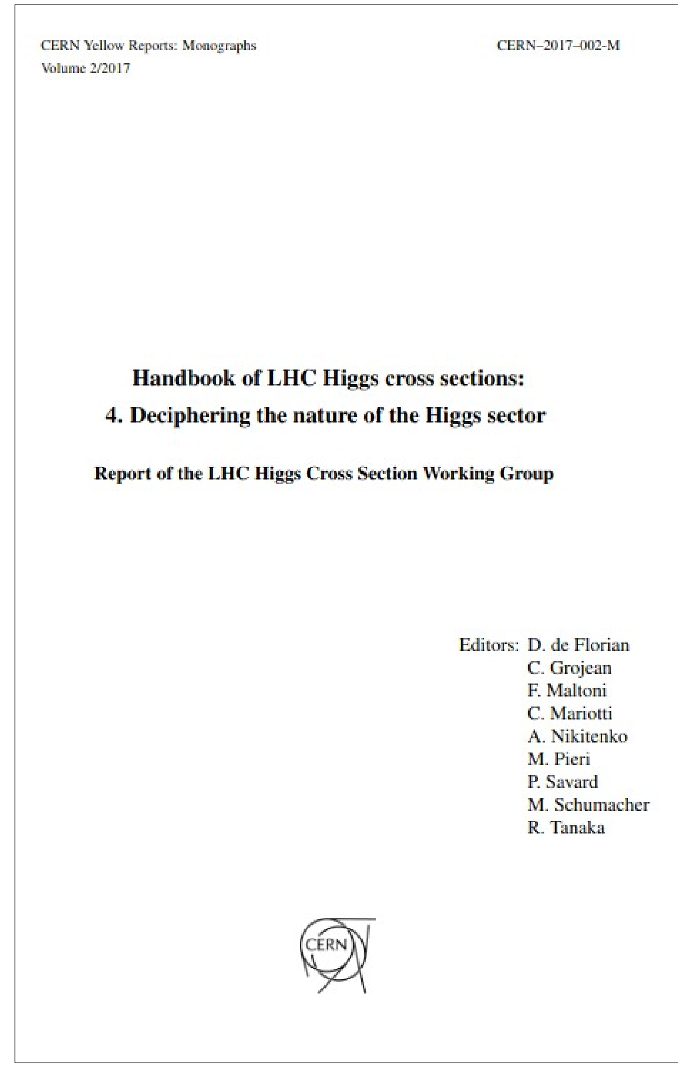
Rare and Exotic Higgs decays

Nikolaos Rompotis (Liverpool)
on behalf of the ATLAS and CMS collaborations

Why rare & exotic Higgs decays?

[...] among the SM particles the Higgs is unique in its sensitivity to new physics. The tiny SM width of the Higgs [~4 MeV] [...] combined with the ease with which the Higgs can couple to physics beyond the SM (BSM), make exotic decays of the SM Higgs a natural and often leading signature of a broad class of theories of physics beyond the SM. Within the SM, the observation of rare exclusive decay modes involving mesons would provide either confirmation or disproof of the SM origin of mass for light quarks, which would otherwise remain out of reach at the LHC.


CERN Yellow Reports: Monographs CERN–2017–002-M
Volume 2/2017

Handbook of LHC Higgs cross sections:
4. Deciphering the nature of the Higgs sector

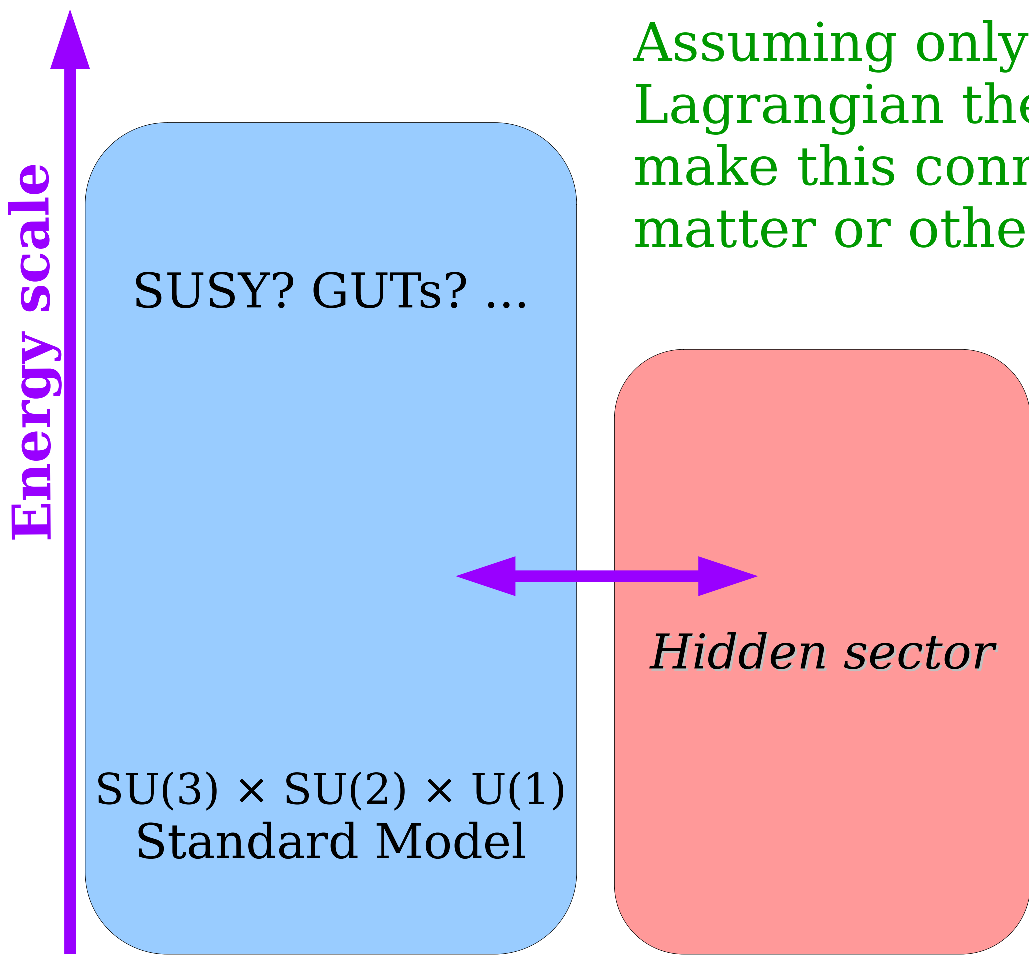
Report of the LHC Higgs Cross Section Working Group

Editors: D. de Florian
C. Grojean
F. Maltoni
C. Mariotti
A. Nikitenko
M. Pieri
P. Savard
M. Schumacher
R. Tanaka

CERN

Why rare & exotic Higgs decays?

- Connecting to a Hidden sector



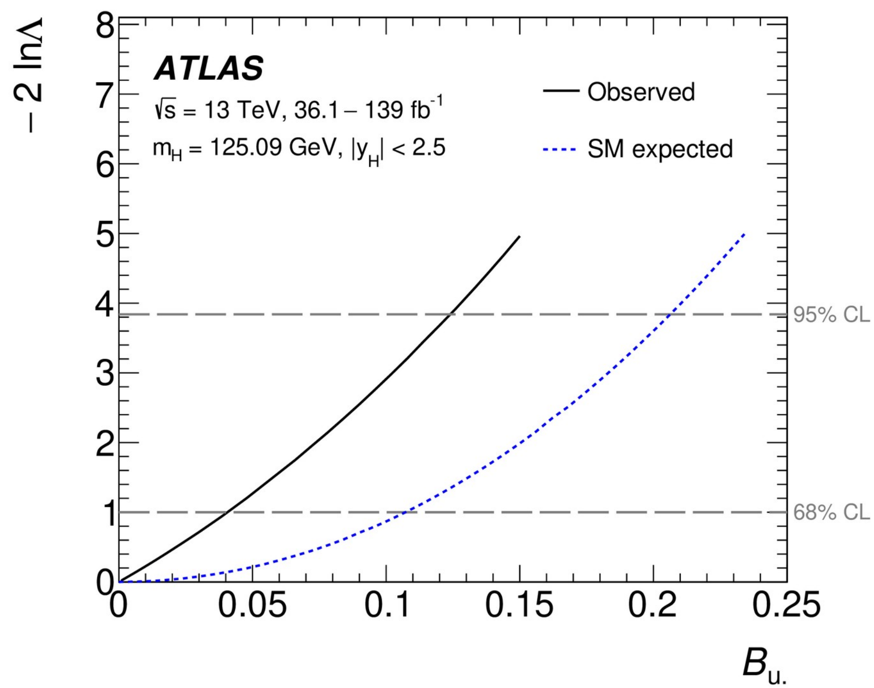
Assuming only renormalizeable terms in the Lagrangian there are only a handful of ways to make this connection! Potential access to Dark matter or other new physics in colliders

$\phi\phi S S$	**Higgs portal**
$\phi L \psi$	Neutrino portal
$F_{\mu\nu} F'^{\mu\nu}$	Vector and Axion portal

Higgs to “other particles”

- Is there space for Higgs to decay to other particles given the so many measurements that have be done already?
  - Answer: yes, plenty of space: ATLAS & CMS look for Higgs to invisible or undetected

One way to do that would be to consider the Higgs coupling measurements and then see how much space is left for “left-out” decays (“undetected”)



95% CL limits on Higgs to undetected:

ATLAS: < 12% arXiv:2207.00092

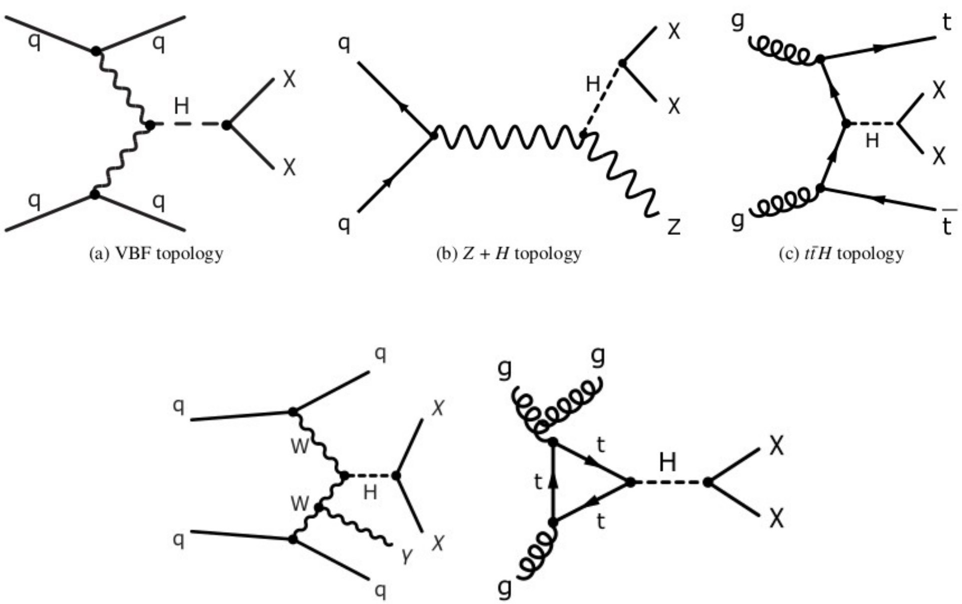
CMS: < 16% arXiv:2207.00043

Higgs to invisible

- Direct searches for Higgs to invisible in ATLAS/CMS

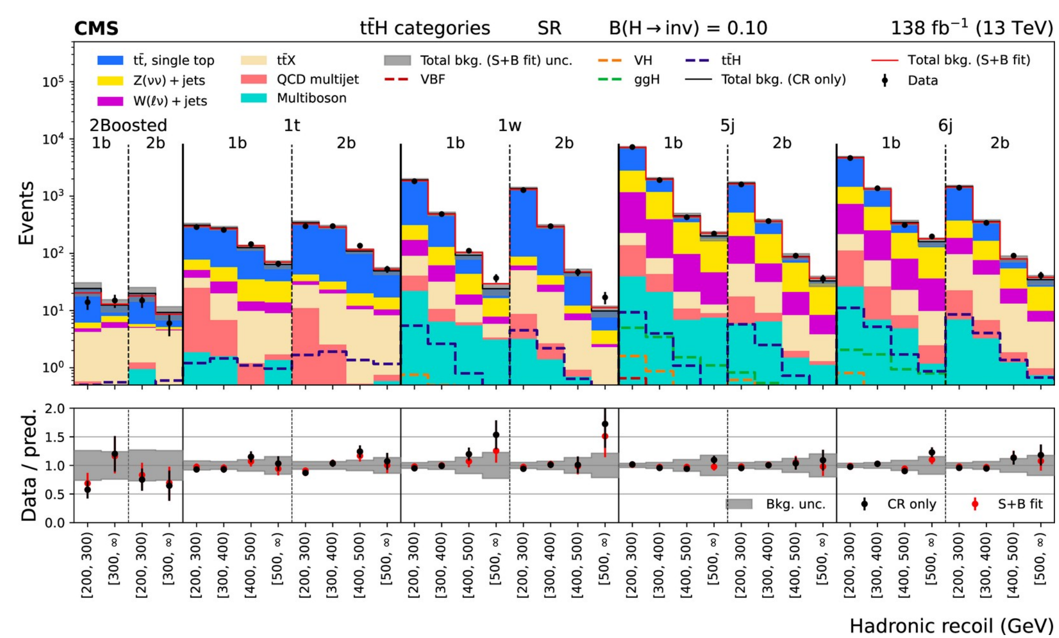
Latest combined results from ATLAS + CMS

ATLAS:arXiv:2301.10731
CMS: arXiv:2303.01214



(a) VBF topology (b) $Z + H$ topology (c) $t\bar{t}H$ topology
(d) VBF + photon topology (e) H+jet topology

CMS ttH with H→inv in the fully hadronic channel is the latest channel

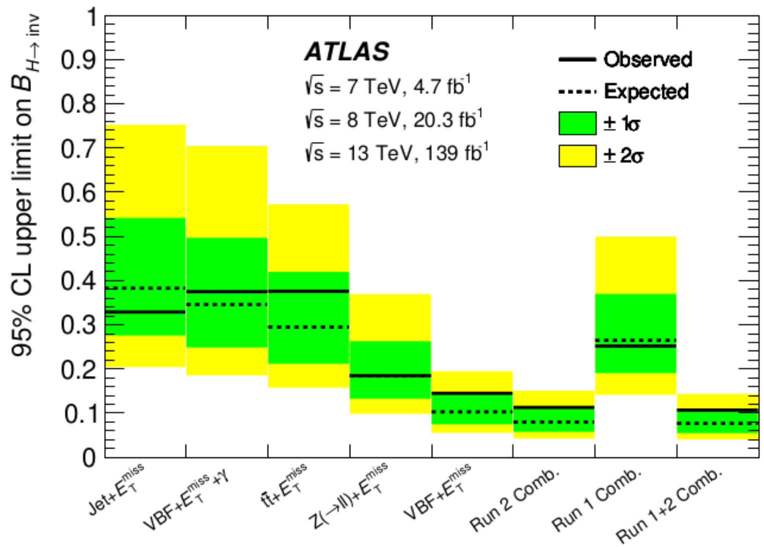


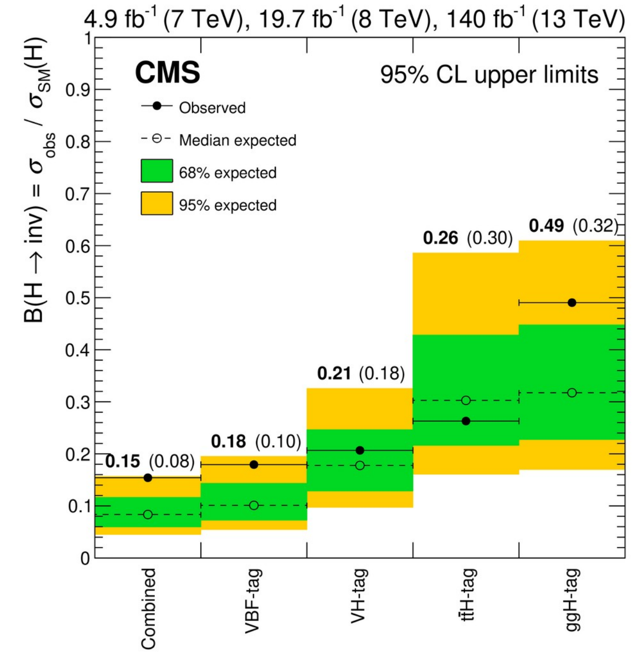
ATLAS:arXiv:2301.10731
CMS: arXiv:2303.01214

Higgs to invisible

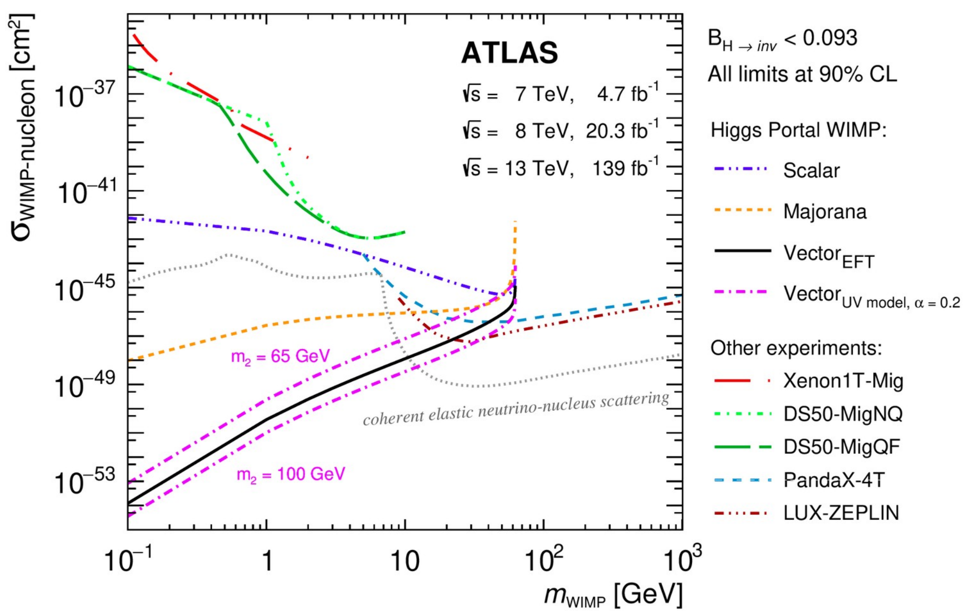
- Results:

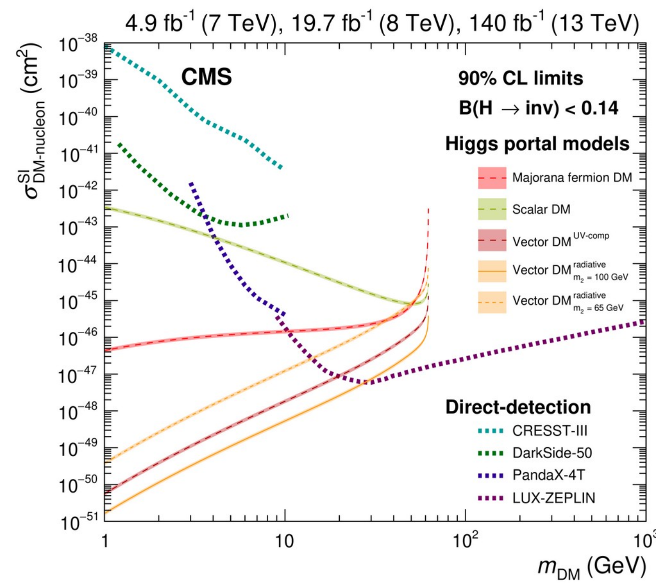
95% CL limit for H→ inv:
ATLAS: 10.7% (7.7% exp.)
CMS: 15% (8% exp.)





Interpretation in DM models

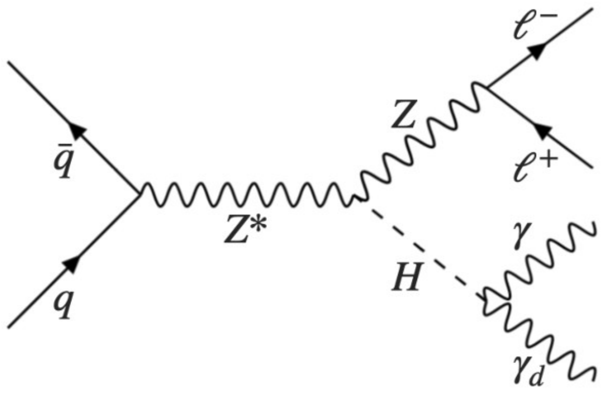


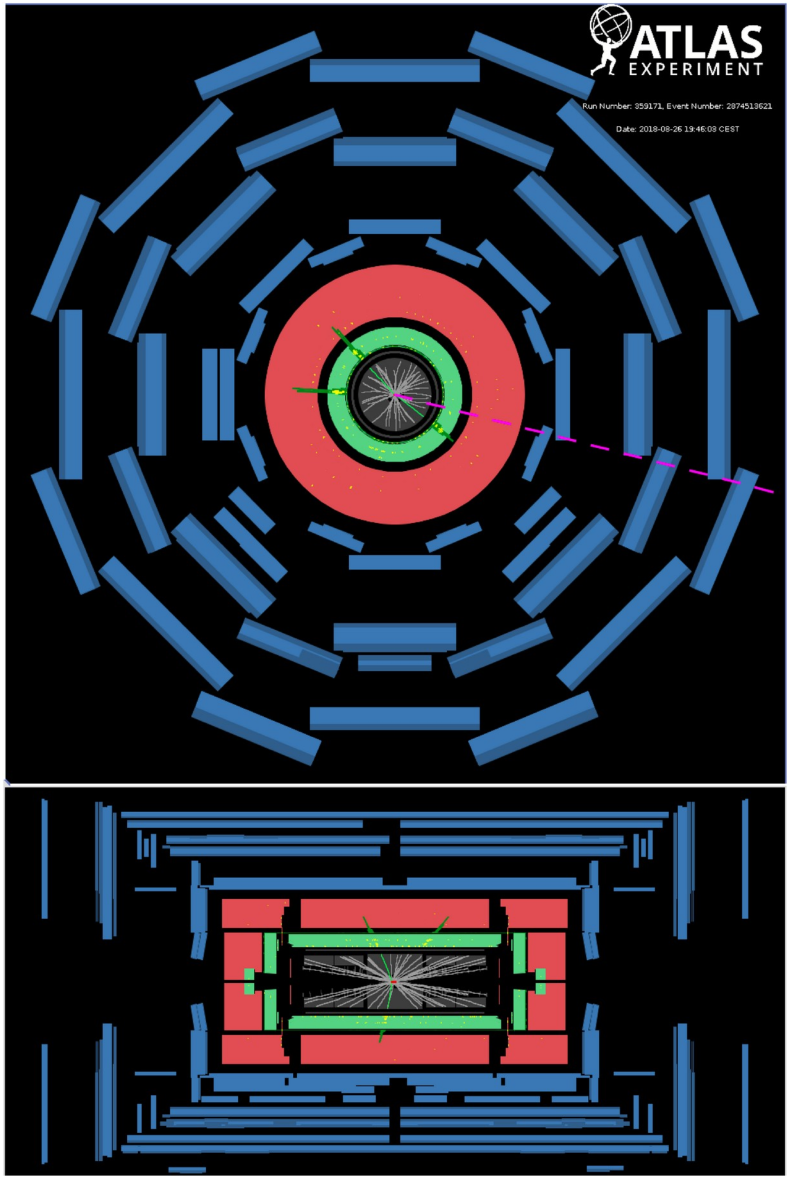


Dark photons in Higgs decays

- $H \rightarrow \gamma\gamma_d$ Analysis

arXiv:2212.09649





Targeted final state: ll + γ + MET

- e^+e^- or $\mu^+\mu^-$ + isolated photon + MET > 60 GeV
- m(ll): 76 – 116 GeV, $\Delta\varphi$(MET, p_T(llγ)) > 2.4
- b-jet veto, < 3 jets

Main backgrounds: VVγ, fake MET, fake photons, top

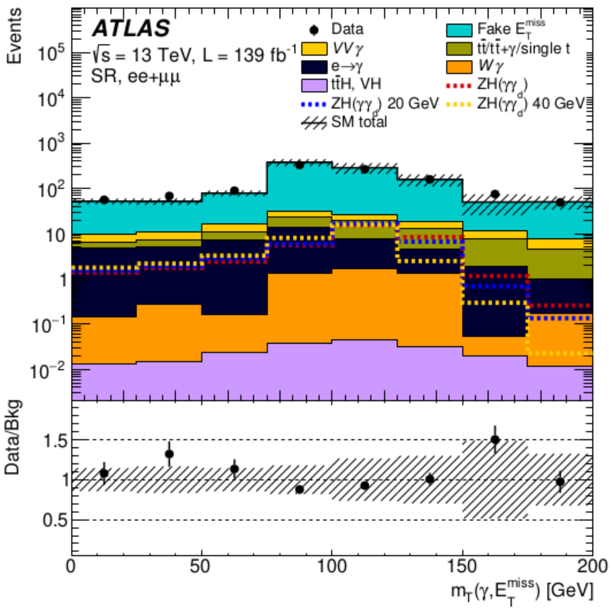
Signal extraction: BDT using 6 variables

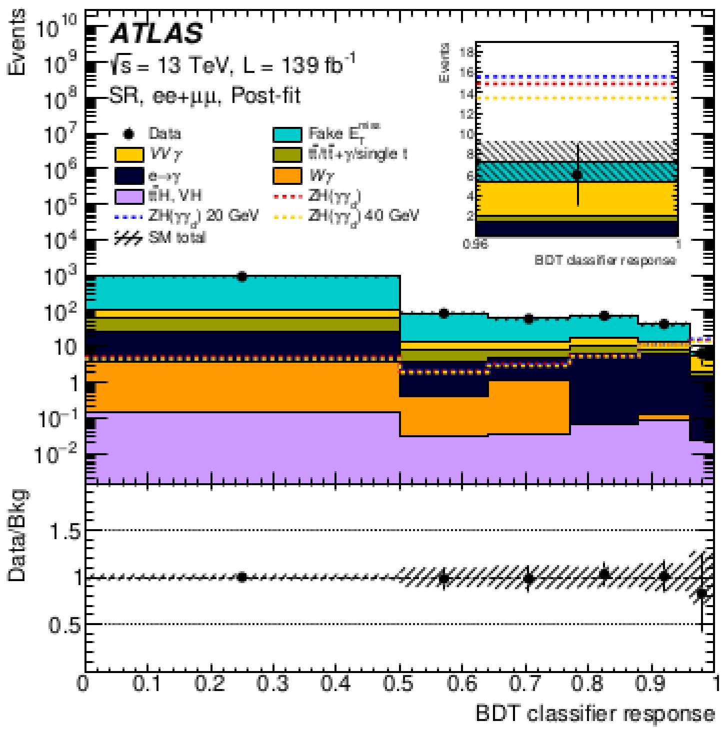
Dark photons in Higgs decays

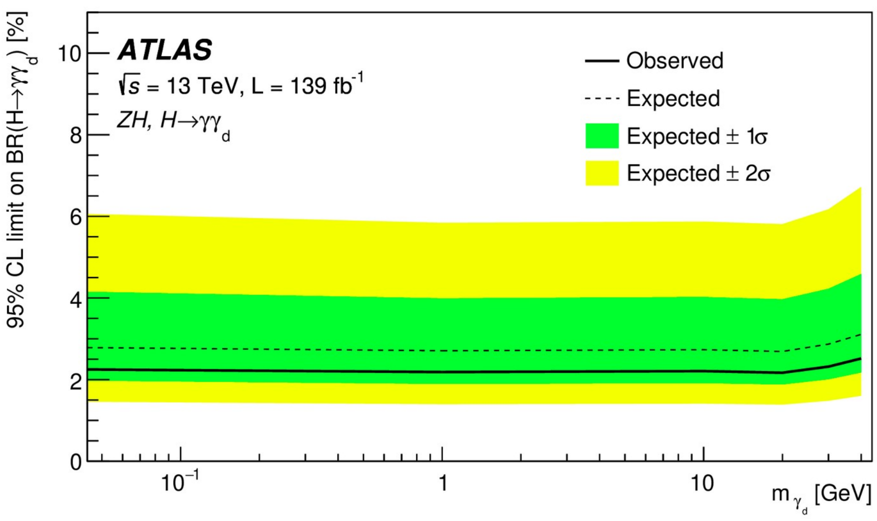
arXiv:2212.09649

- $H \to \gamma\gamma_d$ Results

Upper limits for BR($H \to \gamma\gamma_d$) around 3% assuming m(γ_d) up to 40 GeV







$H \to aa$

- The decay of the Higgs boson to two pseudoscalars appears in many BSM physics scenarios
  - Extended Higgs sections (2HDM, 2HDM+S, singlets), NMSSM, axion models, …
- … and has been extensively studied at the LHC
- Here I will show you some recent results from CMS

$H \to aa \to 2\tau\ 2b$
$H \to aa \to 2\mu\ 2b$ HIG-22-007

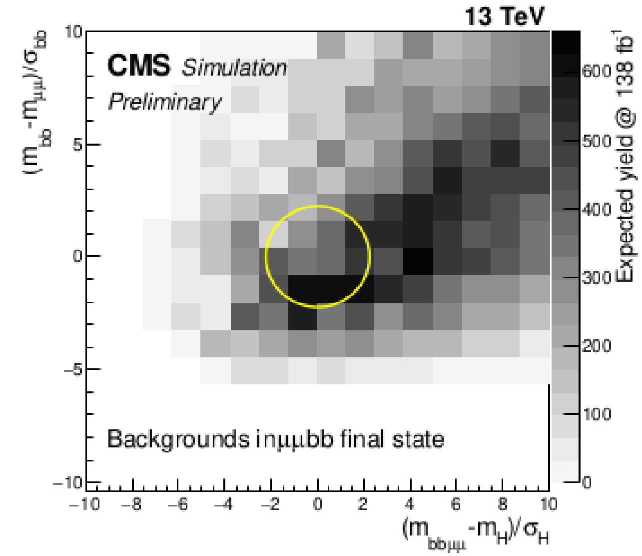
HIG-22-007

H → aa → μμbb and ττbb

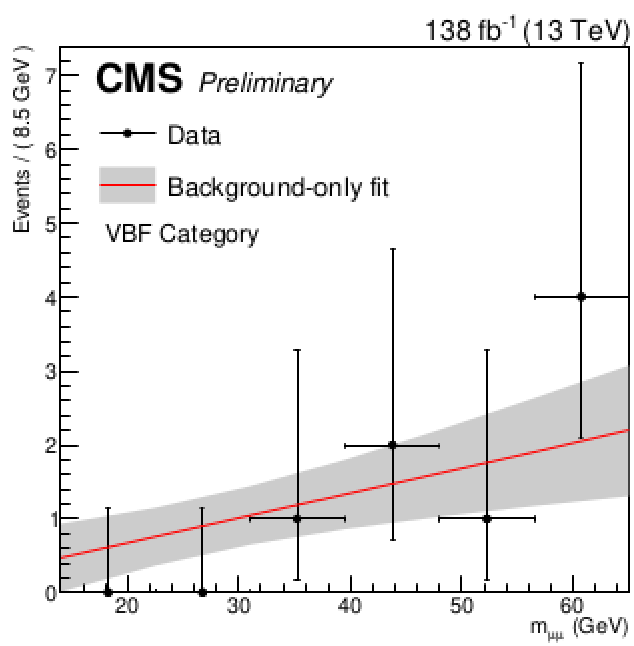
- H → aa → μμbb

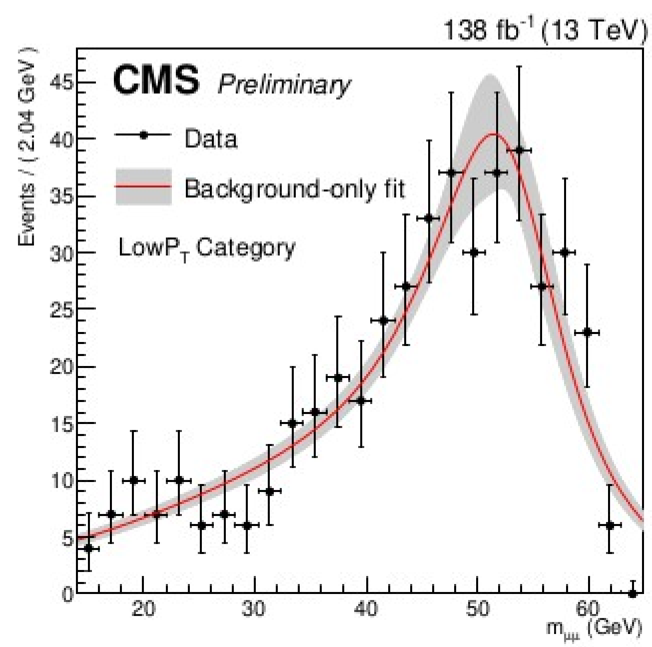
- single or double muon trigger
- $m_{\mu\mu}$: 14 – 70 GeV, targeting signals with m_a: 15–62.5 GeV
- ≥2 jets b-tagged, MET < 60 GeV
- Optimized requirement (corrected+decorrelated)

$$\chi^2_{tot} = \chi^2_{bb} + \chi^2_{H} \qquad \chi_{bb} = \frac{(m_{bb} - m_{\mu\mu})}{\sigma_{bb}} \qquad \chi_{H} = \frac{(m_{\mu\mu bb} - 125)}{\sigma_{H}}$$



- 5 categories based on (b)-jet selection
- Leading backgrounds: DY, top-pair production
- Background estimated by parametric fit
- Fit on $m_{\mu\mu}$ to extract signal



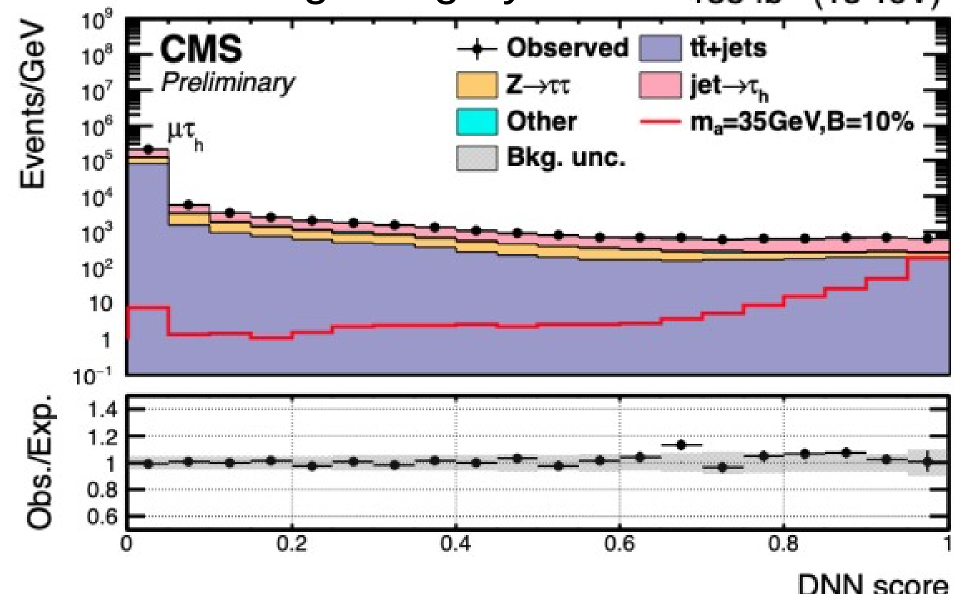


H → aa → μμbb and ττbb

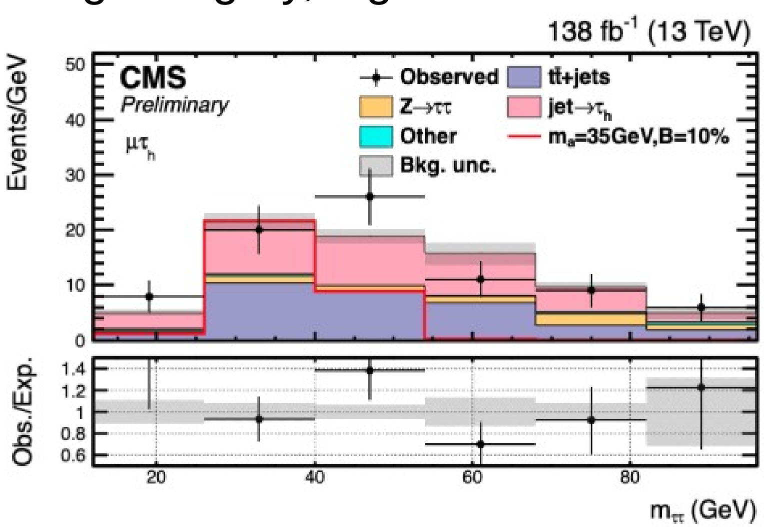
HIG-22-007

- H → aa → ττbb
  - Triggers containing electron, muons or hadronic taus to select events for 3 final states: **eμ**, **eτ_h**, **μτ_h**
  - ≥2 jets; 2 categories based on b-tagging
  - Deep neural net using kinematics to refine signal and control region definitions
  - Main backgrounds: Z → ττ, multijet, fake tau, top
  - Fit on visible mass $m_{\tau\tau}$ to extract signal

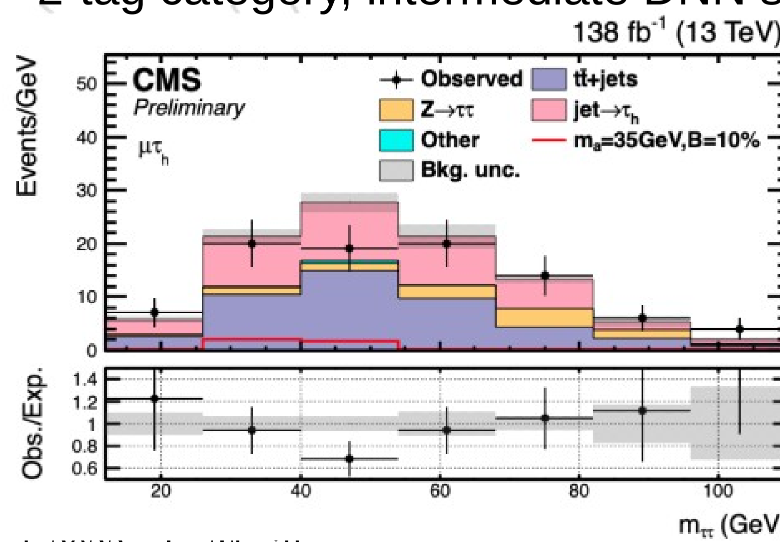
2-tag category



2-tag category, high DNN score



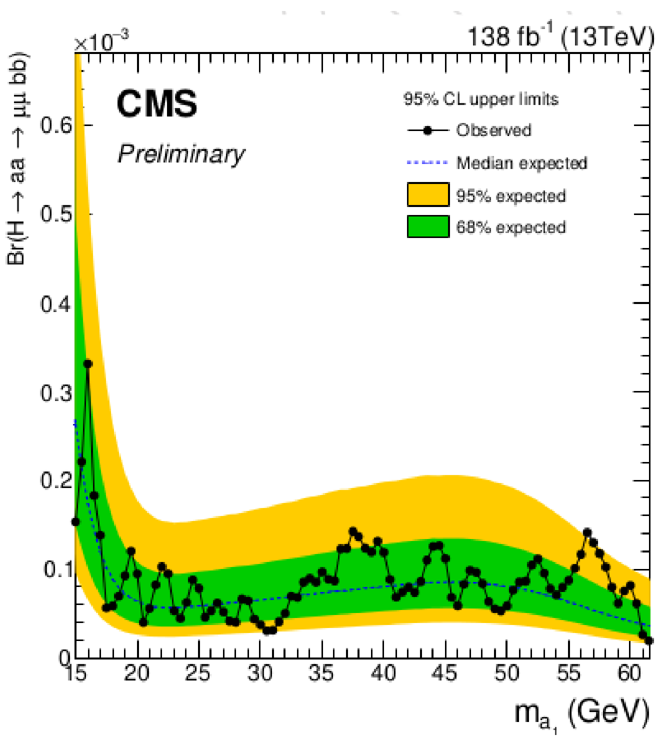
2-tag category, intermediate DNN score

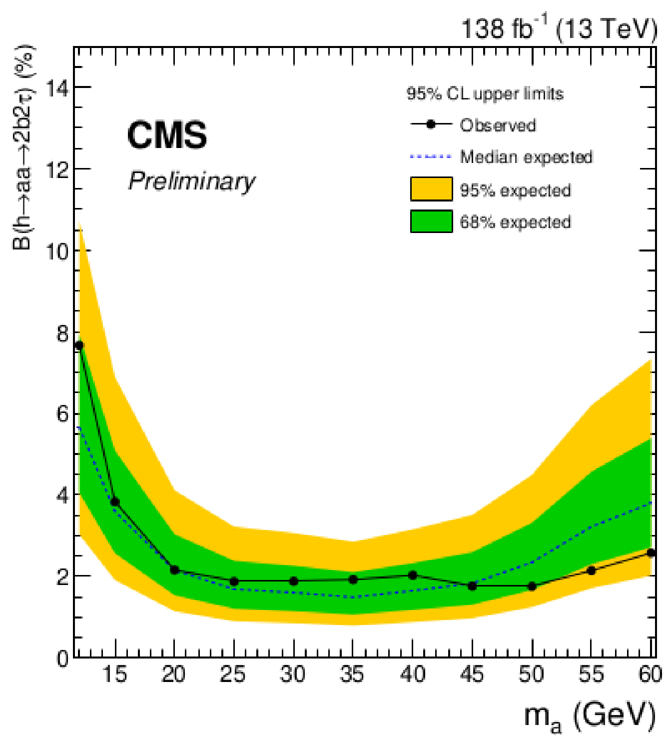


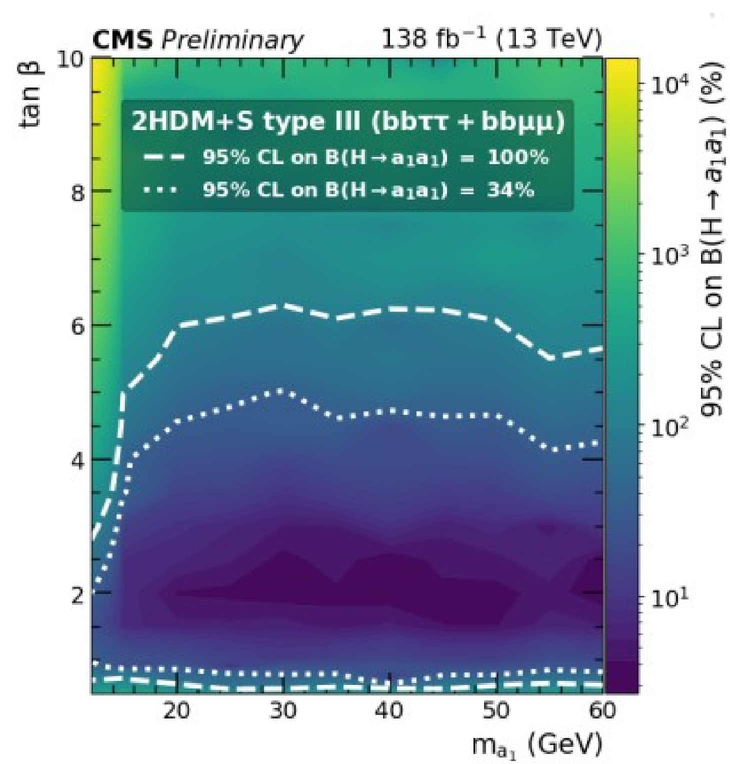
H → aa → μμbb and ττbb

HIG-22-007

- Results
  - Branching ratio limits and an example of an interpretation plot





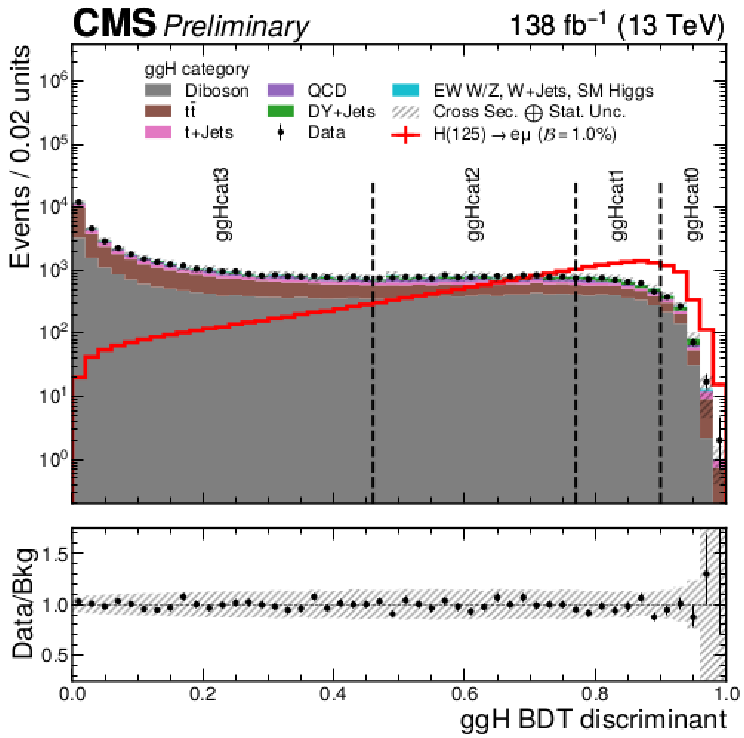


Lepton-flavour violating Higgs decays

- The Higgs sector is one of the best places to look for flavour violation, since it is less or only indirectly constrained
  - CMS search for **H → eμ** for m_H: 110–160 GeV HIG-22-002
  - ATLAS search for **H → eτ** and **H → μτ** arXiv:2302.05225

CMS search for H → eμ

- Signature: eμ pair, ΔR > 0.3, $m_{e\mu}$: 100–170 GeV
- categories based on jets: VBF and ggF
- BDTs used in each category using kinematics to refine the categories
- Fit the $m_{e\mu}$ mass in each category using parametric function for the background



Lepton-flavour violating Higgs decays

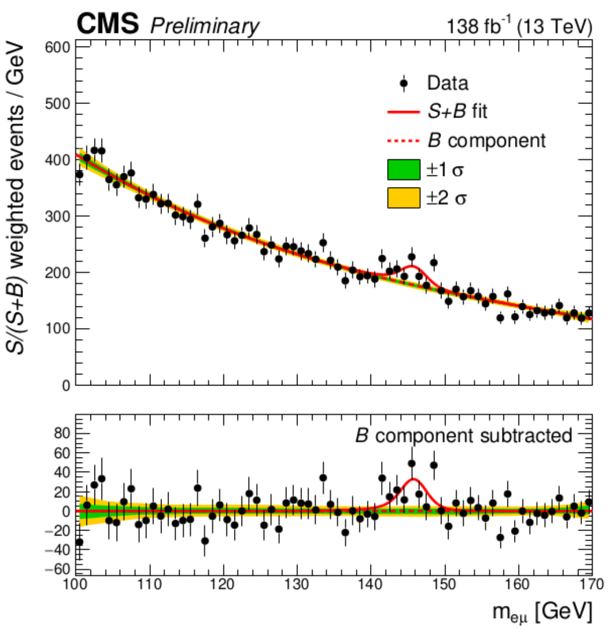
HIG-22-002

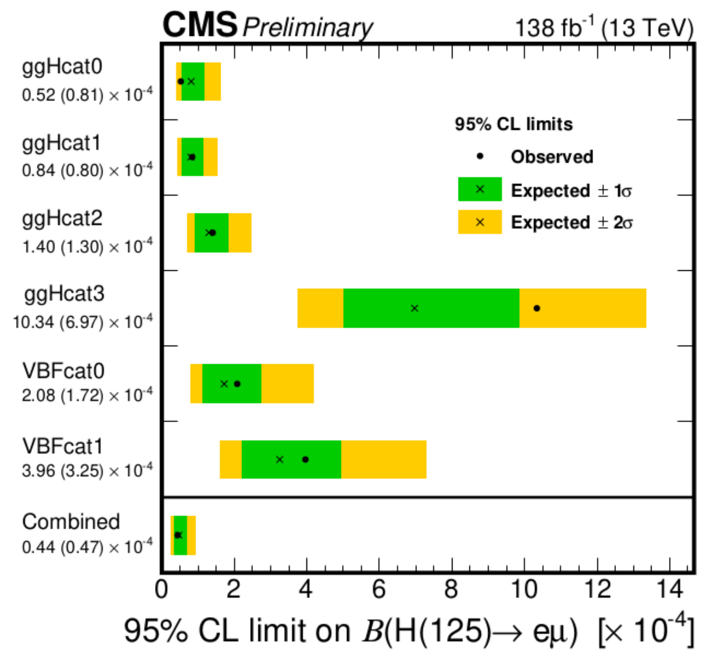
CMS search for H → eμ

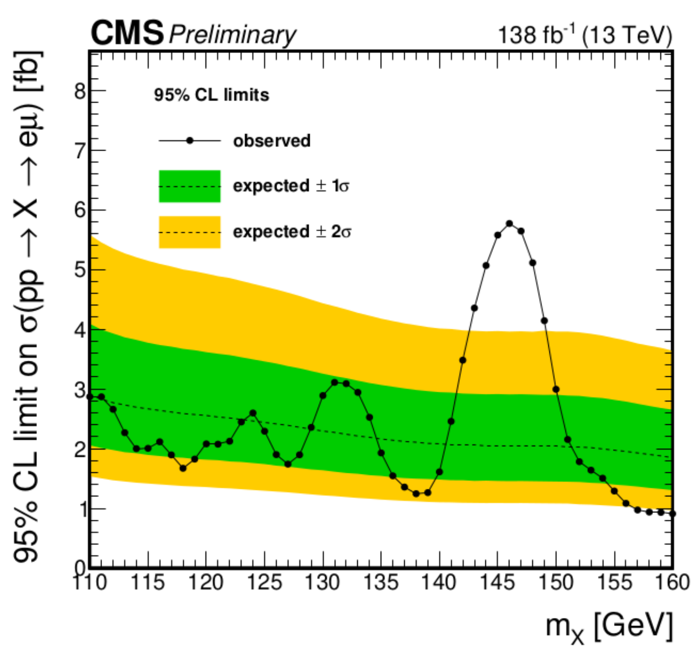
- Results BR(H (125) → eμ) < 4.4 (4.7 exp) × 10^{-5} at 95% CL

Sensitivity per channel

For other masses: 2.8 sigma excess at m_H ~ 146 GeV







Lepton-flavour violating Higgs decays

arXiv:2302.05225

- ATLAS searches for $H \rightarrow \ell\tau$ in different channels:
  - $H \rightarrow e\,\tau_h$ / $e\,\tau_\mu$ and $H \rightarrow \mu\,\tau_h$ / $\mu\,\tau_e$
  - Two complementary techniques for background estimation: MC-template and Symmetry method
  - Selections optimized for several categories aiming at VBF and ggF production
  - BDT/NN for each category which is fitted to obtain the final result

MC-template method

- Background estimation is done using data-driven methods for events containing jets misidentified as e/μ/τ
- Rest of backgrounds by simulation which is corrected or validated using dedicated control regions in data

Symmetry method

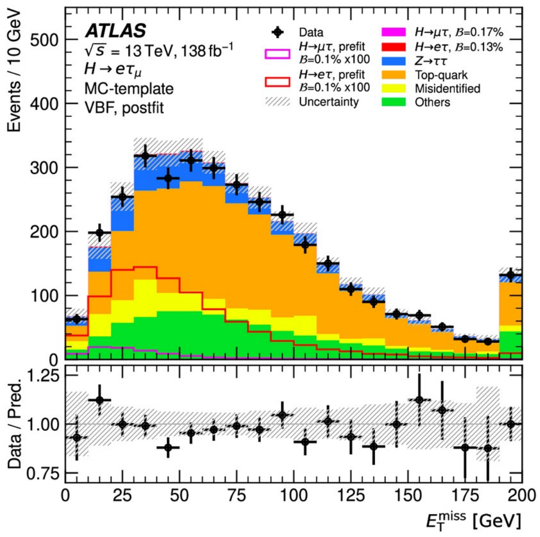
- Assumes that SM backgrounds are the same if you exchange electrons for muons, i.e. they are the same between the $e\tau_\mu$ / $\mu\tau_e$ datasets
- But you need to correct for detector effects and fake rates that are different for electrons and muons

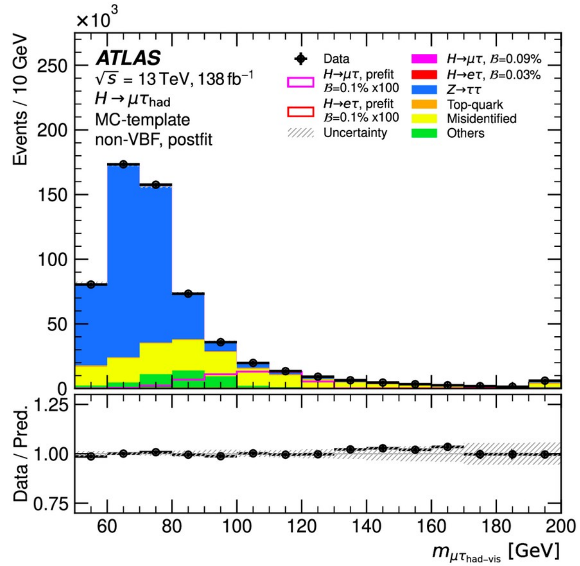
UNIVERSITY OF LIVERPOOL

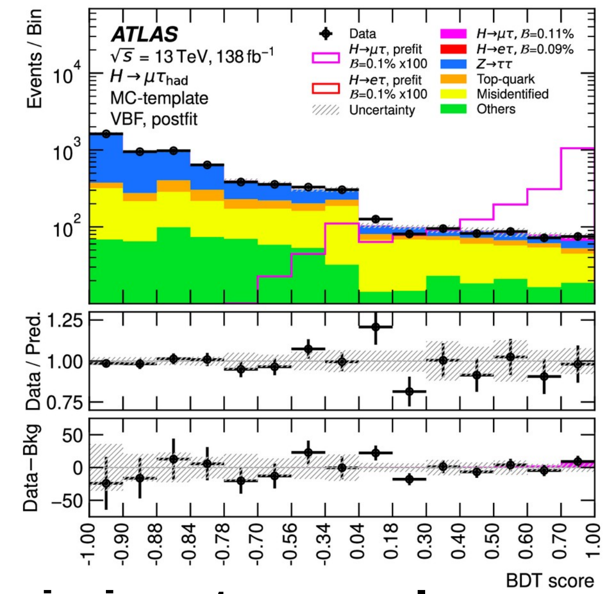
arXiv:2302.05225

Lepton-flavour violating Higgs decays

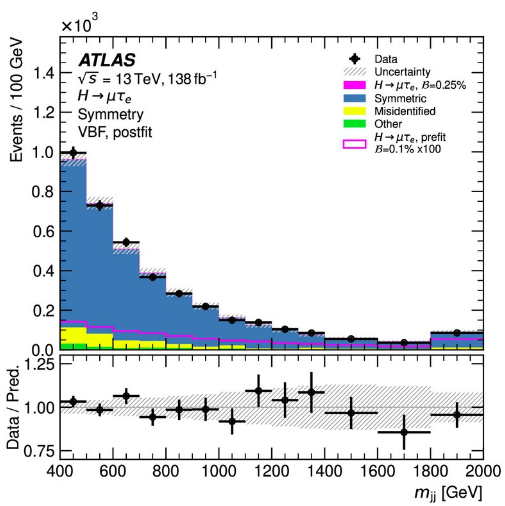
MC-template method: background modeling + final discriminant examples

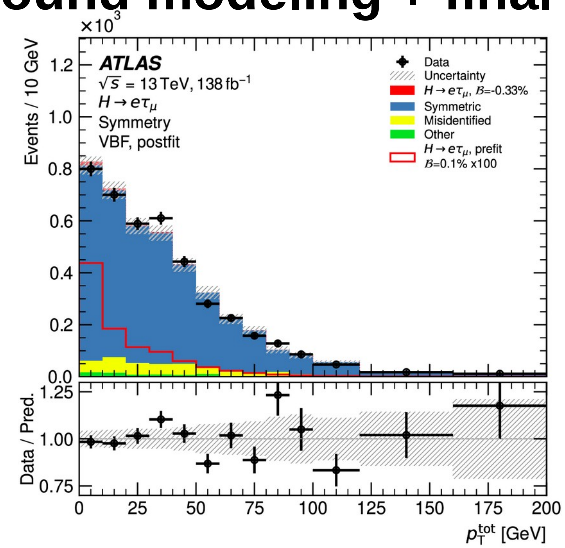


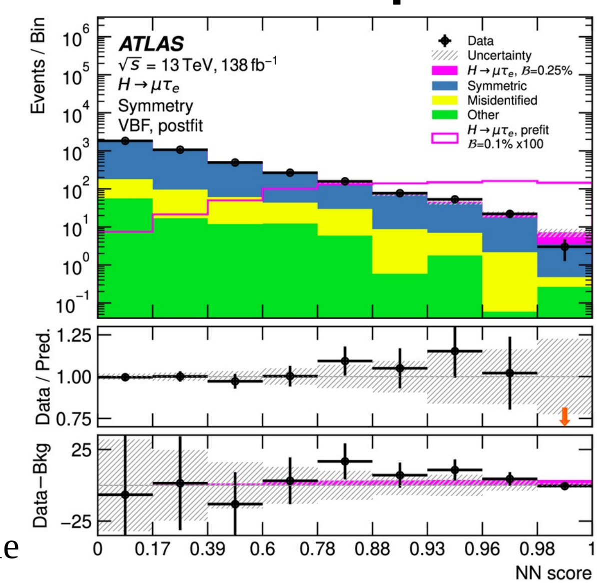




Symmetry method: background modeling + final discriminant examples





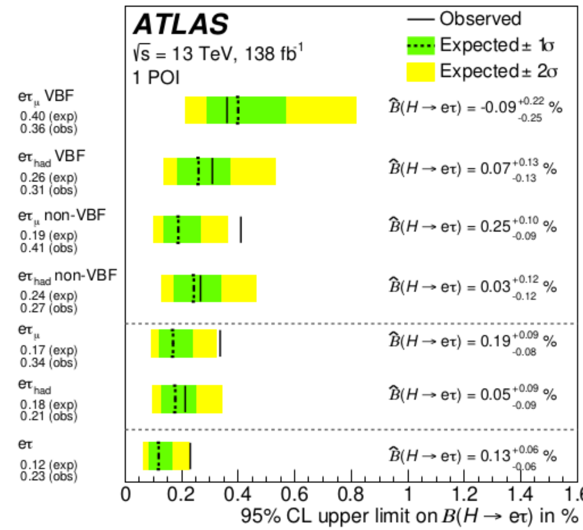


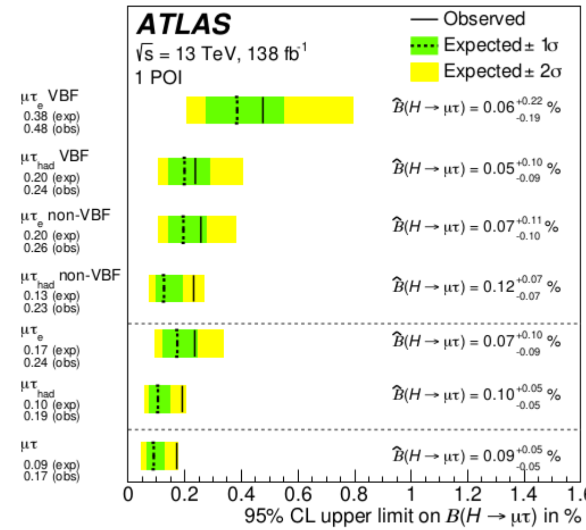
arXiv:2302.05225

Lepton-flavour violating Higgs decays

1 POI fit: Search for
H → eτ assuming BR(H → μτ) = 0
or for
H → μτ assuming BR(H → eτ) = 0

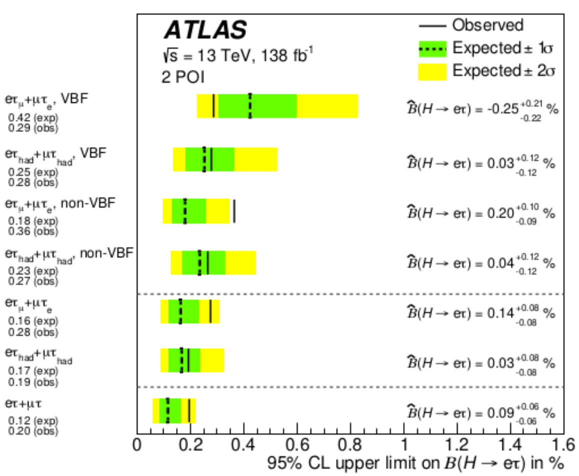
BR(H → eτ) < 0.23% (0.12% exp)
BR(H → μτ) < 0.17% (0.09% exp)

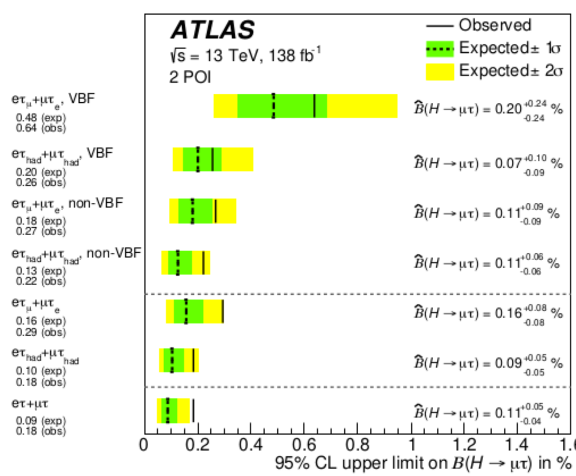


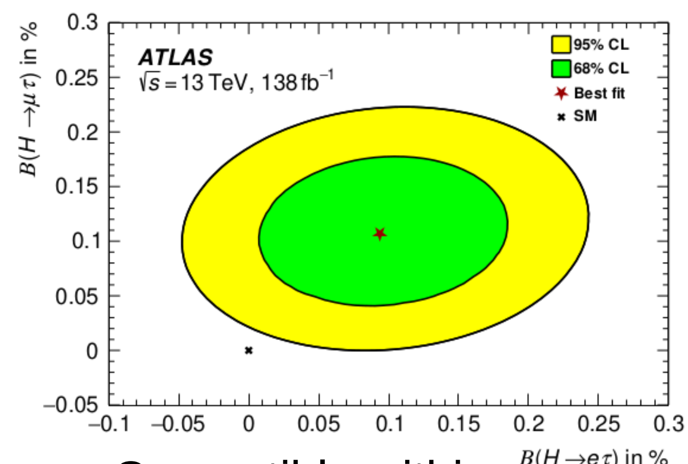


2 POI fit: Simultaneous search for **H → eτ** and **H → μτ**

BR(H → eτ) < 0.20% (0.12% exp)
BR(H → μτ) < 0.18% (0.09% exp)







Compatible within 2.1σ with the SM

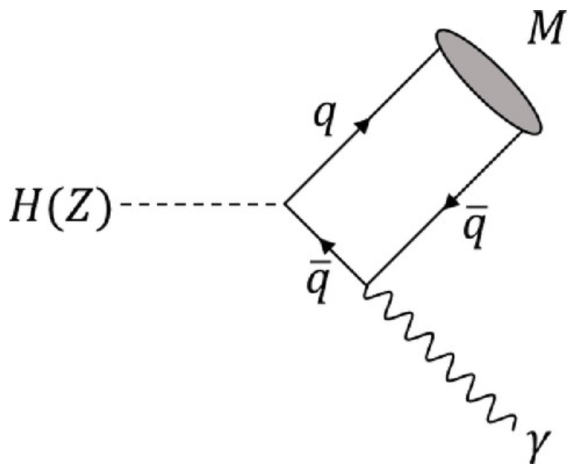
Higgs/Z to meson + photon

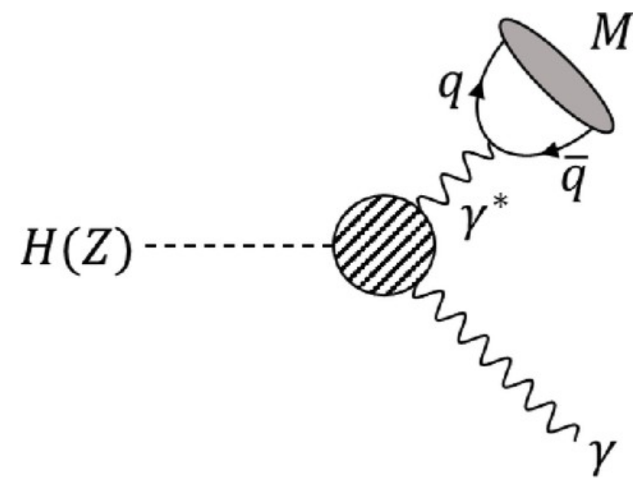
arXiv:2301.09938

- H/Z → ωγ & H→ K* γ

Up / down quark coupling

Flavour violating down / strange quark coupling





A way to probe Higgs couplings to light quarks

Ultra rare decays:
BR(H→ ωγ) ~ 10^{-6}, BR(H→ K*γ) < 10^{-11}, BR(Z → ωγ) ~ 10^{-8}

How to look for them:
Aim to reconstruct meson decays ω → $\pi^+\pi^-\pi^0$ and K* → $K^+ \pi^-$ and then take the invariant mass of the meson-photon system

Higgs/Z to meson + photon

arXiv:2301.09938

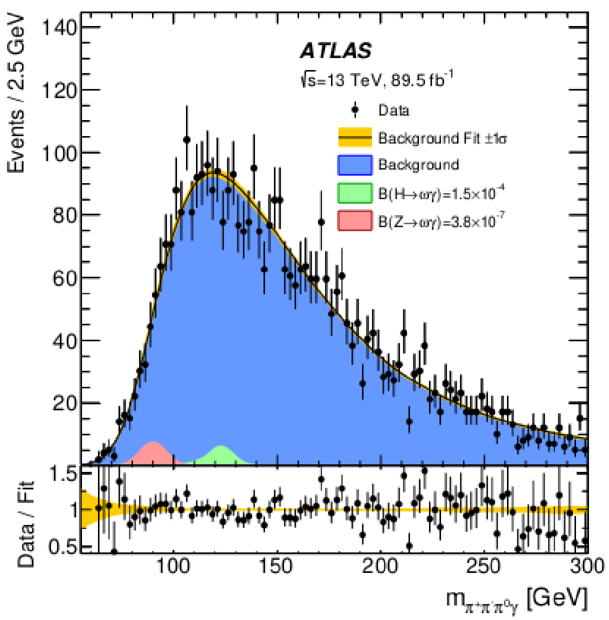
- ## Strategy

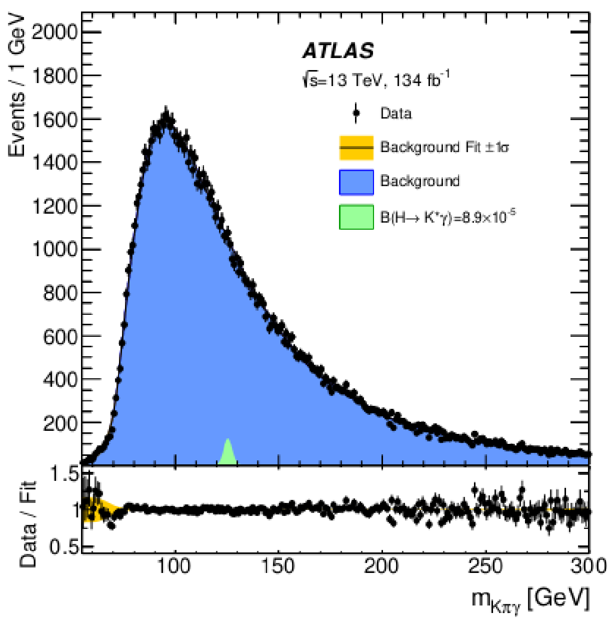
➢ Use a dedicated one photon + 2 tracks + calo deposit trigger

➢ Isolated photon pT > 35 GeV

➢ Meson reconstruction using tracks, calo deposits and invariant mass constraints

➢ Background estimation: ωγ and K*γ candidates from data passing without isolation to produce templates for the mass of the ωγ and K*γ systems





~ 100 x SM

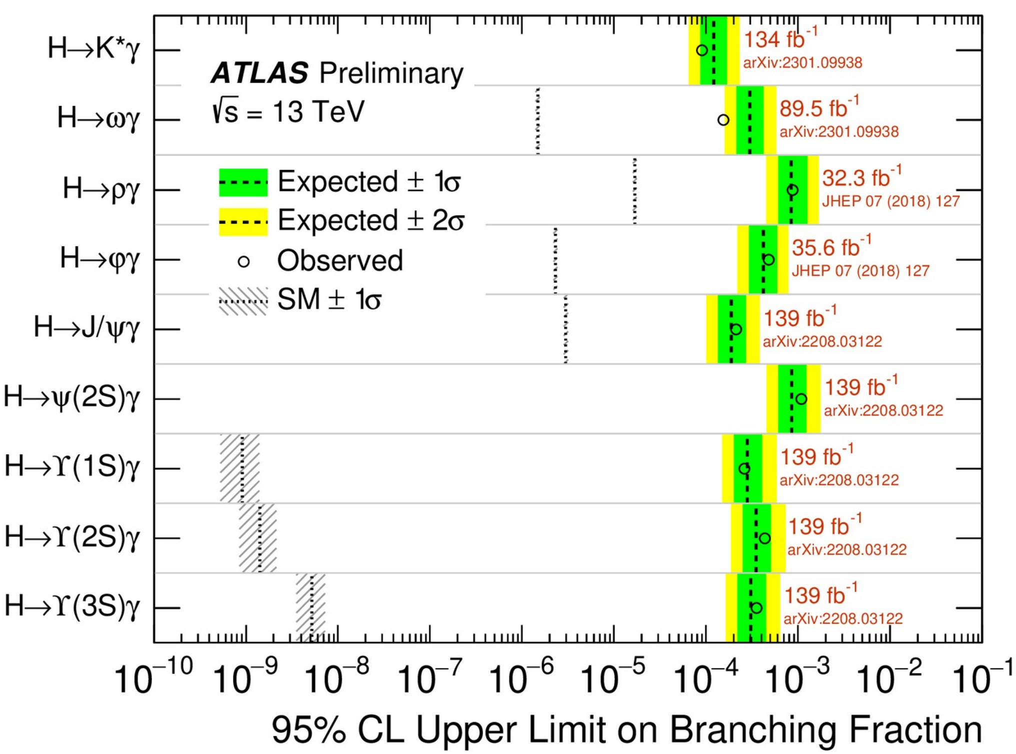
Channel	95% CL upper limit	
	Expected	Observed
$H \to \omega\gamma\ [10^{-4}]$	$3.0^{+1.2}_{-0.8}$	1.5
$Z \to \omega\gamma\ [10^{-7}]$	$5.7^{+2.3}_{-1.6}$	3.8
$H \to K^{*}\gamma\ [10^{-5}]$	$12.2^{+4.9}_{-3.4}$	8.9

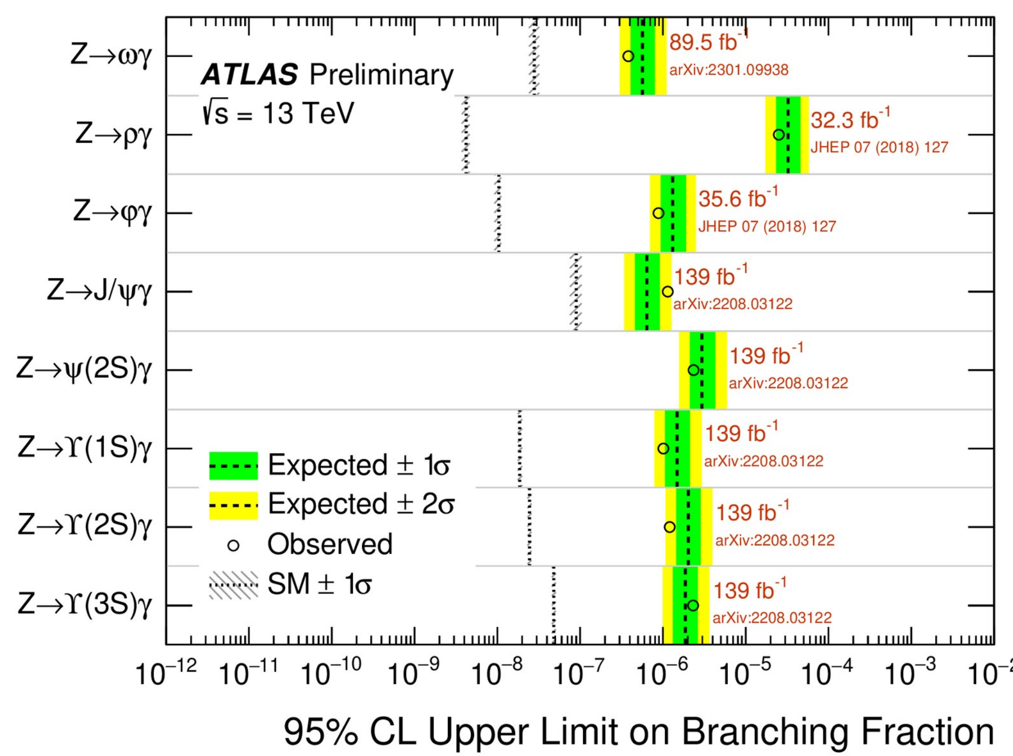
~ 17 x SM and ~1000x better wrt previous limit

Higgs/Z to meson + photon

- Summary plot for all results so far from ATLAS

ATL-PHYS-PUB-2023-004





Conclusions

- Rare (even not-so-rare) or exotic Higgs boson decays are still compatible with Higgs measurements
- These searches push the limits of our understanding of physics beyond the Standard Model
  - And they provide an opportunity to discover new physics

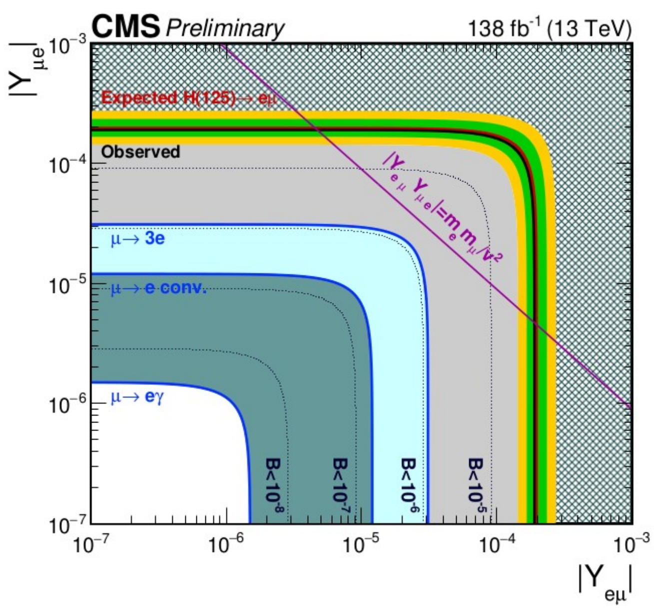
Additional slides

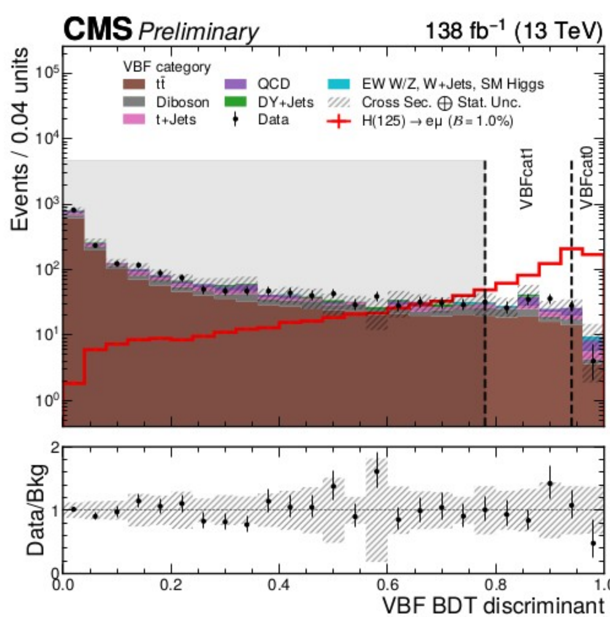
Lepton-flavour violating Higgs decays

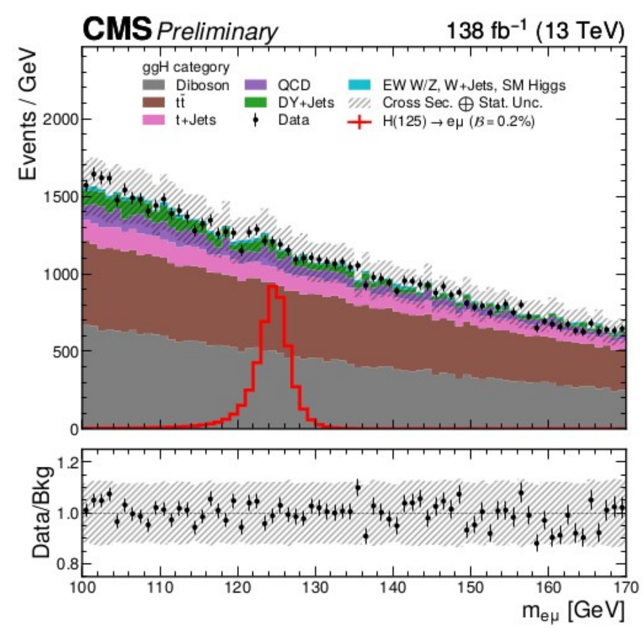
CMS search

Table 4: Observed (expected) 95% CL upper limits, best fit, and local significance in unit of standard deviation (σ) of $\sigma(pp \to X(146) \to e\mu)$ for each individual analysis category and for the combination of all analysis categories.

Category	ggH cat 0	ggH cat 1	ggH cat 2	ggH cat 3	VBF cat 0	VBF cat 1	Combined
Observed limit (fb)	< 7.57	< 4.56	< 11.68	< 53.25	< 12.60	< 22.11	< 5.77
Expected limit (fb)	< 3.62	< 3.51	< 5.96	< 34.01	< 6.53	< 12.52	< 2.05
Best fit (fb)	$4.11^{+2.02}_{-1.84}$	$1.29^{+1.81}_{-1.29}$	$6.50^{+3.11}_{-3.02}$	$23.13^{+11.87}_{-17.11}$	$5.34^{+3.91}_{-2.95}$	$8.87^{+7.35}_{-6.24}$	$3.82^{+1.16}_{-1.09}$
Local significance (σ)	2.3	0.7	2.2	1.4	2.1	1.5	3.8



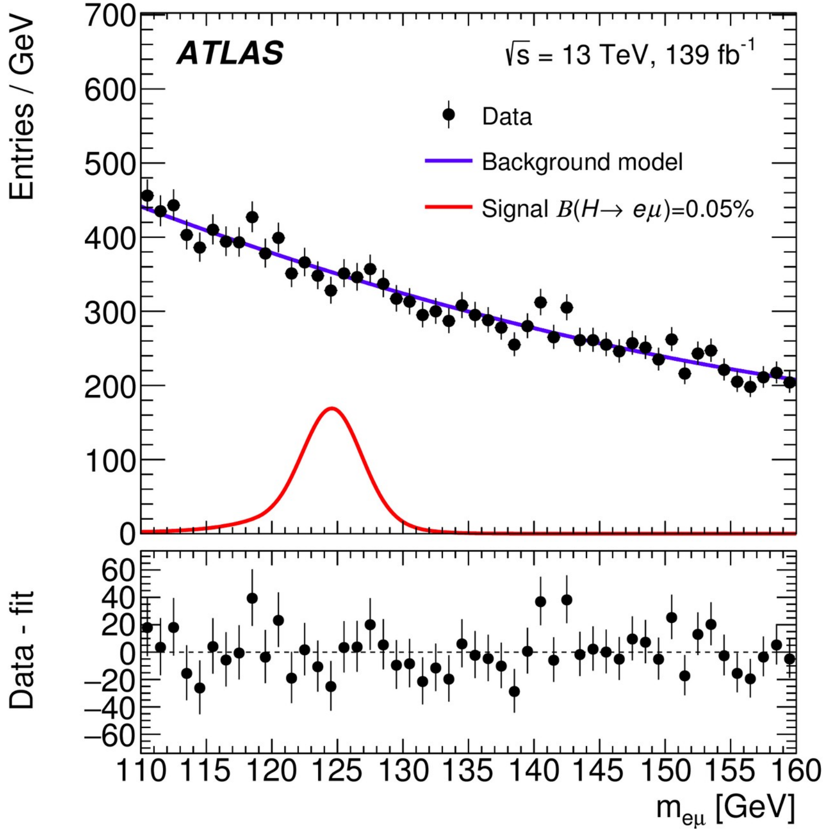




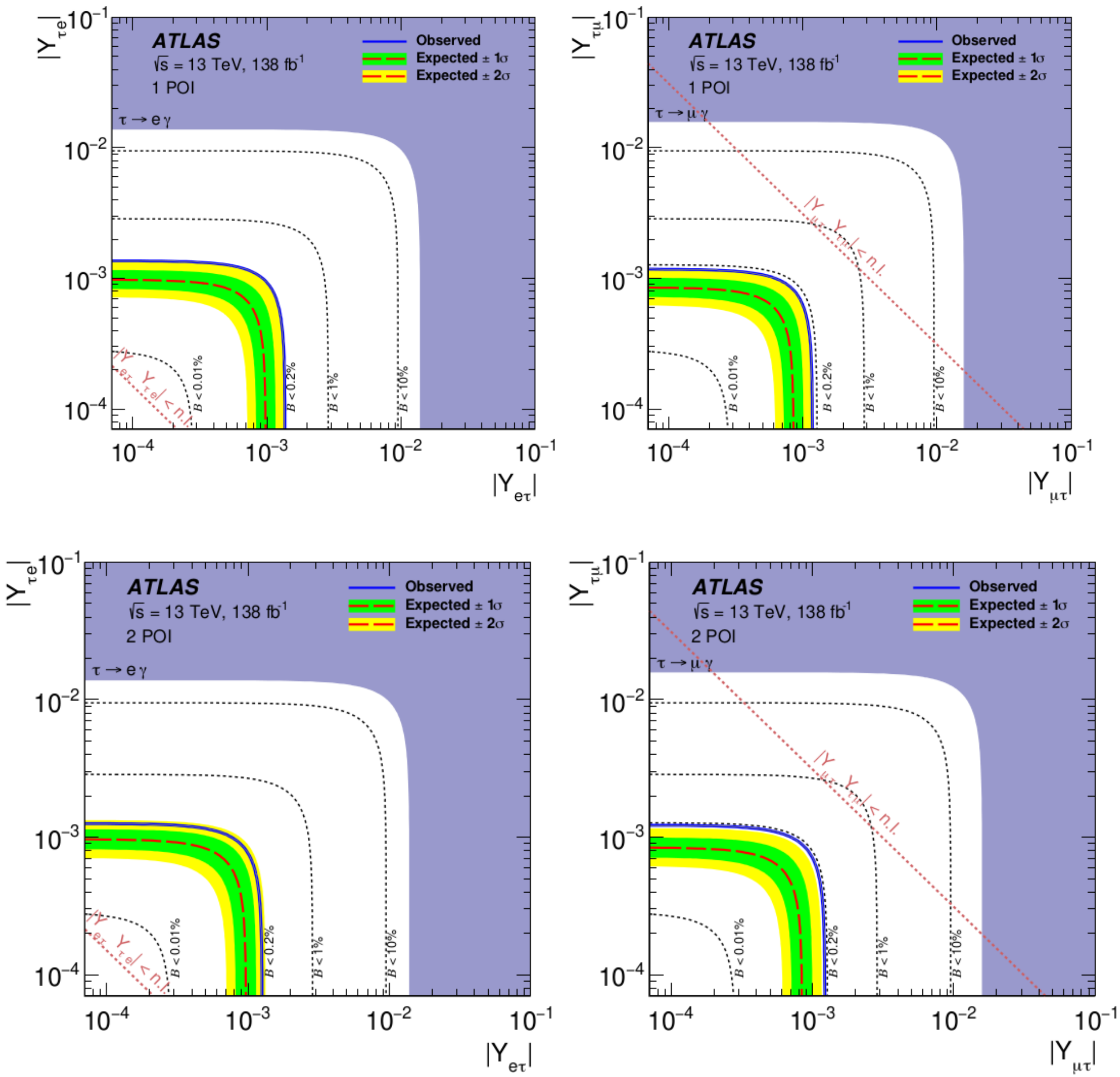
$\sqrt{(|Y_{e\mu}|^2 + |Y_{\mu e}|^2)} < 1.9\ (2.0) \times 10^{-4}$ at 95% CL

Lepton-flavour violating Higgs decays

Latest ATLAS search dedicated to H→ eμ: HIGG-2018-58
BR(H→eμ) < 6.2 (5.8)×10^{-5} at 95% CL

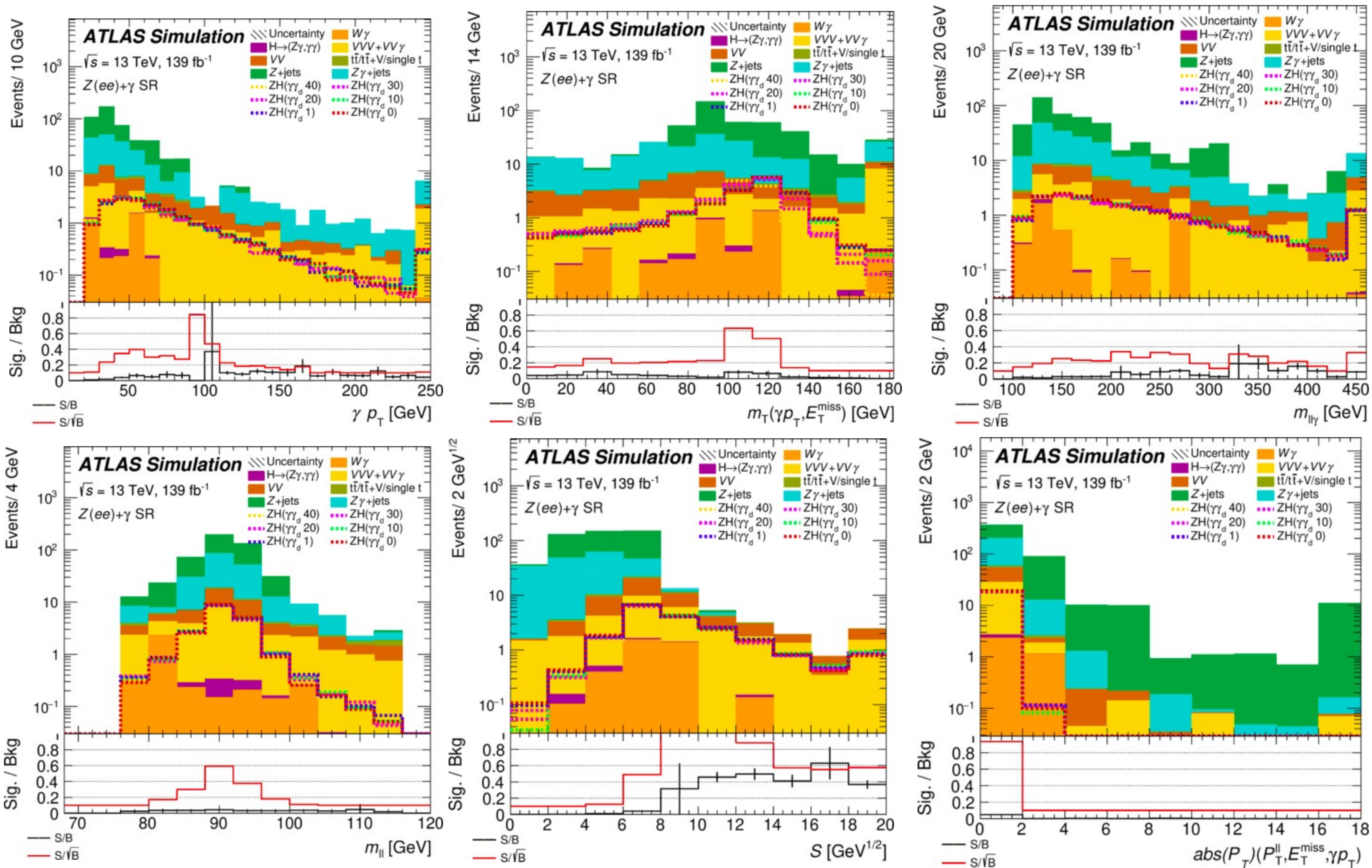


Lepton-flavour violating Higgs decays



Dark photons in Higgs decays

- Variables used in the BDT



H → aa → μμbb and ττbb

- Categories in ττbb

Table 7: Event categories for the $\tau\tau$bb channel. The values correspond to the transformed DNN score used to define the signal (SRn) and control (CR) regions.

	Exactly one b-tagged jet				At least two b-tagged jets		
	SR1	SR2	SR3	CR	SR1	SR2	CR
$e\mu$ 2018	> 0.99	$\in [0.95, 0.99]$	$\in [0.85, 0.95]$	< 0.85	> 0.98	$\in [0.94, 0.98]$	< 0.94
$e\mu$ 2017	> 0.985	$\in [0.95, 0.985]$	$\in [0.85, 0.95]$	< 0.85	> 0.97	$\in [0.93, 0.97]$	< 0.93
$e\mu$ 2016	> 0.99	$\in [0.95, 0.99]$	$\in [0.85, 0.95]$	< 0.85	> 0.98	$\in [0.94, 0.98]$	< 0.94
	One b-tagged jet				Two b-tagged jet		
	SR1	SR2	SR3	CR	SR1	SR2	CR
$e\tau_h$ 2018	> 0.97	$\in [0.945, 0.97]$	$\in [0.90, 0.945]$	< 0.90	> 0.96	NA	< 0.96
$e\tau_h$ 2017	> 0.985	$\in [0.965, 0.985]$	$\in [0.93, 0.965]$	< 0.93	> 0.985	NA	< 0.985
$e\tau_h$ 2016	> 0.985	$\in [0.965, 0.985]$	$\in [0.93, 0.965]$	< 0.93	> 0.96	NA	< 0.96
	SR1	SR2	SR3	CR	SR1	SR2	CR
$\mu\tau_h$ 2018	> 0.98	$\in [0.95, 0.98]$	$\in [0.90, 0.95]$	< 0.90	> 0.99	$\in [0.96, 0.99]$	< 0.96
$\mu\tau_h$ 2017	> 0.97	$\in [0.94, 0.97]$	$\in [0.90, 0.94]$	< 0.90	> 0.98	$\in [0.94, 0.98]$	< 0.94
$\mu\tau_h$ 2016	> 0.97	$\in [0.94, 0.97]$	$\in [0.89, 0.94]$	< 0.89	> 0.97	$\in [0.93, 0.97]$	< 0.93