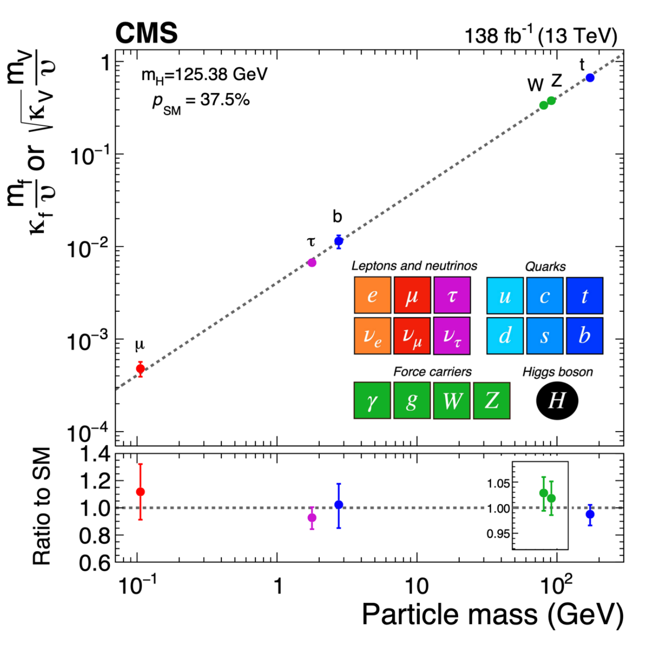
Searches for BSM decays of the Higgs boson at the LHC

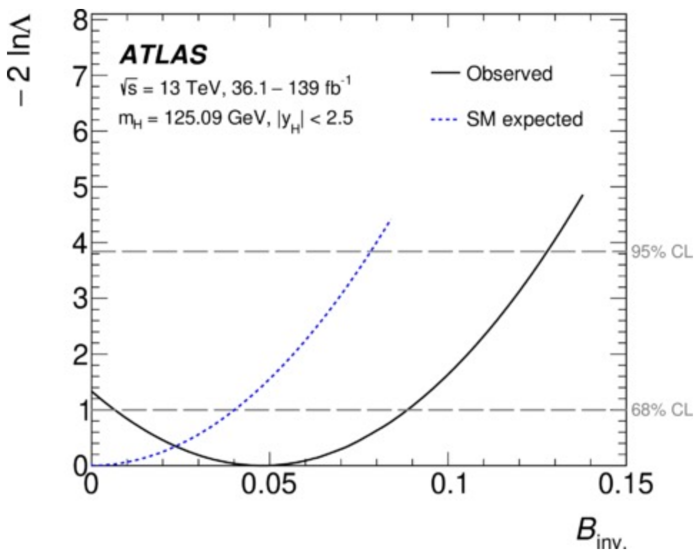
Mingshui Chen (IHEP Beijing)

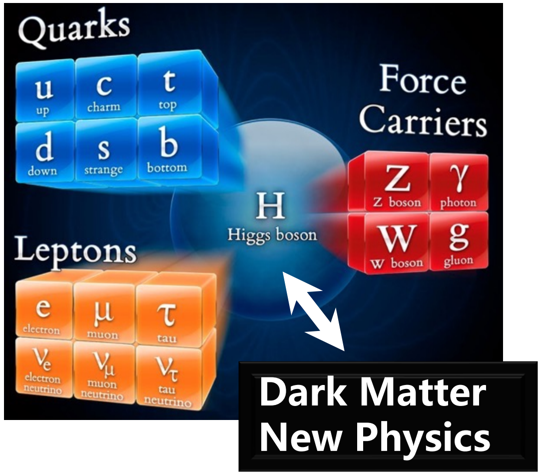
Introduction

Nature 607 (2022) 60-68
Nature 607 (2022) 52-59

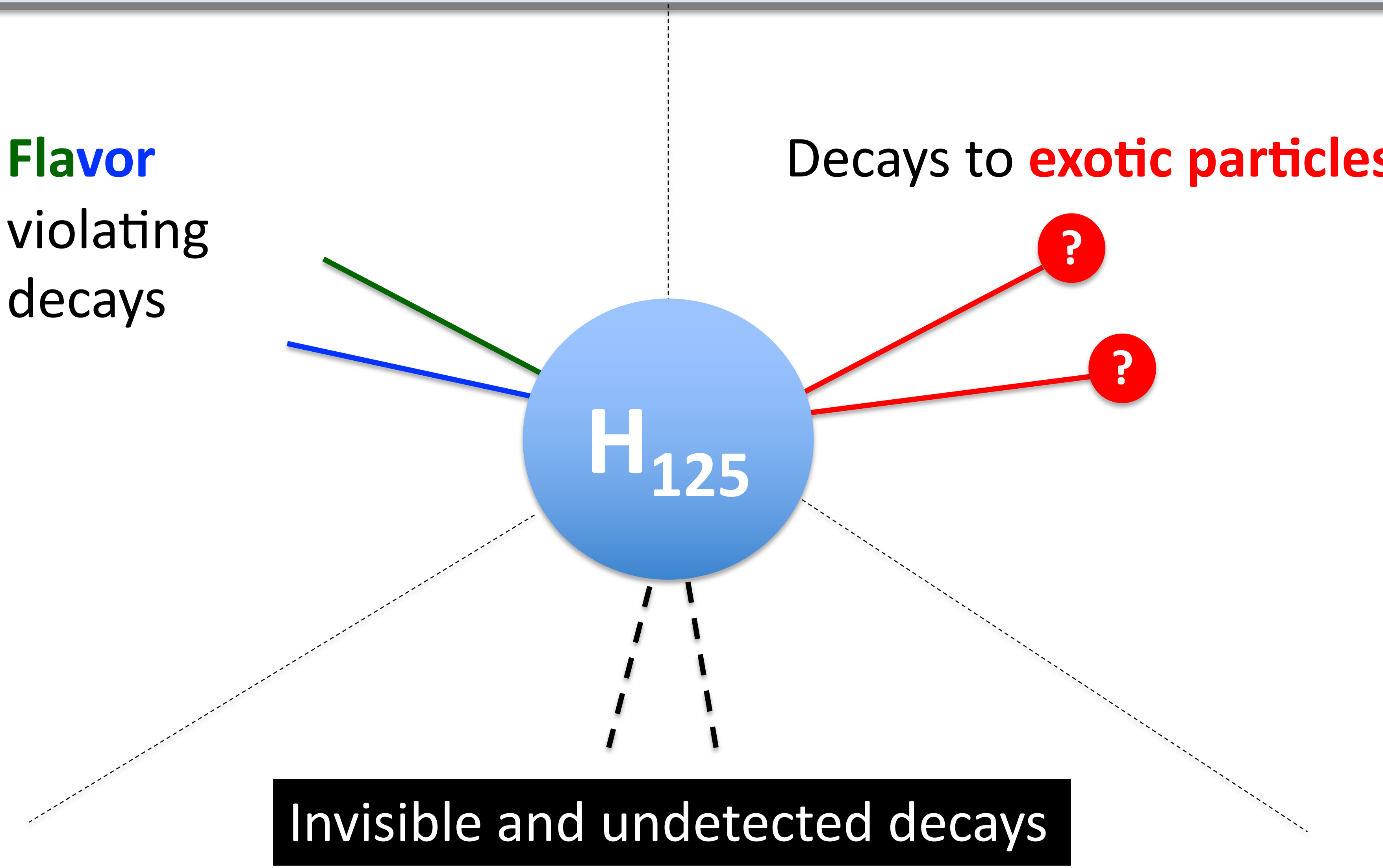
- Higgs discovery in 2012, last building block discovered
- Since then, ATLAS and CMS recorded 30 times more Higgs bosons, more precise measurements
  - Data in agreement with SM predictions, so far
- Still plenty of rooms for the Higgs boson to connect with BSM





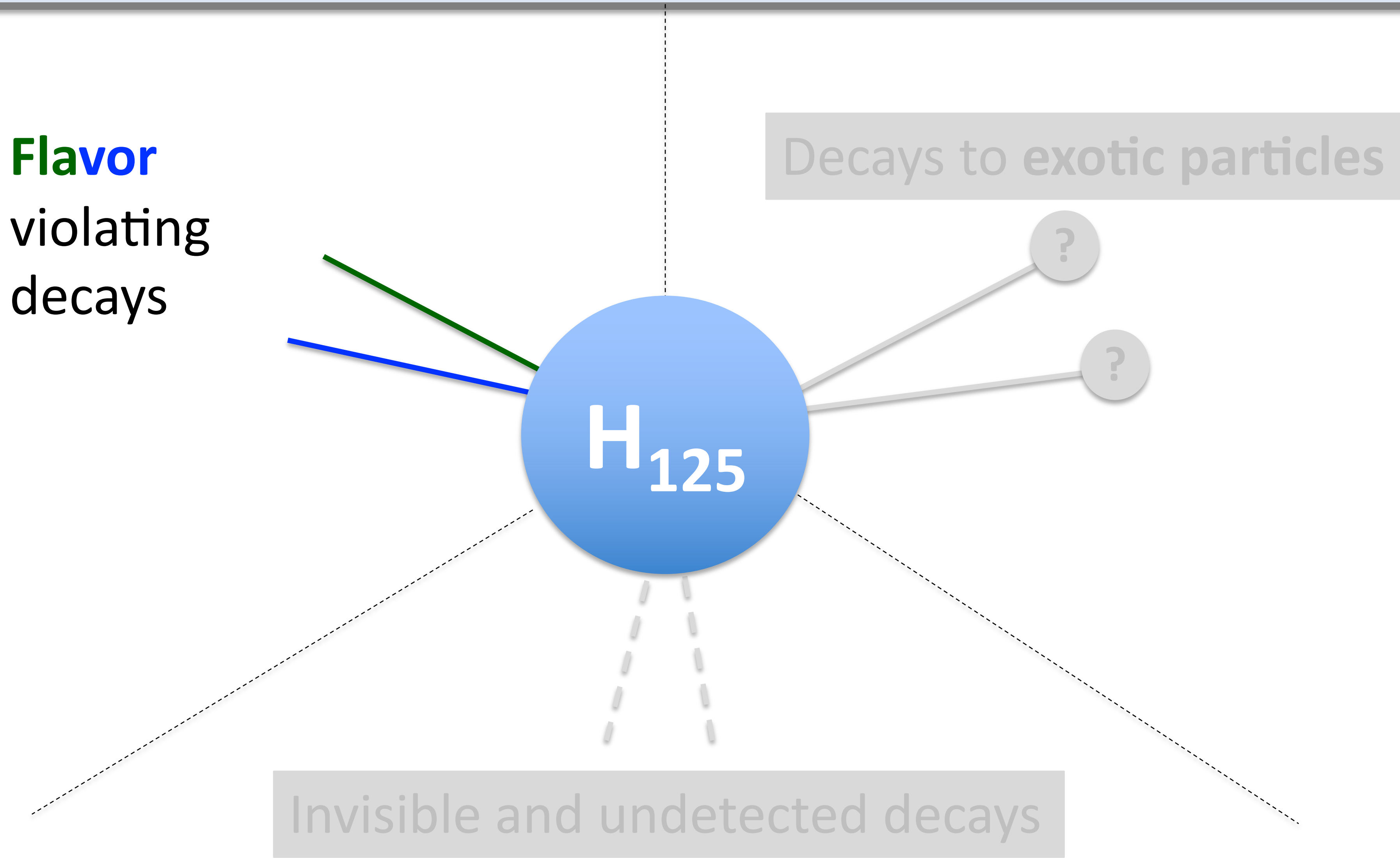


Higgs BSM decays: direct probe for new physics



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

Higgs BSM decays: direct probe for new physics



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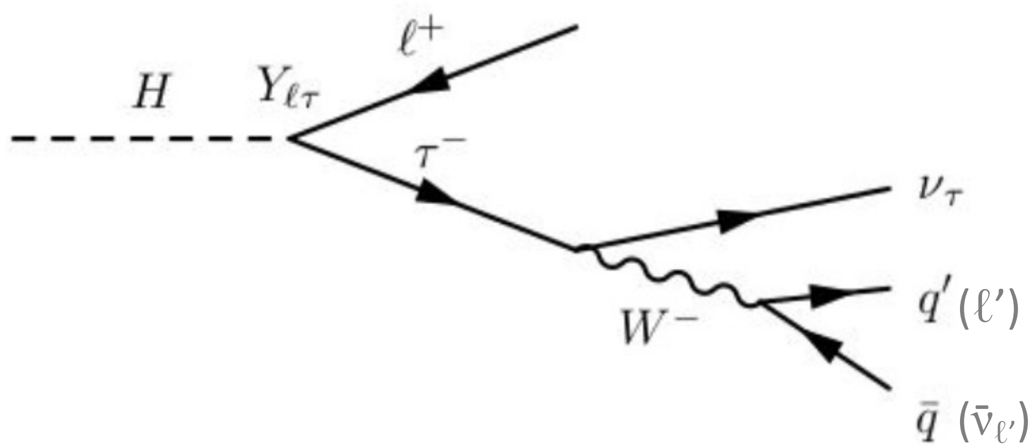
Lepton-Flavor Violating decays

ATLAS : arXiv:2302.05225
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 $\mu \to e\gamma$)

$$\begin{pmatrix} Y_{ee} & Y_{e\mu} & \boxed{Y_{e\tau}} \\ & Y_{\mu\mu} & \boxed{Y_{\mu\tau}} \\ & & Y_{\tau\tau} \end{pmatrix}$$



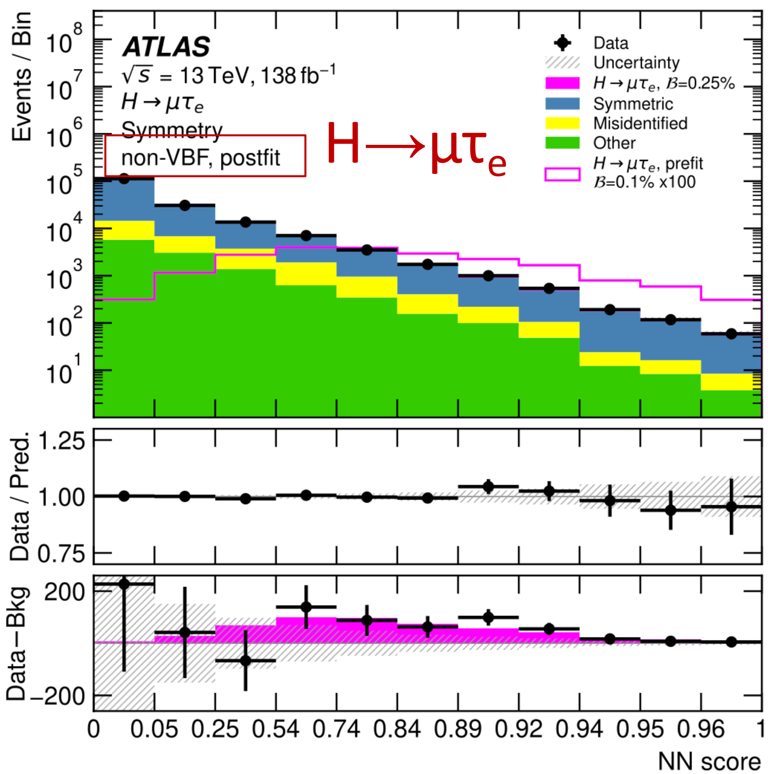
Main backgrounds:

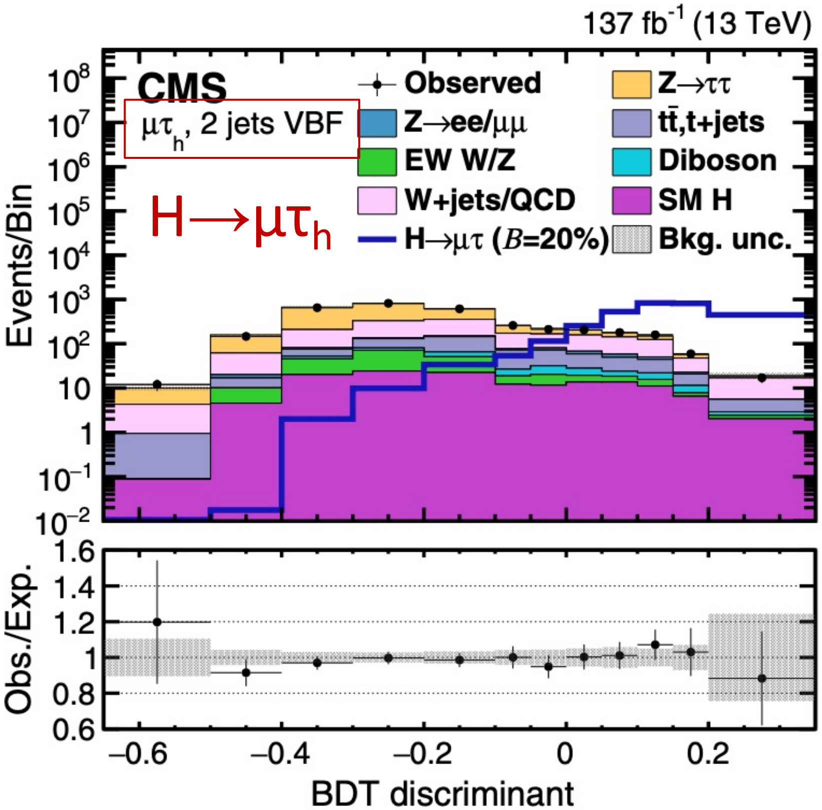
- $Z \to \tau\tau$; W + jets
- multi-jet events with at least one jet misidentified as an electron, muon or τ_{had}

Lepton-Flavor Violating decays

ATLAS : arXiv:2302.05225
CMS: PRD 104 (2021) 032013

- Channels: $e\tau_{\mu}$, $e\tau_h$, $\mu\tau_e$, $\mu\tau_h$
- Categories in VBF and non-VBF (further separated into 0j, 1j and 2j in CMS)
- BDT/NN to enhance signal/background ratio
- Join fit to BDT/NN outputs





Lepton-Flavor Violating decays

ATLAS : arXiv:2302.05225
CMS: PRD 104 (2021) 032013

ATLAS:

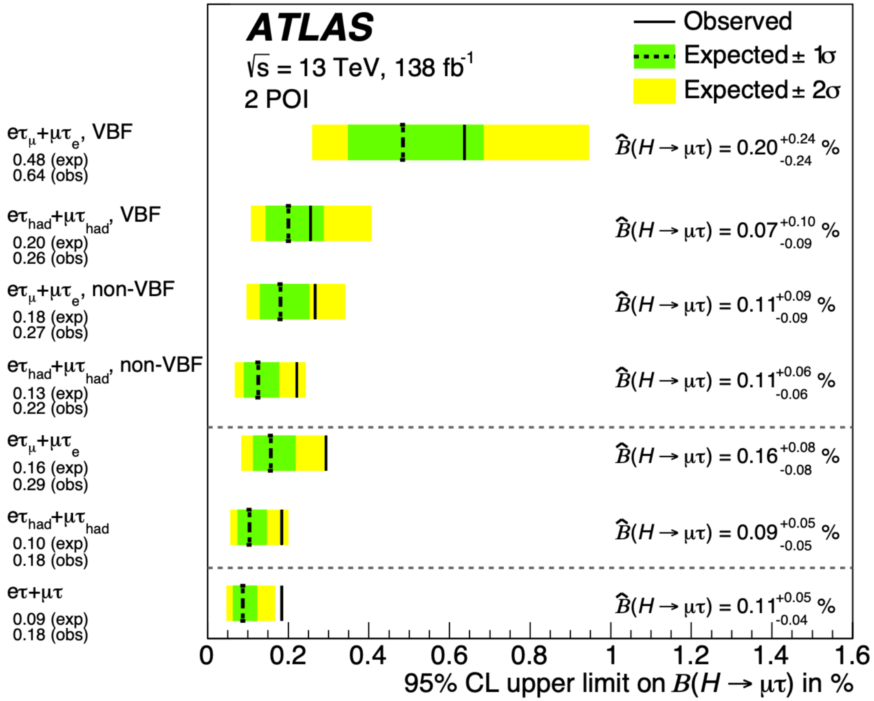
Obs. (exp.) upper limits on branching ratios

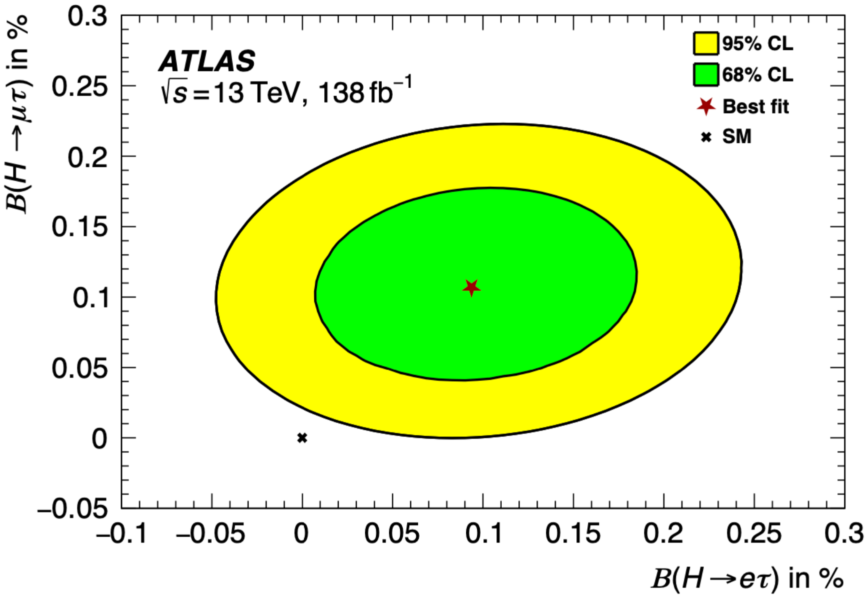
H→μτ: BR < 0.18% (0.09%) at 95% CL

H→eτ: BR < 0.20% (0.12%) at 95% CL

For the H → μτ (H → eτ) signal,

a 2.4σ (1.6σ) excess observed





CMS:

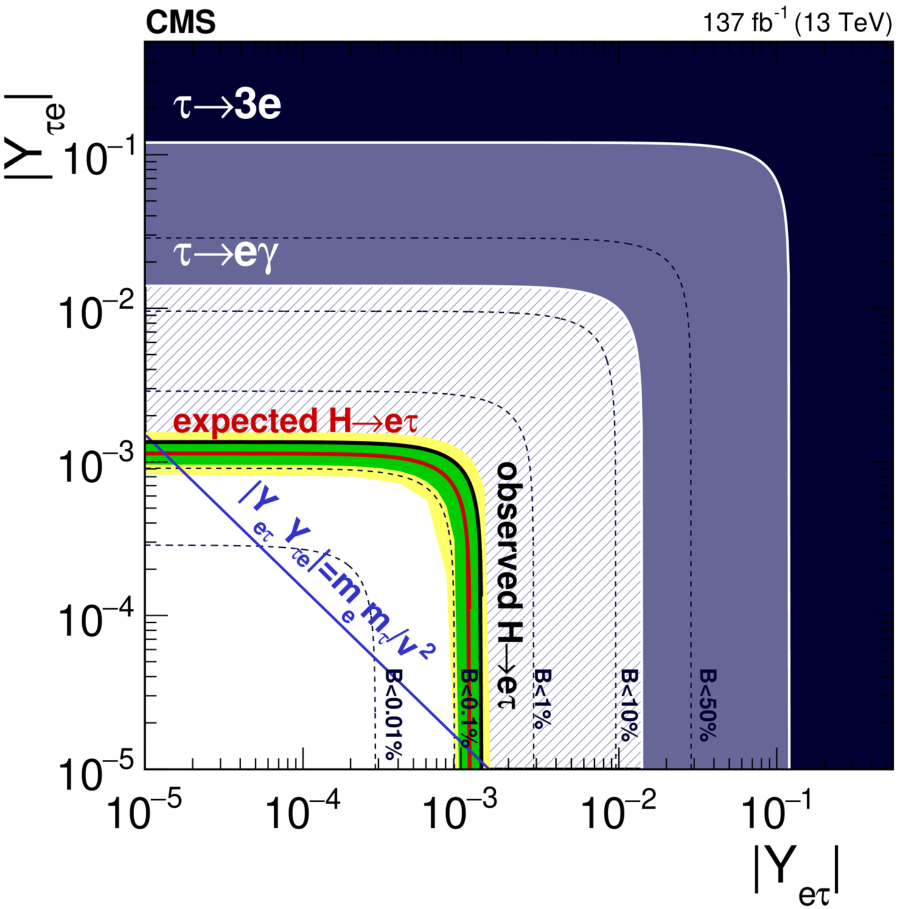
Obs. (exp.) upper limits on BRs

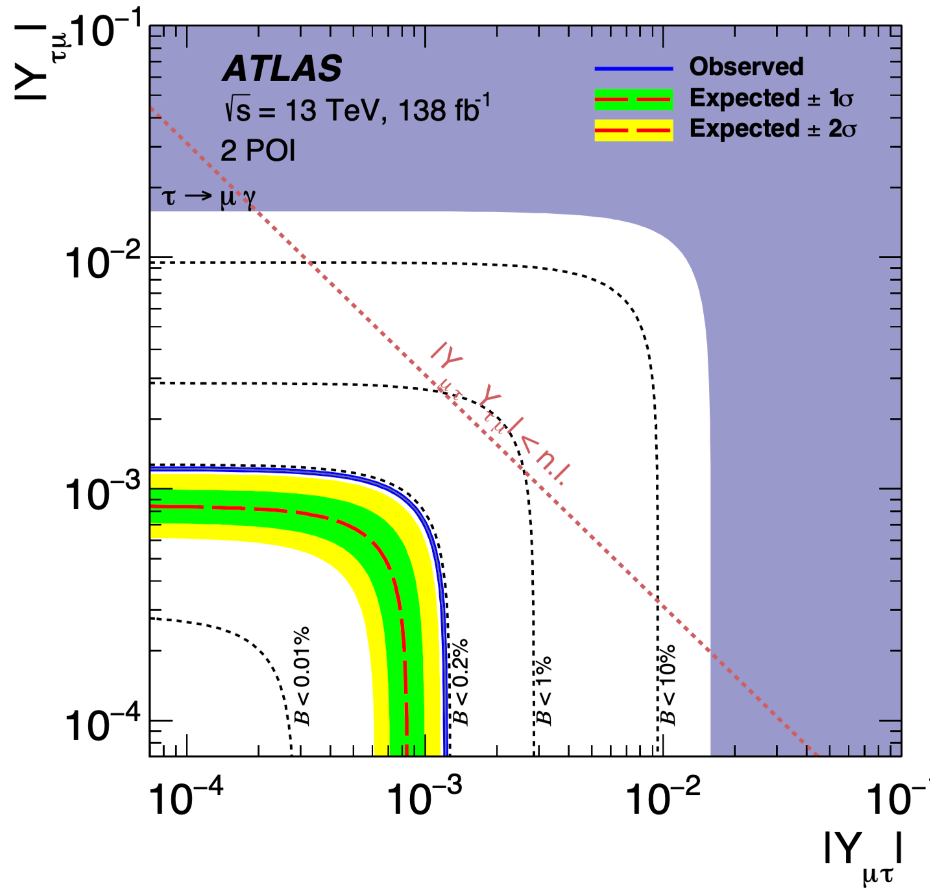
H→μτ: BR < 0.15% (0.15%) at 95% CL

H→eτ: BR < 0.22% (0.16%) at 95% CL

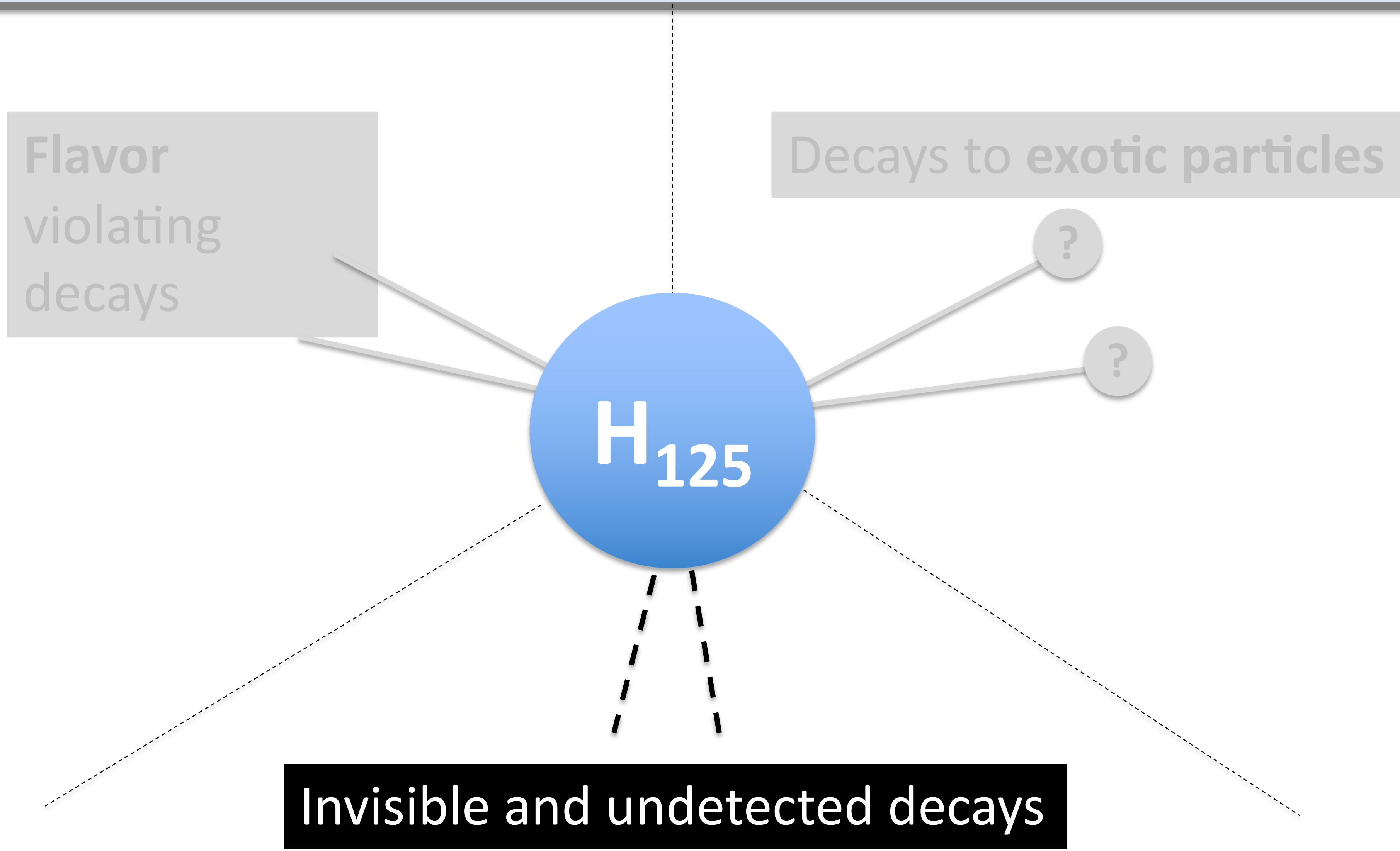
Lepton-Flavor Violating decays

- Limits are used to put constraints on $Y_{e\tau}$ and $Y_{\mu\tau}$
- Better than constraints from other experiments, and for $Y_{\mu\tau}$ within the naturalness limit





Higgs BSM decays: direct probe for new physics



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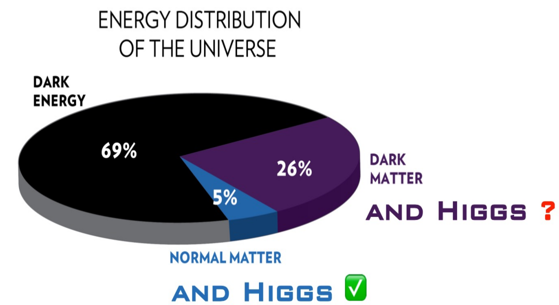
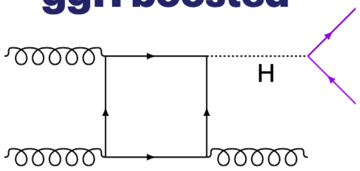
H to invisible

- SM H→invisible only via H→ZZ*→4ν with B_{inv} of ~0.1%
- Several BSM scenarios ⇒ B_{inv} is significantly enhanced
- Dark Matter particles could have mass from Higgs mechanism
- 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**



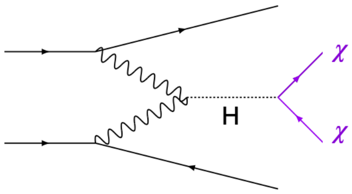
ggH boosted



ATLAS: Phys.Rev.D 103 (2021) 11, 112006

CMS: JHEP 11 (2021) 153

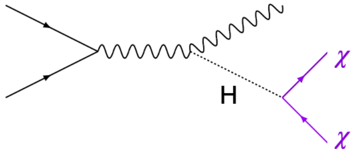
VBF



ATLAS: JHEP 08 (2022) 104
Eur.Phys.J.C 82 (2022) 2, 105

CMS: Phys.Rev.D 105 (2022) 092007

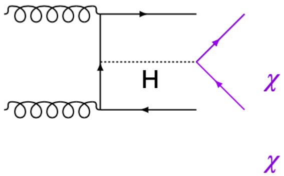
Associated production



ATLAS: Phys.Lett.B 829 (2022) 137066

CMS: CMS-PAS-HIG-21-007
Eur.Phys.J.C 81 (2021) 1, 13
JHEP 11 (2021) 153

ttH



ATLAS: arXiv:2211.05426

CMS: CMS-PAS-HIG-21-007
JHEP 05 (2020) 032
Eur. Phys. J. C 81 (2021) 3

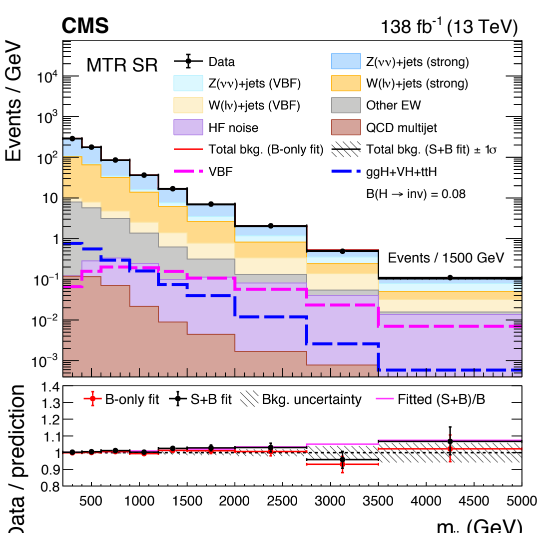
VBF H to invisible

ATLAS: JHEP 08 (2022) 104
CMS: PRD 105 (2022) 092007

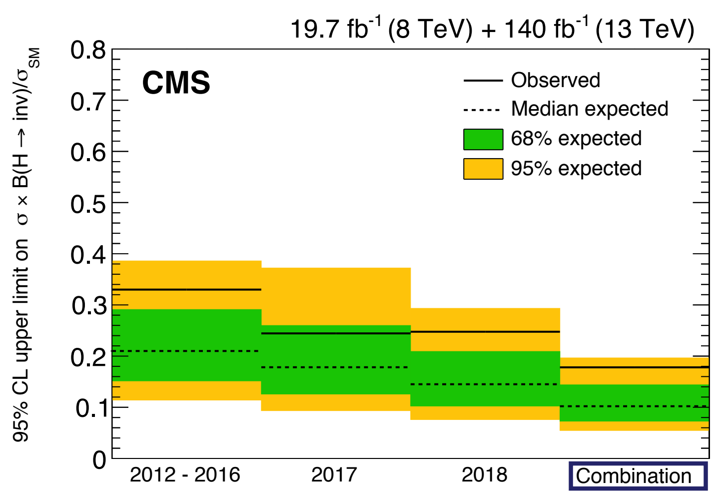
The **VBF** production mechanism drives the overall sensitivity in the direct search for invisible decays of the Higgs boson, thanks to its large production cross section and distinctive event topology

- **2 jets with large angular separation $\Delta\eta_{jj}$ and large invariant mass m_{jj}**
- Veto on other objects (leptons/photons)
- High missing transverse momentum (trigger constraint) → reject QCD
- Low | Δϕjj | → reject QCD

⇒ Main remaining backgrounds: Z(νν) + jets and W(lν) + jets



One analysis category

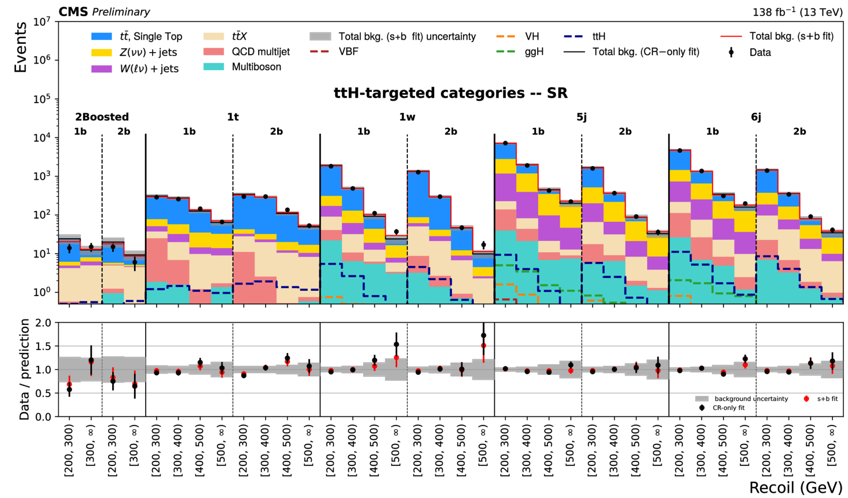


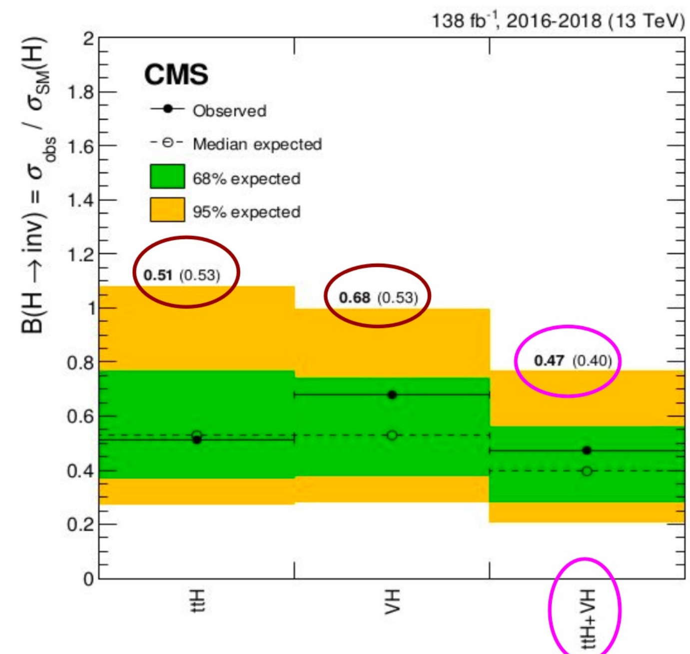
UL on Br(H→inv) @ 95% C.L
CMS : 0.18 (0.10 exp.)
ATLAS : 0.15 (0.10 exp.)

H to invisible: ttH and VH

- **Fully hadronic final state**
- Resolved and Boosted regimes
  - ttH boosted : boosted Ws or tops, DeepAK8 algorithm
  - ttH resolved : resolved top jets
  - VH : requires exactly 2 jets
- Recoil (MET- no leptons and photons): discriminating variable
- Main backgrounds: tt + jets and W + jets and Z(νν̄)+jets
- No excess of events above the estimated backgrounds

UL on Br(H→inv) @ 95% C.L
ttH : 0.51 (0.53 exp.)
VH : 0.68 (0.53 exp.)
ttH+VH : 0.47 (0.40 exp.)

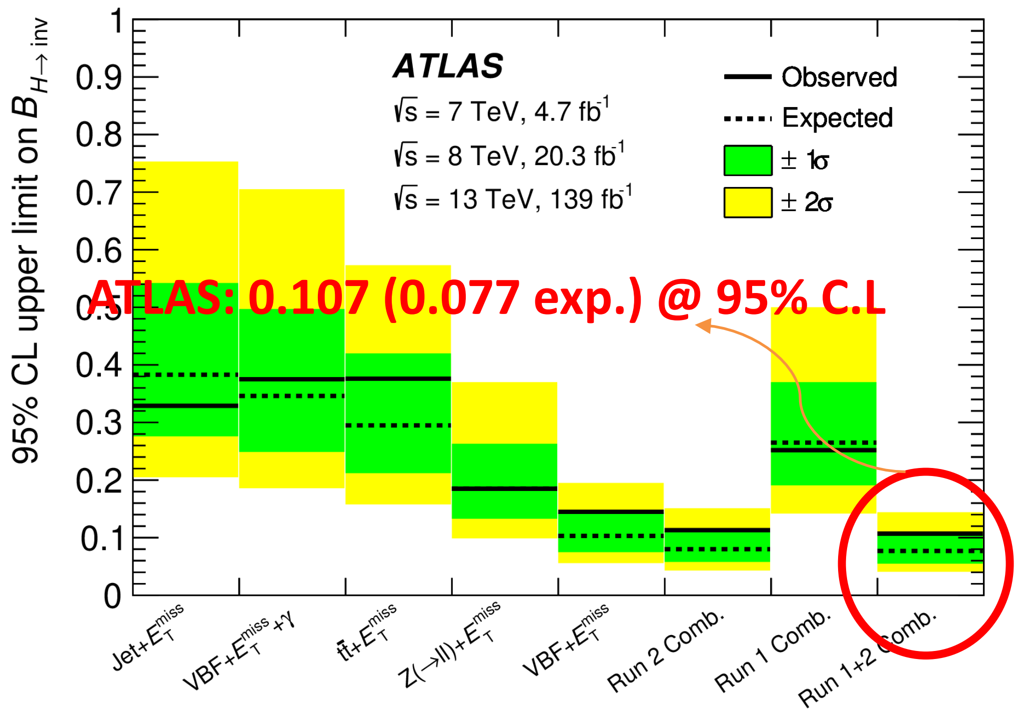


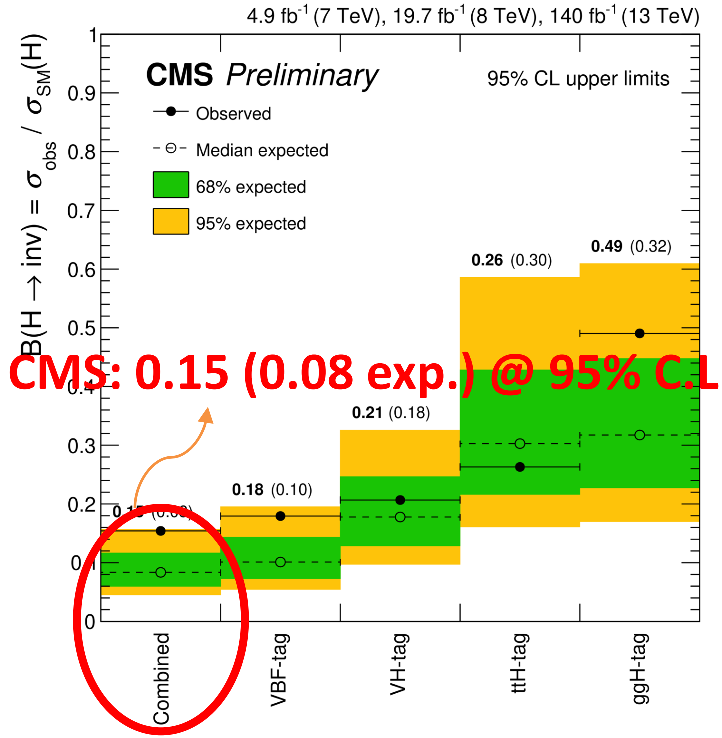


H to invisible: combination

CMS-PAS-HIG-21-007
ATLAS: arXiv:2301.10731

- Adding ttH, VH and ggH production modes improves a bit

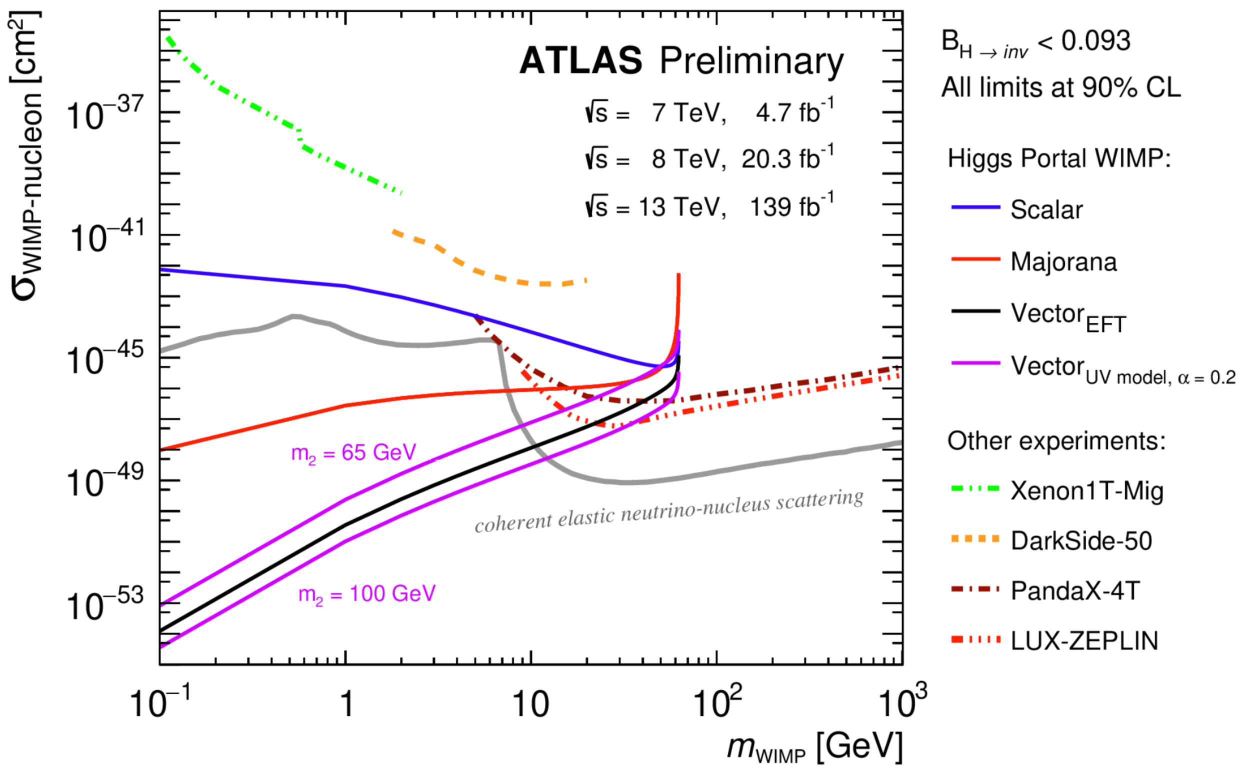




Interpretations

CMS-PAS-HIG-21-007
ATLAS: arXiv:2301.10731

- Convert the BR(H → inv) limit to the limit on **spin independent DM-nucleon elastic scattering cross section**
  - Complementary to direct detection results
- Assume several WIMP (weakly interacting massive particle) hypotheses:
  - Scalar, Majorana fermion, vector



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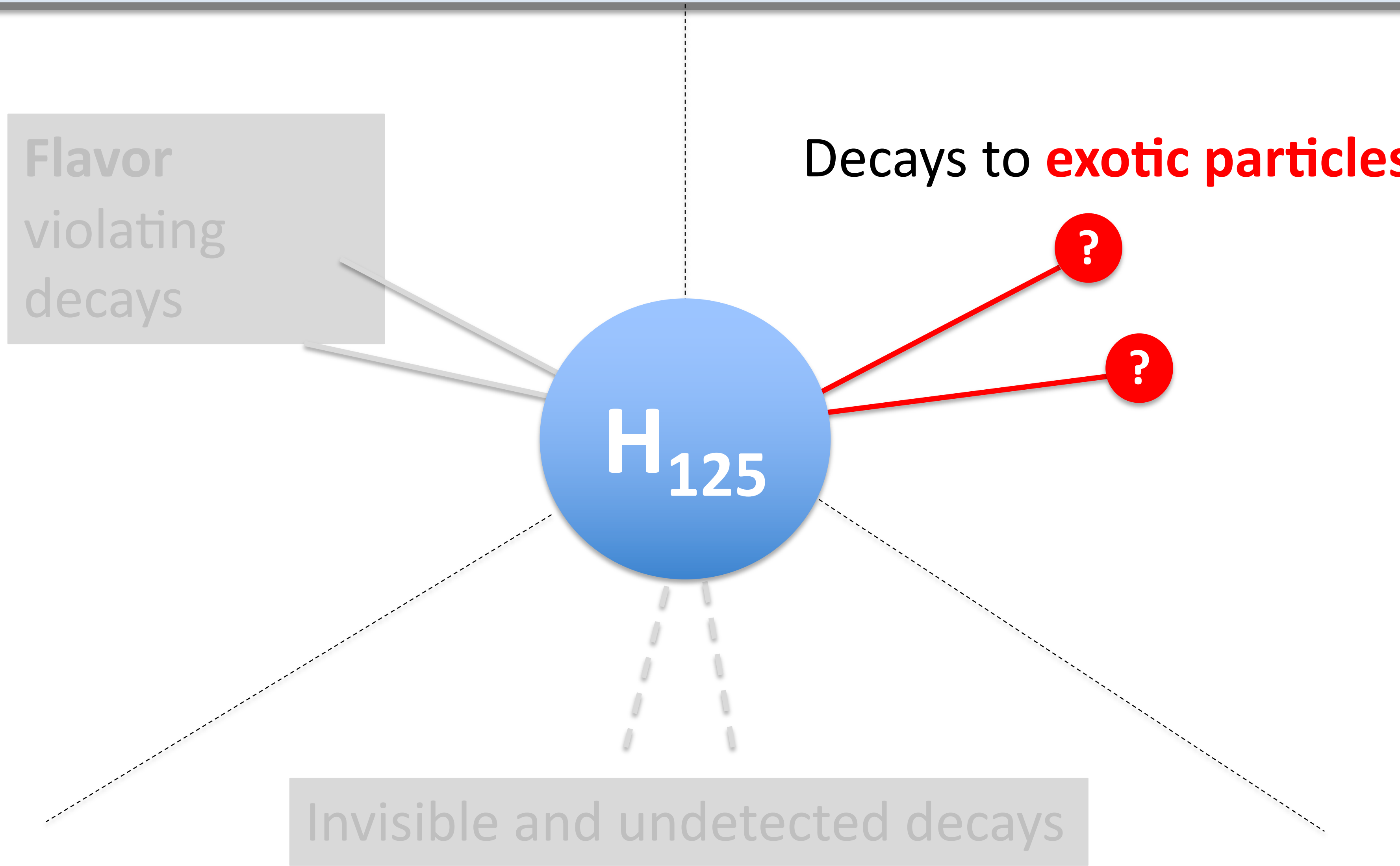

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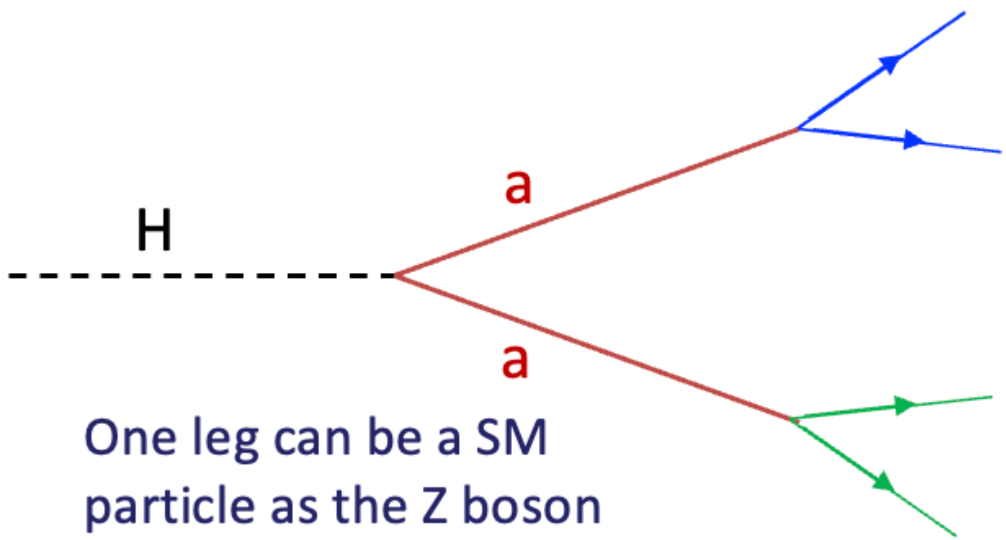
H to exotic particles

- 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



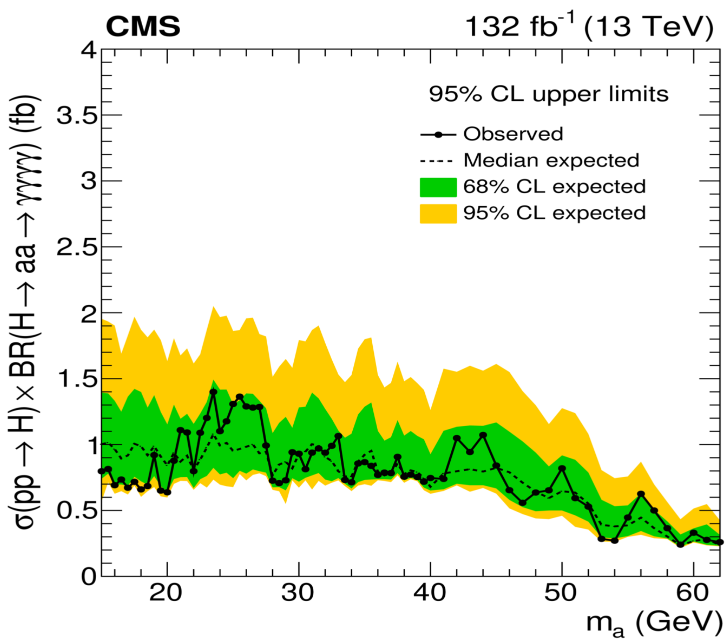
- Searches down to 15–20 GeV have resolved final states, below that, decay products start to merge

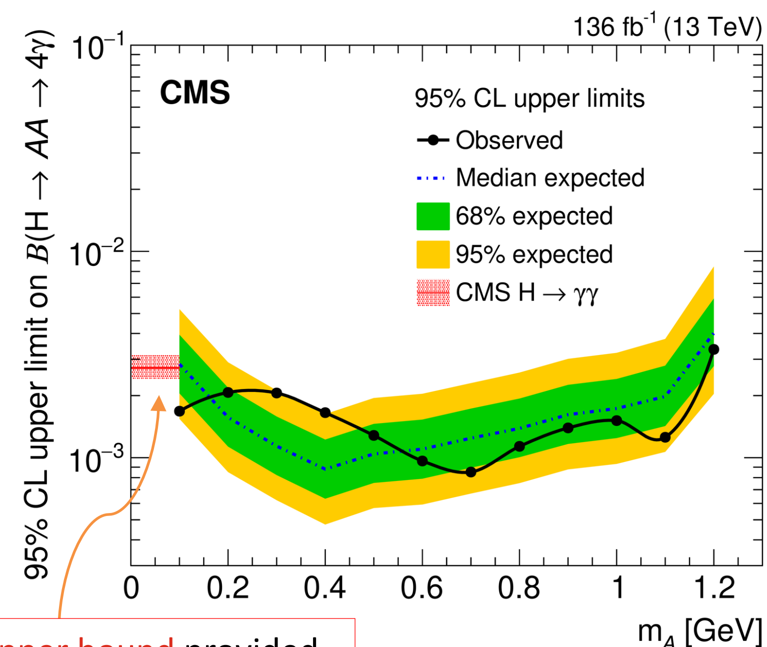
H to exotic particles: H→aa→4γ

CMS: arXiv:2208.01469
CMS: arXiv:2209.06197

- 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



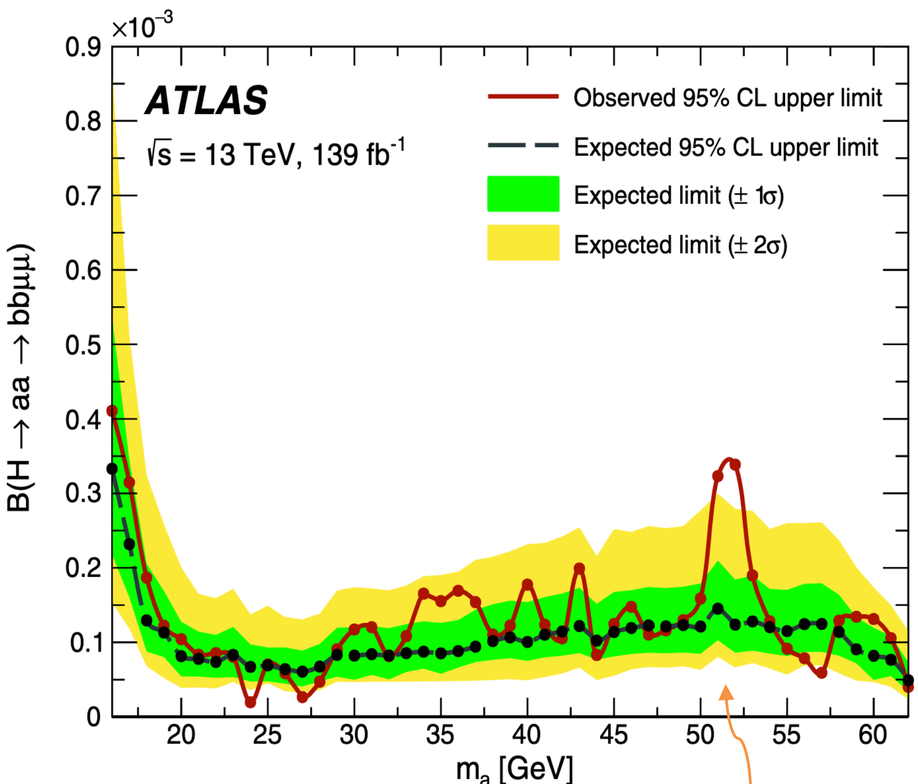


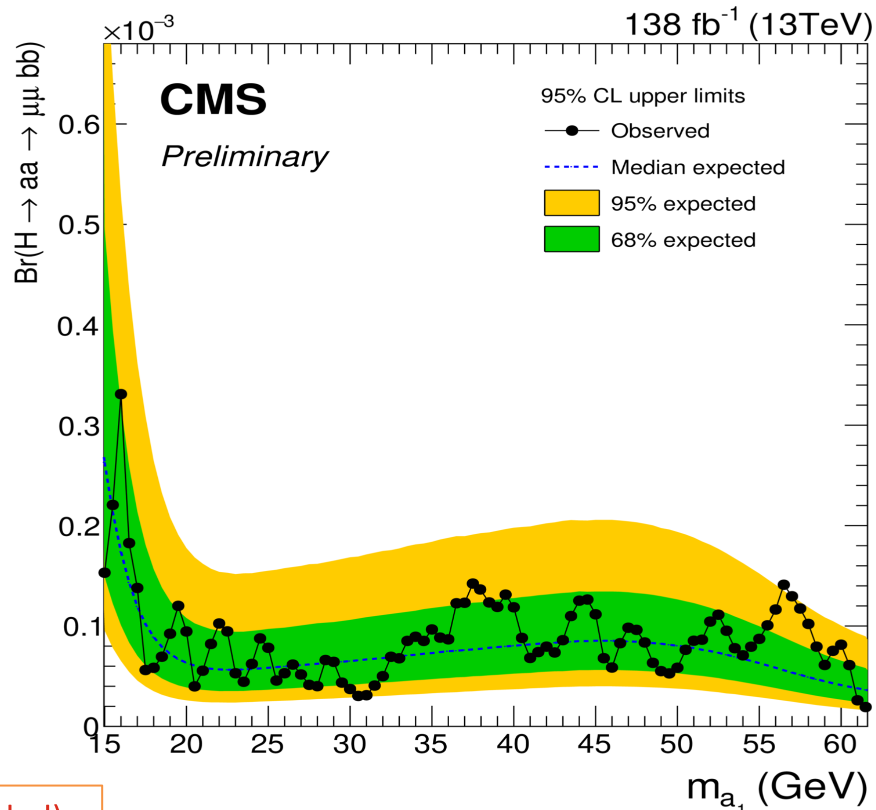
Upper bound provided by SM H→γγ

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)



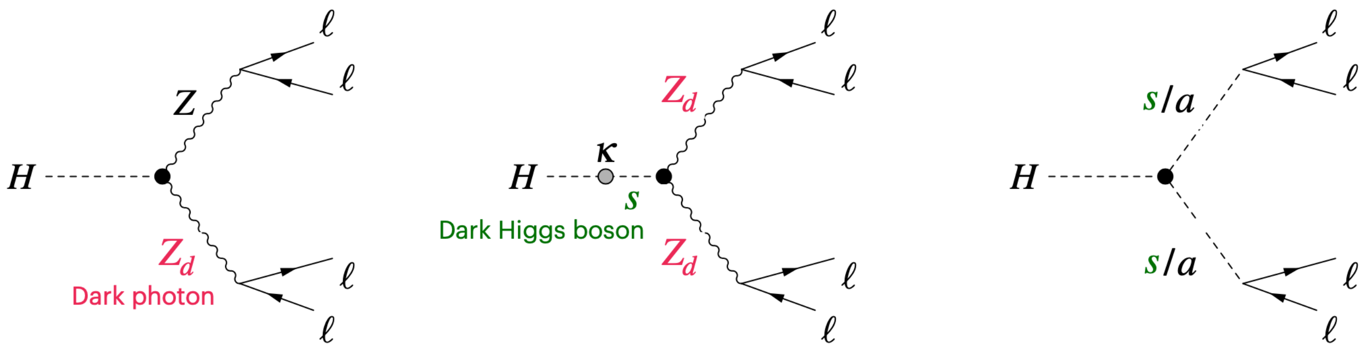


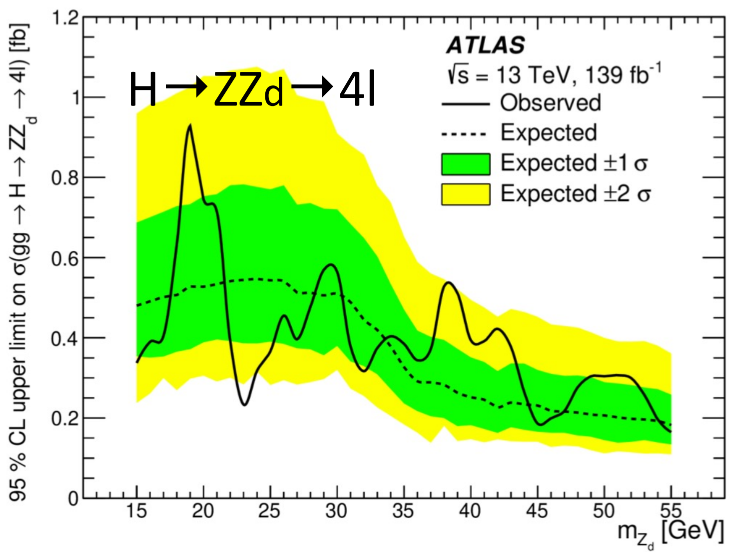
3.3σ (1.7σ) local (global) significance at 52 GeV

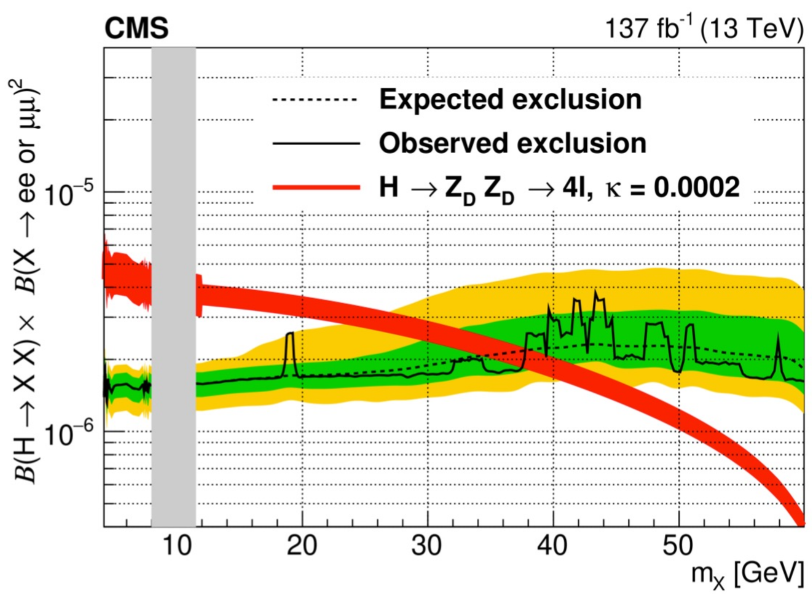
H to exotic particles: $H \to Z_d Z_d / ZZ_d / ss/aa \to 4l$

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



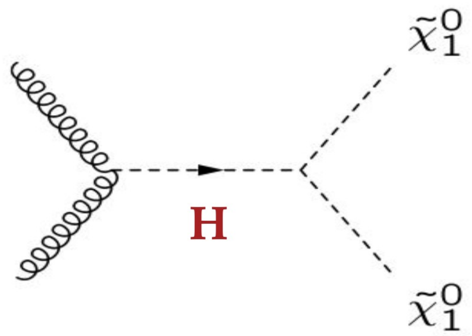


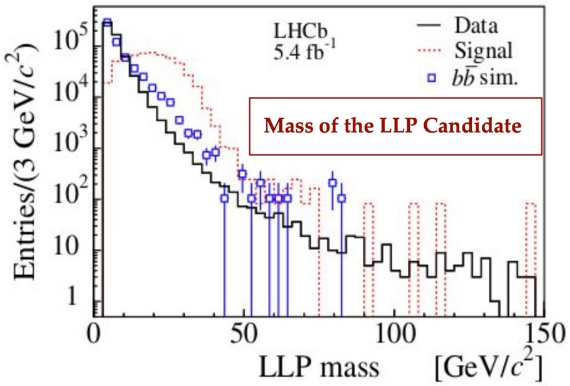


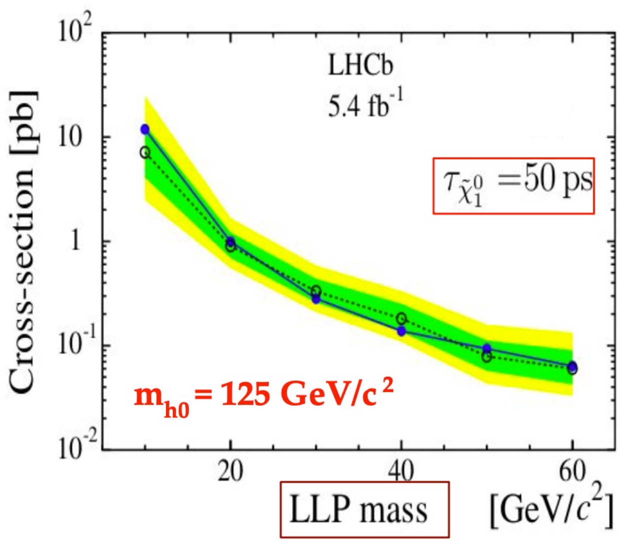
H to Long-lived particles

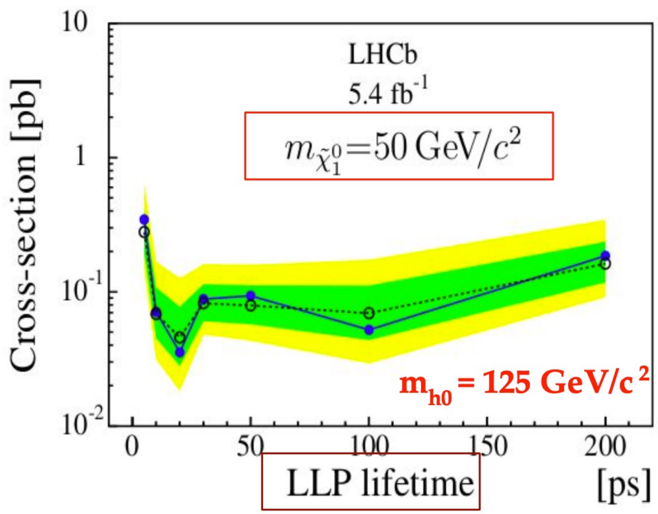
LHCb: Eur. Phys. J C82 (2022) 82

- 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

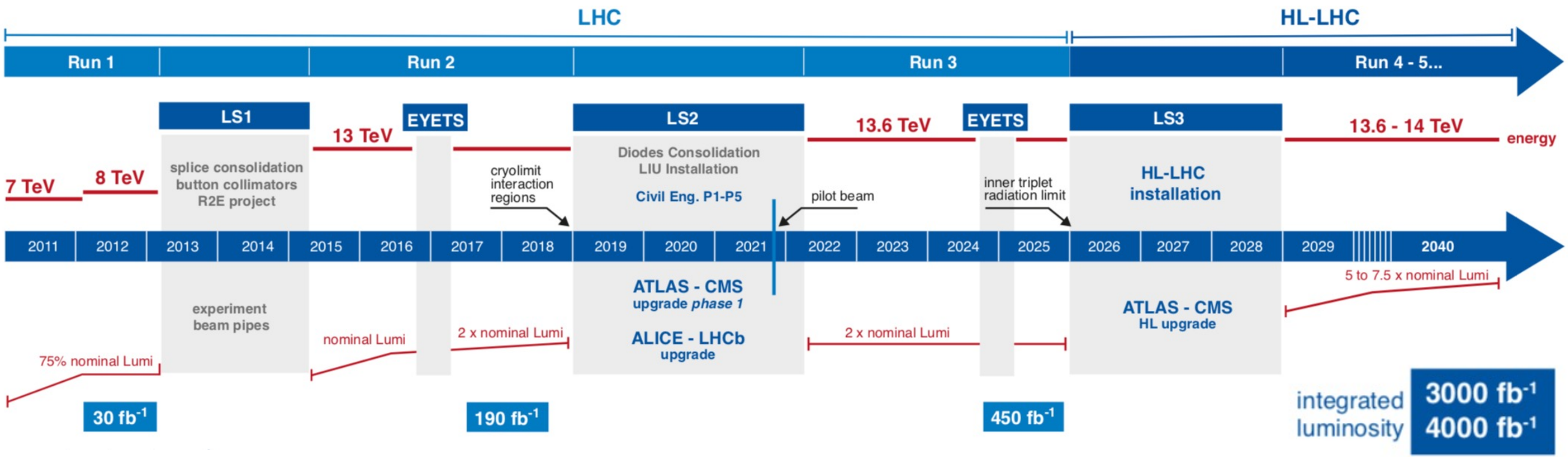




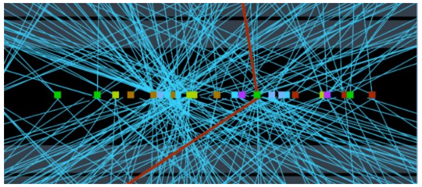




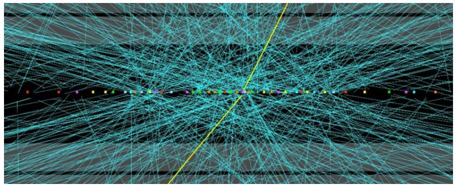
Towards HL-LHC



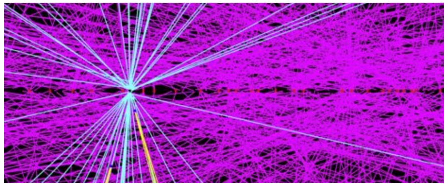
Run 2



Run 3



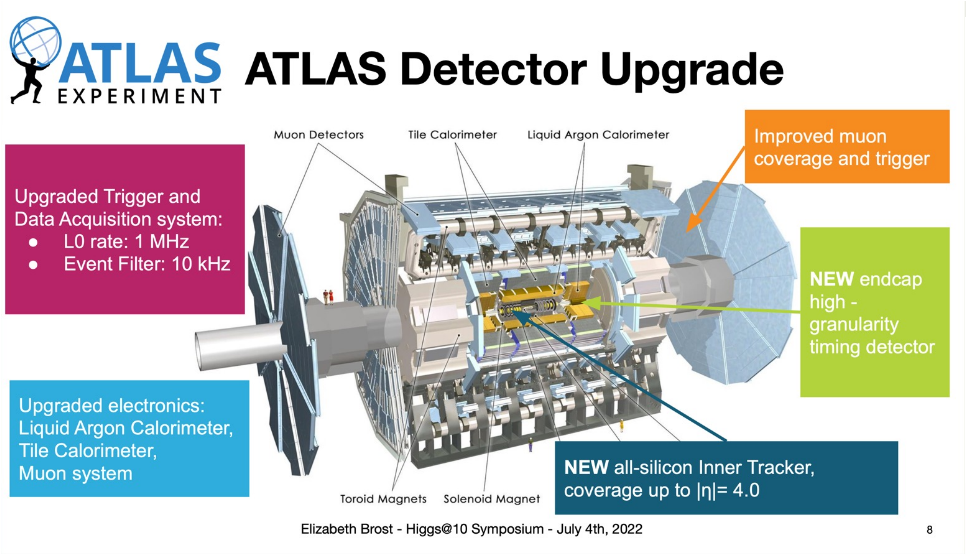
Run 4-6

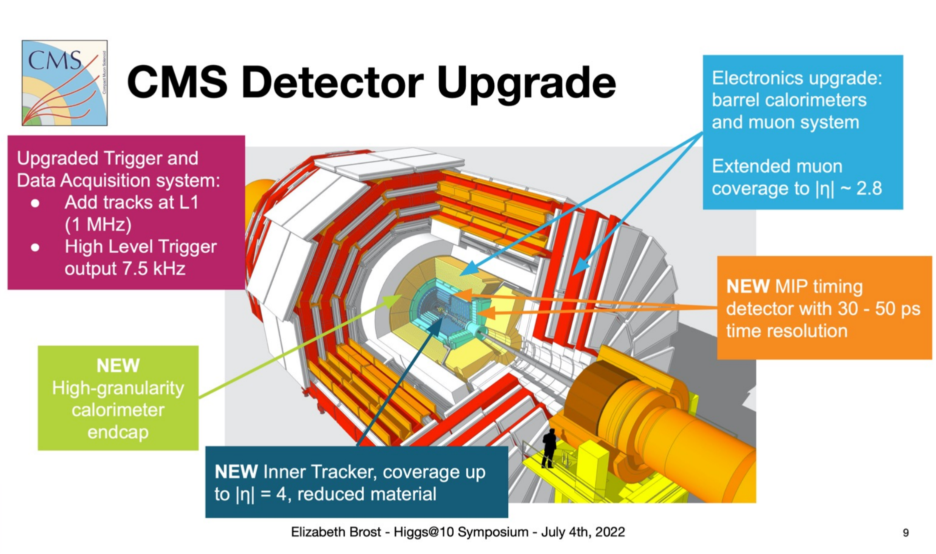


- **Total HL-LHC dataset (3000-4000 fb^{-1}) will be 20 times more data than what has been analyzed.**
  - ~180M Higgs bosons produced per experiment!
- **Mean Pileup will increase from ~30@Run2 to ~200@HL-LHC**

→ detector irradiation, higher detector occupancy, higher trigger rates

Experiment Upgrades for the HL-LHC





The harsh conditions at the HL-LHC will challenge the experiments in all areas, and will require improvements to:

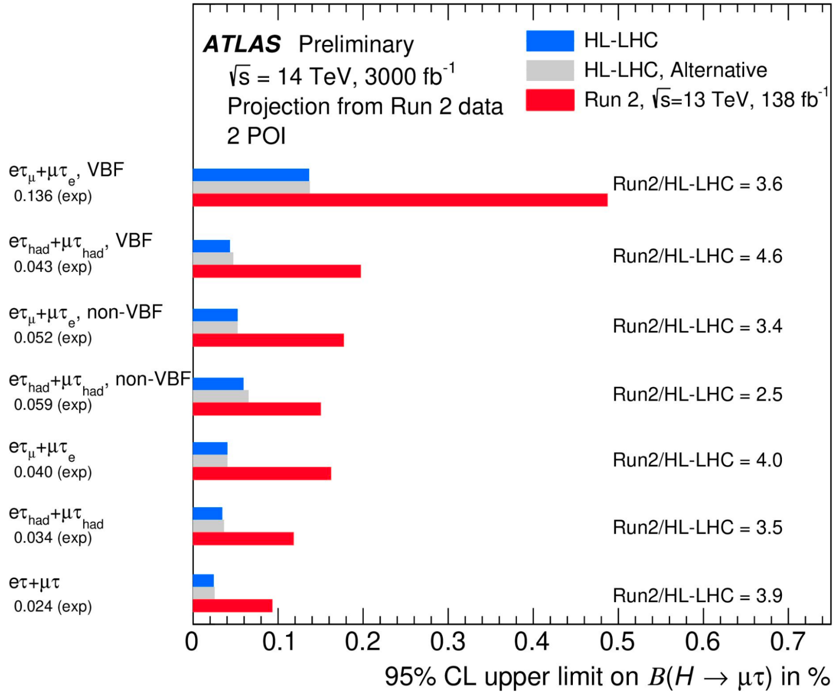
- Detectors themselves
- Trigger menu and hardware
- Event reconstruction
- Software & computing
- Physics analysis techniques

With the planned and ongoing upgrades, the detector and trigger performance after phase 2 upgrades, are supposed to be comparable to or better than Run 2

Projections of LFV and H→invisible at HL-LHC

LFV decays: H→eτ and H→μτ,
ATLAS's projection based on its full Run 2 studies

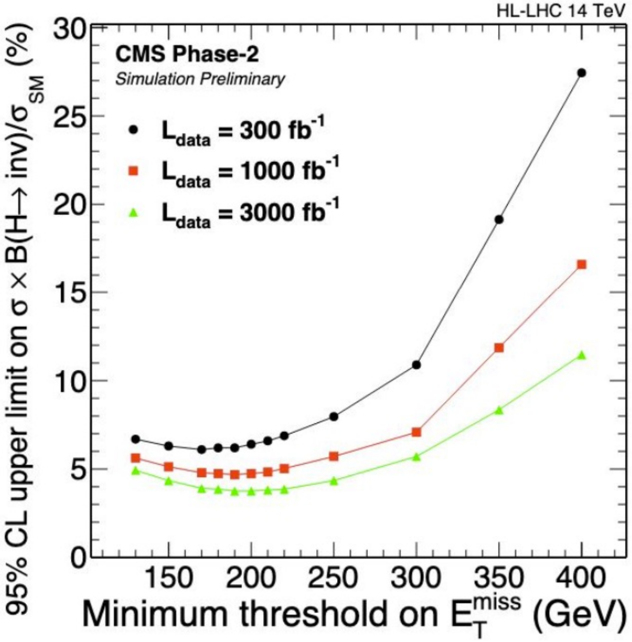
- Limits **improved by factors 4-5** wrt Run 2



ATL-PHYS-PUB-2022-054

H → invisible searches rely on the MET trigger, significantly more difficult with more pileup

- CMS search in VBF events: BR(H→invisible) < 3.8%, for MET > 190 GeV



CMS-PAS-FTR-18-016

- **ATLAS+CMS VBF+VH** combination gives **BR(H→invisible) < 2.5%**

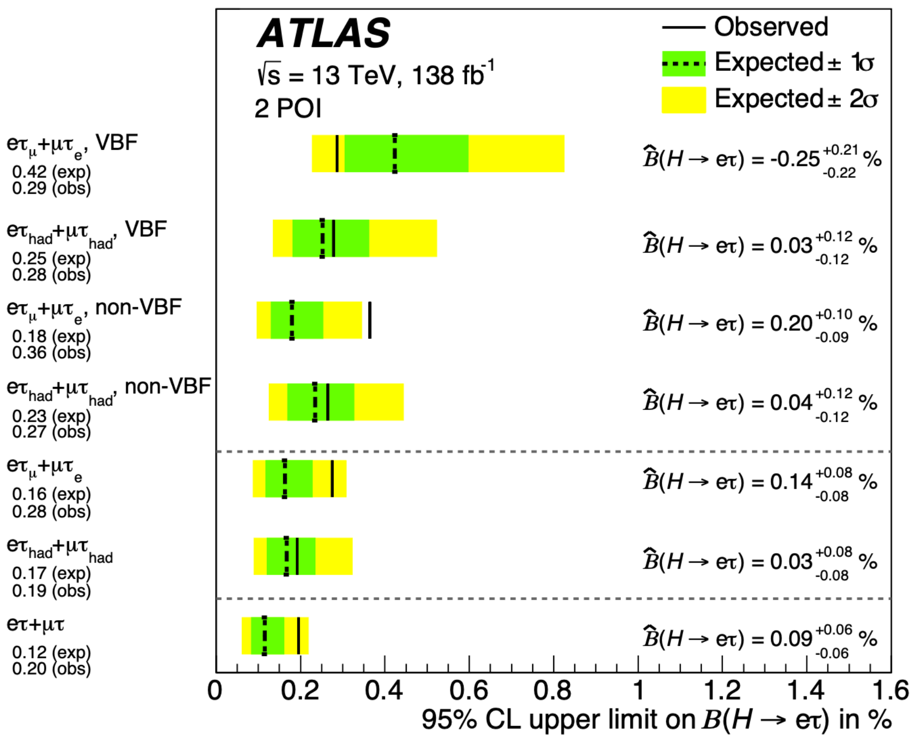
CERN-2019-007

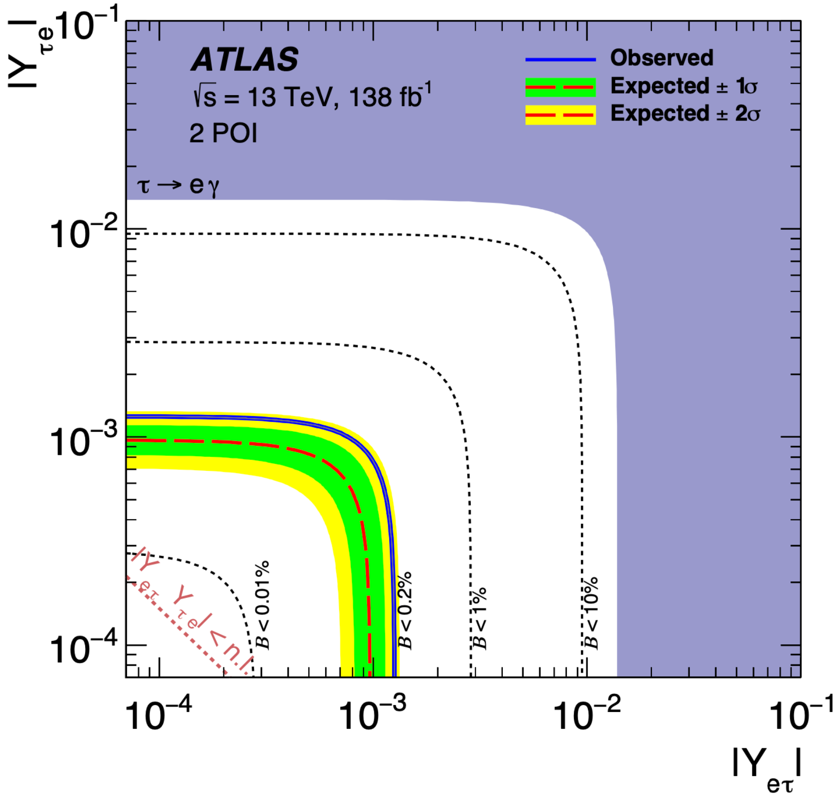
Summary

- **ATLAS and CMS** are highly active in searching for 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
- 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!

LFV


ATLAS
√s = 13 TeV, 138 fb-1
2 POI
Observed
Expected ± 1σ
Expected ± 2σ
eτμ+μτe, VBF
0.42 (exp)
0.29 (obs)
eτhad+μτhad, VBF
0.25 (exp)
0.28 (obs)
eτμ+μτe, non-VBF
0.18 (exp)
0.36 (obs)
eτhad+μτhad, non-VBF
0.23 (exp)
0.27 (obs)
eτμ+μτe
0.16 (exp)
0.28 (obs)
eτhad+μτhad
0.17 (exp)
0.19 (obs)
eτ+μτ
0.12 (exp)
0.20 (obs)
B̂(H → eτ) = -0.25 +0.21 -0.22 %
B̂(H → eτ) = 0.03 +0.12 -0.12 %
B̂(H → eτ) = 0.20 +0.10 -0.09 %
B̂(H → eτ) = 0.04 +0.12 -0.12 %
B̂(H → eτ) = 0.14 +0.08 -0.08 %
B̂(H → eτ) = 0.03 +0.08 -0.08 %
B̂(H → eτ) = 0.09 +0.06 -0.06 %
95% CL upper limit on B(H → eτ) in %


ATLAS
√s = 13 TeV, 138 fb-1
2 POI
Observed
Expected ± 1σ
Expected ± 2σ
τ → eγ
B < 0.01%
B < 0.2%
B < 1%
B < 10%
|Yτe|
|Yeτ|