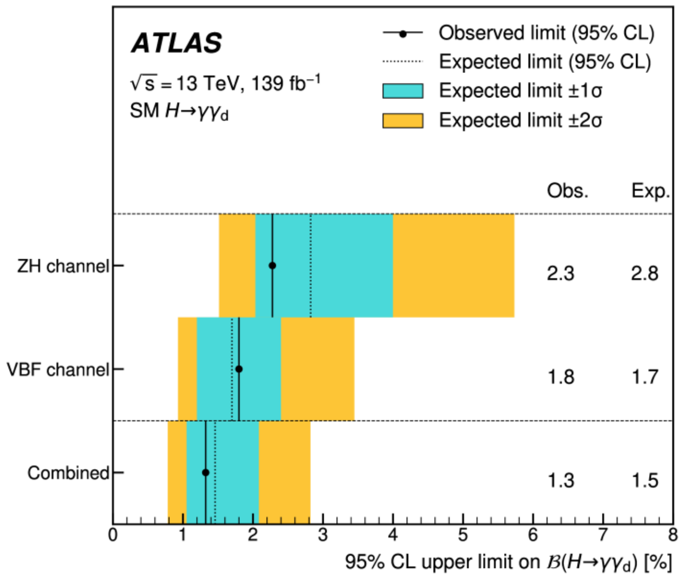
Many similar LHC searches are becoming systematic-dominated.
It is crucial to reassess strategies in run 3 and HL-LHC.

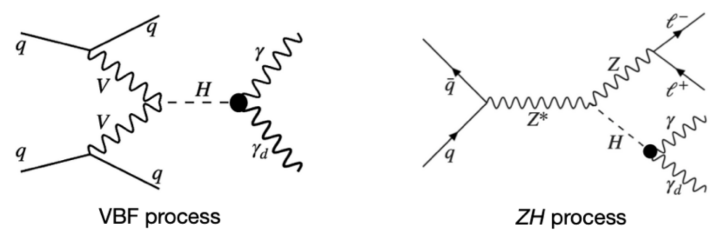
Could Higgs decays to a dark photon?

Massless dark photon retain small couplings to Higgs, modifying SM Higgs decay

- A relatively under-explored scenario. Experimental limits were far above the theoretical constraint.

- In Run 2, ATLAS and CMS had combined ZH and VBF channels to maximize the sensitivity.





VBF		ZH		VBF+ZH	
Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)
3.5	$2.8^{+1.3}_{-0.8}$	4.6	$3.6^{+2.0}_{-1.2}$	2.9	$2.1^{+1.0}_{-0.7}$

ATLAS results: JHEP 08 (2024) 153

CMS results: JHEP 03 (2021) 011

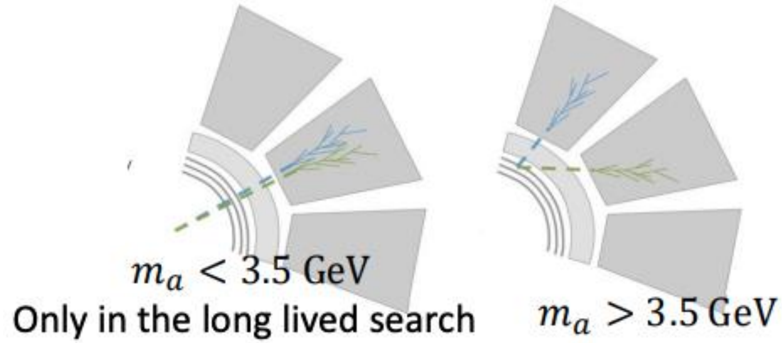
New photon + MET trigger strategy to benefit from the ggF production rate?

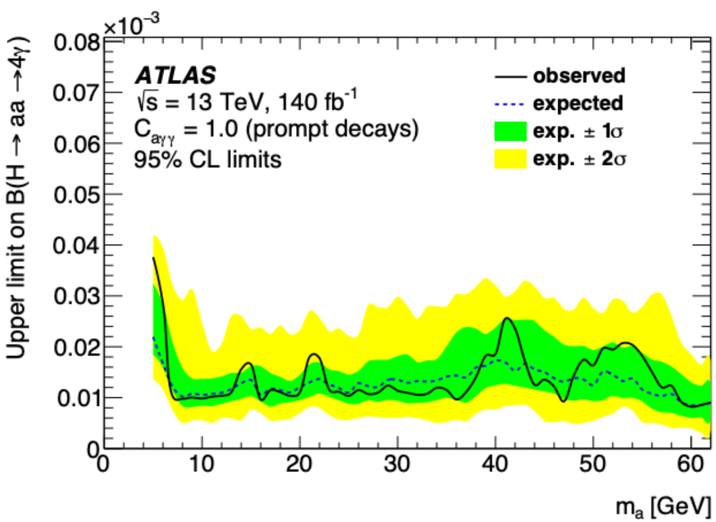
Could Higgs decay to ALPs?

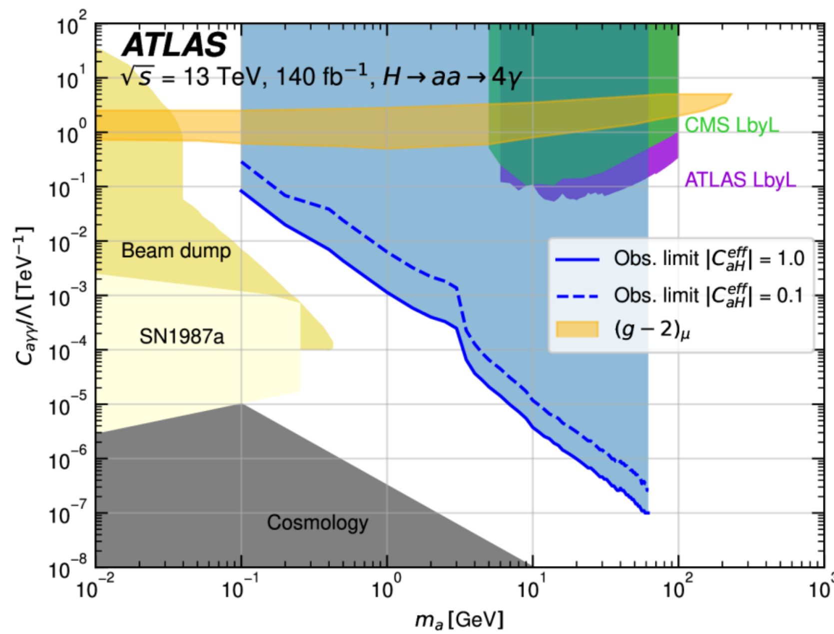
ATLAS probed ALPs through $H \to aa \to 4\gamma$

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

- **Collimated signature:** identified as single object when $m_a < 3.5$ GeV
- Both **Prompt (major sensitivity)** and **long-lived** signatures included





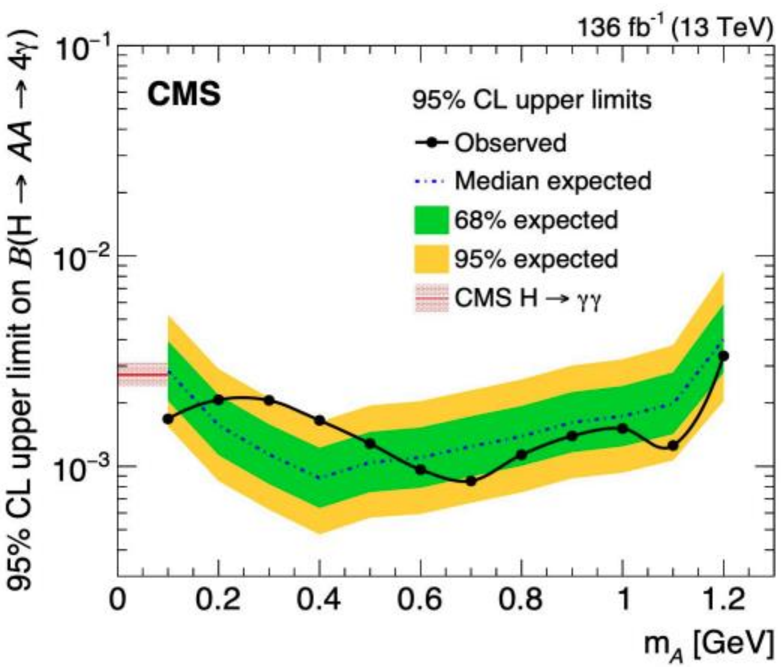


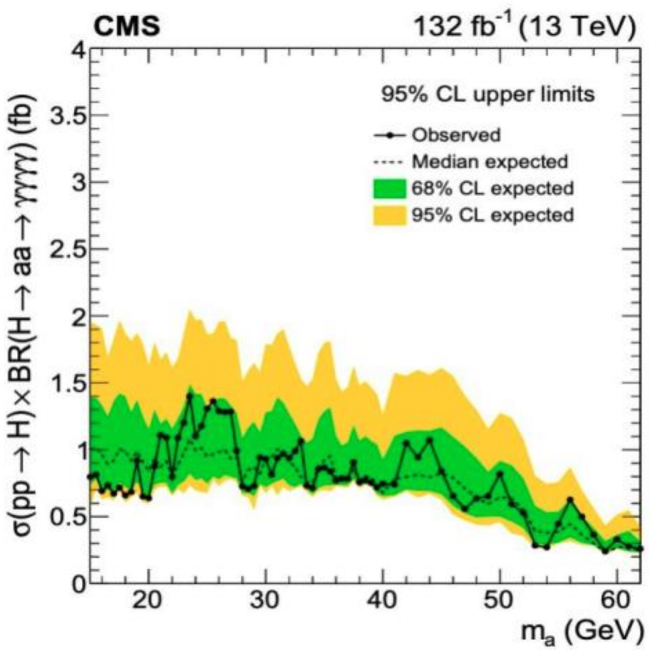
- Coverage of the mass range: 0.1 to 62 GeV

Could Higgs decay to ALPs?

CMS probed ALPs through $H \rightarrow aa \rightarrow 4\gamma$

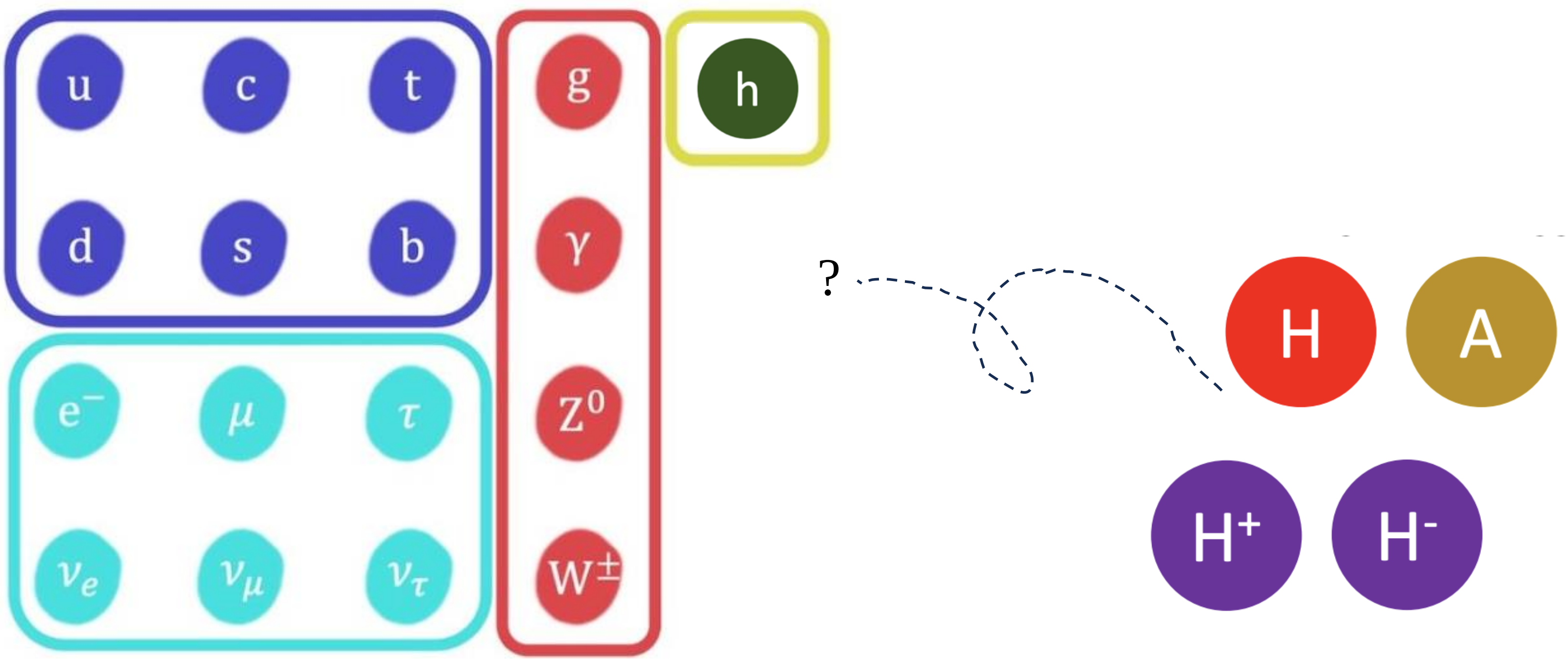
- **Low Mass: 0.1 - 1.2 GeV** Phys. Rev. Lett. 131 (2023) 101801
  - Merged $\gamma\gamma$ object
- **Higher Mass: 15 – 62 GeV** JHEP 07 (2023) 148
  - Well isolated and fully reconstructed photons





Many extensions of the SM predict additional Higgs bosons, incorporating solutions to the puzzles SM cannot explain:

- Two Higgs Doublet Models (2HDM), Higgs-MSSM (hMSSM), Georgi-Machacek model + many more

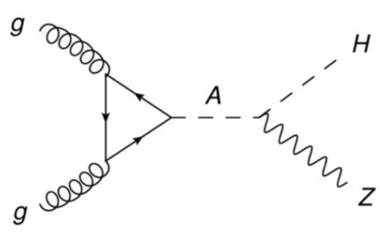


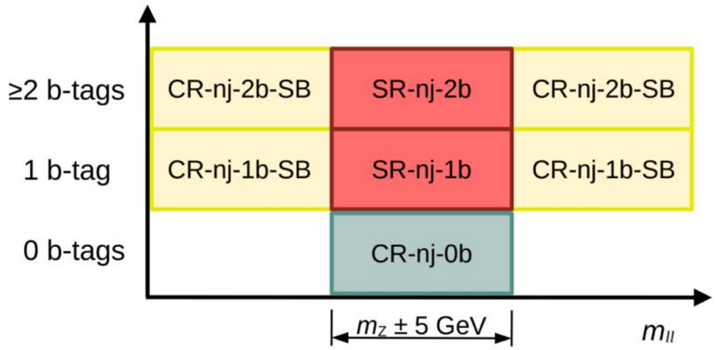
Search for two BSM scalars at once

***A → ZH → llt$\bar{t}$* Search:** 2412.00570

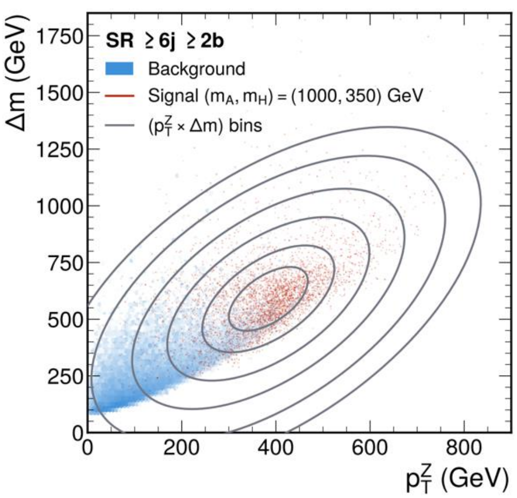
Region with 400 GeV < $mH \ll mA$ is unexplored.

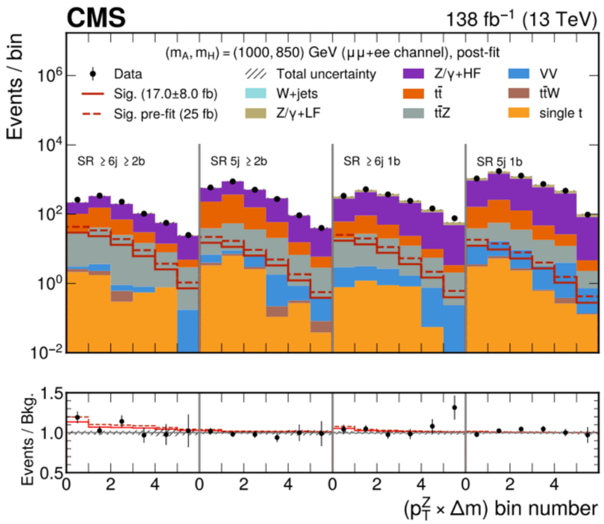
- This region is favored by some electroweak baryogenesis scenarios.

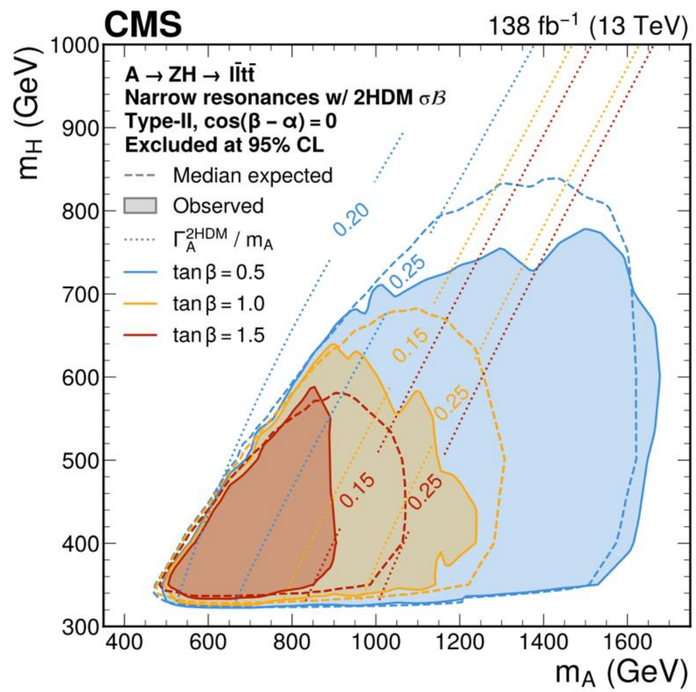




with n = 5, ≥6





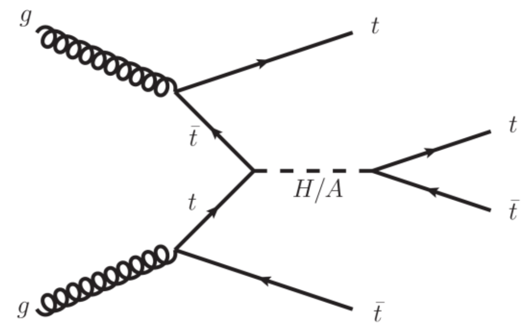


Exclusions at various tan**β**

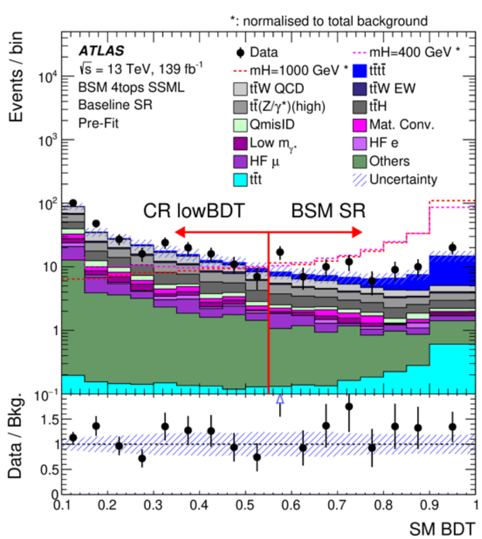
Elliptical bins (Δm(A,H), p_T^Z) is the discriminant

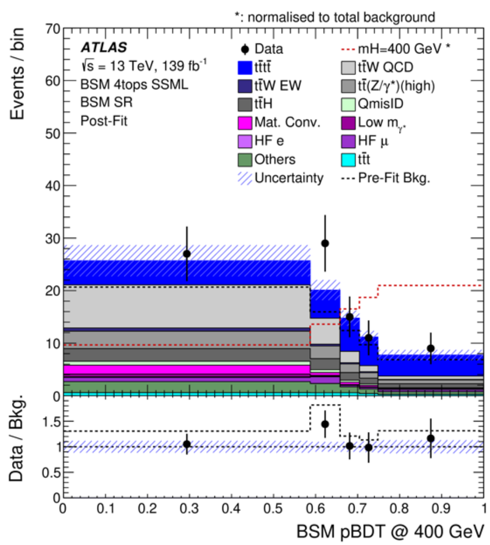
***ttH/A → 4-top* Search:** [JHEP 07 (2023) 203]

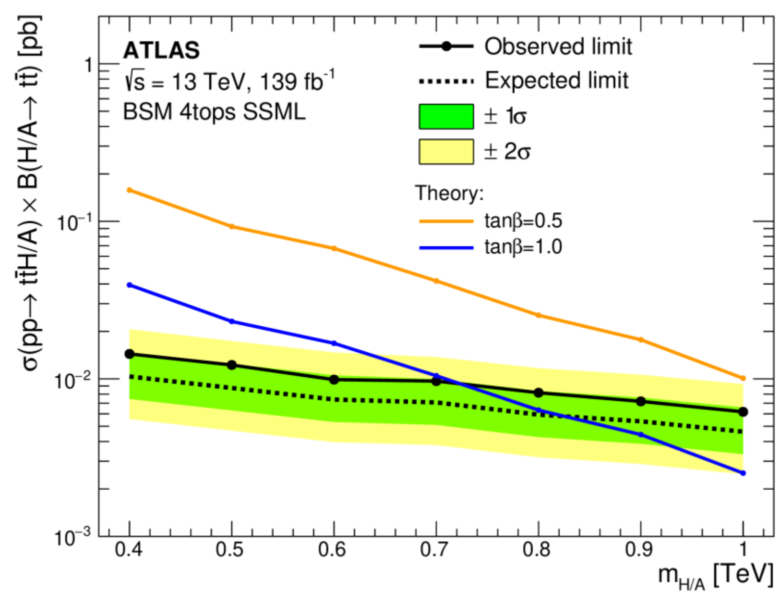
Targeting **Type-II 2HDM**, looking into multi-lepton signatures.



A **SM-BDT** to discriminate SM backgrounds from $tttt$ events, then a **BSM-pBDT** to distinguish BSM $tttt$ events from SM $tttt$ events and other backgrounds

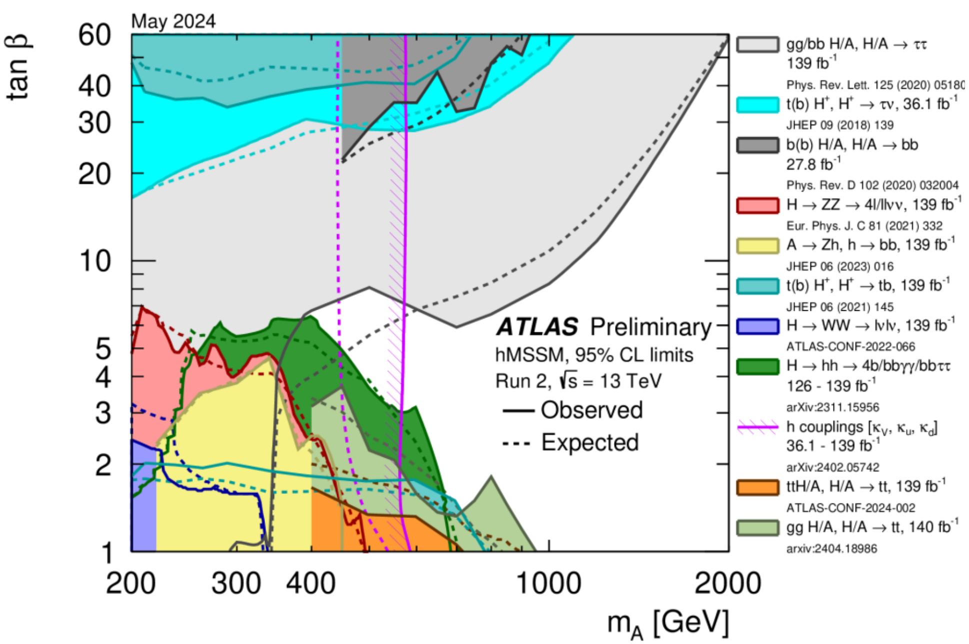


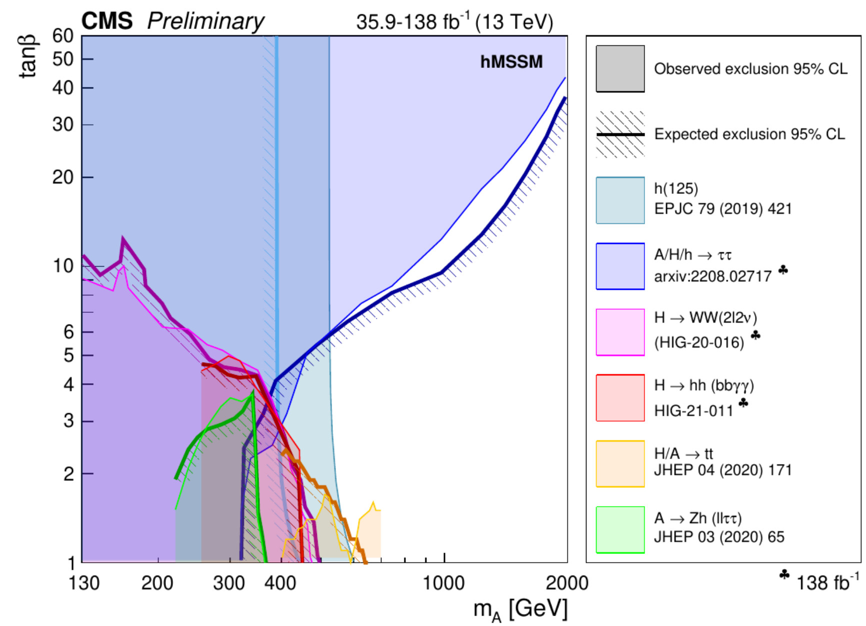




BSM Higgs search summary

- Complementarity from different signatures are clearly shown.
- Single Higgs coupling measurements play an important role.



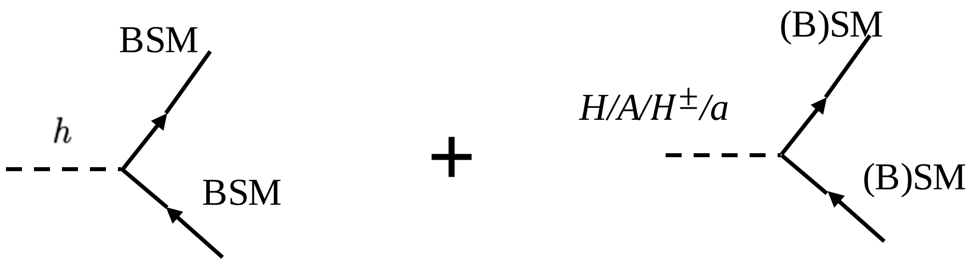


ATLAS hMSSM summary

CMS hMSSM summary

On LHC, **Theoretical benchmarks** are important to sharpen the regions of interest.

- **Optimize searches** and **characterize a possible discovery**



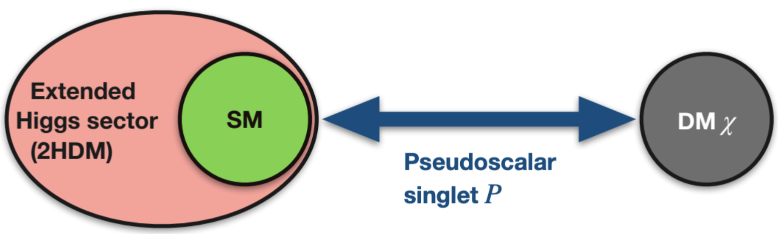
With the strategic use of benchmark models, we can synergize **Higgs BSM decays** and **direct searches for BSM Higgs** to achieve greater sensitivity and broaden our understanding of BSM

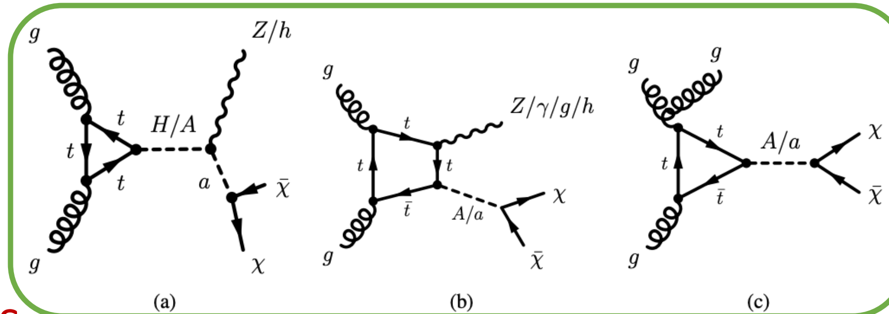
Search for DM with the extended Higgs sector

DM with an extended Higgs sector: **simple** but **realistic**

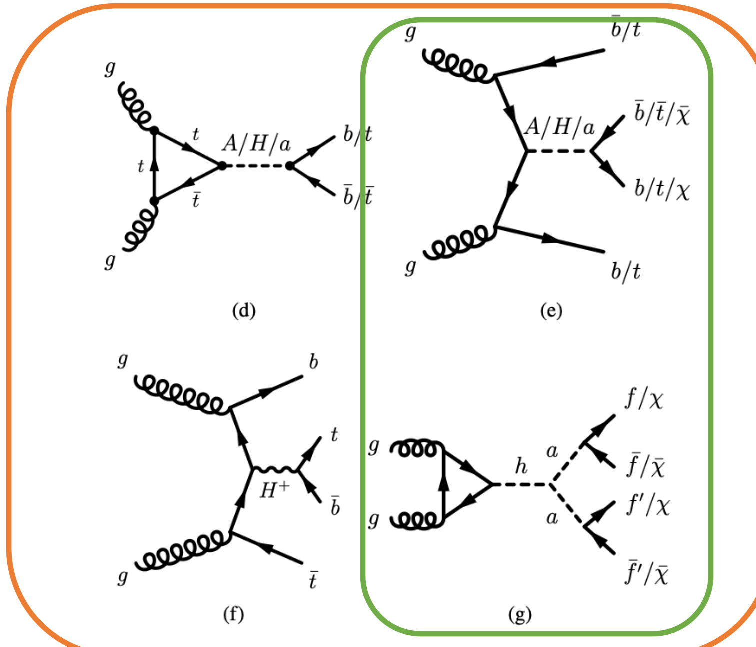
2HDM+a is a minimal and UV-complete benchmark DM model on LHC:

- Collider is more sensitive than DD-SD experiments.
- Rich phenomenology → one of the most extensive DM search projects in ATLA and CMS.



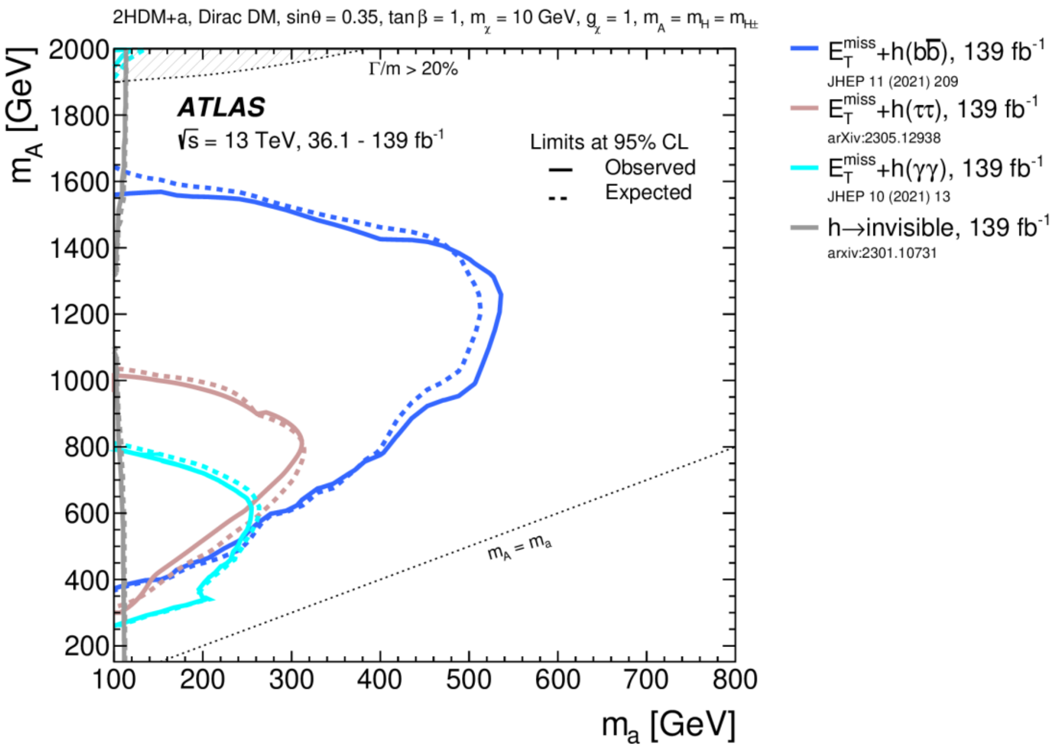


- Access to DM-SM interaction via
  - MET+X (mediator -> invisible, including h -> inv decay)
  - Non-MET (mediator -> visible, including exotic scalar searches and higgs exotic decays)



How does the sensitivity evolve?

Science Bulletin 69 (2024) 3005

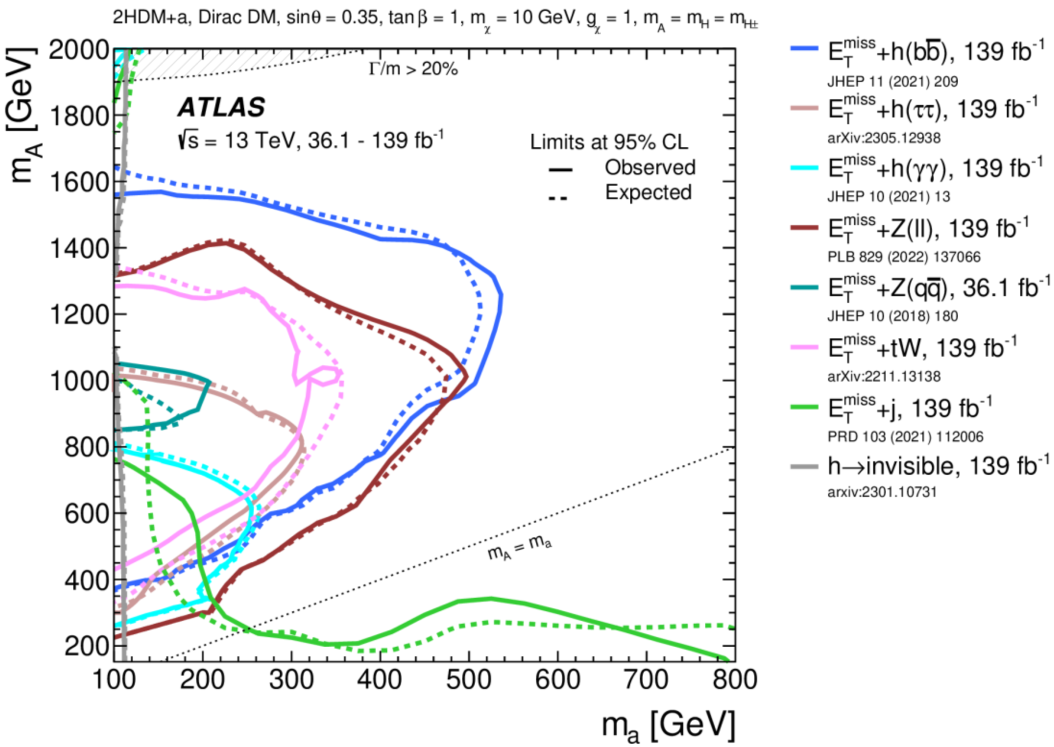


Higgs + DM signatures

DM appears in the final state together with Higgs

How does the sensitivity evolve?

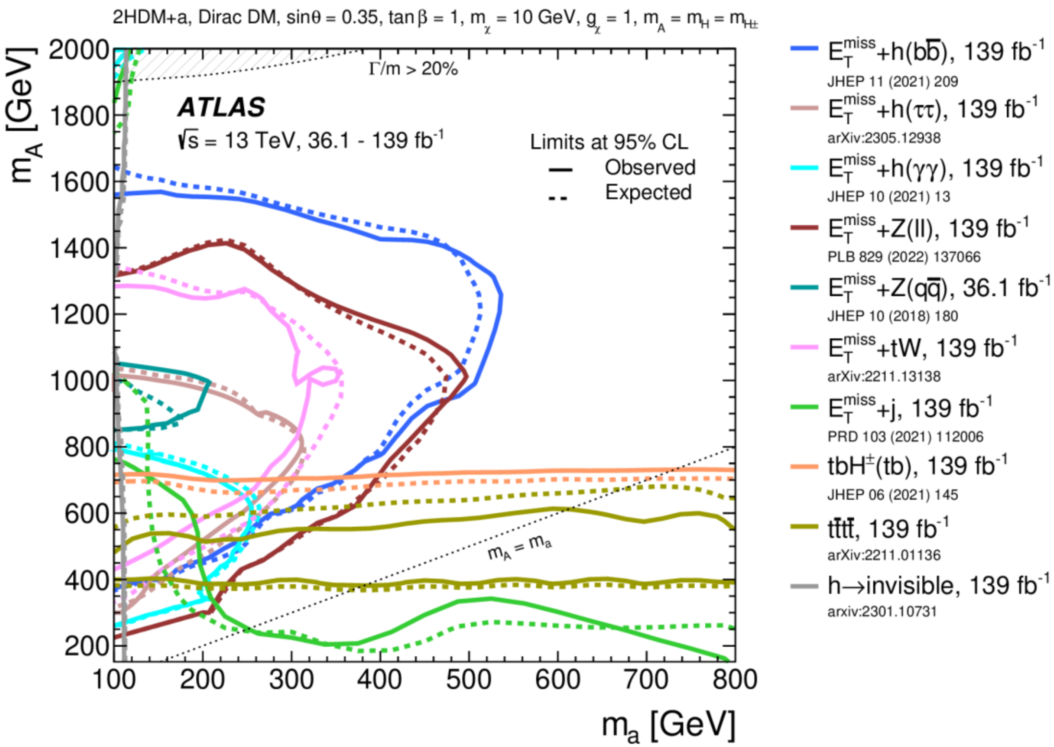
Science Bulletin 69 (2024) 3005



Add X + DM signatures, sensitivities largely improved at lower m_A

DM appears in the final state together with other SM particles

Science Bulletin 69 (2024) 3005

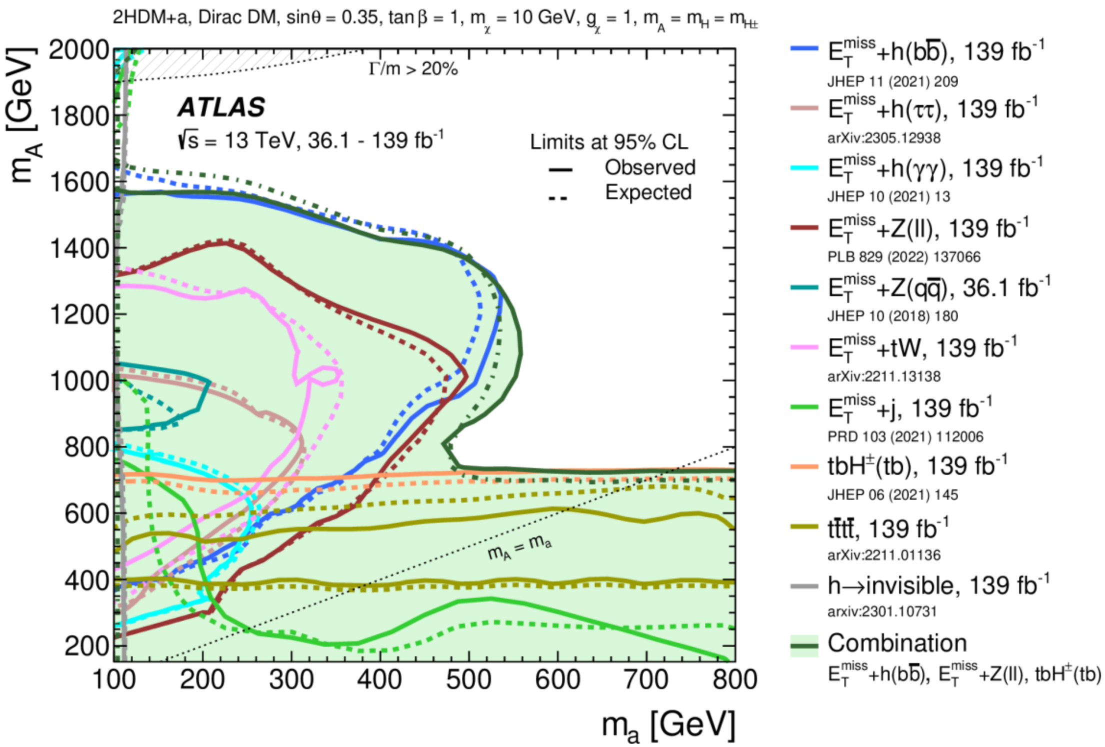


Add **exotic Higgs boson signatures**, complementarity obtained from resonant signatures.

DM doesn’t need to appear in the final state

How does the sensitivity evolve?

Science Bulletin 69 (2024) 3005

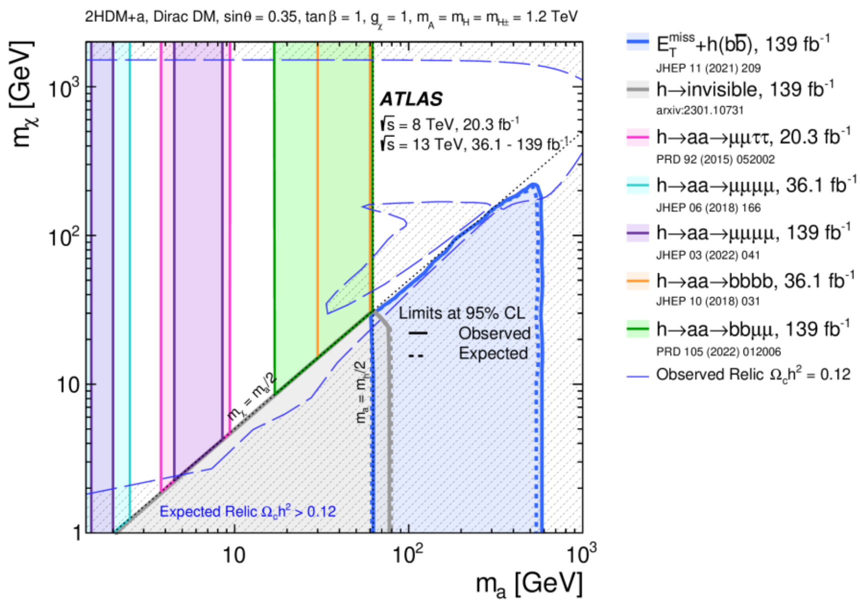


Combine analyses – reaching the best sensitivity!

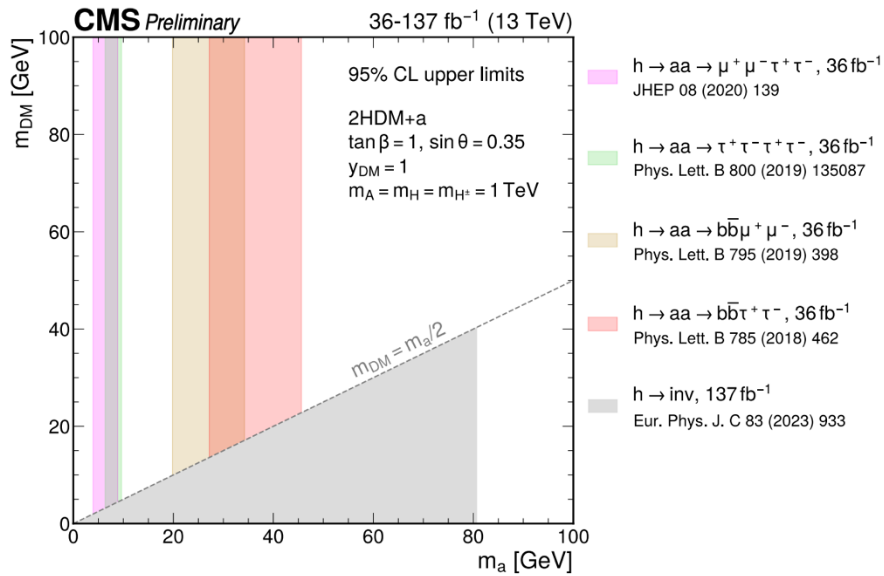
Having three most sensitive channels combined

Higgs exotic decays also helps

Science Bulletin 69 (2024) 3005



CMS DM Summary Plots

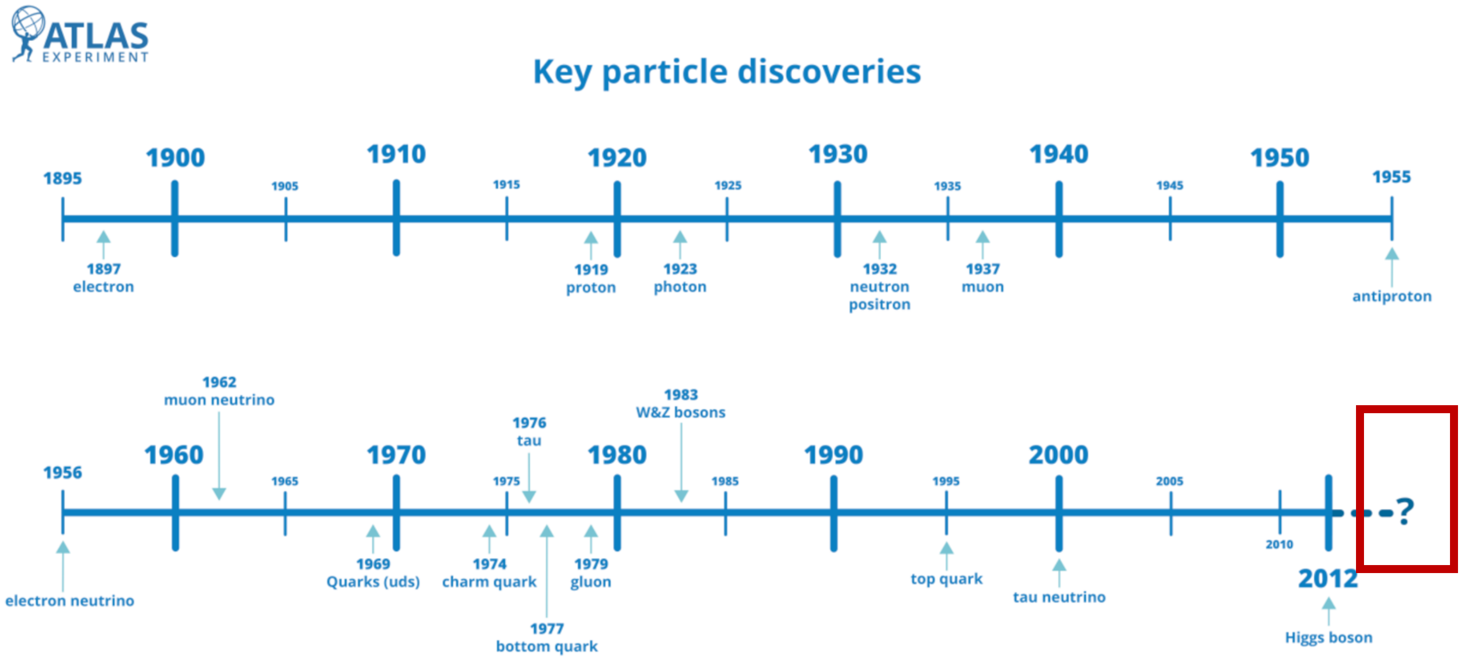


Exclusions from multiple channels in a DM-mediator mass plane

- The sensitivities of ***H → aa → 4f*** and ***H → inv*** complement each other effectively, and dominated the parameter space searched.
- BSM Higgs searches shed light on the dark matter searches!

Summary

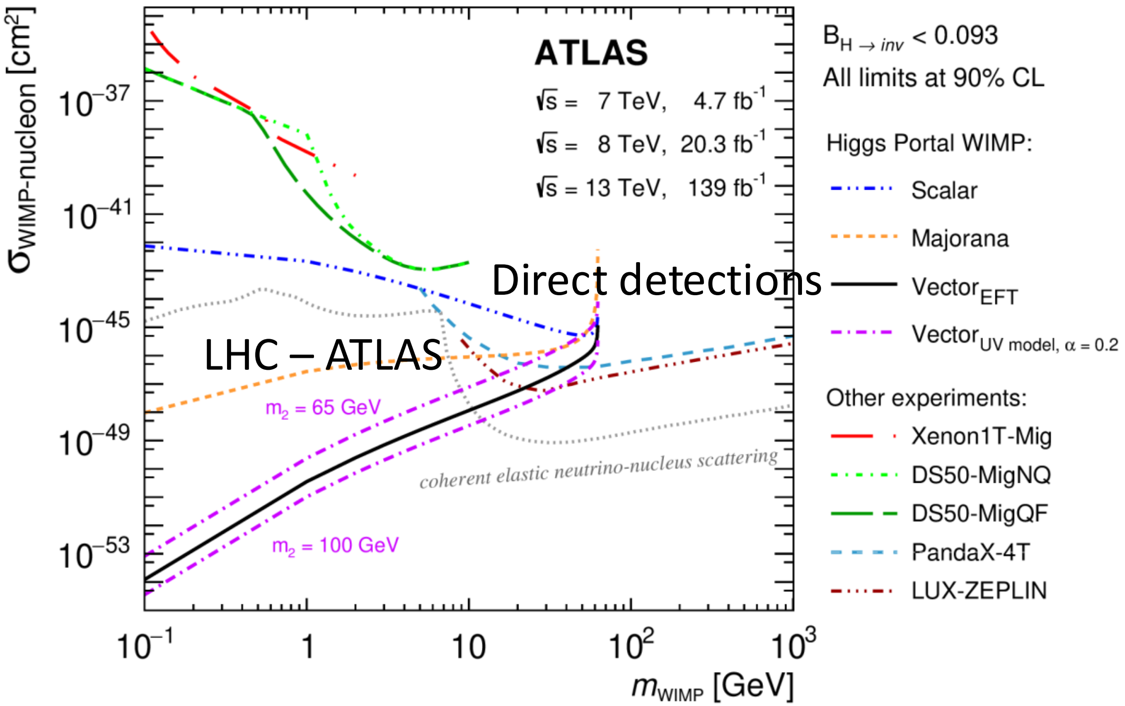
- Many theories, of various degrees of complexity, bridging Higgs and BSM.
- It is important to cover all this ground and also prepare for unexpected, not-yet-theorised discoveries.
- **No stone must be left unturned till probing the New Physics!**



Thanks

Backup

A better result on the Higgs portal



DM-nucleon cross-section limits

- **Significant complementarity** between LHC and direct detection experiments on DM-nucleon cross-section limits through the Higgs-portal model.

Hinv error decomposition

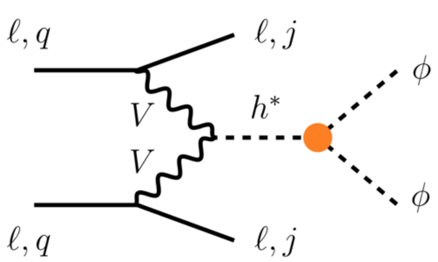
Source of uncertainty	Jet +	VBF + + γ	$t\bar{t}$ +	$Z(\rightarrow \ell\ell)$ +	VBF +	Run 2	Run 1	Run 1+2
Luminosity / pile up	0.037	0.022	0.004	0.016	0.002	0.005	0.010	0.005
Leptons / Photons	0.135	0.020	0.016	0.016	0.017	0.014	0.007	0.013
Jets	0.077	0.037	0.038	0.032	0.019	0.013	0.061	0.013
Flavour tagging	0.039	0.000	0.022	0.002	0.000	0.002	0.005	0.001
E_T^{miss}	0.049	0.012	0.014	0.011	0.007	0.004	0.009	0.003
MC statistics	0.018	0.037	0.007	0.017	0.019	0.013	0.049	0.012
All experimental	0.163	0.064	0.050	0.046	0.032	0.024	0.078	0.023
V+jets modelling	0.104	0.071	0.006	0.017	0.026	0.019	0.054	0.018
Other background Modelling	0.024	0.000	0.066	0.050	0.009	0.014	0.058	0.014
Data-driven Backgrounds	0.080	0.012	0.004	0.013	0.016	0.011	0.017	0.010
Signal Modelling	0.023	0.008	0.012	0.011	0.003	0.002	0.044	0.003
All theory	0.138	0.072	0.067	0.055	0.032	0.025	0.088	0.024
Total systematic uncertainty	0.189	0.099	0.090	0.077	0.046	0.037	0.116	0.035
Data statistics	0.017	0.120	0.094	0.051	0.017	0.011	0.058	0.011
Background normalization	0.020	0.022	0.053	0.010	0.018	0.012	0.055	0.012
Total statistical uncertainty	0.026	0.122	0.108	0.052	0.024	0.017	0.080	0.016
Total uncertainty	0.191	0.157	0.140	0.092	0.052	0.041	0.141	0.039

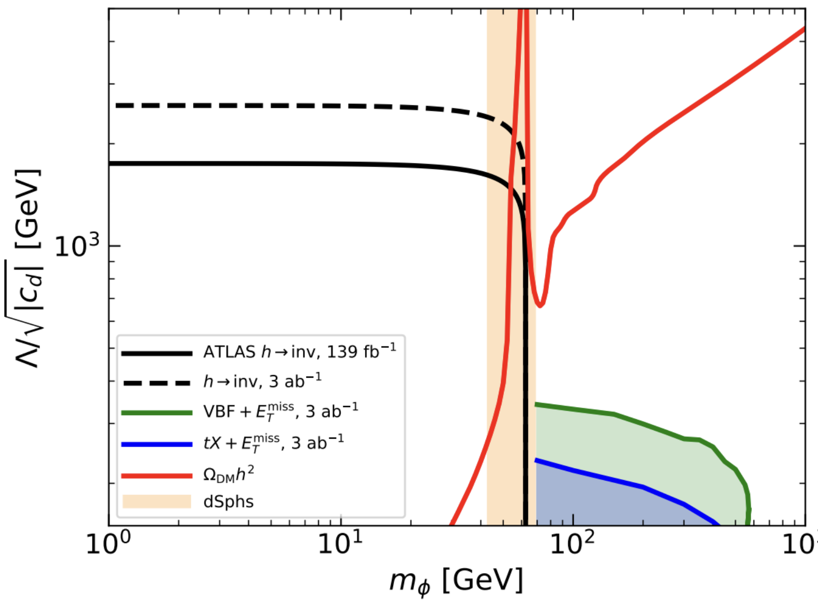
- The Combined results and VBF/ZH channels **already dominated by systematics**.

Look into offshell Higgs portal

Offshell Higgsportal: Postulate a derivative Higgs portal, with extra pNGB scalar makes attractive DM candidates (Theory talk on CDM).

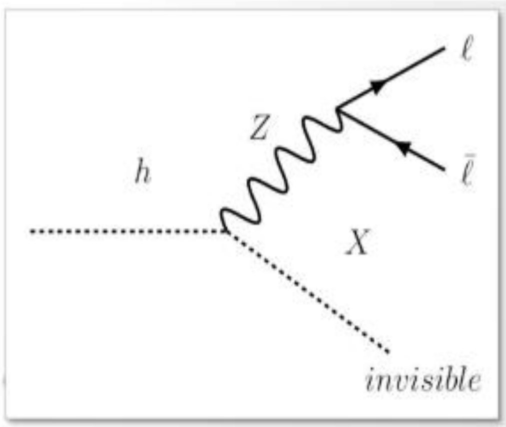
- Evade direct detection constraints by the momentum suppression.
- Dominant interactions are with heavy particles.
- VBF+MET, tt/tW+MET are important signatures.
- Signal process is being studied by Run 3 VBF+MET and tt+MET.





New in Run 3: if Higgs decay semi-visibly?

- **Partially invisible (semi-dark) Higgs boson decays** constitutes a much less explored avenue. h->ZX is particularly unexplored previously.
- Such searches are fully complementary to searches for invisible Higgs decays
- Pheno study: 2206.01214



Aguilar-Saavedra, Cano, Cerdeño, No, 2206.01214

- Higgs $\rightarrow$ visible
- Higgs $\rightarrow$ invisible
- Higgs $\rightarrow$ semi-invisible **poorly explored so far...**

Th.

Englert, Spannowsky, Wymant, Phys.Lett.B 718 (2012), 538

$h \rightarrow aa$ (jets + MET)

Petersson, Romagnoni, Torre, JHEP 10 (2012), 016

$h \rightarrow \gamma$ + MET

Reviews by Curtin et al. (1312.4992), Cepeda et al. (2111.12751) cover few more channels/models:

bb + MET, $\tau\tau$ + MET, $\gamma\gamma$ + MET...

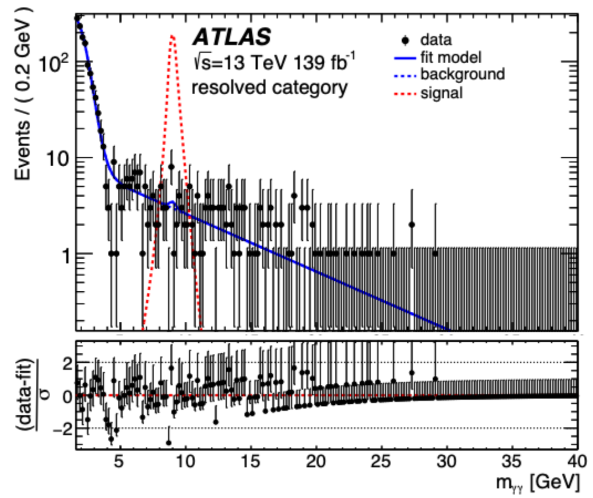
Exp.

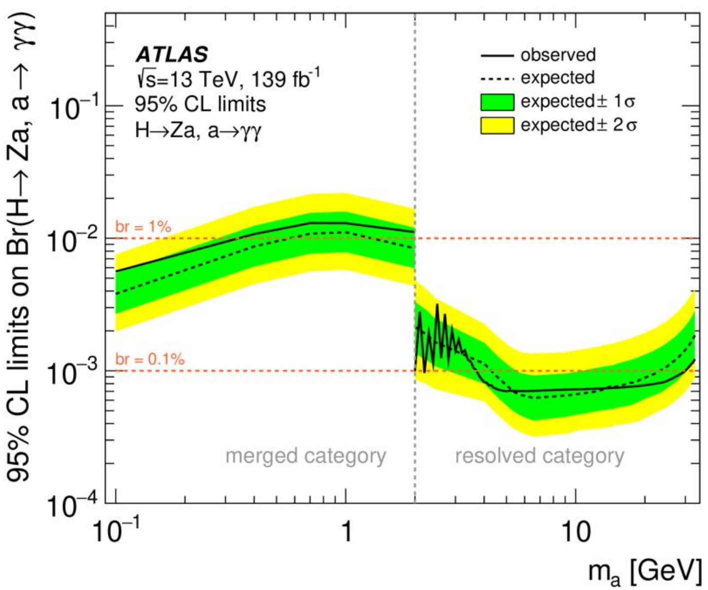
$h \to s/v + E_T^{miss}$					
Decay	Mode	Reference	$\sqrt{s}$ (TeV)	$\int \mathcal{L}$ (fb^{-1})	Interpretations
$E_T^{miss} + \gamma$	VBF	CMS [113]	13	130	SM+v
	VBF	ATLAS [114]	13	139	SM+v
	Zh	CMS [109]	13	137	SM+v
	ggF, Zh	CMS [115]	8	19.4	Other
$E_T^{miss} + bb$	Zh	ATLAS [116]	13	139	NMSSM

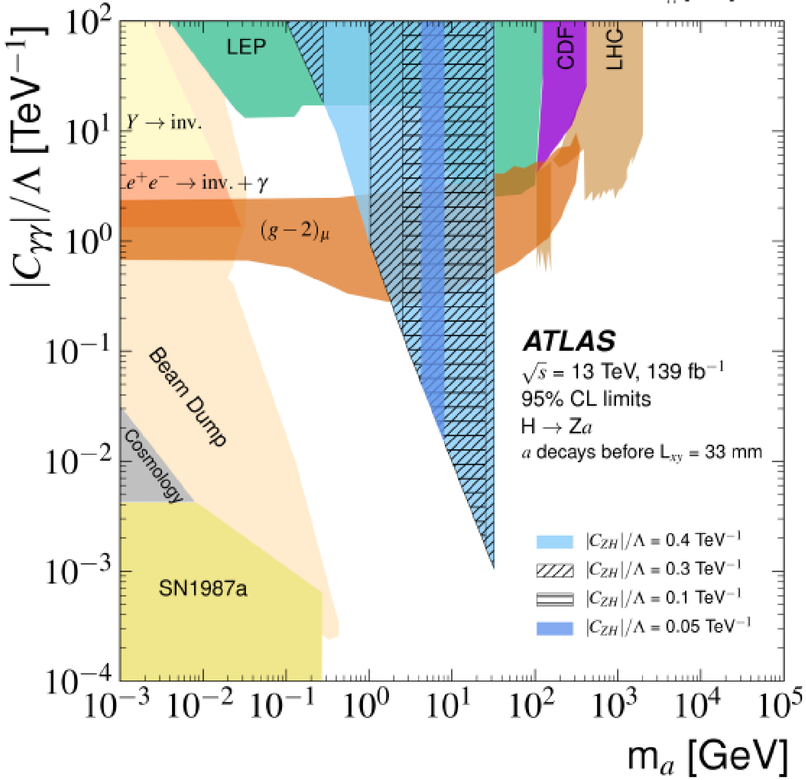
ALPs through $H \to Za$, $a \to \gamma\gamma$

ALP mass range probed: $0.1 < m_a < 33$ GeV
Phys. Lett. B 848 (2024) 138536

- **Collimated signature:** identified as single object when $m_a < 2$ GeV
- Final state contains a lepton pair from Z decay and one (merged) or two (resolved) photons from a







Complementary sensitivities between **merged** and **resolved** categories