Rare Higgs decays, Higgs BSM and di-Higgs production

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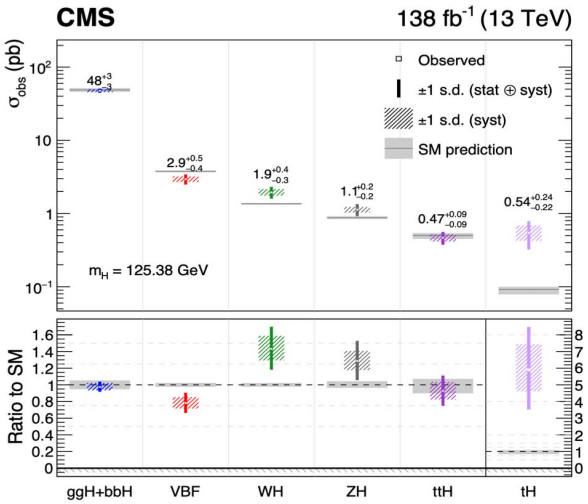
on behalf of the ATLAS & CMS collaborations

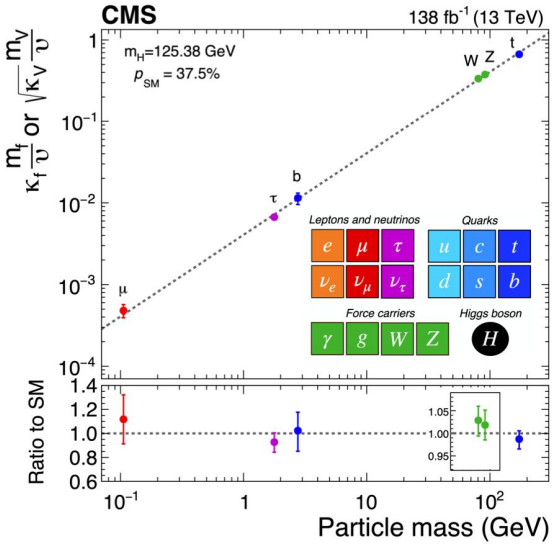
LA THUILE 2024 - Les Rencontres de Physique de la Vallée d'Aoste
8 march 2024

Higgs boson

It is the only elementary particle with spin0. It has zero electric charge
It is even under parity and charge conjugation.

$$J^{PC} = 0^{++}$$





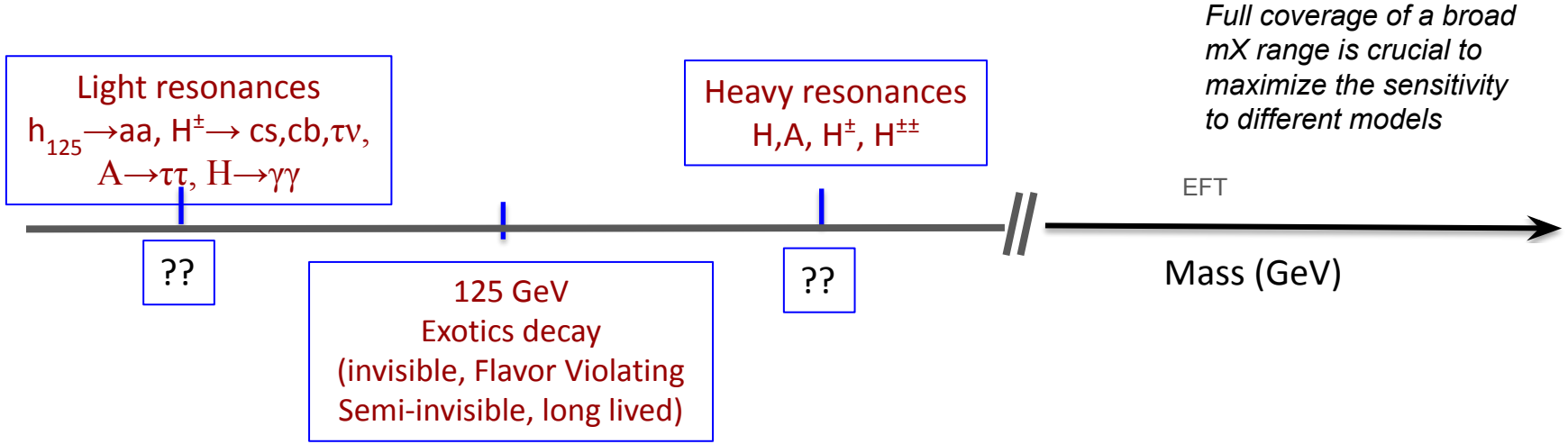
SM test over many orders of magnitude

more to measure $\sigma_{HH} \sim 10\text{-}3\ \sigma_H$

Introduction into BSM Higgs Sector

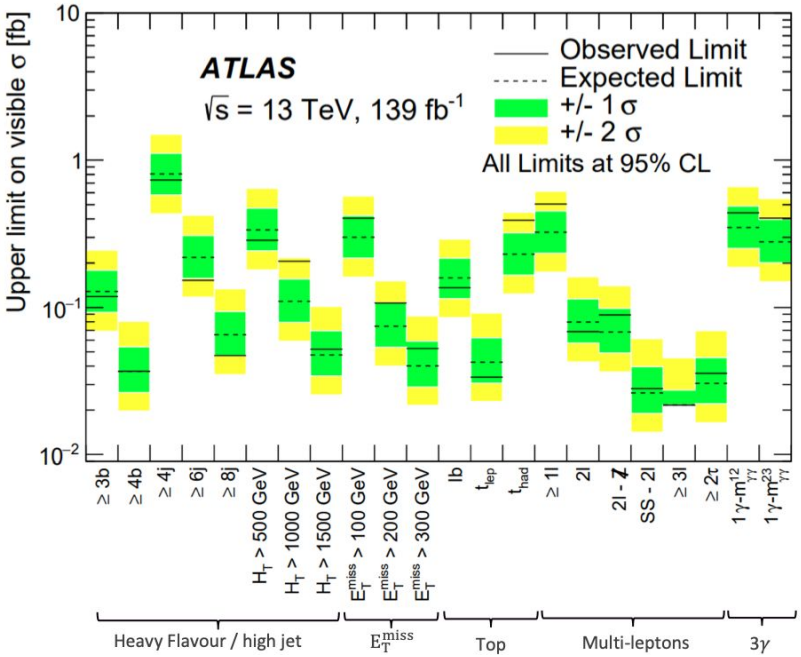
Many extensions of the SM introduce additional fields that produce additional physical Higgs bosons, for example:

- Electroweak Singlet Model: SM Higgs doublet + additional singlet
- Two Higgs Doublet Model (2HDM, e.g. MSSM): SM Higgs doublet + additional doublet
- 2HDM + singlet (e.g. NMSSM): SM Higgs doublet + additional doublet + additional singlet
- Higgs triplet model: SM Higgs doublet + additional triplet
- Georgi-Machacek model (GM): SM Higgs doublet + 2 additional triplets



Model independent search with $h_{125} \rightarrow \gamma\gamma$

Although small x-sections, channels w/ $\gamma\gamma$ provide the **cleanest signature to discover new physics.**

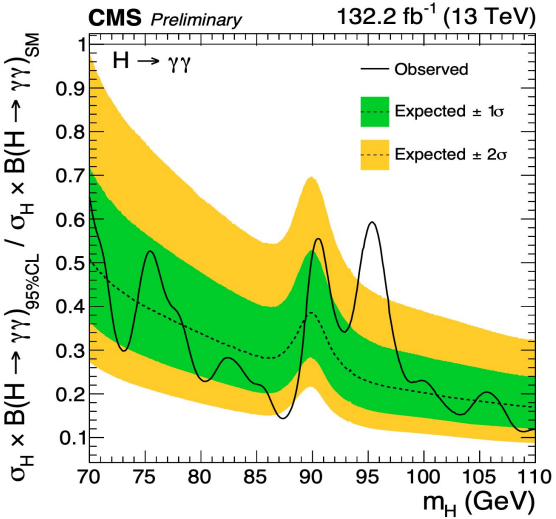


JHEP 07 (2023) 176
https://arxiv.org/abs/2301.10486

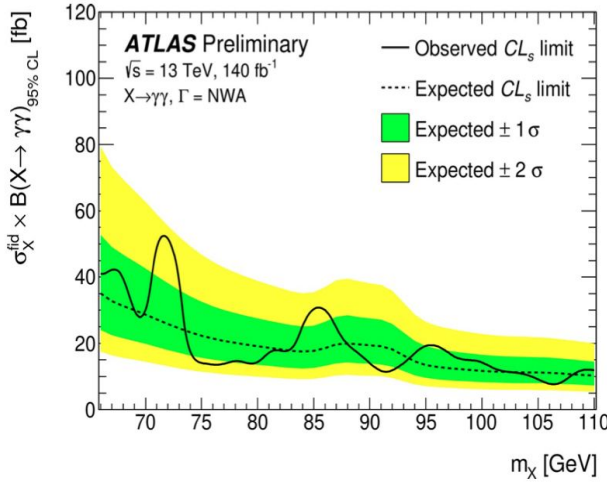
Low Mass H→ $\gamma\gamma$

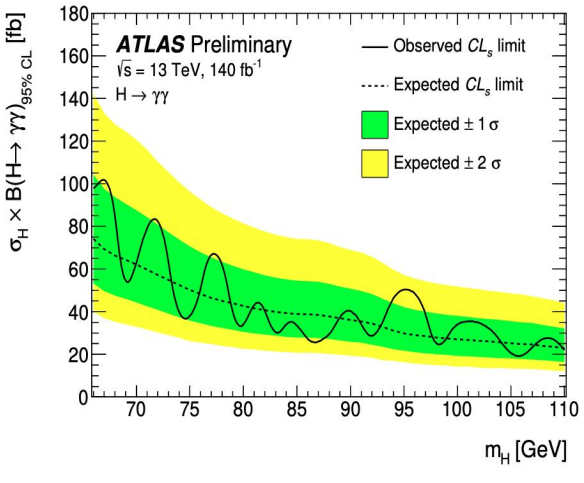
Motivation: a small tension (2 σ) of excess events w.r.t. background was observed at LEP. H→ $\gamma\gamma$ is a clean final state

CMS-PAS-HIG-20-002



ATLAS-CONF-2023-035





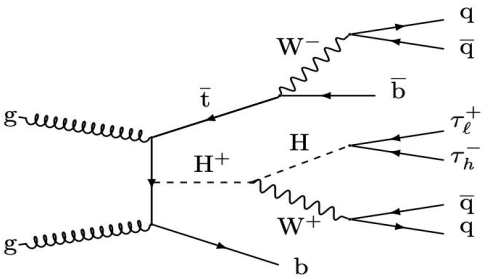
for mass hypothesis of 95.4 GeV excess with approximately 2.9σ local (1.3σ global) significance is observed, consistent in all production modes.

not seen by ATLAS

Heavy Charged Higgs in WH decays

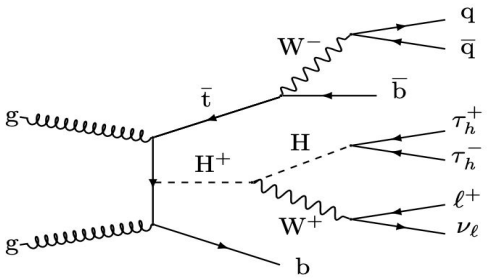
H+ → H W+
  ↳ ττ

JHEP 09 (2023) 032



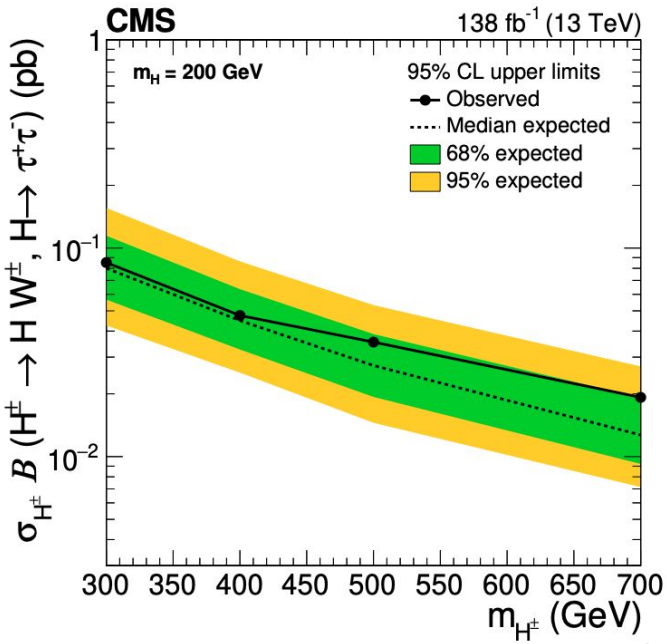
$\tau_\ell\tau_h$ (BR = 30.7%):

final discriminant: an MVA boosted decision tree with gradient boost (BDTG)



$\ell\,\tau_h\tau_h$ (BR = 12.3 %):

final discriminant:
the transverse mass of the H+

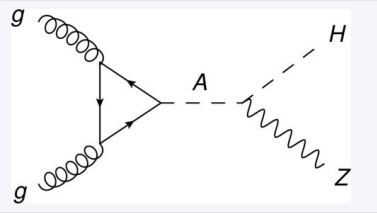


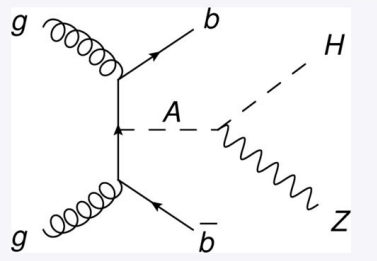
Heavy neutral A → HZ

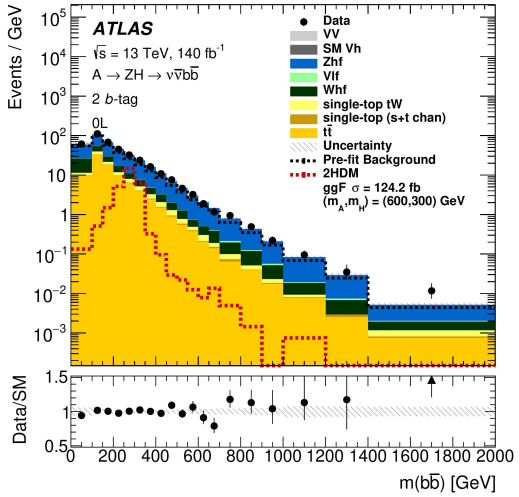
A → H Z

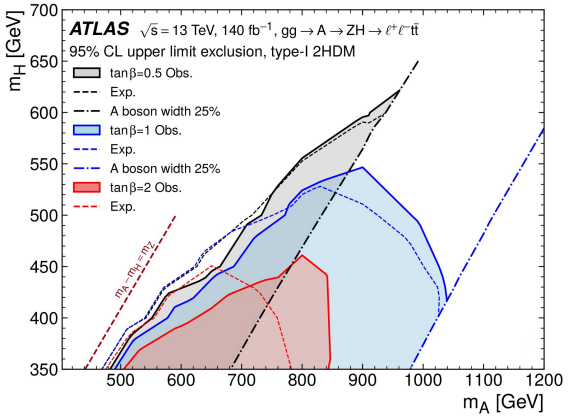
- tt + l^+l^-
- bb + νν

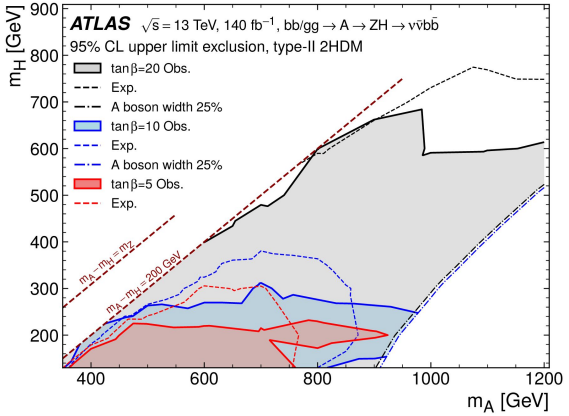
HDBS-2021-02











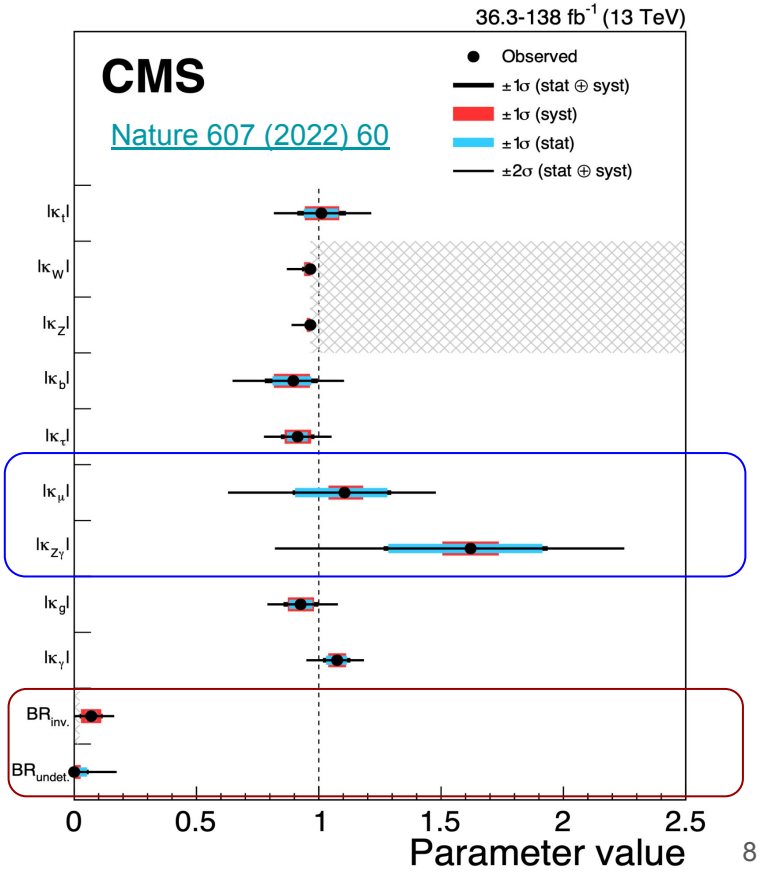
Higgs coupling

Probing the H decays with increasing precision → narrowing down window for undetected decays !

can we observe the Higgs decaying 1st/2nd gen?
Hee / Hμμ/ Hcc Huu/Hdd/Hss

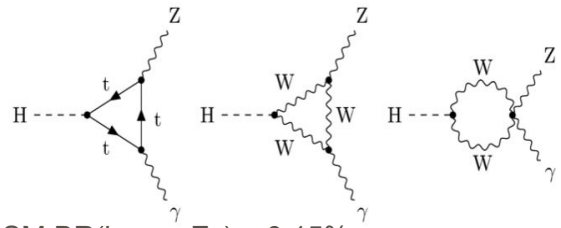
Theoretical frameworks motivate direct search for Higgs exotic decays.

Dark Matter: $h_{125} \rightarrow$ invisible
Dark Sector: $h_{125} \rightarrow$ LLP, dark photons
LFVs decays: $h_{125} \rightarrow e/\mu\tau$, $h_{125} \rightarrow e\mu$
Axion like: $h_{125} \rightarrow aa \rightarrow 4\gamma$, $h_{125} \rightarrow Za \rightarrow ll\gamma\gamma$



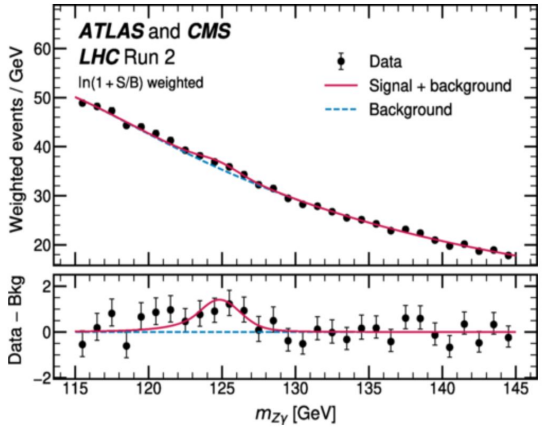
$Z\gamma$ + llγ

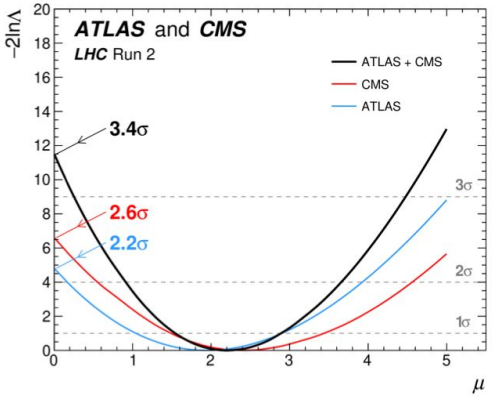
Rare decay



SM BR($h_{125}\rightarrow Z\gamma$) = 0.15%

https://doi.org/10.1103/PhysRevLett.132.021803





Excess compatible with SM decay of **H→ Zγ**

- Combination of both measurements: Evidence! 3.4σ, μ = 2.2 ± 0.7

High Mass

High Mass search for MX: 220 GeV -3.5 TeV

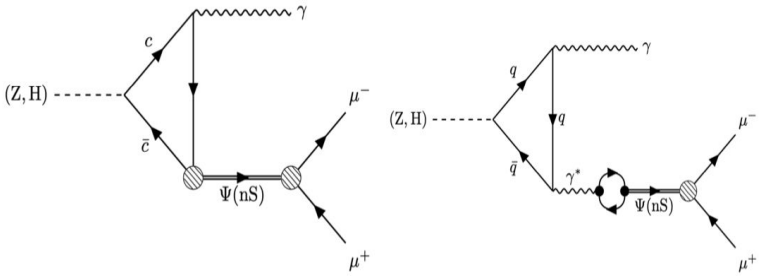
ATLAS Phys. Lett. B 848 (2024) 138394

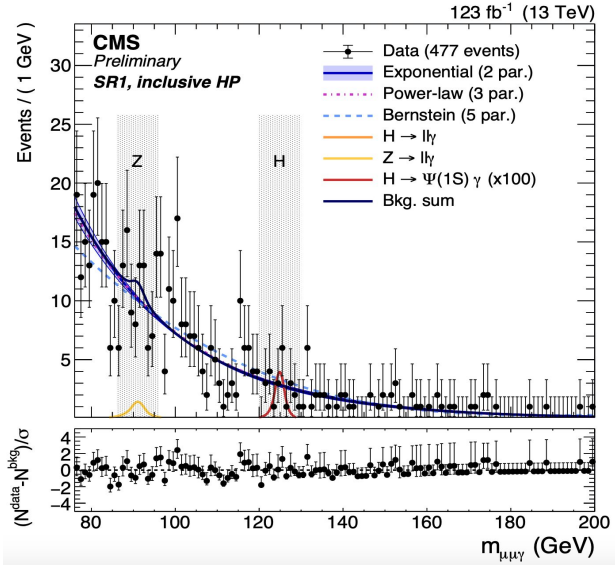
95% CL upper limits on $\sigma(pp \rightarrow X) \cdot \mathcal{B}(X \rightarrow Z\gamma)$	Observed	Expected
ggX spin-0	65.5 fb – 0.6 fb	43.3 fb – 0.6 fb
ggX spin-2	77.4 fb – 0.6 fb	50.8 fb – 0.6 fb
$q\bar{q}X$ spin-2	76.1 fb – 0.5 fb	50.3 fb – 0.5 fb

$h_{125} \rightarrow$ Meson + γ (1)

BSM effects in the Yukawa sector

SMP-22-012



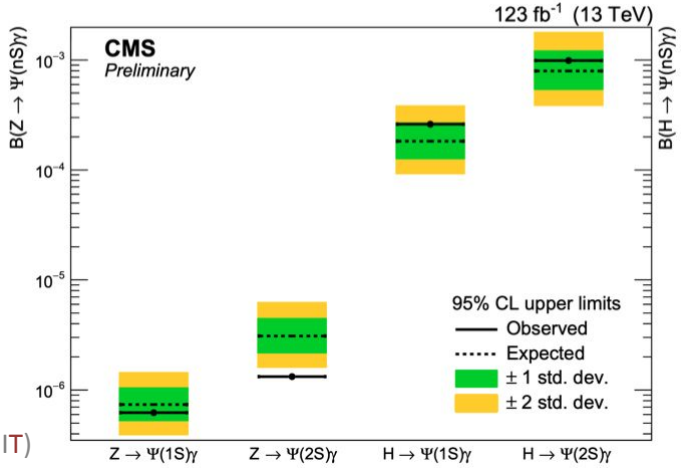


Visible peak in the vector meson mass and Higgs boson invariant mass

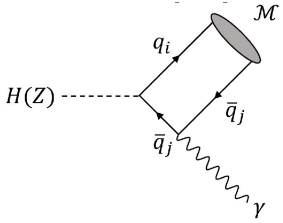
Categorization for Higgs analysis

→ **1** inclusive category for ψ(2S)

→ **4** exclusive categories for ψ(1S): **2 ggH** categories high and low purity (HP or LP); **VBF; High flavor lepton** (HFL): at least 1 b-jet

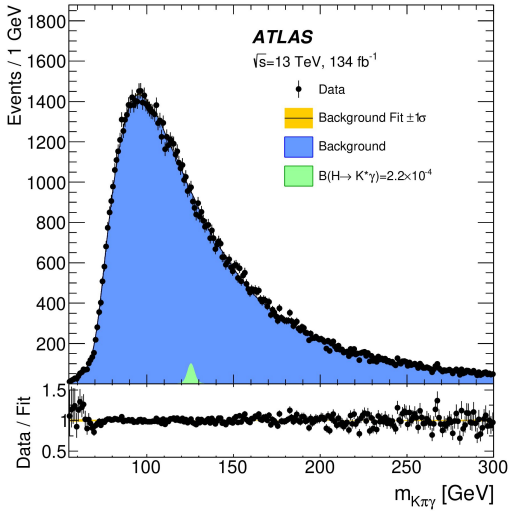


$h_{125} \rightarrow$ Meson + γ



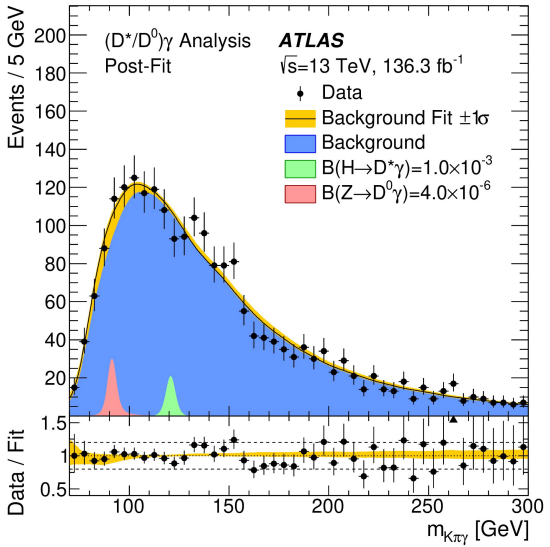
Flavor violating coupling

BSM effects in the Yukawa sector



$K^{*0} \rightarrow$ down/strange

Phys. Lett. B. 847 (2023) 138292

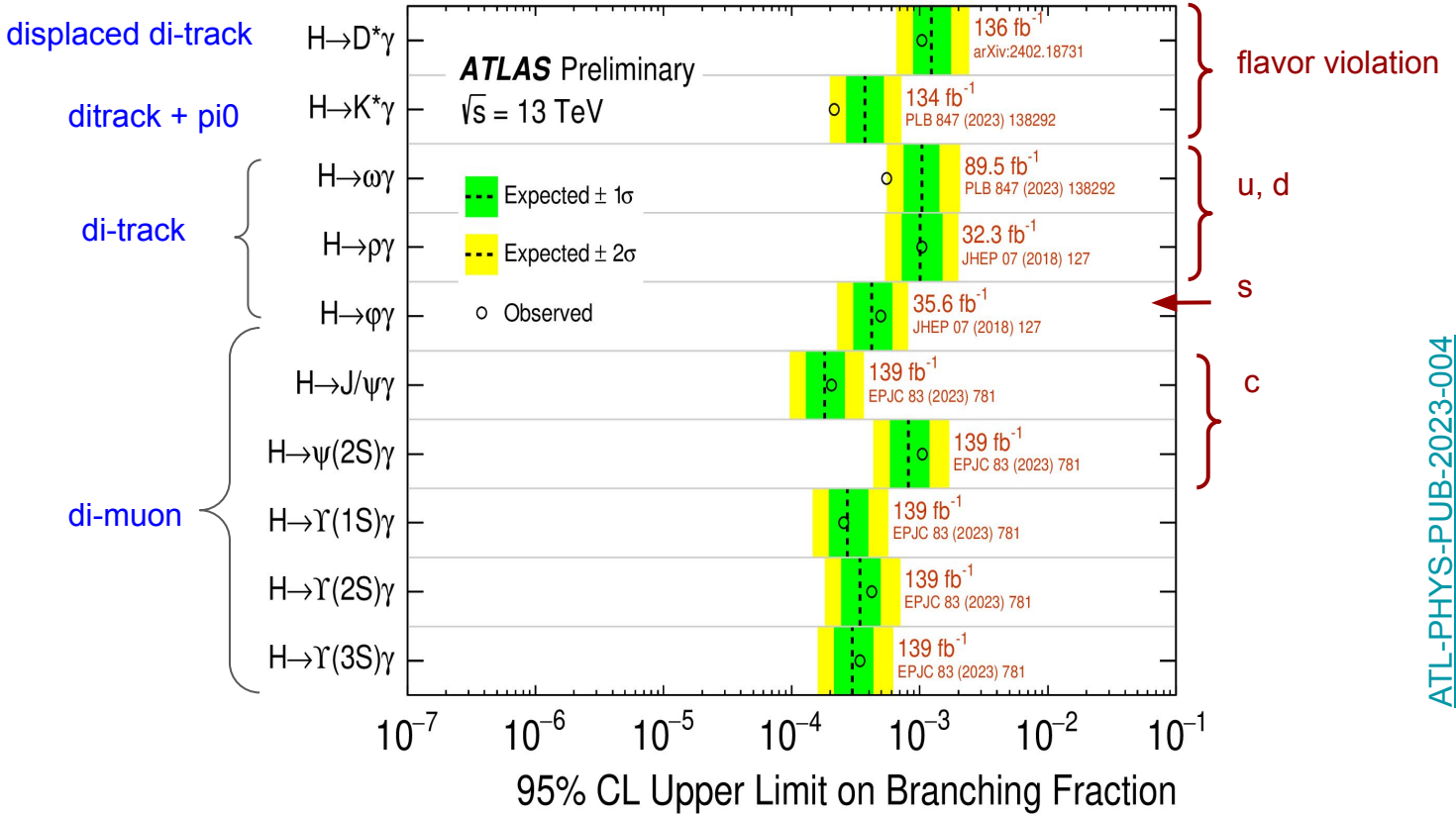


$D^{*0} \rightarrow$ up/charm

HDBS-2018-52

$h_{125} \rightarrow$ Meson + γ (3)

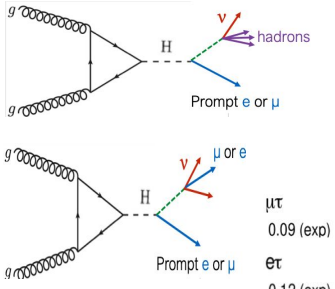
BSM effects in the Yukawa sector



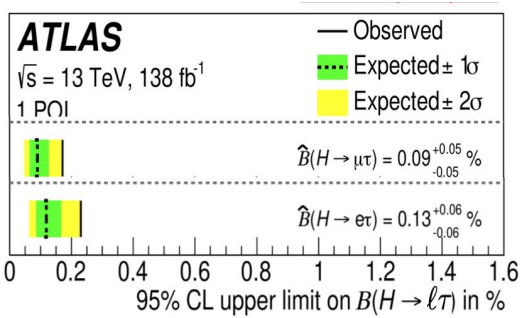
ATL-PHYS-PUB-2023-004

Leptonic Yukawa

Is the Higgs responsible for ILFV ?



Flavor violation



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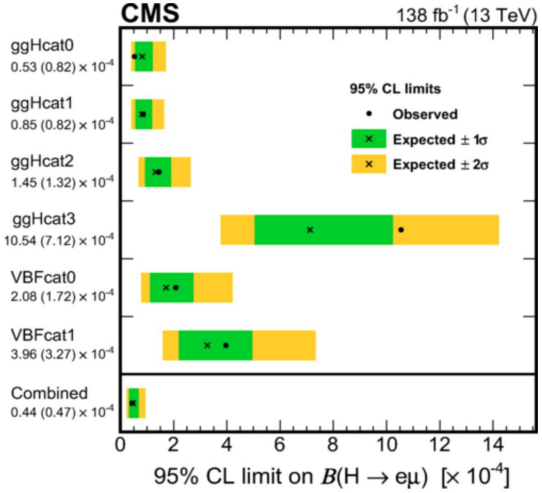
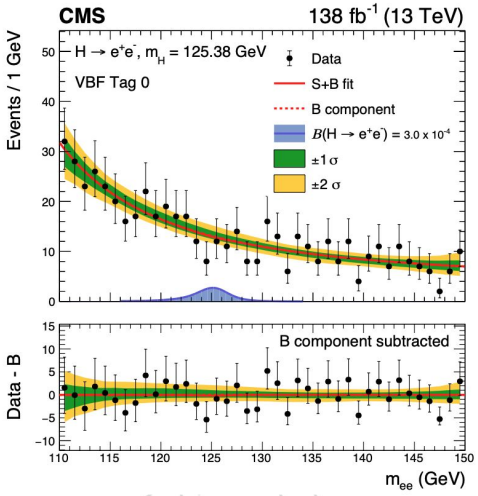
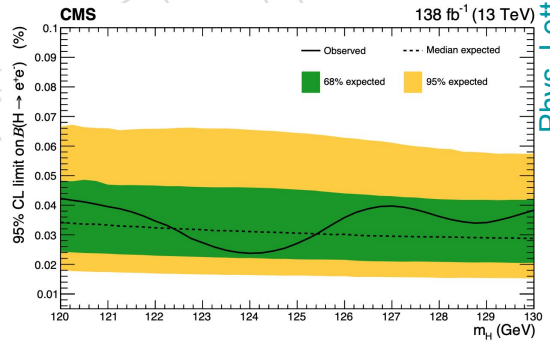


PRD 108 (2023) 072004

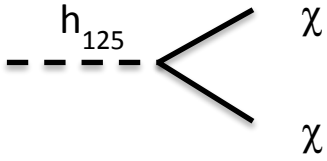
$$\mathcal{B}(H \to e^+e^-) \approx 5 \times 10^{-9}$$





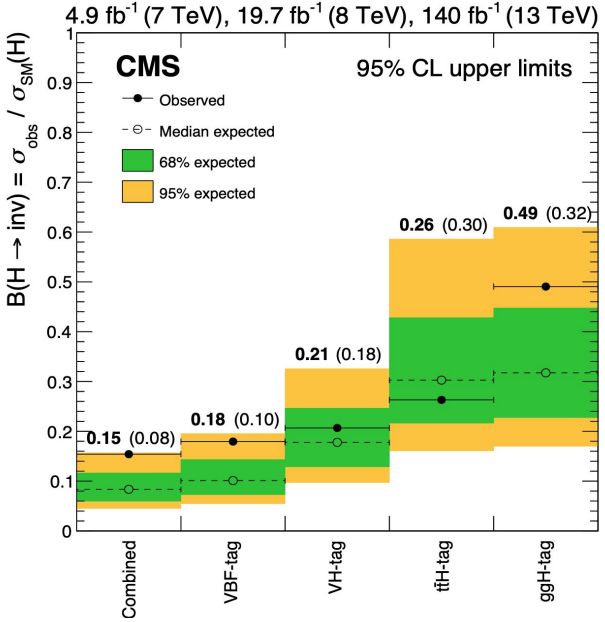
Phys. Lett. B 846 (2023) 137783

$h_{125} \rightarrow$ invisible



χ gives MET signature

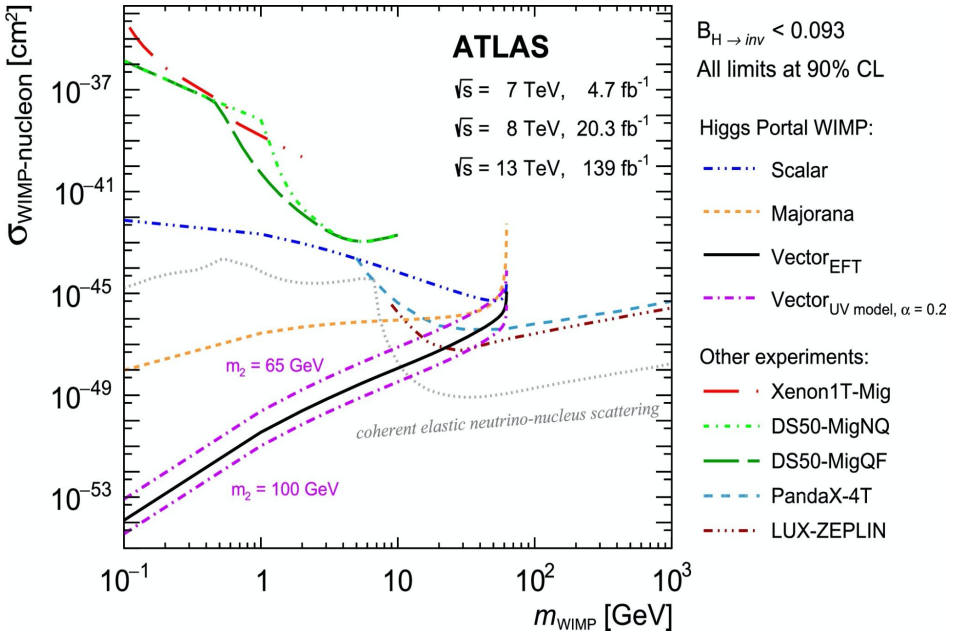
invisible decays for Dark Matter



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

BR(Hinv)@HL-LHC < 2.5%

BR(H→ZZ→4v)~0.1%



Phys. Lett. B 842 (2023) 137963

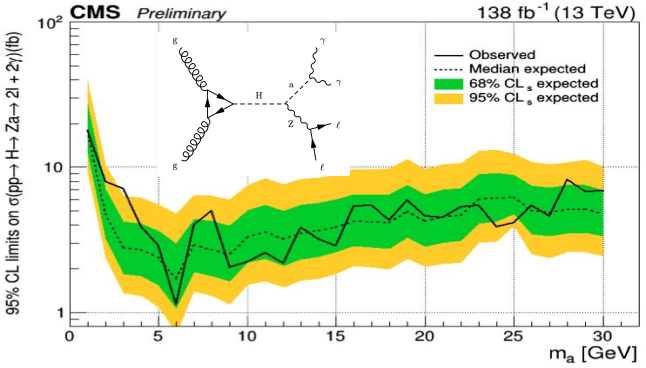
The constraint from the combined observed Run 1+2 exclusion limit of BR(Hinv) ~ 0.093 at 90% CL is compared to the results from representative direct DM detection experiments

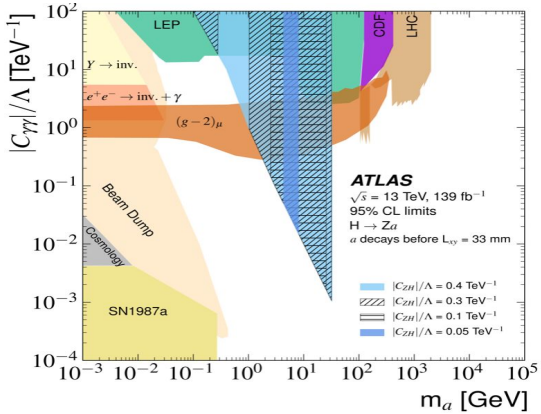
$h_{125} \rightarrow Za \rightarrow ll\gamma\gamma$ and $h_{125} \rightarrow aa$

anomalous decays

2HDM or 2HDM+S models can have additional light pseudoscalars ‘a’ with significant BR(h→Za)

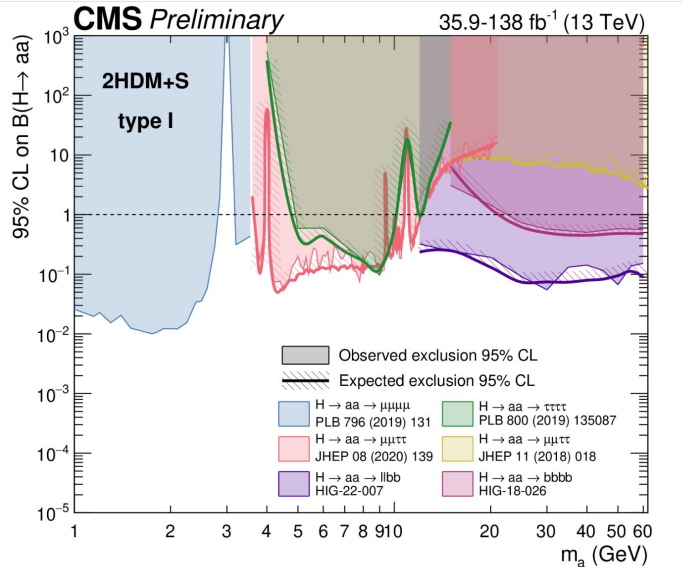
CMS-HIG-22-003, *Submitted to Phys. Lett. B*





Phys. Lett. B 848 (2024) 138536

A rich set of searches for H → aa

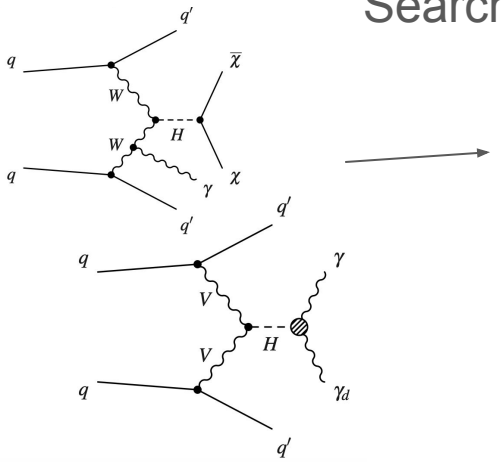


see also H → aa → 4γ HDBS-2019-19 providing sensitivity to recently proposed models that could explain the $(g\text{-}2)_\mu$ discrepancy

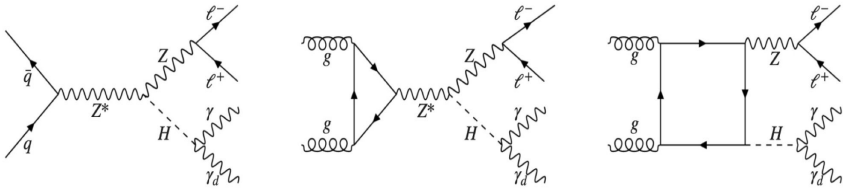
Dark photon H → γγ^D

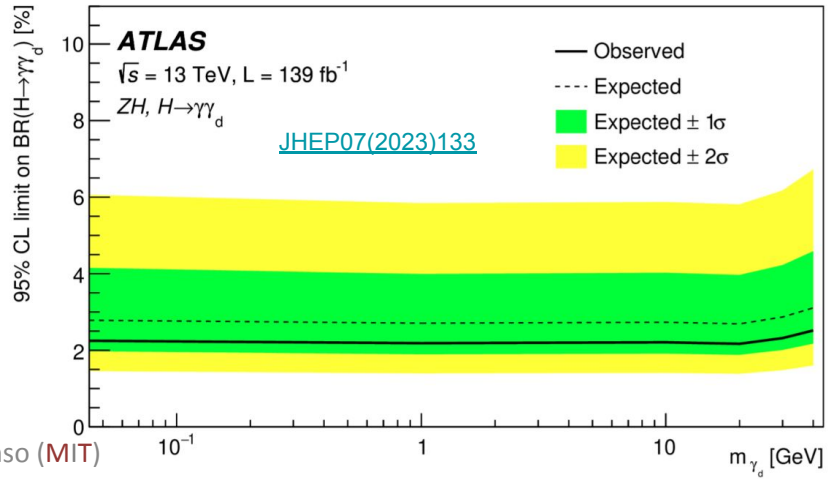
Exotic decays

Search for prompt, invisible and low mass dark photon



	ATLAS	CMS
VBF	Eur. Phys. J. C 82 (2022) 105	JHEP03(2021)011
ZH	JHEP07(2023)133	JHEP10(2019)139





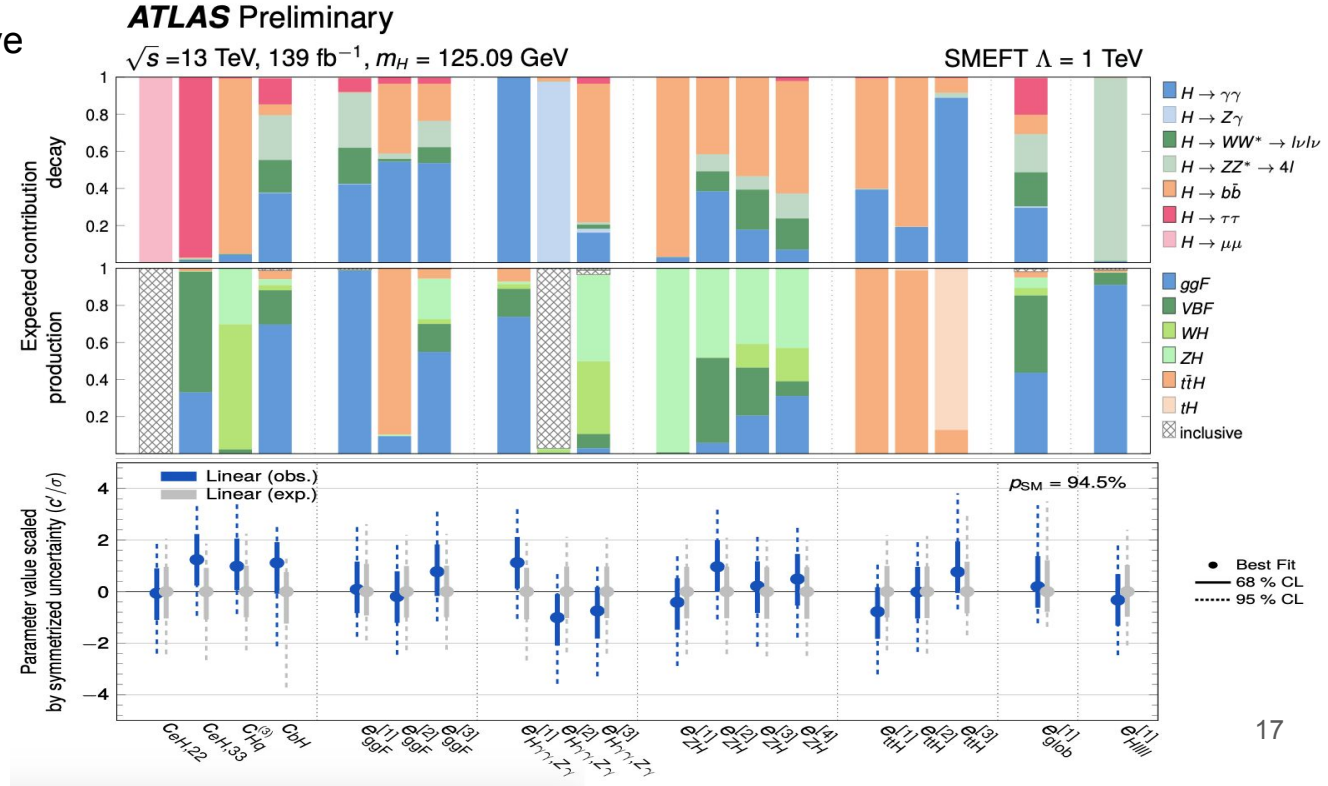
for long lived see Vanneron's talk

Interpretations based on SM Effective Field Theory

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d=6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d=8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots,$$

the effects of BSM dynamics above some high energy scale, can be parametrized in terms of higher-dimensional operators.

Rare decays uniquely sensitive to certain directions of the EFT space



[ATLAS-CONF-2023-052]

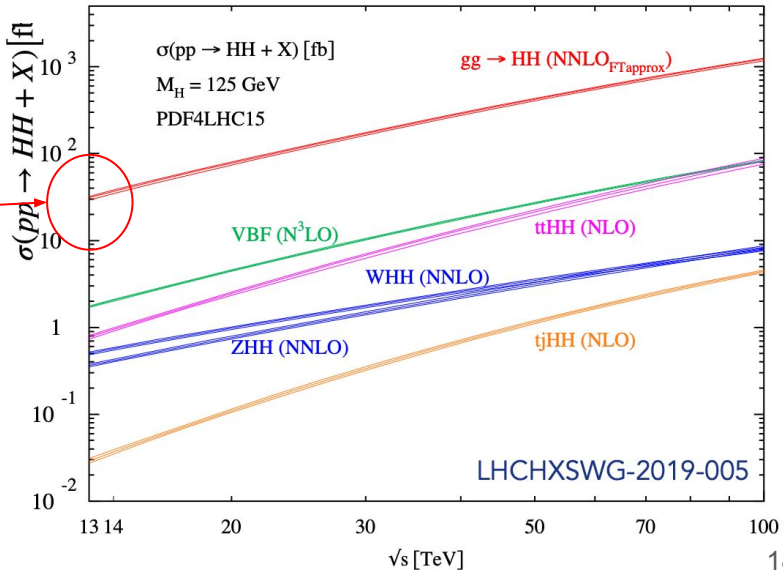
HH production is a test of the SM:

Direct test of HHH vertex only with HH production

$$V(H) = \frac{1}{2}m_{\mathrm{H}}^2 H^2 + \lambda_{\mathrm{HHH}} v H^3 + \frac{1}{4}\lambda_{\mathrm{HHHH}} H^4 - \frac{\lambda}{4}v^4$$

Focus for λ measurements

Run2: 140/fb → 4200 ev



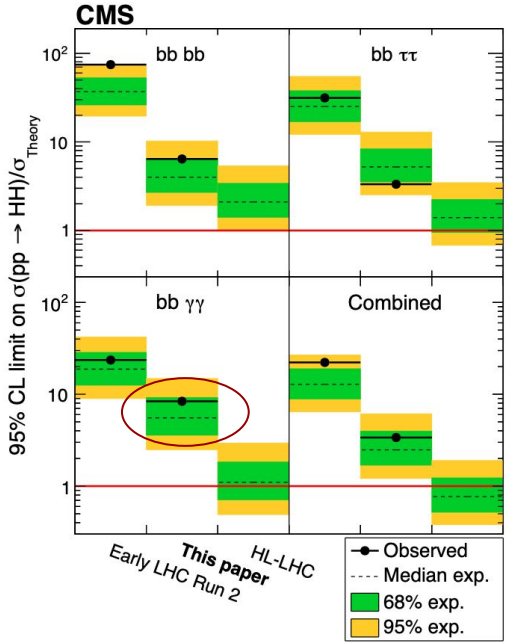
Putting together

Shedding light on Higgs-boson self-interactions

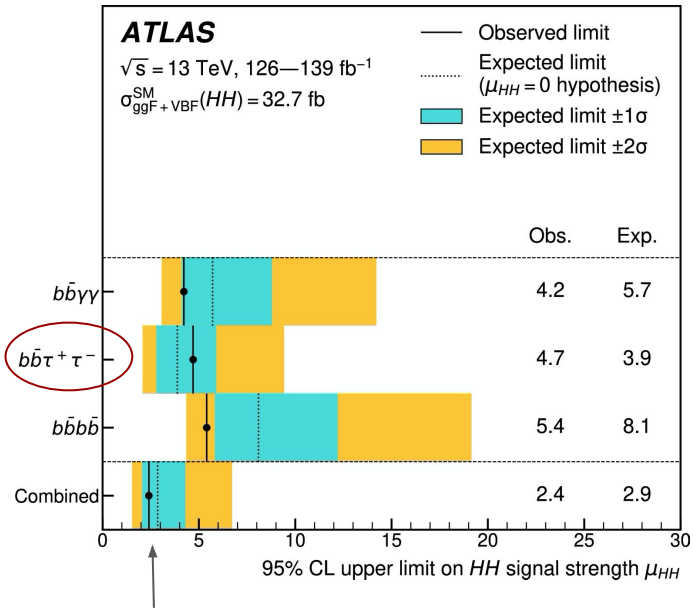
large BR requires one H → bb

bb bb BR = 34%
bb ττ BR = 7.3%
bb $\gamma\gamma$ BR = 0.26%,
but most pure

Nature 607 (2022) 60



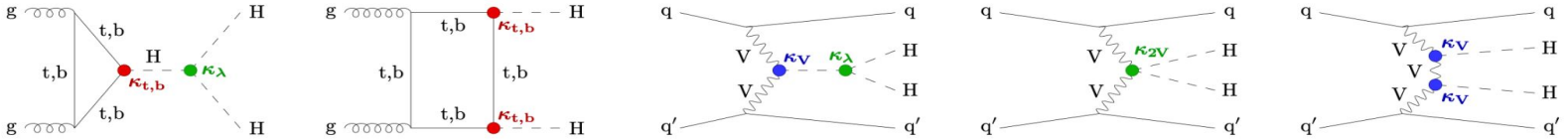
Phys. Lett. B 843 (2024) 137745



3.5x better than 36 fb−1 combination

HH production probe for BSM

Nonresonant signatures



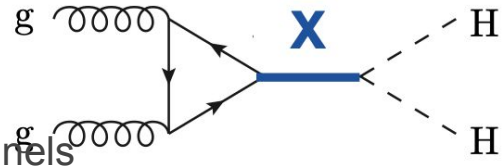
Low energy effect of new physics that modify the Higgs bosons's interactions :
k framework approach: modify HHH, ttH, VVH, VVHH vertices

The ggF process is sensitive to the relative sign between κ_λ and κ_t
The VBF process is sensitive to the relative sign between κ_{2V} and κ_V

EFT approach: introduce operators with a strength given by Wilson coefficient

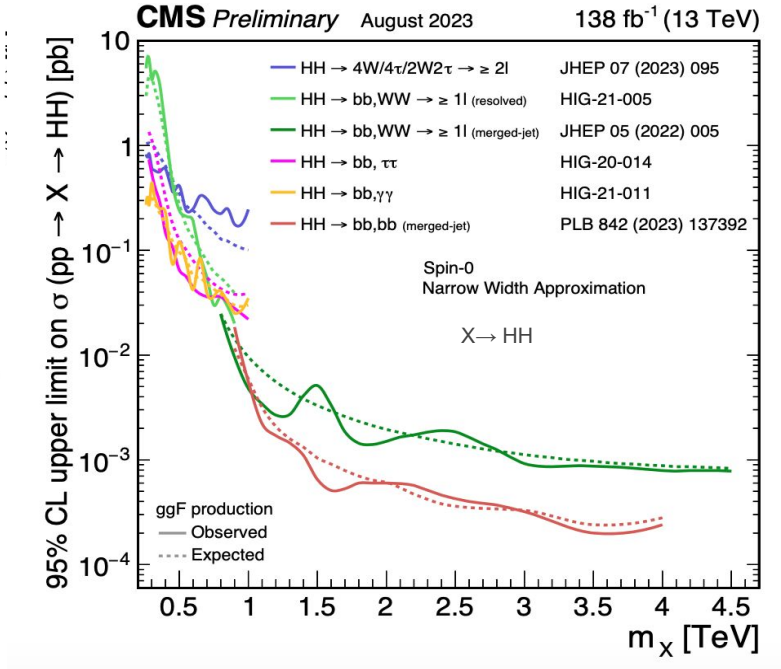
Resonant signatures

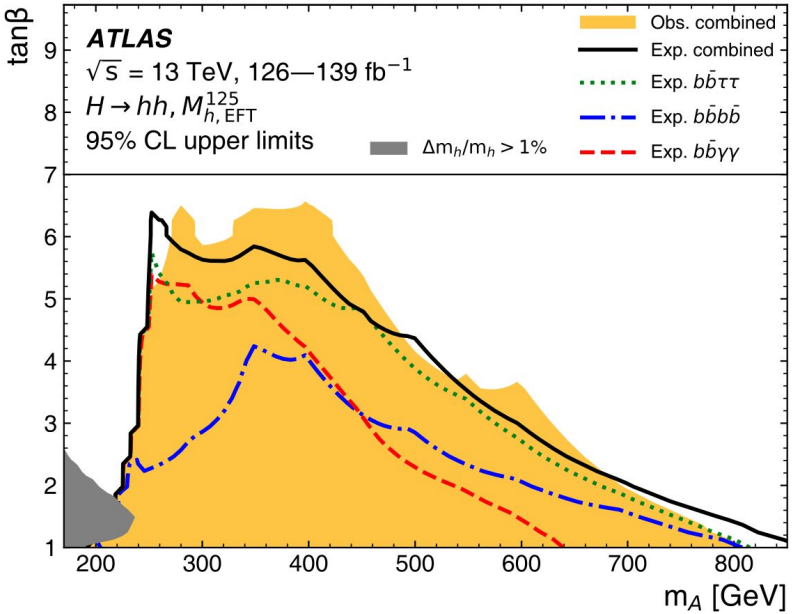
Direct production of a new state X→ HH
Large set of BSM scenarios: varios MX hypothesis, and search channels



HH probe for BSM (resonant)

HH probe for BSM





HH: Most sensitive analysis for **intermediate tan β**

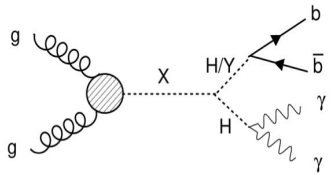
PAPERS HDBS-2023-17/

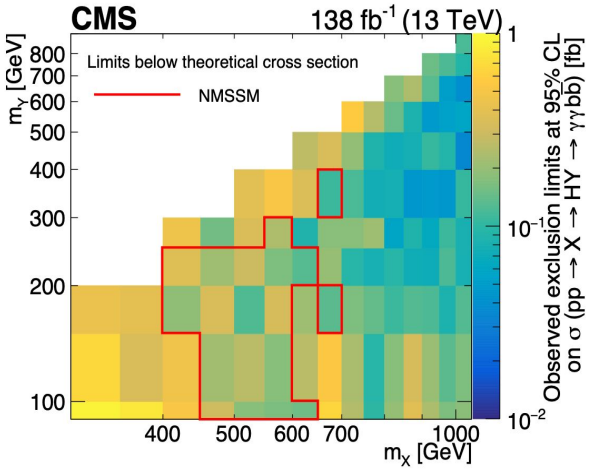
submitted to Phys. Rev. Lett

X-> YH , X→YY probe for BSM (resonant)

HH probe for BSM

Larger extended Higgs sectors: E.g. two additional singlets (TRSM), 2-Higgs-doublet + singlet (2HDM+S including NMSSM), Y branching fractions can be very non-SM-H-like

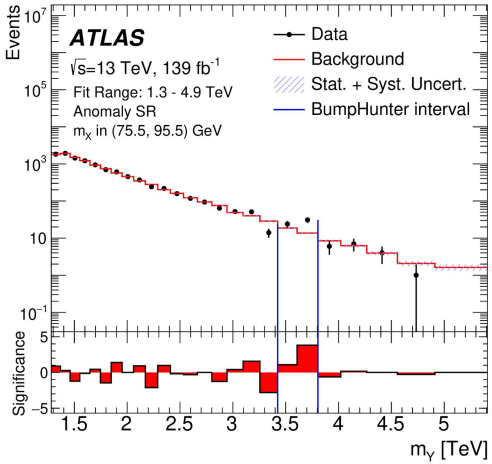




Submitted to the JHEP

Anomaly signal region: Targets generic signals - non-compatibility with learned background model

or set limits on $pp \to Y \to XH \to q\bar{q}b\bar{b}$

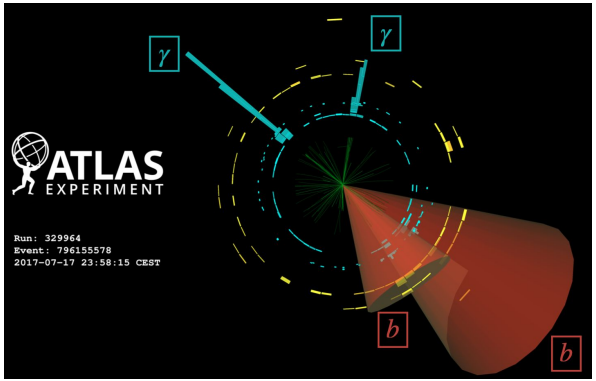


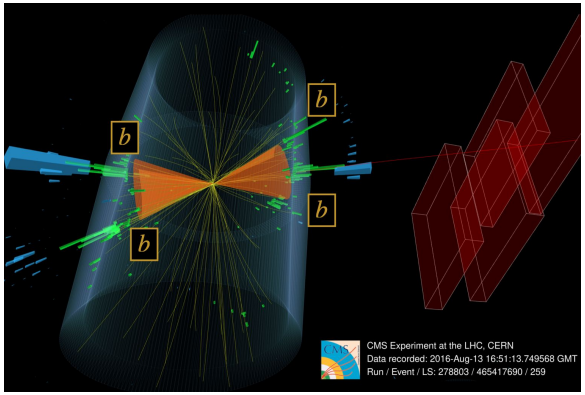
Phys. Rev. D 108 (2023) 052009

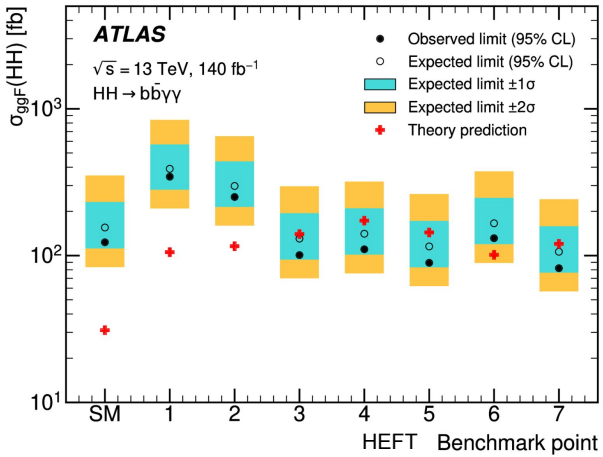
HH probe for BSM (non resonant)

Access the shape of the Higgs potential

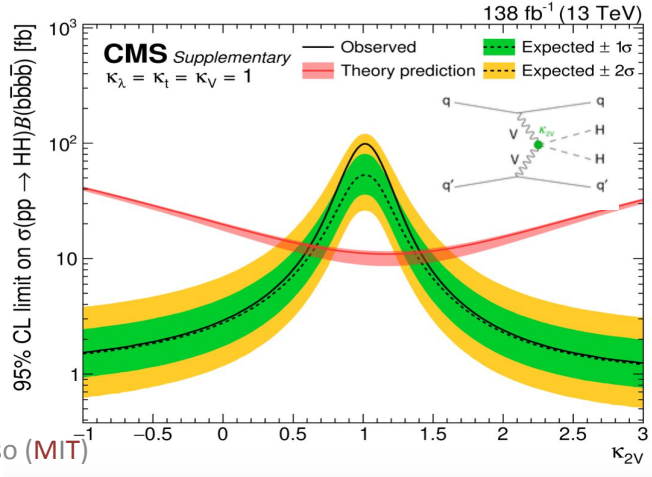
very clean signature







JHEP 01 (2024) 066

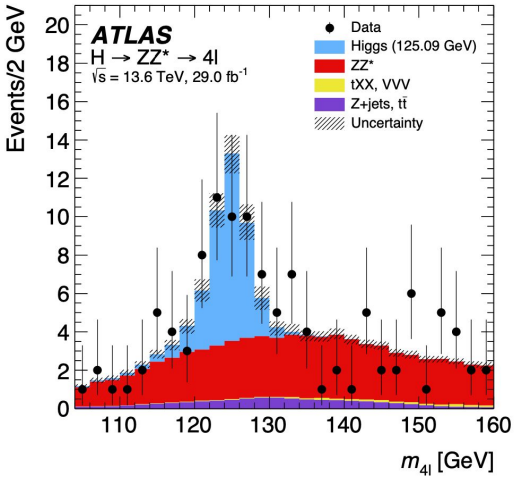


PhysRevLett.131.041803

Run3 prospects

Near Future

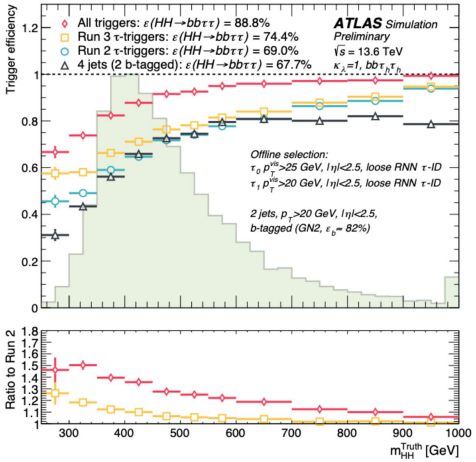
1. Rediscover the Higgs



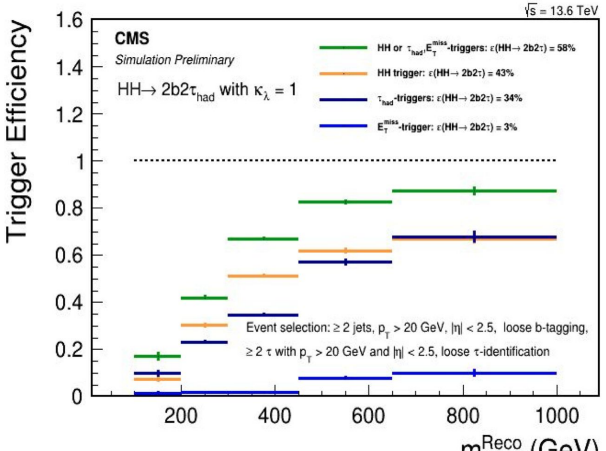
2. Improved sensitivity leads to tighter BSM constraints beyond simple luminosity increase thanks to improved **reconstruction/ID techniques** (Deep-learning vs Graph-based approach) and to advanced **analysis techniques** (BDT/DNN event classifier and more c categories)

3. Improved Triggers

AtlasPublic/TauTriggerPublicResults
see also AtlasPublic/BJetTriggerPublicResults



CERN-CMS-DP-2023-050



Summary

Rich program of ATLAS and CMS searches for rare and forbidden SM Higgs decays, and for production of additional Higgs bosons.

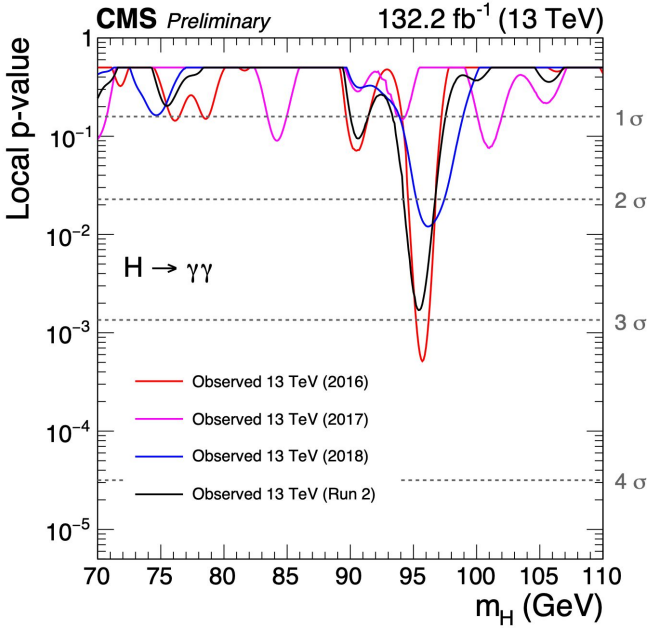
Broad HH experimental program

Many experimental improvements in view of the Run3 and HL-LHC.

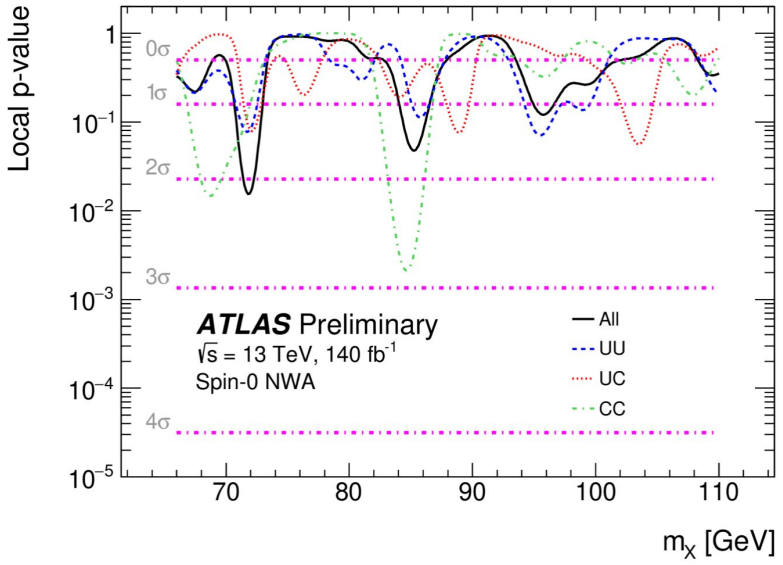
backup

Low Mass H→ $\gamma\gamma$

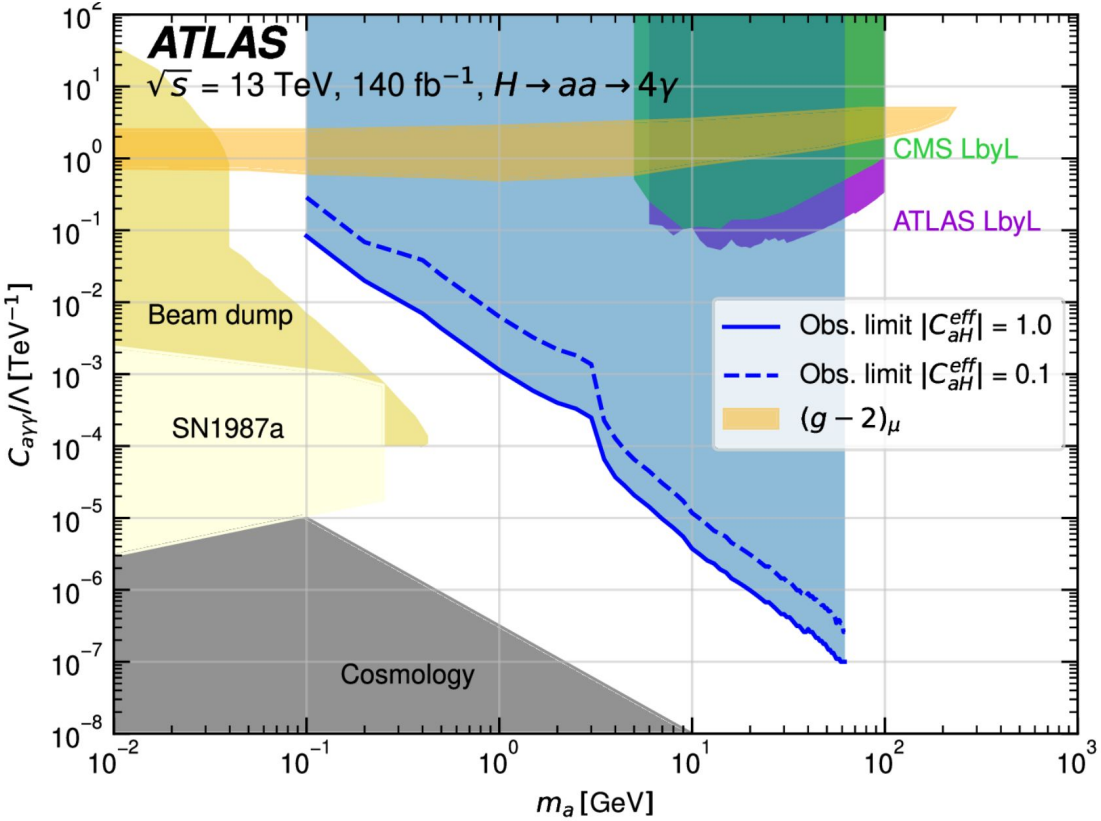
CMS-PAS-HIG-20-002



ATLAS-CONF-2023-035



H→ aa → 4 γ


ATLAS
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}, $H \to aa \to 4\gamma$
CMS LbyL
ATLAS LbyL
Beam dump
SN1987a
Cosmology
Obs. limit $|C_{aH}^{eff}| = 1.0$
Obs. limit $|C_{aH}^{eff}| = 0.1$
$(g-2)_\mu$
$C_{a\gamma\gamma}/\Lambda$ [TeV^{-1}]
m_a [GeV]