第八届中国 LHC 物理研讨会

Searches for Higgs rare decays and BSM Higgs at the LHC

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On behalf of ATLAS, CMS and LHCb Collaborations

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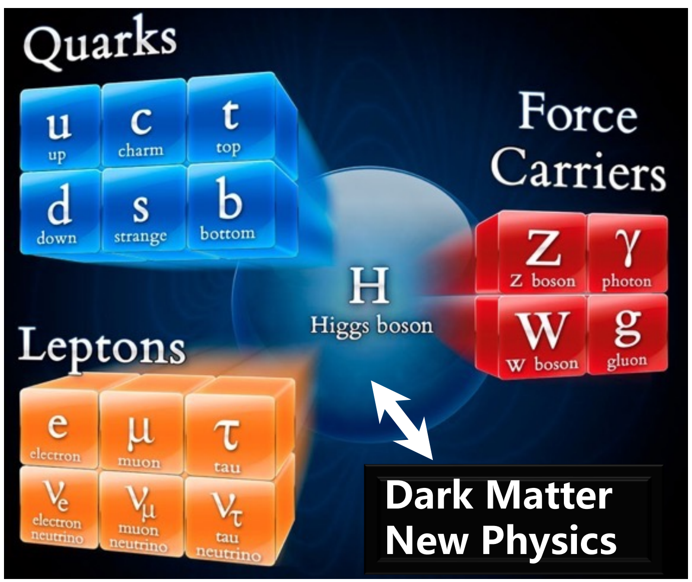
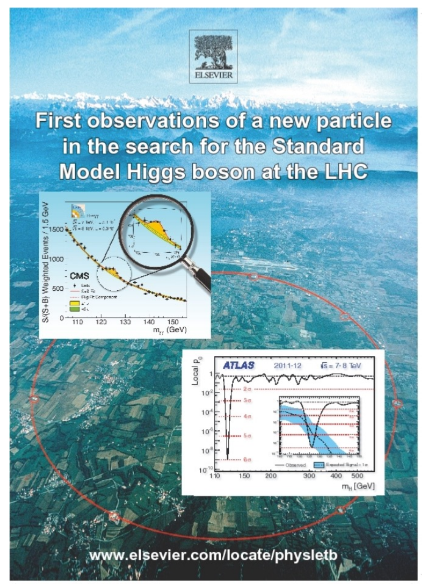
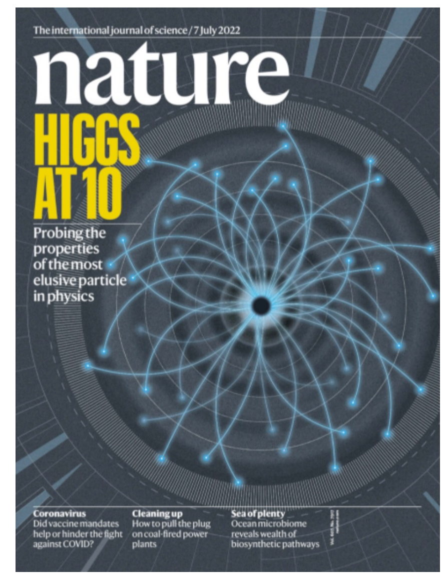
Outline

- **Higgs Rare Decays**
- **Higgs BSM Decays**
- **Additional Higgs bosons**
- **Summary**



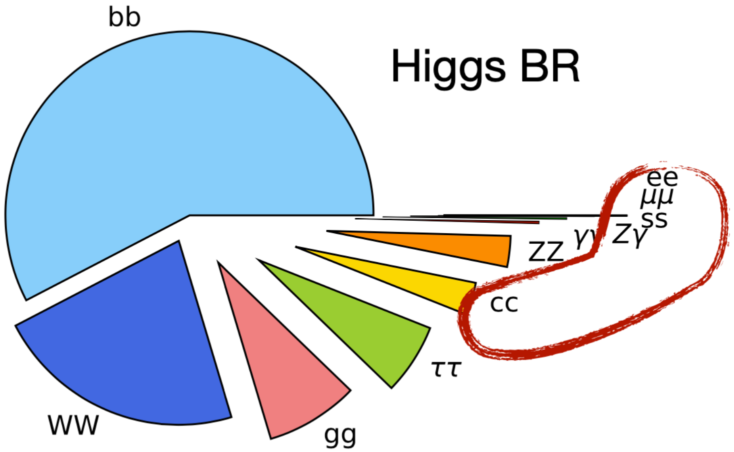




Disclaimer: only a few selected recent updates among all results from the LHC experiments

1、 Rare decays

- The fermionic sector is characterized by **Yukawa couplings** to the Higgs boson
  - **Proportional to the fermion mass**!
- New physics can affect differently the **different fermion generations**
  - Precision mapping of the couplings is key to understand the nature of the Higgs boson
  - Asymmetries in the leptonic vs the quark sector
- **Rare decays** happen also through quantum **loops**
  - Precise measurements give indications on the couplings and particles in the loop, and therefore are **sensitive to new structures and particles**



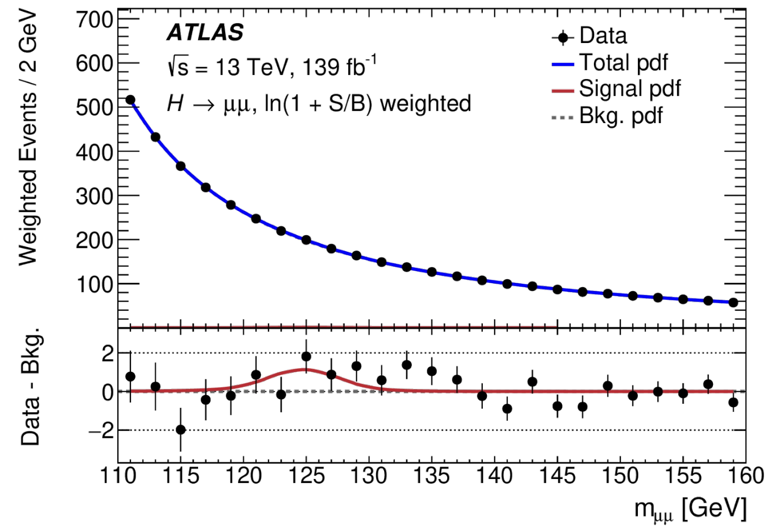
Experimentally challenging:

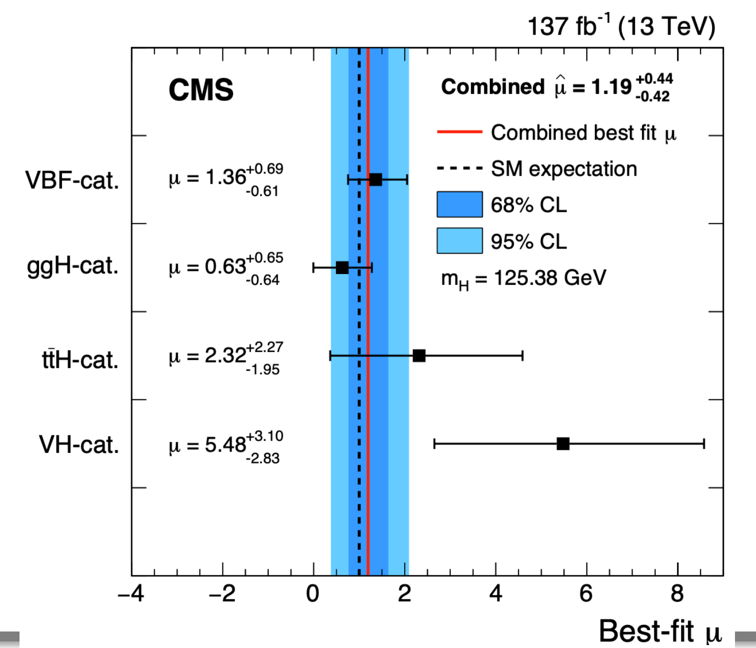
- Small BR
- Low S/B

H→μμ decay

ATLAS: PLB 812 (2021) 135980
CMS: JHEP 01 (2021) 148

- The Higgs decay to two muons offers the best opportunity to observe the Higgs couplings with second-generation fermions at the LHC
  - Small BR in SM (2.2×10^{-4})
  - Large SM irreducible DY→μμ background
  - S/B ~ 0.1% for inclusive events
- Exploit all major production modes, with MVA-based categorization
- **Evidence-level measurement** at the LHC
  - ATLAS: 2.0 σ (1.7 σ) for observed (expected) significance
  - CMS: 3.0 σ (2.5 σ) for observed (expected) significance





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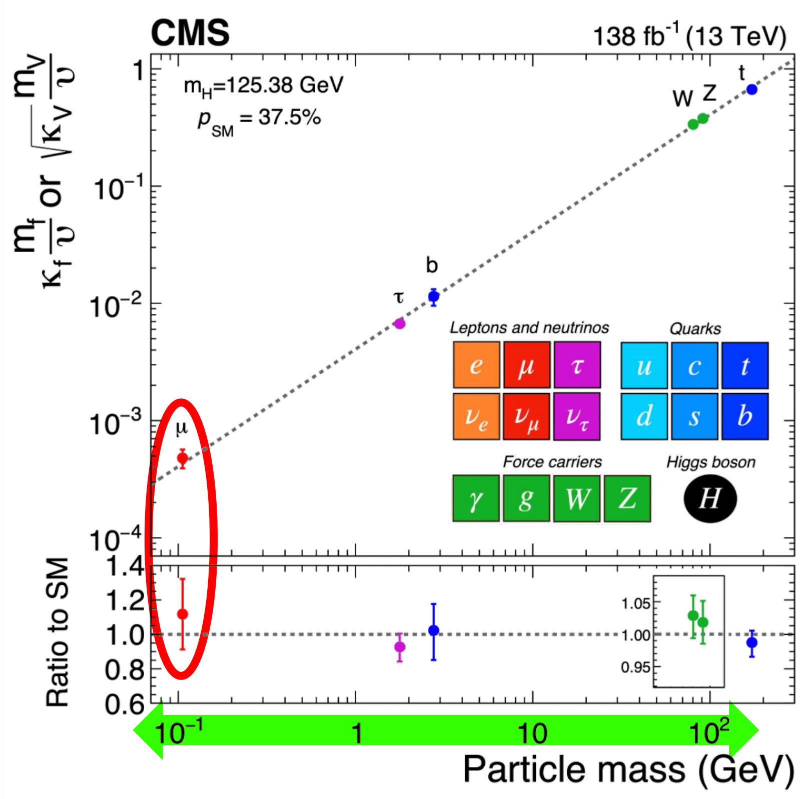


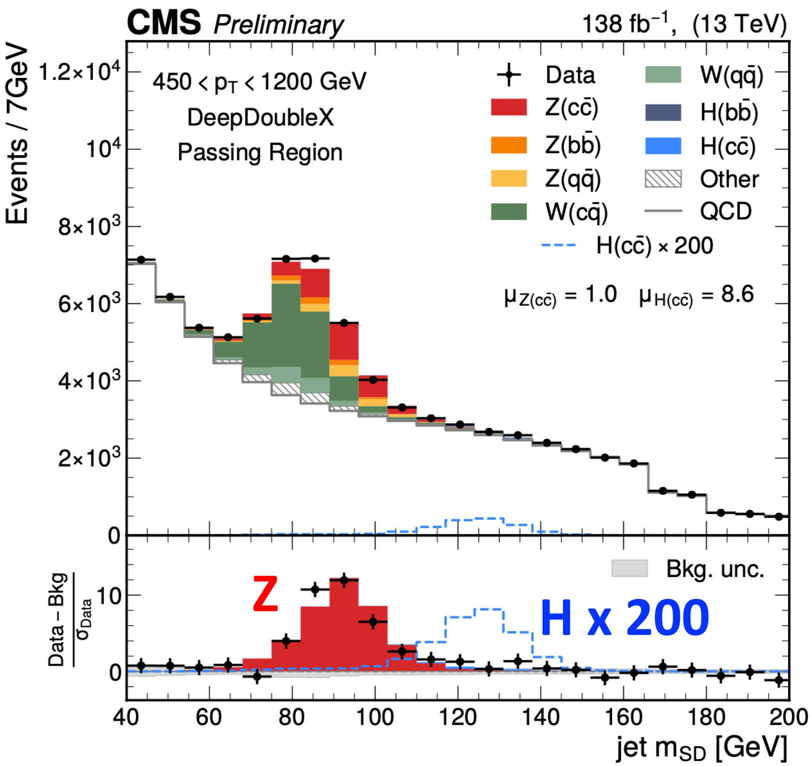
- Mass range probed covers 3 orders of magnitude !

H⟶cc decay

- Charm quarks harder to identify than muons
  - BR(H⟶cc) in SM: 2.8% (H⟶bb is background, 20 times more)
  - Use advanced machine learning techniques
- Large background, tackled by requiring large Higgs pT or associated particles

ggH analysis with **boosted cc** system in the final state

- Higgs reconstructed as single large-radius jet recoiling against a hadronic system
- Main bkg: multi-jet, V+jet
- Obs. (exp.) limit on H⟶cc: 45 (38) x SM @ 95% CL



H→cc decay

ATLAS: arxiv:2201.11428
CMS: arxiv:2205.05550

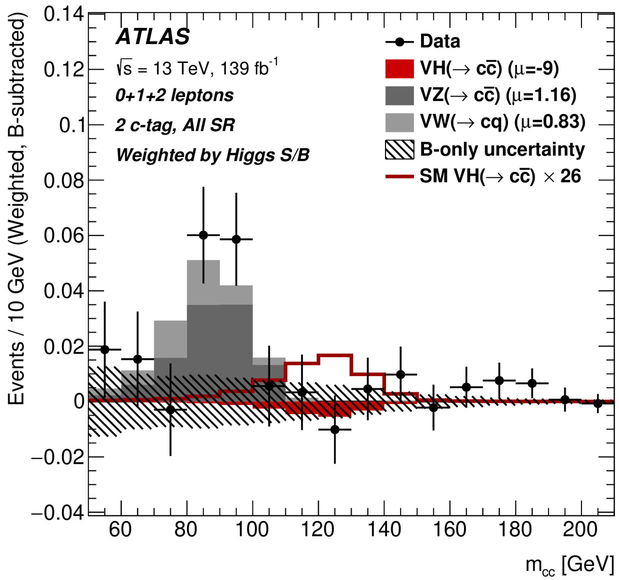
- VH analyses: exploit associated production with a vector boson
  - Tag leptonically decaying W/Z boson
  - Main bkg: W/Z+heavy flavor, $t\bar{t}$

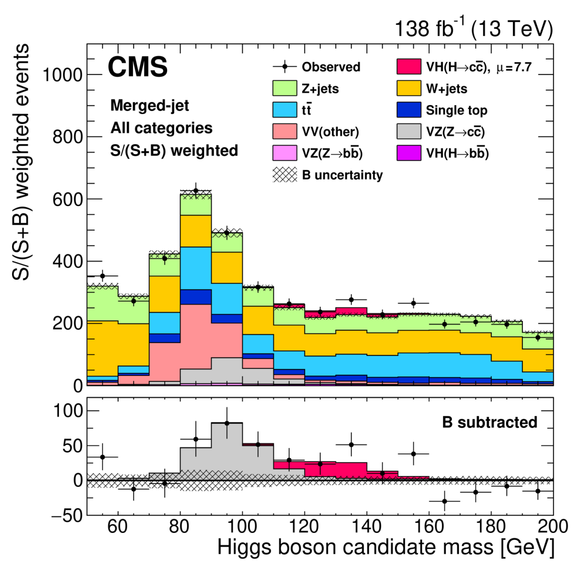
VH - ATLAS: resolved analysis only

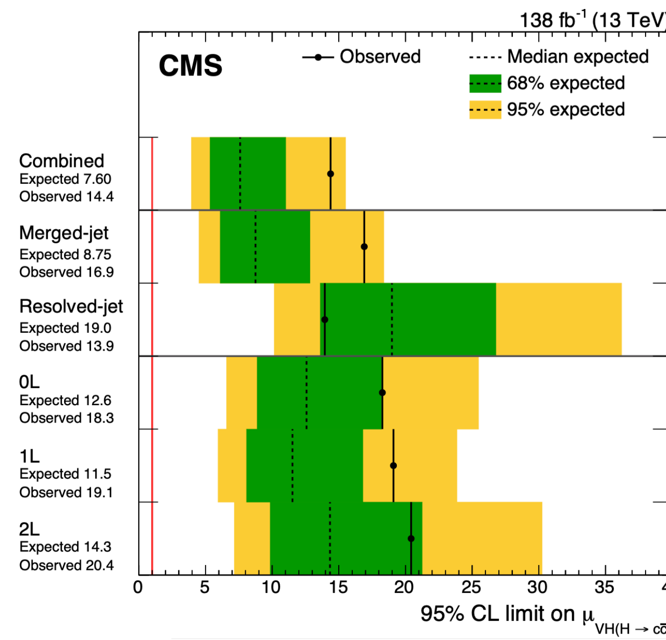
Obs. (exp.) limit on μ(H→$c\bar{c}$) : 31 (26) x SM @ 95% CL

VH - CMS: combine boosted + resolved regimes

- Boosted analysis benefits from **ParticleNet** based charm tagging
- Obs. (exp.) limit on μ(H→$c\bar{c}$) : **14 (7.6)** x SM @ 95% CL



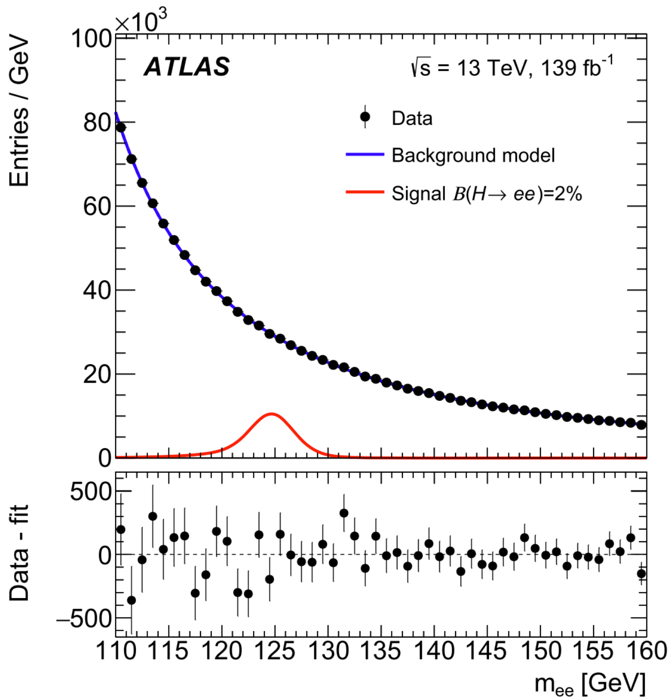


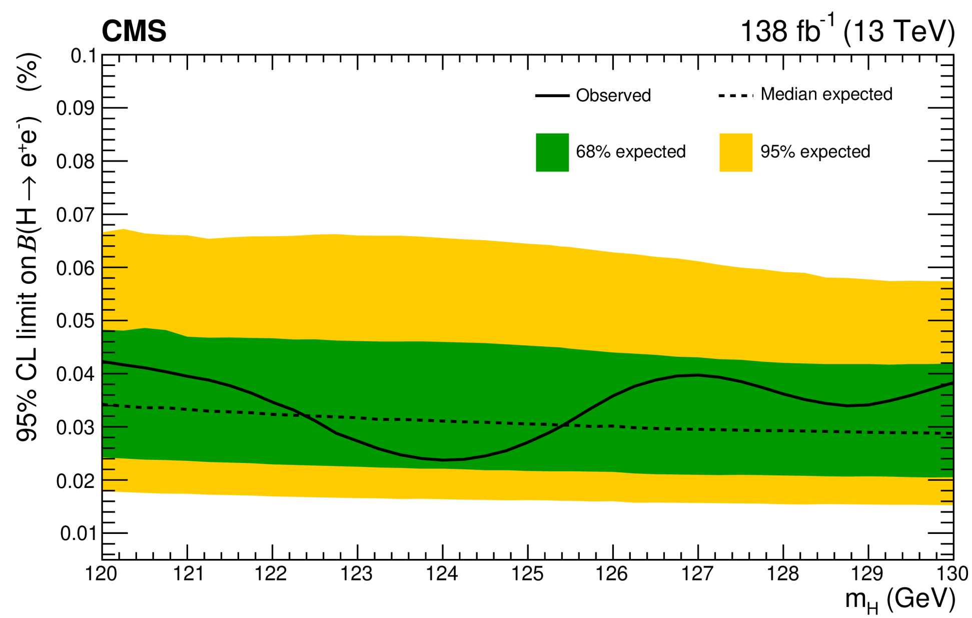


H→ee decay

CMS-HIG-21-015
PLB 801 (2020) 135148

- Direct probe of the Higgs-electron **first generation** fermions Yukawa coupling
  - SM prediction for Br(H→ee) ~ 5×10^{-9}
- Several categories, most sensitive category is VBF (best S/B)
- Parametric fit to the invariant mass distribution simultaneously in all categories



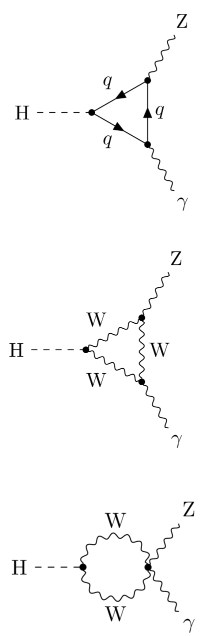


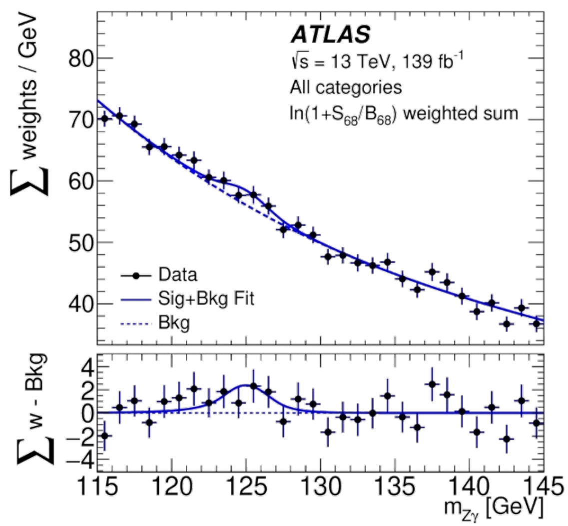
ATLAS: BR < 3.6×10^{-4} @ 95% CL

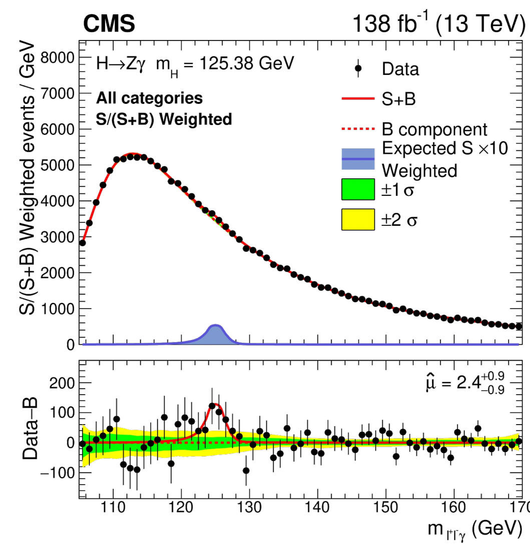
CMS: BR < 3.0×10^{-4} @ 95% CL

Rare loops: H→Zγ

- Sensitive to new physics in the difference between H→Zγ and H→γγ
  - Small BR in SM (1.6×10^{-3})
  - Main bkg: non-Higgs Zγ, Z+jets
- Select Z→ee and Z→μμ events and one additional photon
- Exploit different production modes with multiple categories
- Parametric fit in llγ mass distribution over all categories





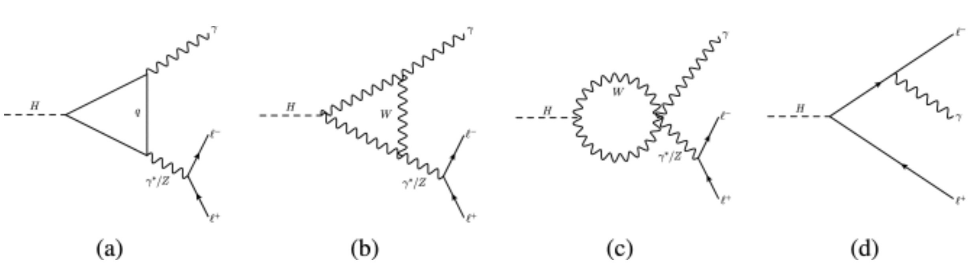


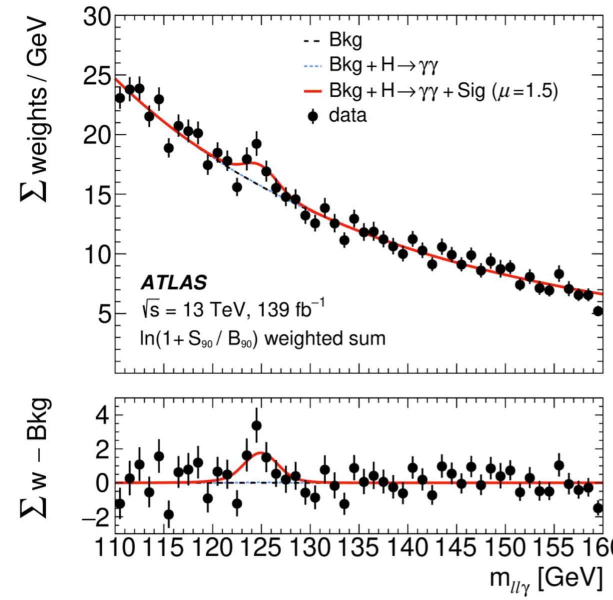
ATLAS obs (exp): **2.2σ** (1.2σ)   CMS obs (exp): **2.7σ** (1.2σ)

Both experiments seeing intriguing results

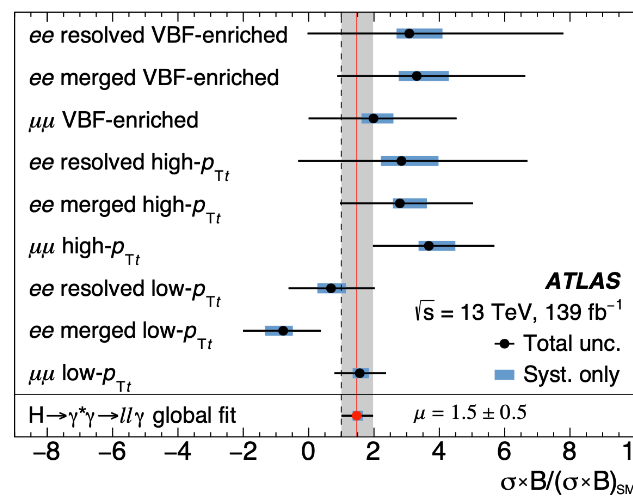
Rare loops: H⟶γ*γ

- Search for H⟶ γ*γ ⟶ eeγ or H ⟶ γ*γ ⟶ μμγ
  - SM Br(H ⟶ eeγ) = 7.2×10^{-5}
  - SM Br(H ⟶ μμγ) = 3.4×10^{-5}



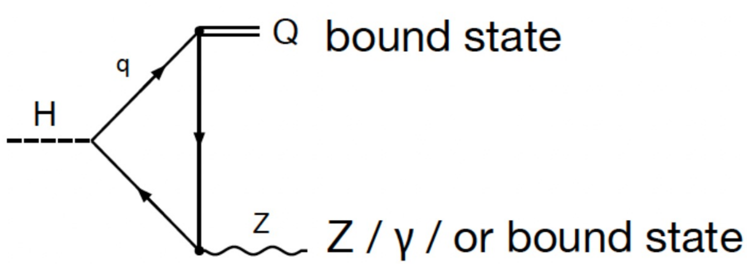


- m_{ll} < 30 GeV, with **pT μ (e) > 3 (5) GeV**
- Analyze events in μμ, resolved ee and merged ee channels
  - Dedicated ID and calibration for merged ee channel
- **First evidence** seen for this process:
  obs (exp) significance: 3.2σ (2.1σ)
  μ = 1.5 ± 0.5



Rare loops: H⟶mesons

- Higgs decays to mesons can be used to study **Higgs couplings to light, charm and bottom quarks**, as well as new physics in the loops
- The quarkonium (J/ψ, Υ) **decays into two muons** leave a clear experimental signature inside the detectors
- Bounds states like **ϕ and ρ** can decay into pairs of kaons and pions, which have good mass resolution at low pT
- Look into production in **association with a Z/γ** to trigger and reduce background



ATLAS HDBS-2018-53 : quarkonium + photon

Decay channel	Branching fraction: Higgs boson [10^{-4}] Expected	Higgs boson [10^{-4}] Observed	Z boson [10^{-6}] Expected	Z boson [10^{-6}] Observed	$\sigma \times \mathcal{B}$: Higgs boson [fb] Observed	Z boson [fb] Observed
	95% CL_s upper limits					
$J/\psi\,\gamma$	$1.9^{+0.8}_{-0.5}$	2.1	$0.6^{+0.3}_{-0.2}$	1.2	12	71
$\psi(2S)\,\gamma$	$8.5^{+3.8}_{-2.4}$	10.9	$2.9^{+1.3}_{-0.8}$	2.3	61	135
$\Upsilon(1S)\,\gamma$	$2.8^{+1.3}_{-0.8}$	2.6	$1.5^{+0.6}_{-0.4}$	1.0	14	59
$\Upsilon(2S)\,\gamma$	$3.5^{+1.6}_{-1.0}$	4.4	$2.0^{+0.8}_{-0.6}$	1.2	24	71
$\Upsilon(3S)\,\gamma$	$3.1^{+1.4}_{-0.9}$	3.5	$1.9^{+0.8}_{-0.5}$	2.3	19	135

CMS arXiv:2206.03525 : quarkonium +Z and 2 quarkonium

Process	Observed	Expected	Observed	
Higgs boson channel	Longitudinal	Longitudinal	Unpolarized	Transverse
$\mathcal{B}(H \to ZJ/\psi)$	1.9×10^{-3}	$(2.6^{+1.1}_{-0.7}) \times 10^{-3}$	2.4×10^{-3}	2.8×10^{-3}
$\mathcal{B}(H \to Z\psi(2S))$	6.6×10^{-3}	$(7.1^{+2.8}_{-2.0}) \times 10^{-3}$	8.3×10^{-3}	9.4×10^{-3}
$\mathcal{B}(H \to J/\psi J/\psi)$	3.8×10^{-4}	$(4.6^{+2.0}_{-0.6}) \times 10^{-4}$	4.7×10^{-4}	5.2×10^{-4}
$\mathcal{B}(H \to \psi(2S)J/\psi)$	2.1×10^{-3}	$(1.4^{+0.6}_{-0.4}) \times 10^{-3}$	2.6×10^{-3}	2.9×10^{-3}
$\mathcal{B}(H \to \psi(2S)\psi(2S))$	3.0×10^{-3}	$(3.3^{+1.5}_{-0.9}) \times 10^{-3}$	3.6×10^{-3}	4.7×10^{-3}
$\mathcal{B}(H \to \Upsilon(nS)\Upsilon(mS))$	3.5×10^{-4}	$(3.6^{+0.2}_{-0.3}) \times 10^{-4}$	4.3×10^{-4}	4.6×10^{-4}
$\mathcal{B}(H \to \Upsilon(1S)\Upsilon(1S))$	1.7×10^{-3}	$(1.7^{+0.1}_{-0.1}) \times 10^{-3}$	2.0×10^{-3}	2.2×10^{-3}
Z boson channel				
$\mathcal{B}(Z \to J/\psi J/\psi)$	11×10^{-7}	$(9.5^{+3.8}_{-2.6}) \times 10^{-7}$	14×10^{-7}	16×10^{-7}
$\mathcal{B}(Z \to \Upsilon(nS)\Upsilon(mS))$	3.9×10^{-7}	$(4.0^{+0.3}_{-0.3}) \times 10^{-7}$	4.9×10^{-7}	5.6×10^{-7}
$\mathcal{B}(Z \to \Upsilon(1S)\Upsilon(1S))$	1.8×10^{-6}	$(1.8^{+0.1}_{-0.0}) \times 10^{-6}$	2.2×10^{-6}	2.4×10^{-6}

ATLAS JHEP 07 (2018) 127 : ϕγ and ργ

Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)\,[\,10^{-4}\,]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z \to \phi\gamma)\,[\,10^{-6}\,]$	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H \to \rho\gamma)\,[\,10^{-4}\,]$	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z \to \rho\gamma)\,[\,10^{-6}\,]$	33^{+13}_{-9}	25

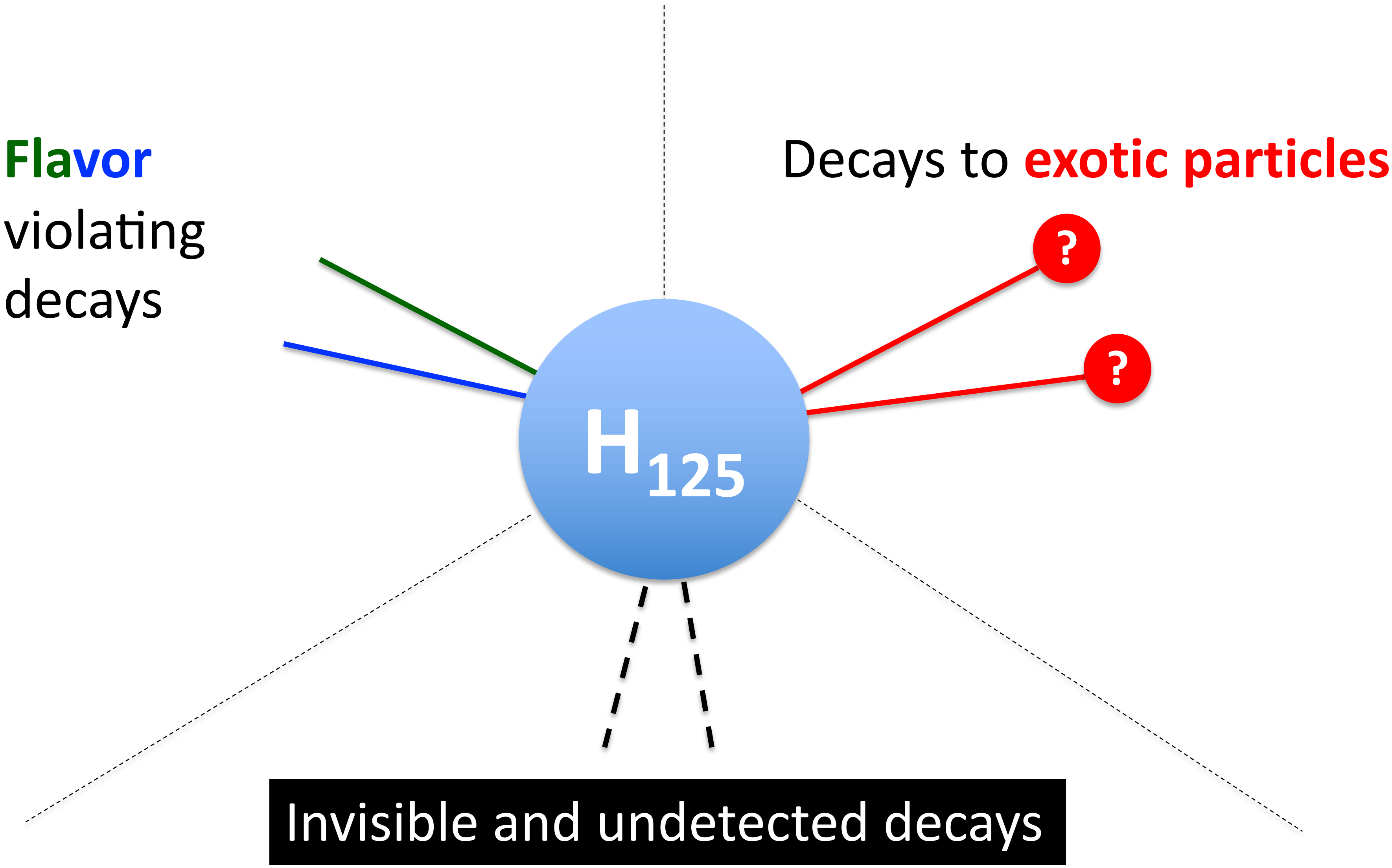
CMS JHEP 11 (2020) 039 : ϕZ and ρZ

	Observed	Median expected	±68% expected	±95% expected
Isotropic decay	0.36%	0.33%	0.23–0.46%	0.18–0.61%
Z and ϕ longitudinally polarized	0.31%	0.27%	0.20–0.39%	0.15–0.52%
Z and ϕ transversely polarized	0.40%	0.36%	0.26–0.50%	0.19–0.68%

	Observed	Median expected	±68% expected	±95% expected
Isotropic decay	1.21%	0.73%	0.52–1.04%	0.38–1.41%
Z and ρ longitudinally polarized	1.04%	0.63%	0.44–0.89%	0.32–1.20%
Z and ρ transversely polarized	1.31%	0.80%	0.57–1.14%	0.41–1.54%

2、BSM decays

Few examples



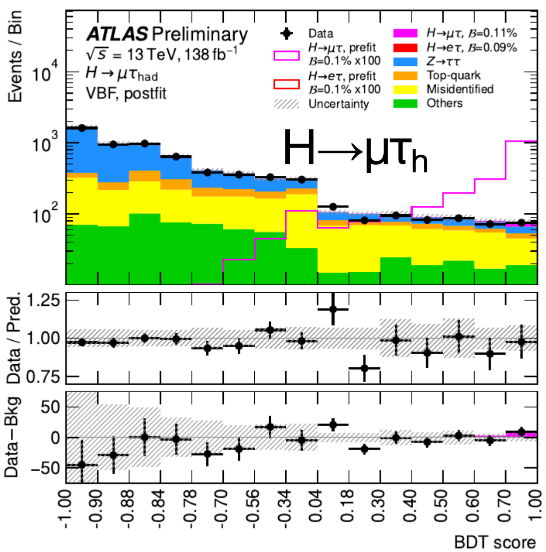
Lepton-Flavor Violating decays

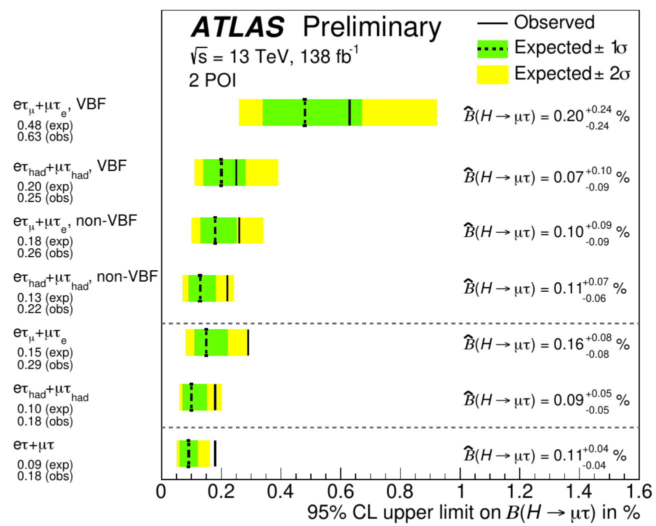
ATLAS-CONF-2022-069
CMS: PRD 104 (2021) 032013

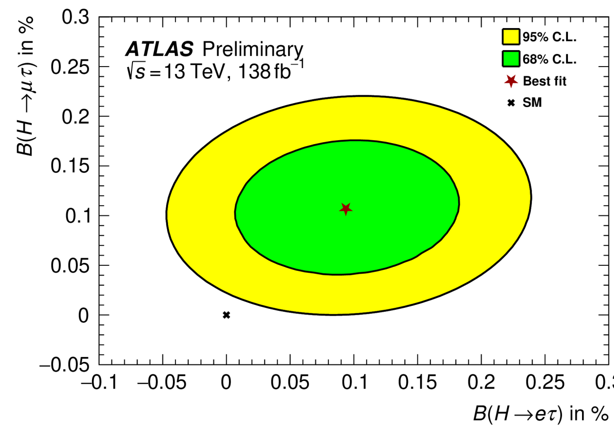
- $H \to e\mu/e\tau/\mu\tau$ decays are forbidden in the SM, but take place through LFV Yukawa couplings $Y_{e\mu}$, $Y_{e\tau}$, or $Y_{\mu\tau}$ arising in SUSY, composite, etc.
- Focus on $Y_{e\tau}$ and $Y_{\mu\tau}$ ($Y_{e\mu}$ strongly constrained by $\mu \to e\gamma$)

Channels: $e\tau_\mu$, $e\tau_h$, $\mu\tau_e$, $\mu\tau_h$
Categories in VBF and non-VBF
BDT/NN to discriminate signal

ATLAS:
Obs. (exp.) upper limits on branching ratios
$H \to e\tau$: BR < 0.19% (0.11%) at 95% CL
$H \to \mu\tau$: BR < 0.18% (0.09%) at 95% CL
For the $H \to \mu\tau$ ($H \to e\tau$) signal,
a 2.5σ (1.6σ) upward deviation observed



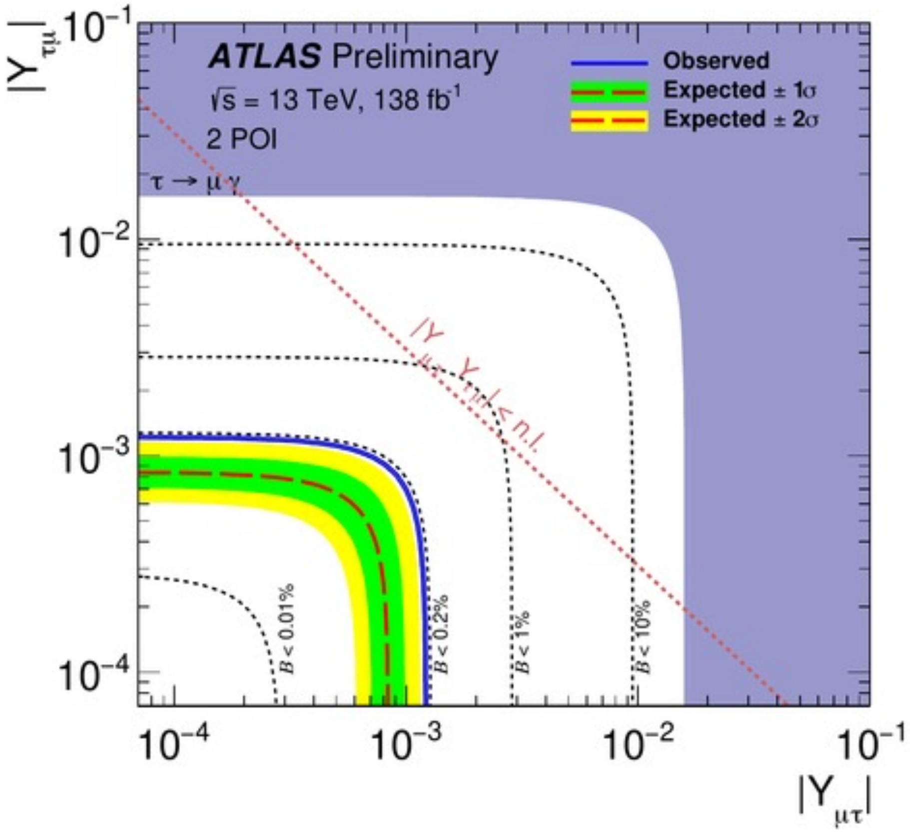


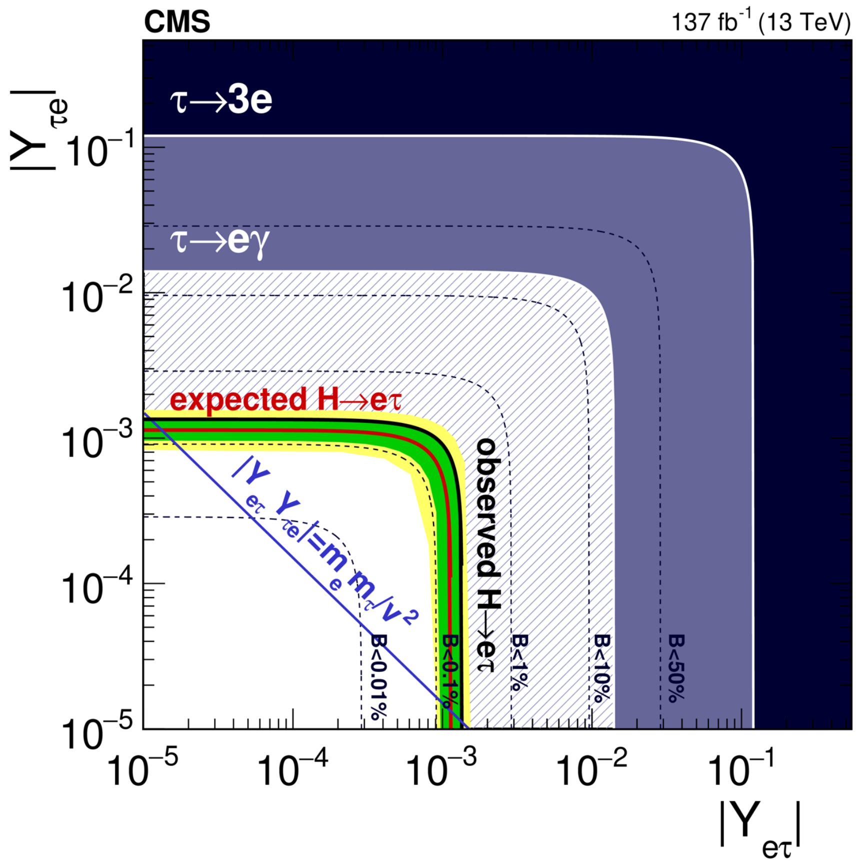


Lepton-Flavor Violating decays

ATLAS-CONF-2022-069
CMS: PRD 104 (2021) 032013

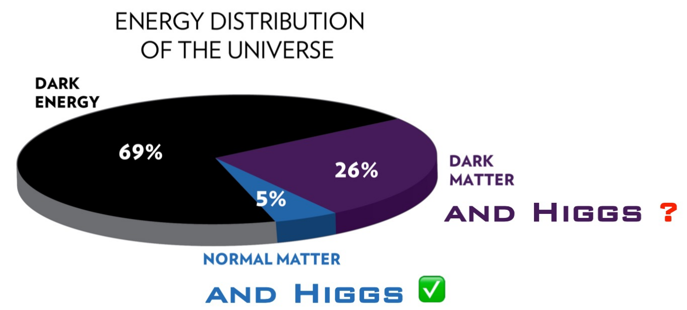
- Limits are used to put constraints on $Y_{e\tau}$ and $Y_{\mu\tau}$

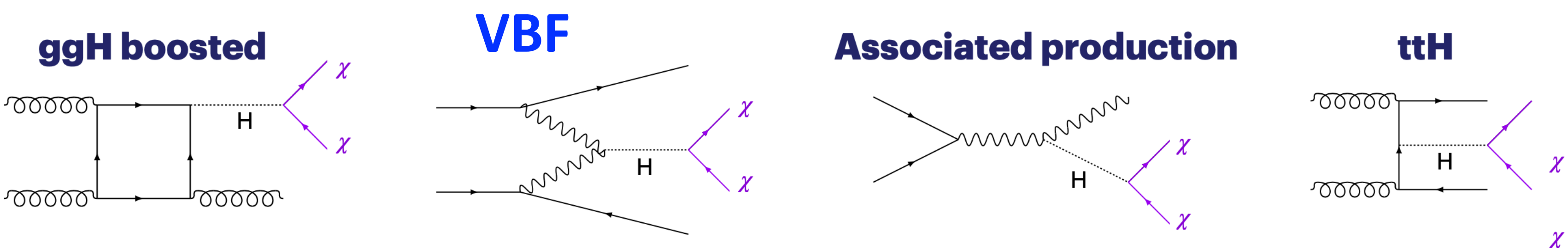




H to invisible

- SM H→invis. only via H→ZZ*→4ν with Br of ~0.1%
- Dark Matter particles could have mass from Higgs mechanism
- Common signature : significant missing transverse momentum from the Higgs boson decay.
- Identify through visible particles recoiling against the Higgs boson



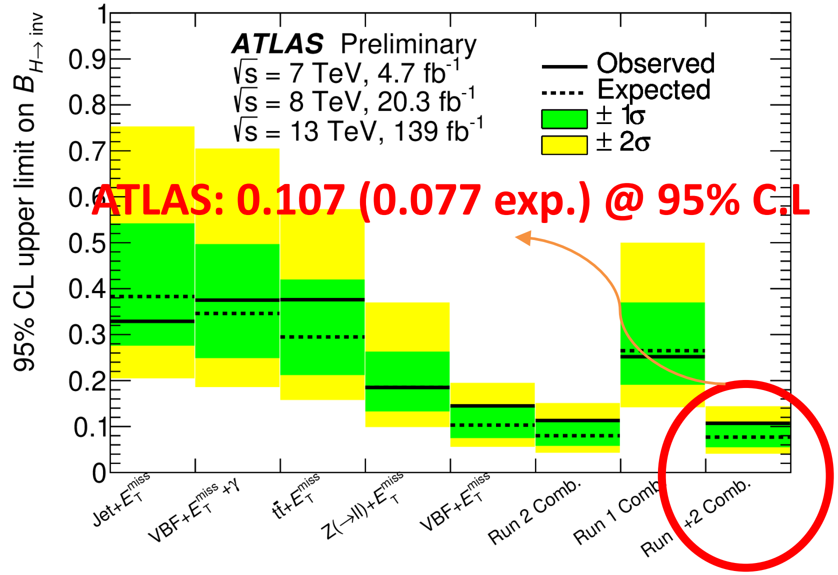


- **ATLAS and CMS probe all production modes**
- The **VBF** production mechanism drives the overall sensitivity in the direct search for invisible decays of the Higgs boson, thanks to its large production cross section and distinctive event topology

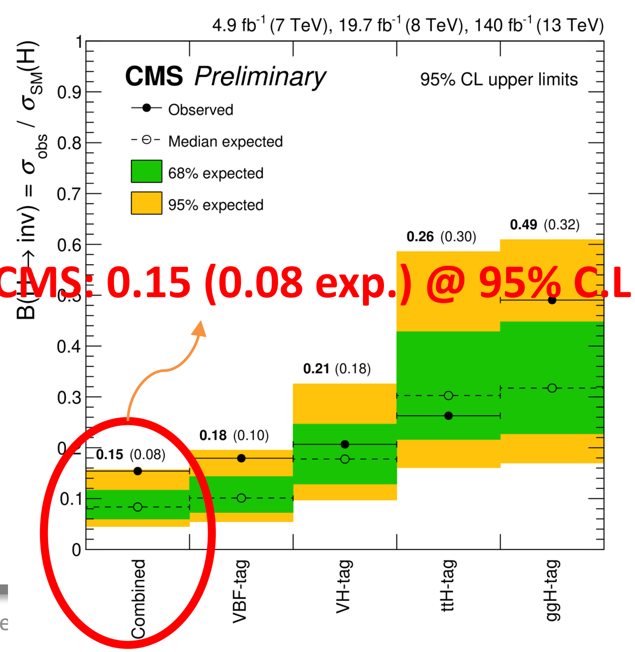
CMS : Br (H → inv) < 0.18 (0.10 exp.) @ 95% C.L
ATLAS : Br (H → inv) < 0.15 (0.10 exp.) @ 95% C.L

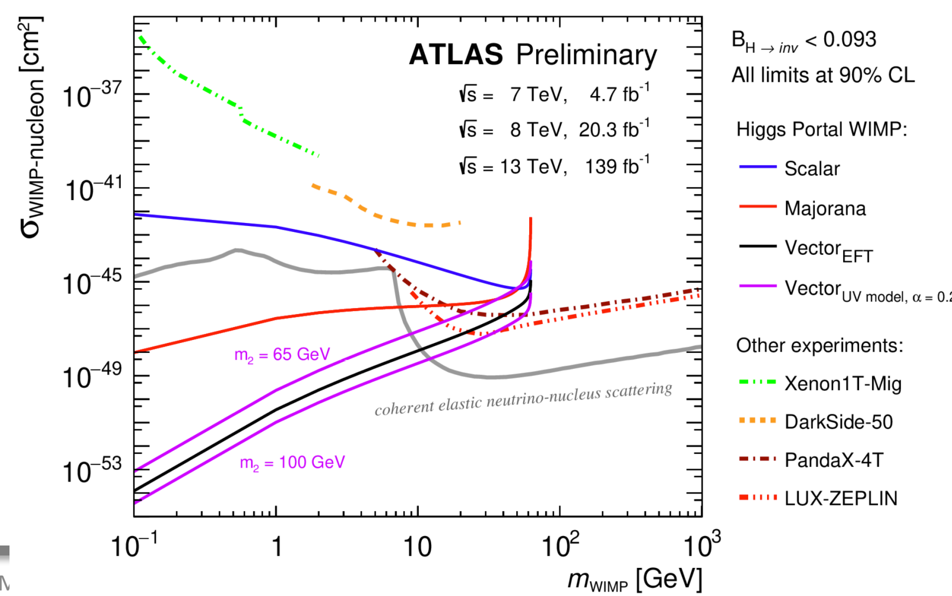
H to invisible

CMS-PAS-HIG-21-007
ATLAS: HIGG-2021-05



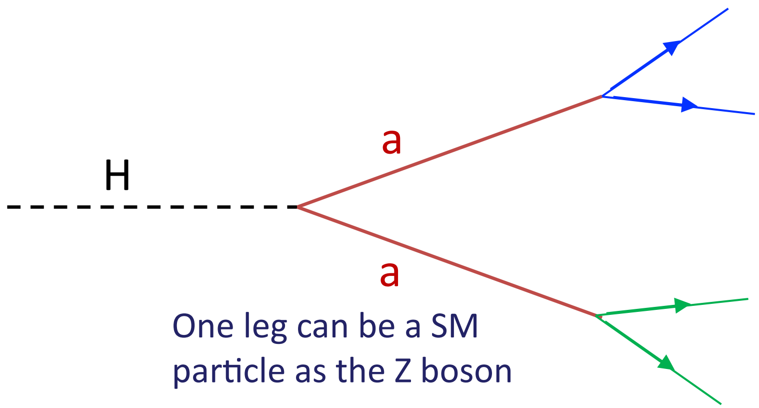
- Adding ttH, VH and ggH production modes improves a bit
- Convert the BR(H → inv) limit to the limit on spin independent DM-nucleon elastic scattering cross section
  - Complement direct detection results
- Assume several WIMP (weakly interacting massive particle) hypotheses:
  - Scalar, Majorana fermion, vector





H to exotic particles

- Many extensions to the SM include Higgs boson decays via one or two hypothetical on-shell new (pseudo)scalar(s) decaying to a pair of SM particles
  - Branching ratio of the new particle a to other particles depend on the model



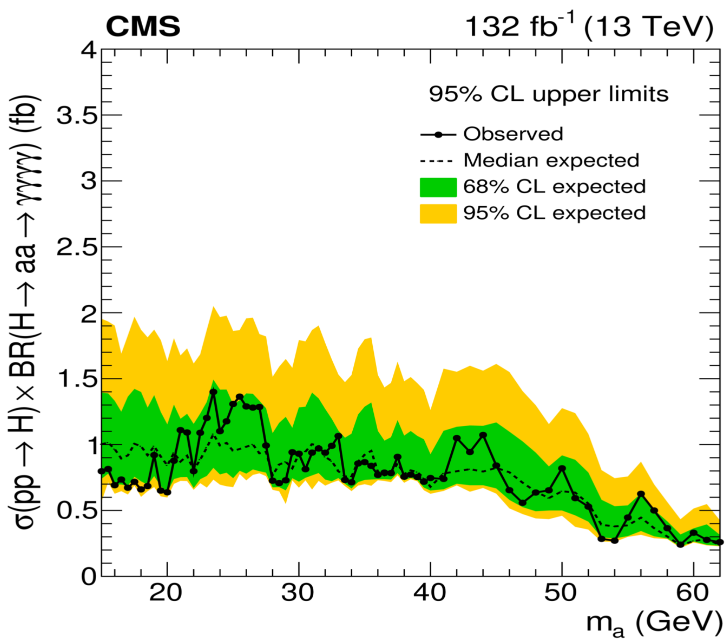
- Searches down to 15–20 GeV have resolved final states, below that, decay products start to merge

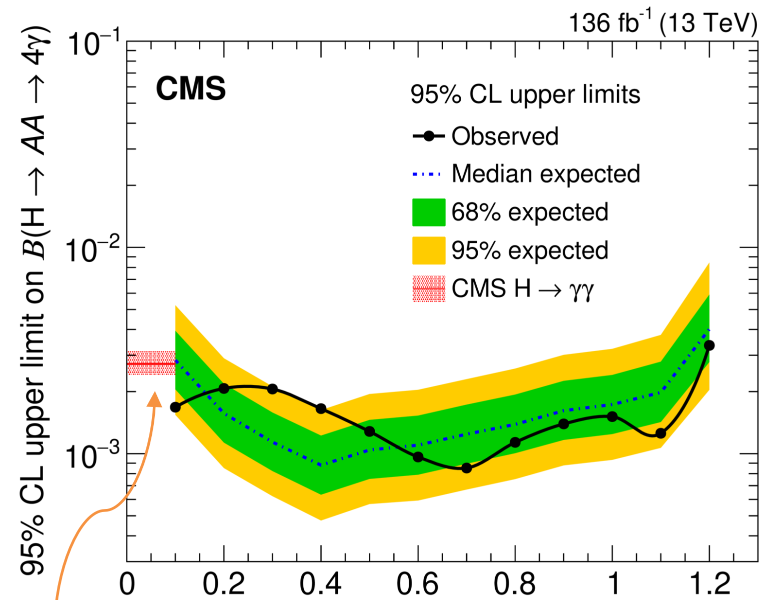
H to exotic particles: H⟶aa⟶4γ

CMS-HIG-21-003
CMS-HIG-21-016

- Searches for a with mass **above 15 GeV,** final-state photons **resolved**

- **Low-mass, boosted** scalar A decays to two highly **merged photons**, mis-reconstructed as a single photon-like object
  ⟶ Dedicated reconstruction of collimated di-γ using deep learning



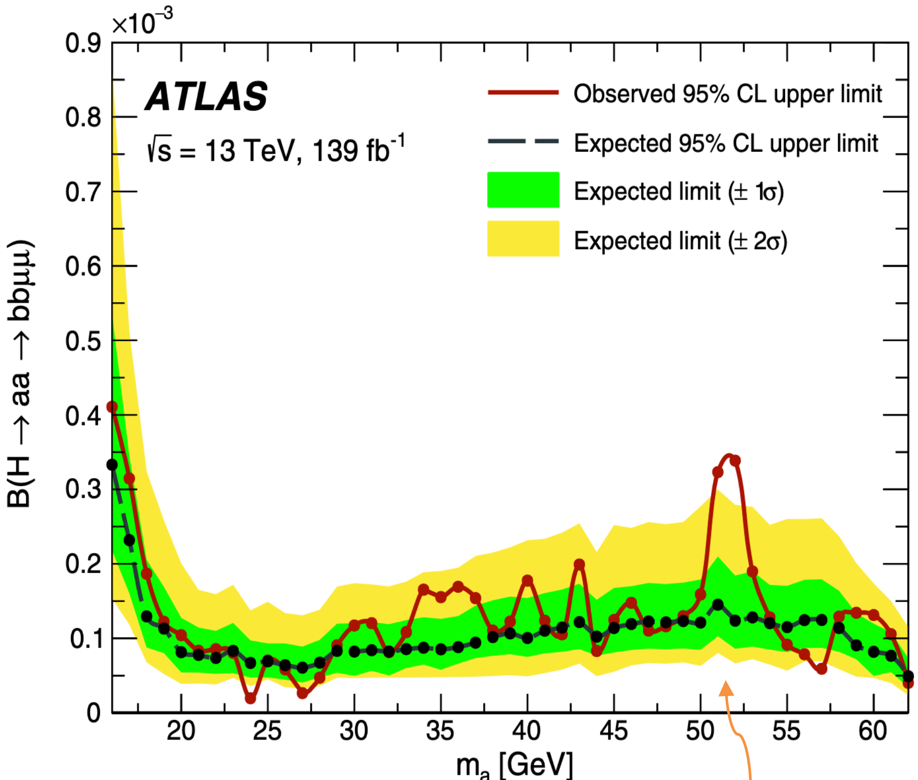


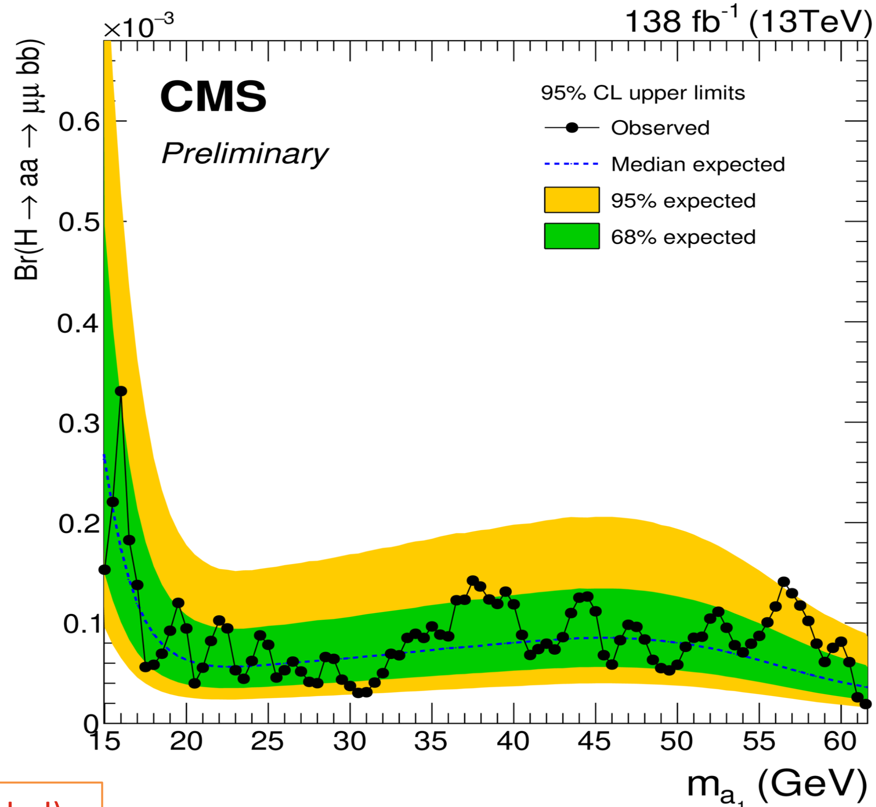
Upper bound provided by SM H⟶γγ

H to exotic particles: H→aa→bbμμ

ATLAS: PRD 105 (2022) 012006
CMS-PAS-HIG-21-021

- The largest Br(aa→μμbb) for large tanβ in 2HDM+S type III
- Kinematic likelihood fit is performed exploiting equal invariant masses of bb and μμ
  - Excellent m(μμ) resolution is used to constrain m(bb)



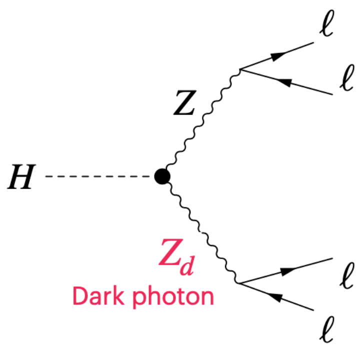


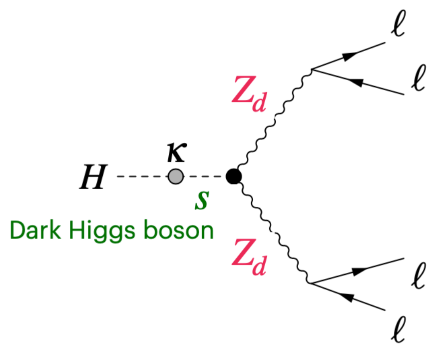
3.3σ (1.7σ) local (global) significance at 52 GeV

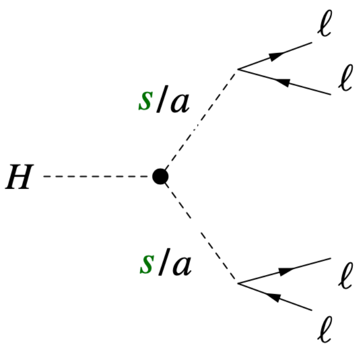
H to exotic particles: $H \to Z_d Z_d / Z Z_d / ss / aa \to 4l$

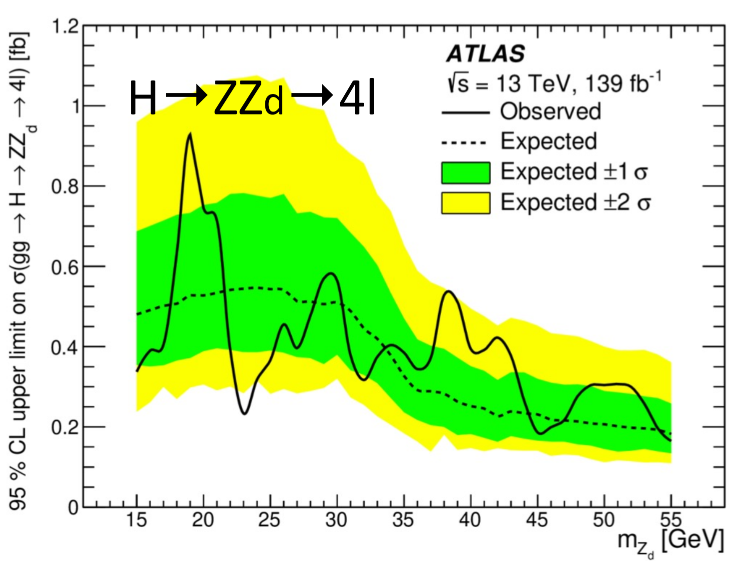
ATLAS: JHEP 03 (2022) 041
CMS: EPJC 82 (2022) 290

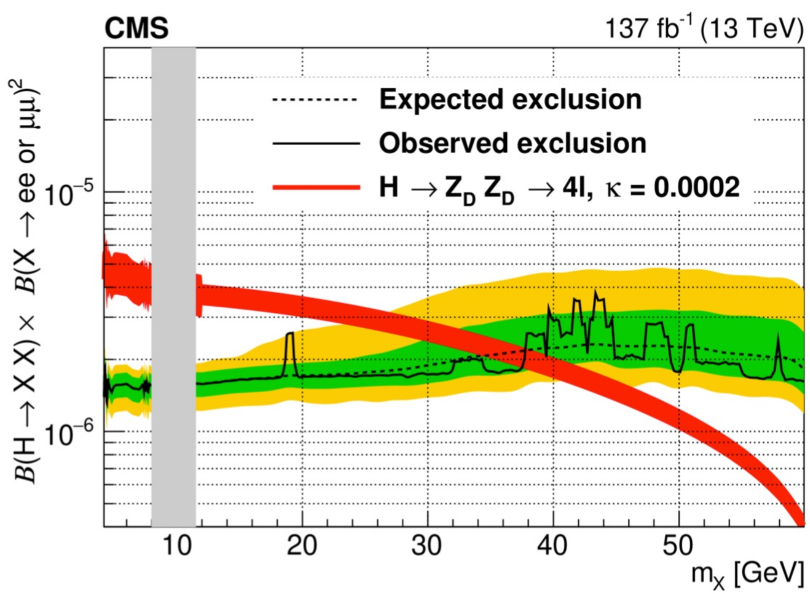
- Very clean final state, results can be interpreted in various theoretical models
  - Hidden Abelian Higgs Model, Axion-Like Particle, Extended Higgs sector







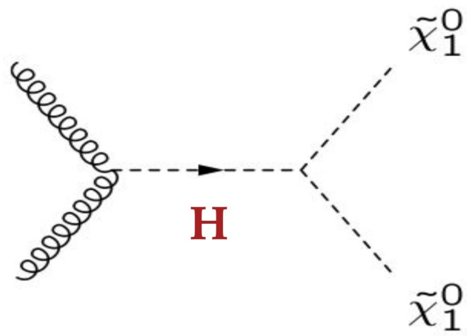


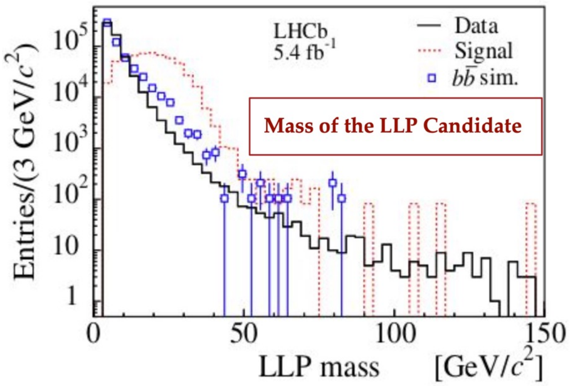


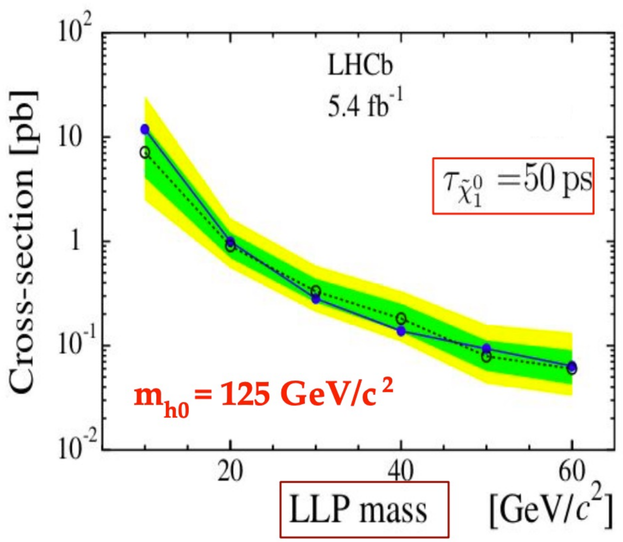
H to Long-Lived Particles

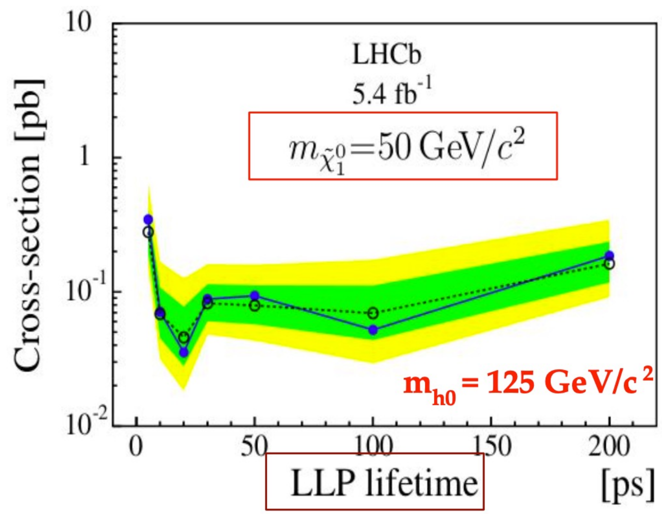
LHCb-PAPER-2021-028

- Long-lived particles (LLPs) appear in many BSM scenarios
  - Compressed SUSY, AMSB, heavy neutral leptons, etc
- **LHCb has searched for a Higgs-like particle, h_0** , produced by ggH and decays into two LLPs
  - $30 < M_{h0} < 200$ GeV
  - LLP lifetimes: [5, 200] ps
  - LLP mass values: [10, $h_0/2$] GeV
  - LLP decays into a muon and two quarks

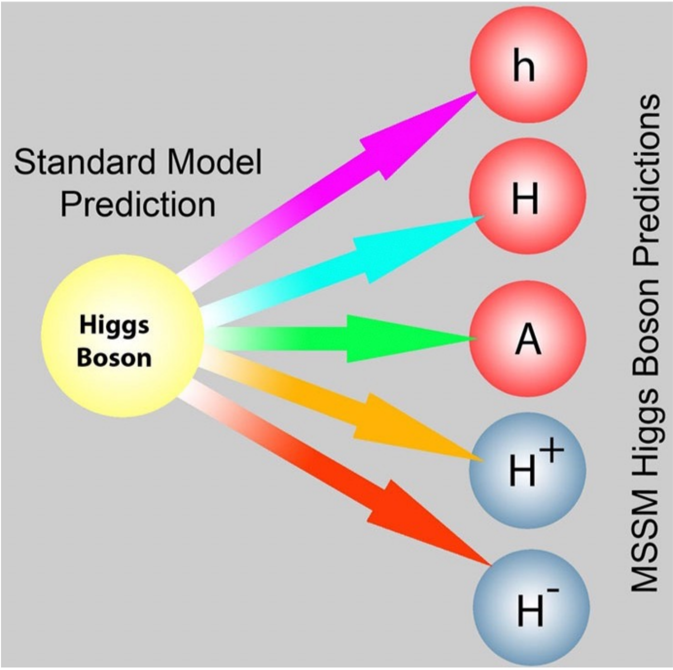




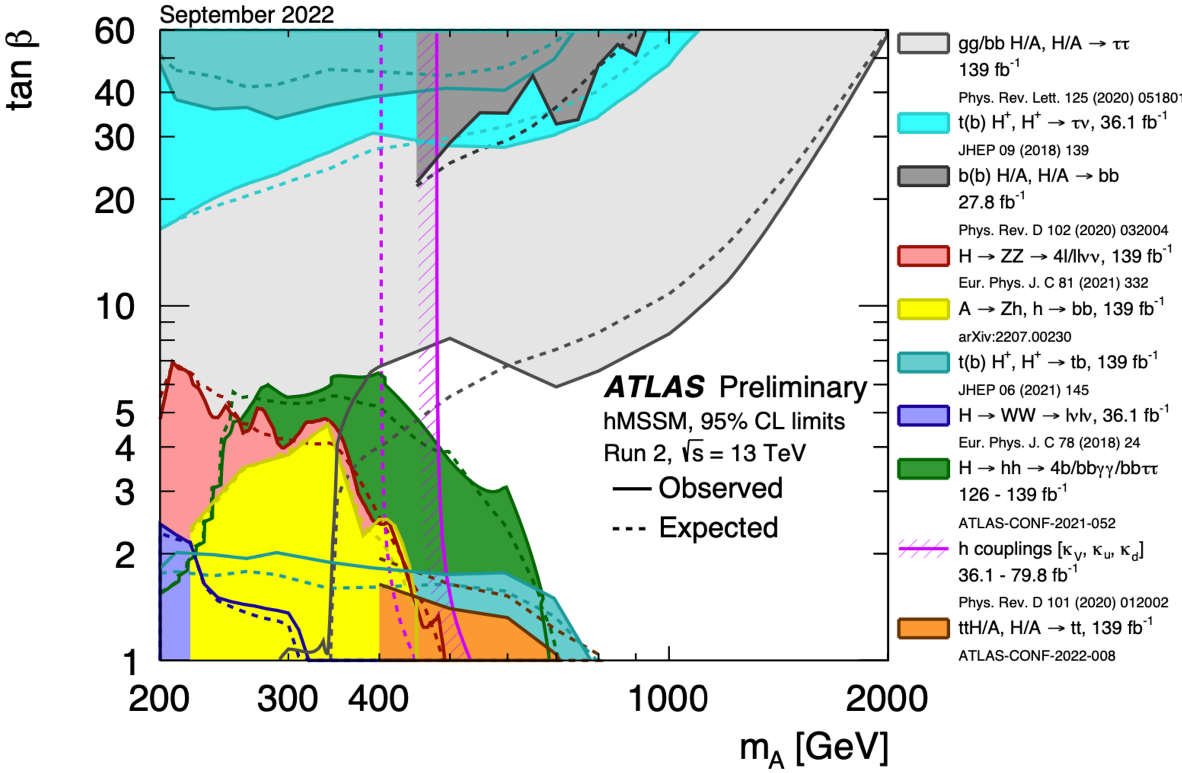




3、 Additional Higgs bosons



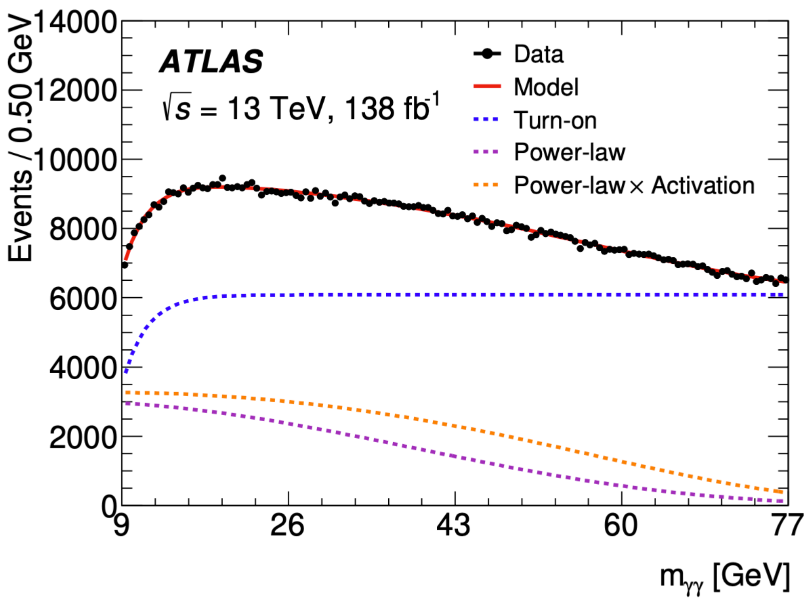
Courtesy of A. David

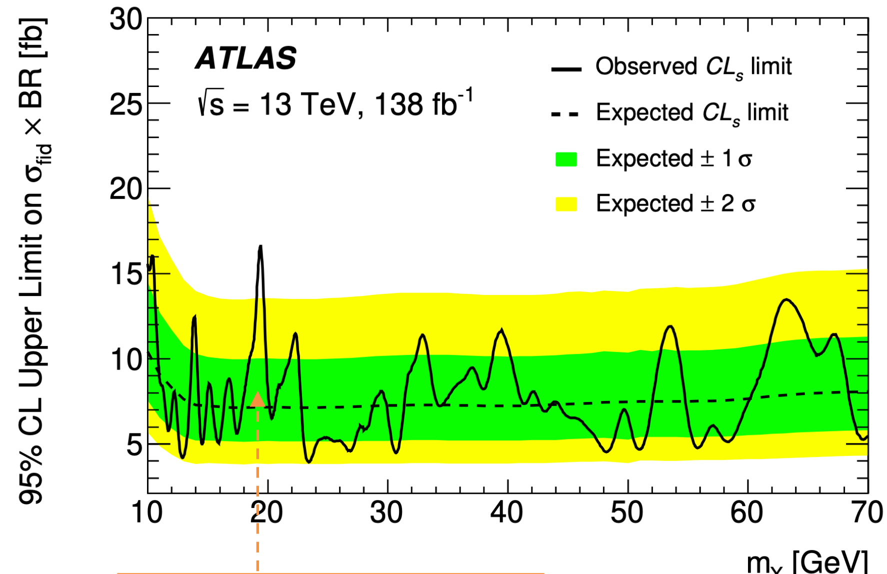


Low mass diphoton resonance

ATLAS: HIGG-2019-23

- **ATLAS** new search for generic γγ resonances in the mass range between 10 to 70 GeV
- Exploit the particular kinematics of events to reach invariant masses down to 10 GeV
  - Select close-by γγ pairs (boosted against a jet) and $p_T^{\gamma\gamma}$ > 50 GeV to overcome trigger energy threshold

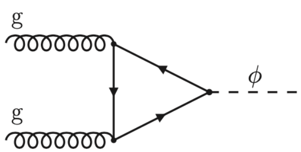


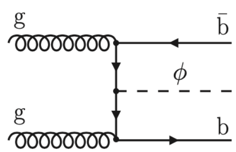


3.1σ (1.5σ) local (global) significance at 19.4 GeV

A/H→ττ

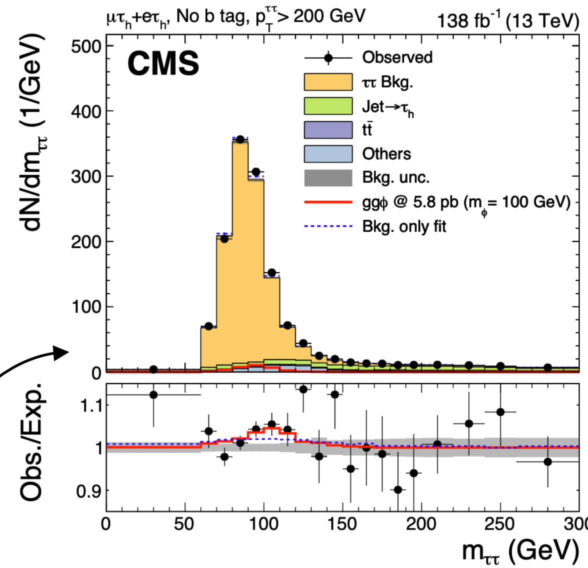
CMS: HIG-21-001

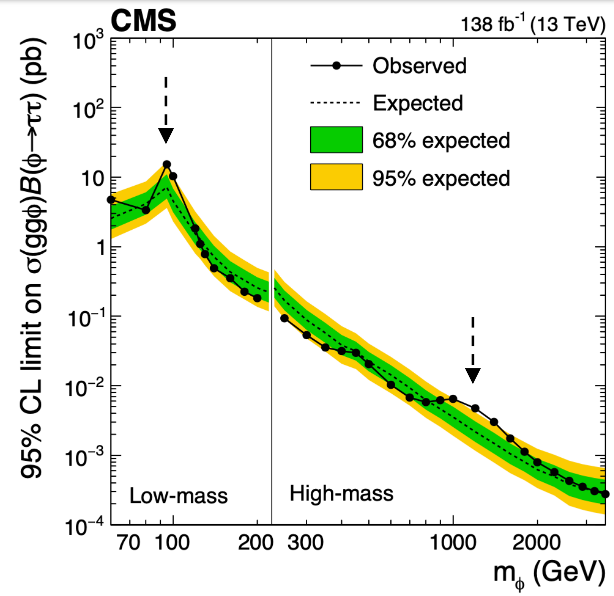


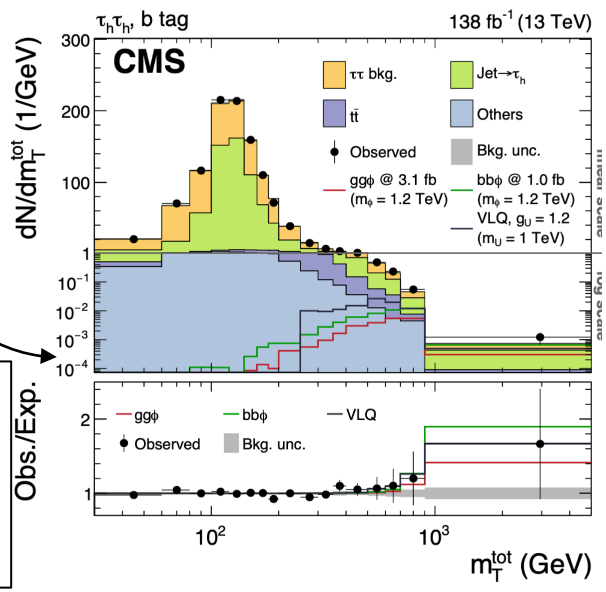


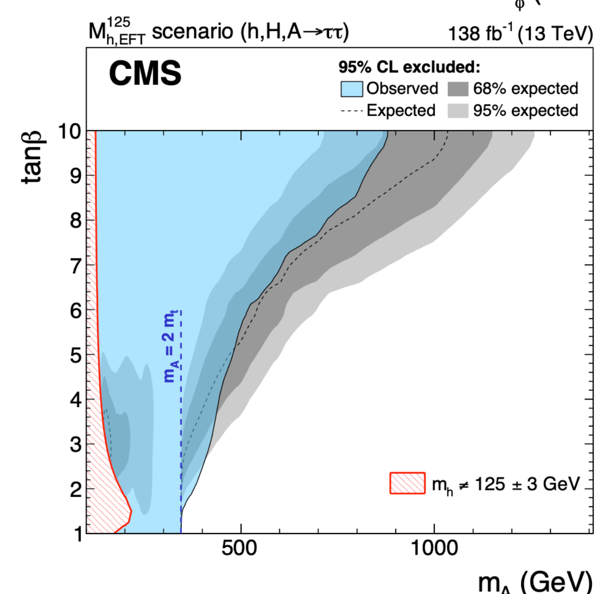
- 4 ττ final states ($\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, eμ)
- b-tag/no b-tag category
- **Low-mass analysis:** Fit m(ττ) in various Higgs pT categories
- **High-mass analysis:** Fit transverse mass variable; few m_T categories

At 100 GeV, local significance 3.1σ (2.7σ with LEE in low-mass analysis)
At 1.2 TeV, local significance 2.8σ (2.4σ with LEE in high-mass analysis)









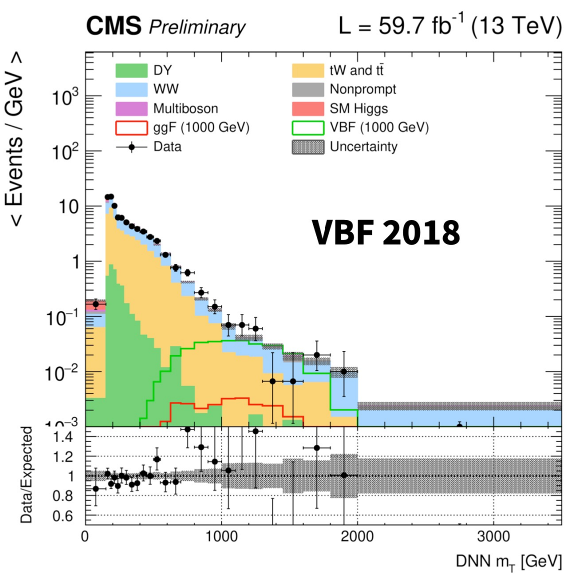
Heavy Higgs to WW

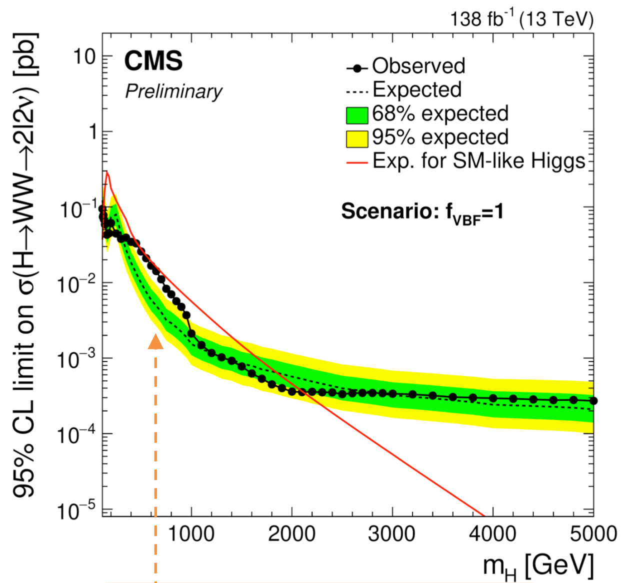
CMS-PAS-HIG-20-016
ATLAS: HIGG-2018-45

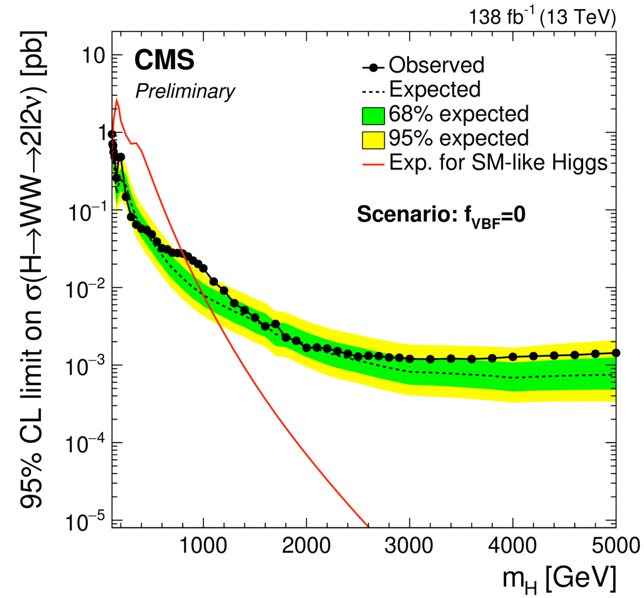
- Search for heavy Higgs in ggH and VBF production modes in a large mass range

CMS:

- H→WW→ee,μμ,eμ + MET, fully leptonic final states
- Fit to DNN-regressed transverse mass variable







VBF only:
3.8σ (2.6σ) local (global) significance at **650 GeV**

ggH only
No significant excess

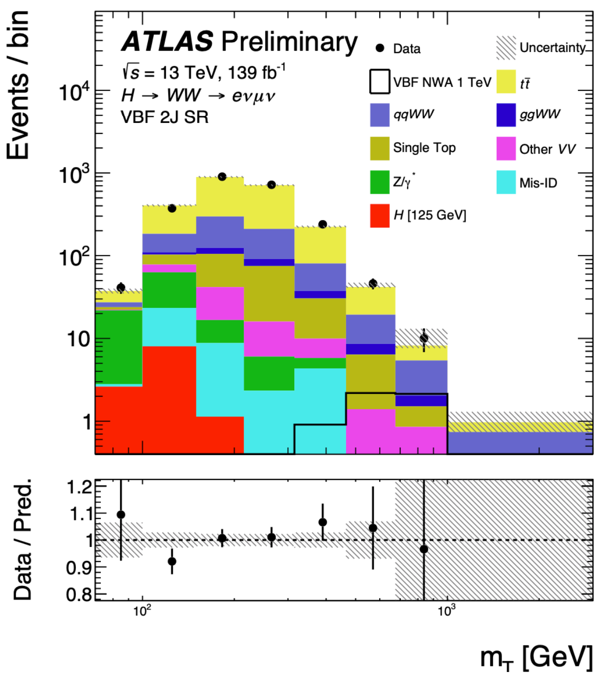
Heavy Higgs to WW

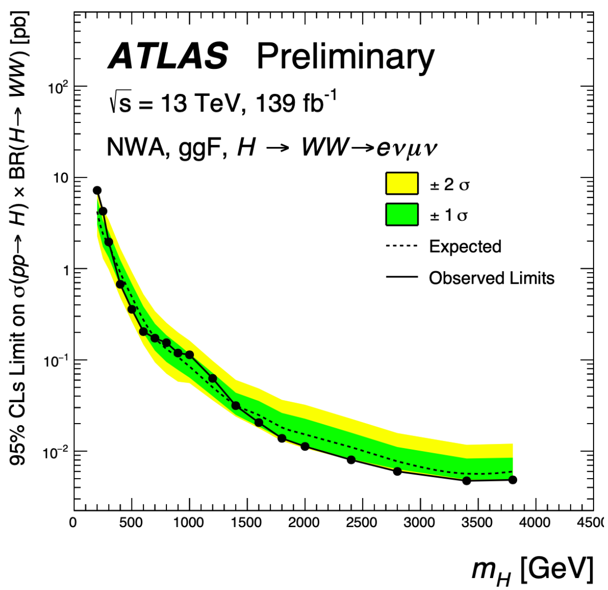
CMS-PAS-HIG-20-016
ATLAS: HIGG-2018-45

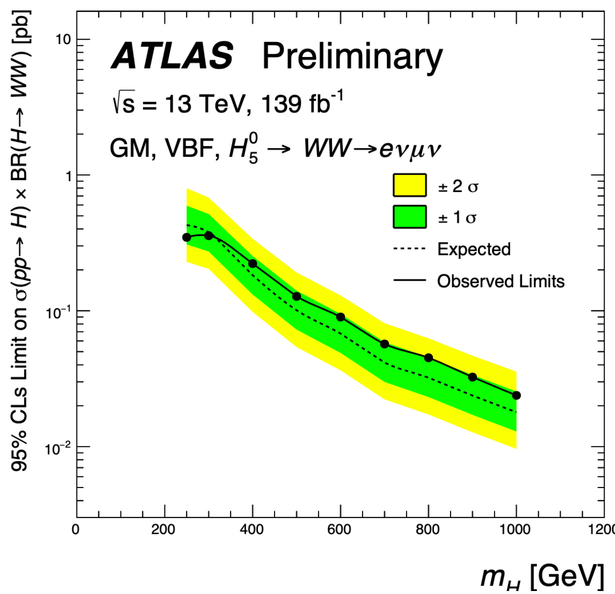
- Search for heavy Higgs in ggH and VBF production modes in a large mass range

ATLAS:

- $H \to WW \to e\nu\mu\nu$ decay channel
- Discriminating variable: transverse mass m_T







No significant excess over SM predictions

Summary

- **ATLAS and CMS** are highly active in searching for both rare decays and BSM phenomena in the Higgs sector
  - Effort to cover maximum topologies
  - **LHCb** also plays an important role
- The full Run 2 datasets still being analyzed, many results released in the past year
- **Second generation sensitivity close to the SM**
- No significant sign of BSM Higgs signal seen in the LHC data yet
  - **Though some small deviations need to be verified with more data**
- Stay tuned for more exciting results as we enter the LHC Run 3 era!

Thank you!