Measurements of Higgs Anomalous Couplings at ATLAS and CMS (LFV, FCNC)

11th International Workshop on the CKM Unitarity Triangle (CKM 2021)
22-26 November 2021, The University of Melbourne

Paul Thompson
University of Birmingham

UNIVERSITY OF BIRMINGHAM

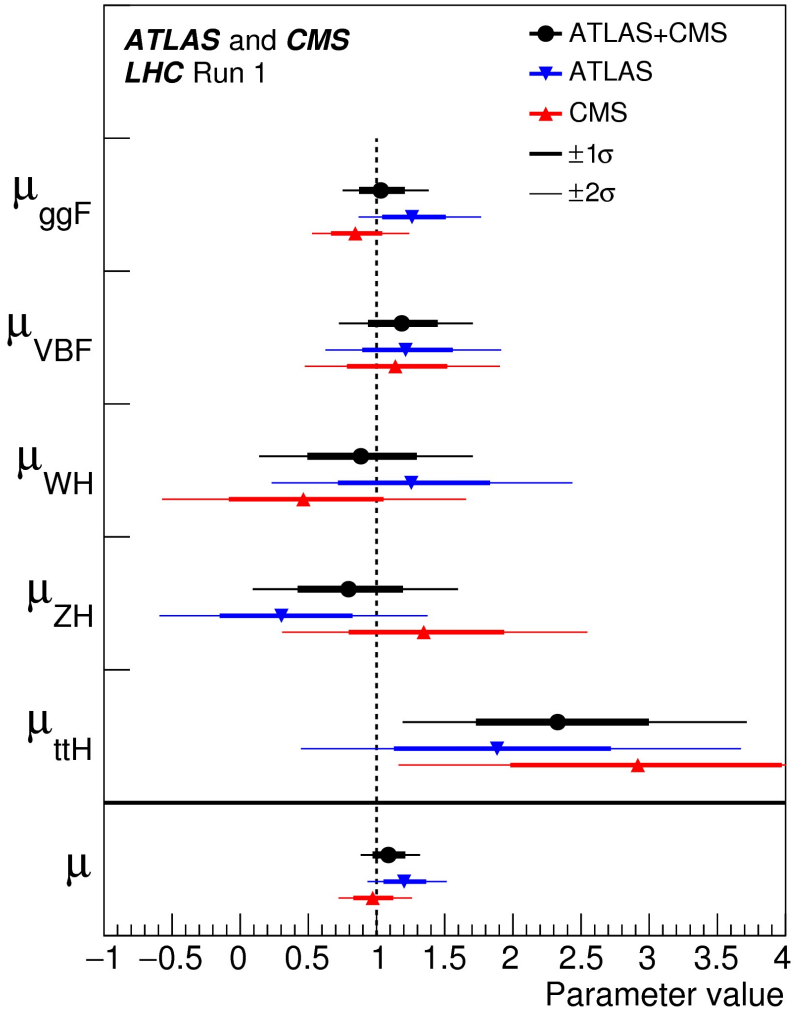
ATLAS EXPERIMENT

CMS

On behalf of the ATLAS and CMS Collaborations

Introduction

- The 125 GeV Higgs boson discovered by CMS and ATLAS experiments in 2012
- Data collected during Run 1 and Run 2 of the LHC used for experimental measurements of the Higgs signal strength compared to the Standard Model (SM)



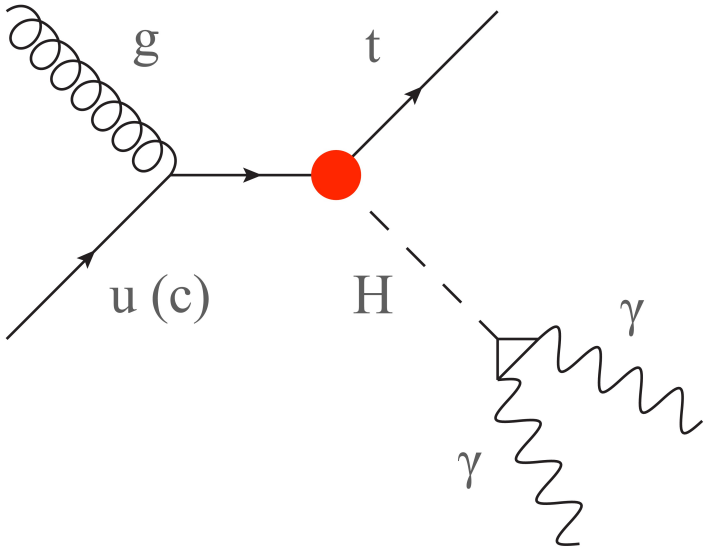
- Higgs appears to be that of the SM
- SM is a highly successful theory but it has several shortcomings
  - Absence of gravity
  - Absence of explanation for Dark Matter
  - CP violation
  - the Hierarchy problem
  - …..

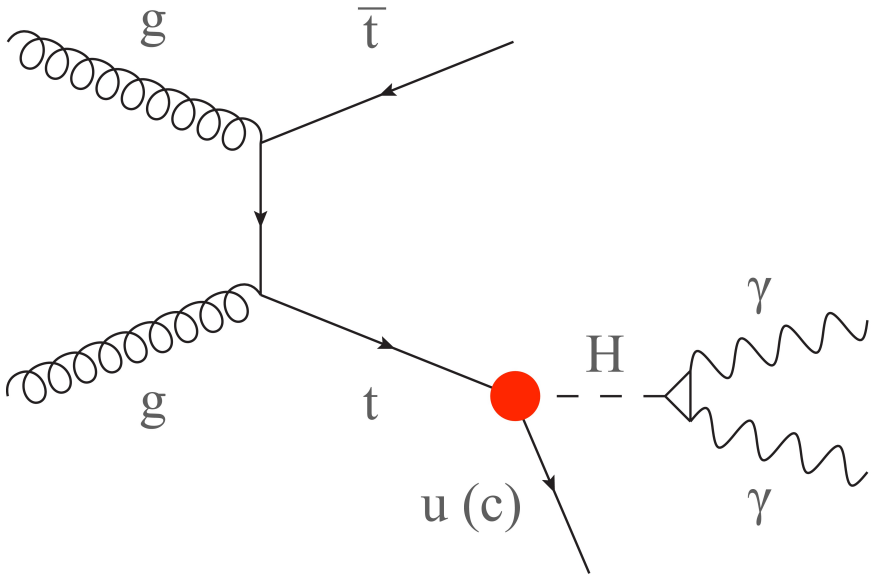
Higgs as a probe for new physics

- Search for decays highly suppressed in the SM
- Observation would point to the physics beyond the Standard Model (BSM)
  - Flavour changing neutral currents (FCNC)
  - Lepton flavour violating (LFV) decays of the Higgs
- **Results** Based on **data analyses from ATLAS and CMS** with LHC **pp collisions at 13 TeV**
- In many cases full Run 2 statistics: **140 fb^{-1}** from results released in the last year
- *Due to time constraints can only show a selection of results with a focus on the most recent ones*
  - FCNC
    - FCNC of the top quark and Higgs final states to 2 photons. CMS, Run 2, 137 fb^{-1}. New submitted 3rd November 2021 arXiv:2111.02219
    - Search for FCNC t → qH using H→bb, H→ $\tau_{l,h}\tau_h$, H→ WW*,$\tau_l\tau_l$,ZZ*, H→γγ ATLAS, Run 2, 36 fb^{-1} JHEP 05 (2019) 123
  - LFV
    - H→eτ/μτ, CMS, Run 2, 137 fb^{-1} Phys. Rev. D 104 (2021) 032013
    - H→eτ/μτ, ATLAS, Run 2, 36 fb^{-1} Phys. Lett. B 800 (2020) 135069
    - H→eμ, ATLAS, Run 2, 139 fb^{-1} Phys. Lett. B 801 (2020) 135148

Flavour Changing Neutral Currents

- Flavour changing quark decays mediated by neutral currents are forbidden at tree level in the Standard Model
- Can proceed at higher orders but heavily supressed by GIM mechanism or CKM unitary constraints
- Decay of a top quark (t) into a Higgs boson (H) and up quark (u), t →Hu, or charm quark (c), t → Hc, are expected to be $O(10^{-17})$ and $O(10^{-15})$
- Any observation of t →Hq would be indication of new physics
- Example single t (ST) and tt production (TT) with H→γγ decay

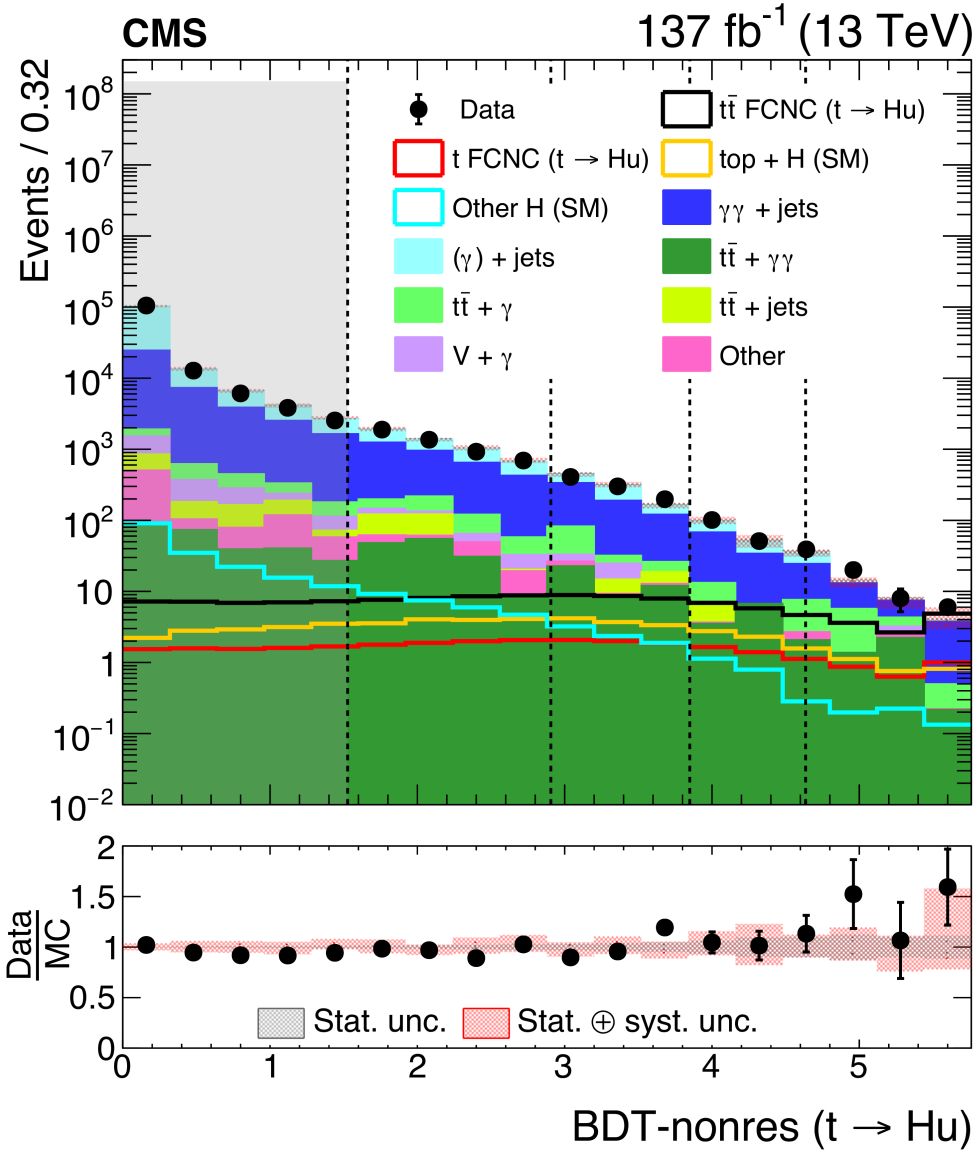




FCNC, t →Hq, H→γγ arXiv:2111.02219

- Full Run 2 data analysis from CMS using H→γγ decays
- The Higgs decay follows a similar strategy to H→γγ analyses
- Background and signal (for t →Hu and t →Hc) separated using BDTs
- With BDTs trained for the two dominant SM backgrounds
  - resonant
  - non-resonant
- Divided into exclusive categories for top decay
  - Leptonic (3 BDT score sub-categories)
  - Hadronic (4 BDT score sub-categories)

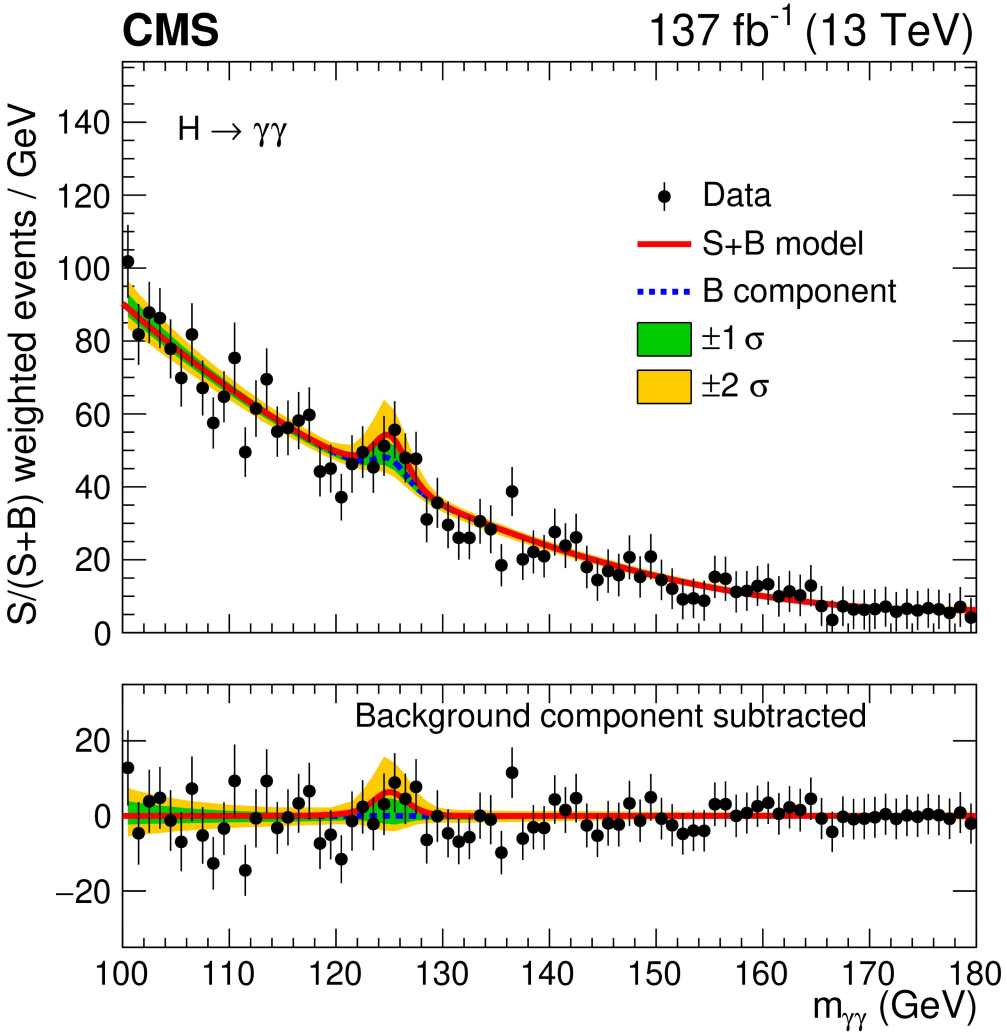
Hadronic categorization



FCNC, t →Hq, H→γγ arXiv:2111.02219

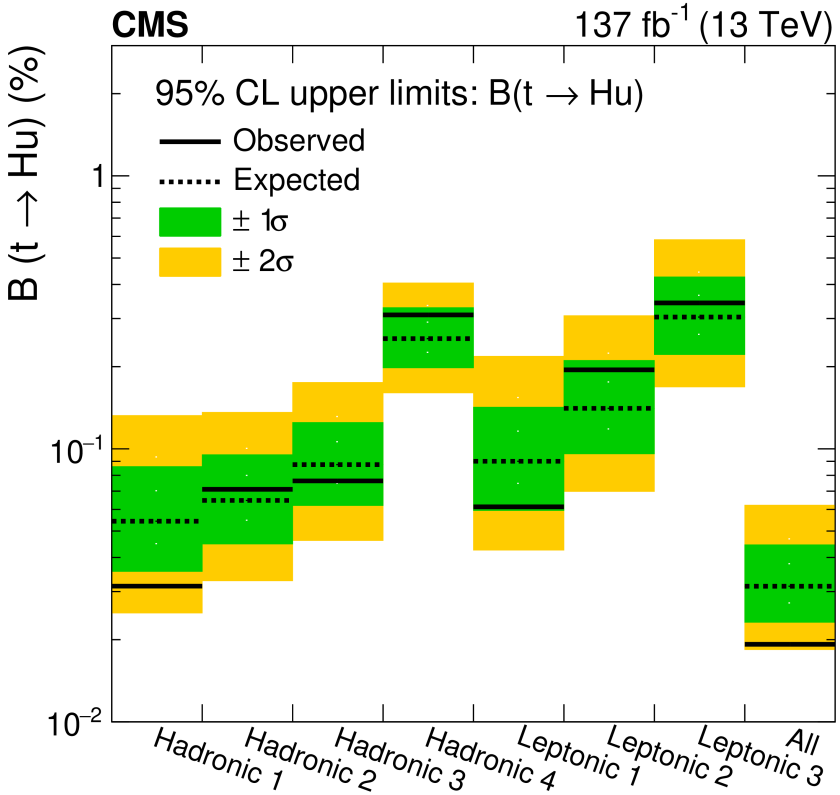
- Invariant mass for H→γγ decay candidates $m_{\gamma\gamma}$
- Expected signal and resonant background $m_{\gamma\gamma}$ distributions modelled using the sum of a double-sided Crystal Ball function and Gaussian
- The non-resonant background is modelled directly from data, using the discrete profiling method
- No excess observed above background observed in data
- Use to place limits of FCNC branching ratios

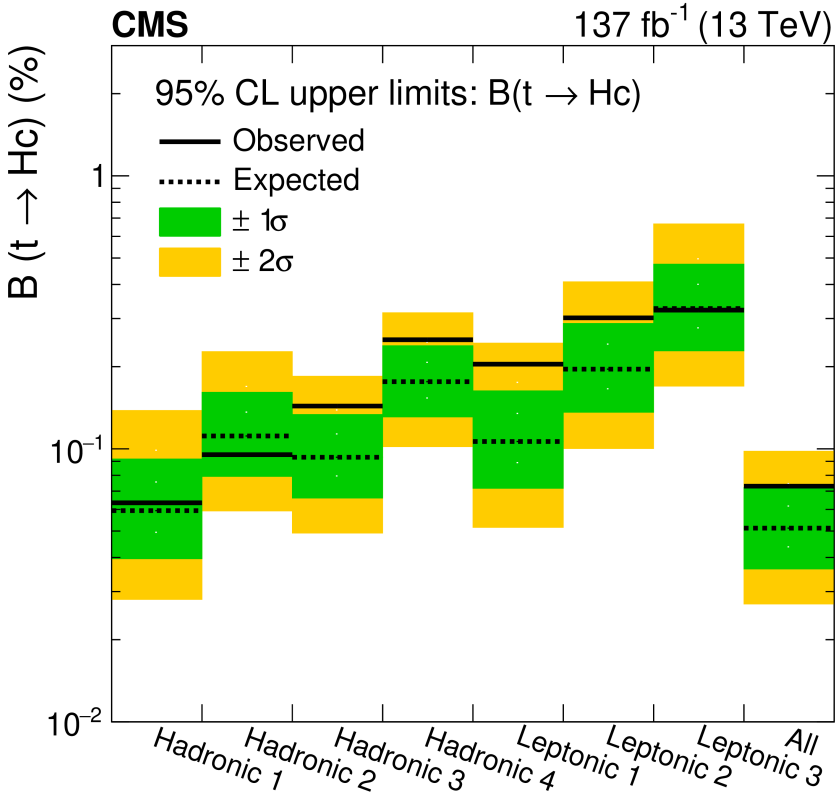
Higgs Candidate invariant mass for 7 categories targetting t →Hc FCNC



FCNC, t →Hq, H→γγ arXiv:2111.02219

- Observed (expected) 95% CL upper limits on B(t → Hu) and B(t → Hc) are 0.019 (0.031)% and 0.073 (0.051)%





- Use to place limits on coupling

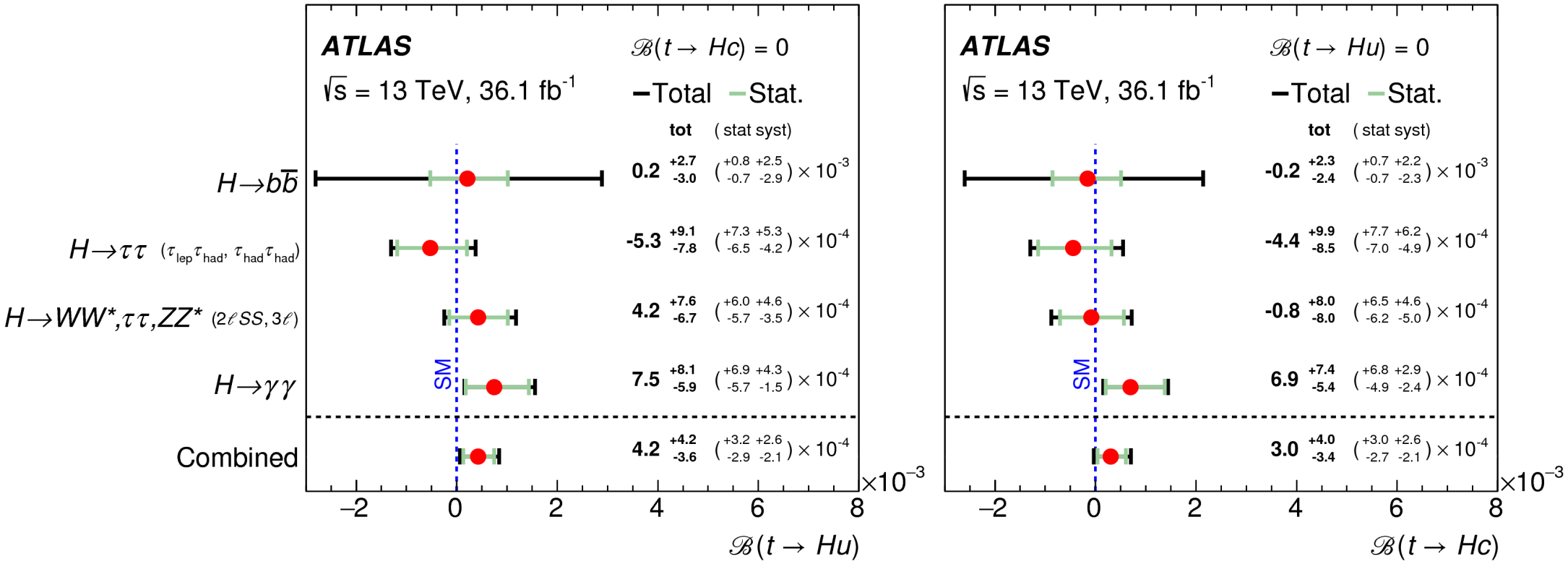
$$\kappa^2_{\mathrm{Hqt}} = \mathcal{B}(\mathrm{t} \to \mathrm{Hq}) \frac{\Gamma_{\mathrm{t}}}{\Gamma_{\mathrm{Hqt}}}$$

  - Observed (expected) 95% CL upper limits on $|\kappa_{\mathrm{Hut}}|$ and $|\kappa_{\mathrm{Hct}}|$ are 0.037 (0.047) and 0.071 (0.060)

FCNC Combination

JHEP 05 (2019) 123

- ATLAS combination using H→bb, H→ $\tau_{l,h}\tau_h$, H→ $WW^*,\tau_l\tau_l,ZZ^*$, H→γγ for 36 fb^{-1} of Run 2 data

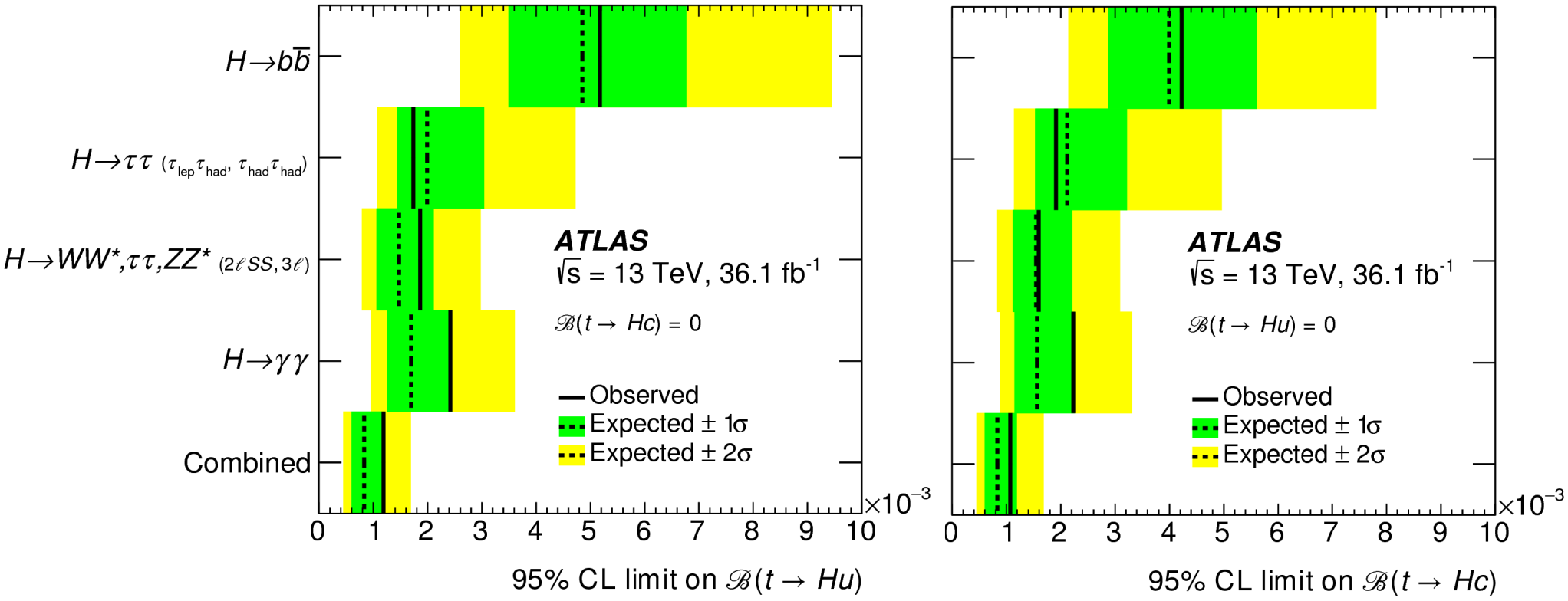


- Results of best fit to data for B(t → Hu) and B(t → Hc)
- All analyses (except H→bb) are statistically limited

ATLAS FCNC Combination

JHEP 05 (2019) 123

- Observed (expected) 95% CL upper limits on B(t → Hu) and B(t → Hc) are 0.12 (0.083)% and 0.11 (0.083)%



- Observed (expected) 95% CL upper limits on $|\kappa_{Hut}|$ and $|\kappa_{Hct}|$ are 0.066 (0.055) and 0.064 (0.055)

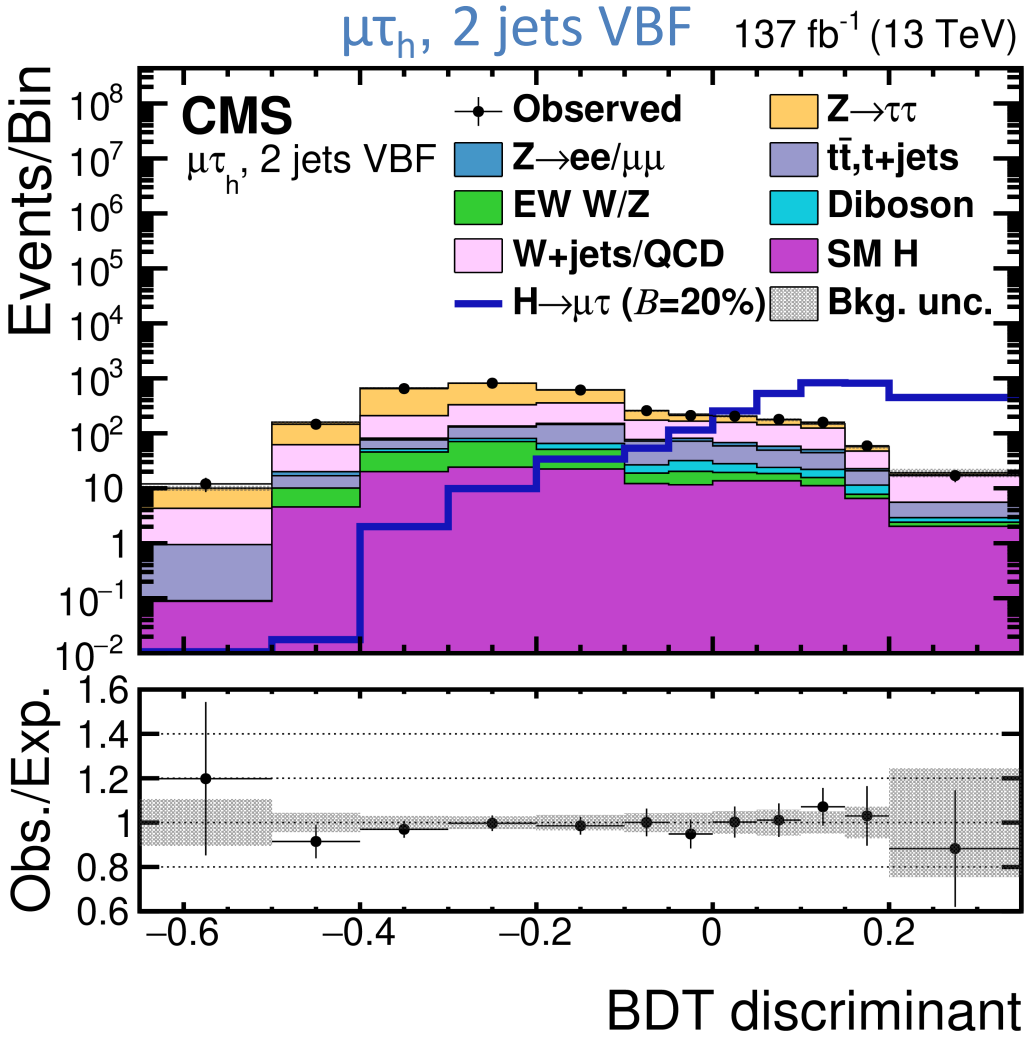
Lepton Flavour Violating Higgs Decays

- Lepton flavour violation is not allowed in the SM. However, the observation of neutrino oscillations indicates that LFV occurs in nature!
- Many BSM models include them e.g. SUSY and some composite Higgs model allow LFV Yukawa couplings $Y_{e\mu}$, $Y_{e\tau}$, $Y_{\mu\tau}$
- ATLAS and CMS searches have been performed in the eτ and μτ channel, with ATLAS additionally in the eμ channel
- H→eτ/μτ, CMS, Run 2, 137 fb^{-1} Phys. Rev. D 104 (2021) 032013
- H→eτ/μτ, ATLAS, Run 2, 36 fb^{-1} Phys. Lett. B 800 (2020) 135069
- H→eμ, ATLAS, Run 2, 139 fb^{-1} Phys. Lett. B 801 (2020) 135148

LFV decays: H→eτ/μτ

- Channels and final states H→μτ_h, H→μτ_e, H→eτ_h, H→eτ_μ :
- Categories:
  - gg→H : 0 jet, 1 jet, 2 jets
  - qq→H : 2 jets (m_{jj}>500(550) GeV eτ(μτ))
- Z→ττ, top quark processes, mis-identified objects are the major backgrounds
  - Background estimation using data driven techniques + simulation
- BDTs trained in each channel separately
  - Maximum likelihood fit to BDT output discriminators
  - Simultaneously over all channels and categories

Phys. Rev. D 104 (2021) 032013

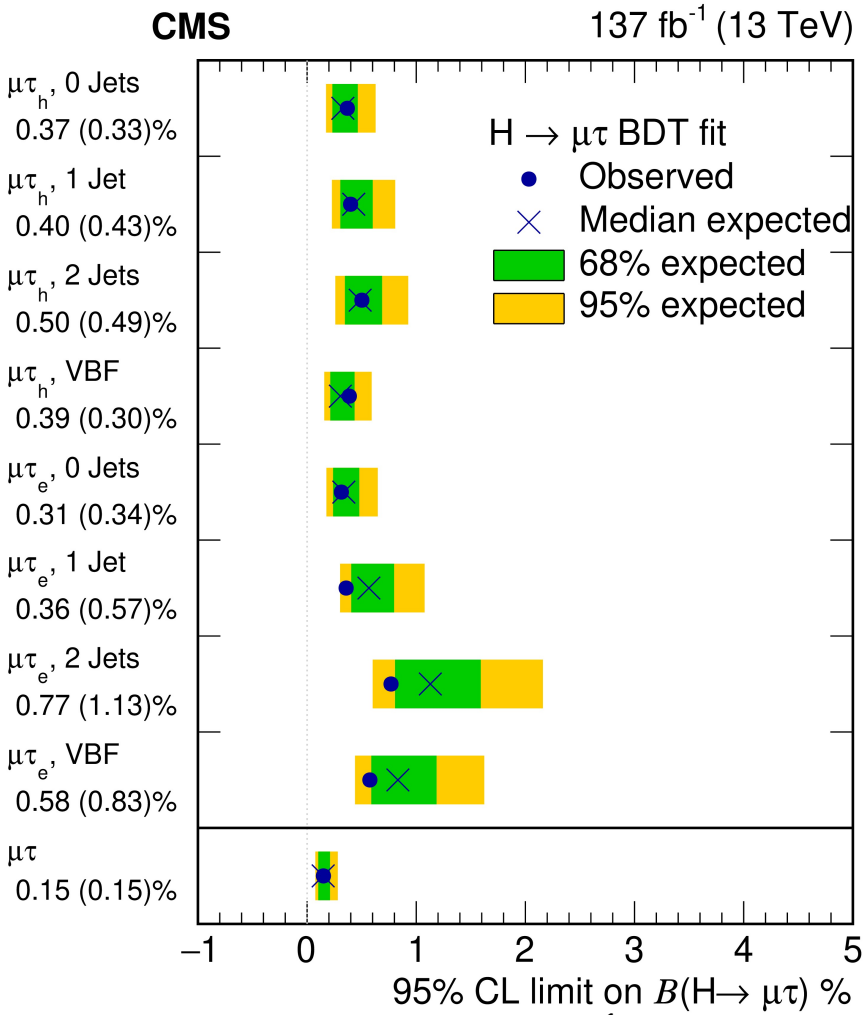


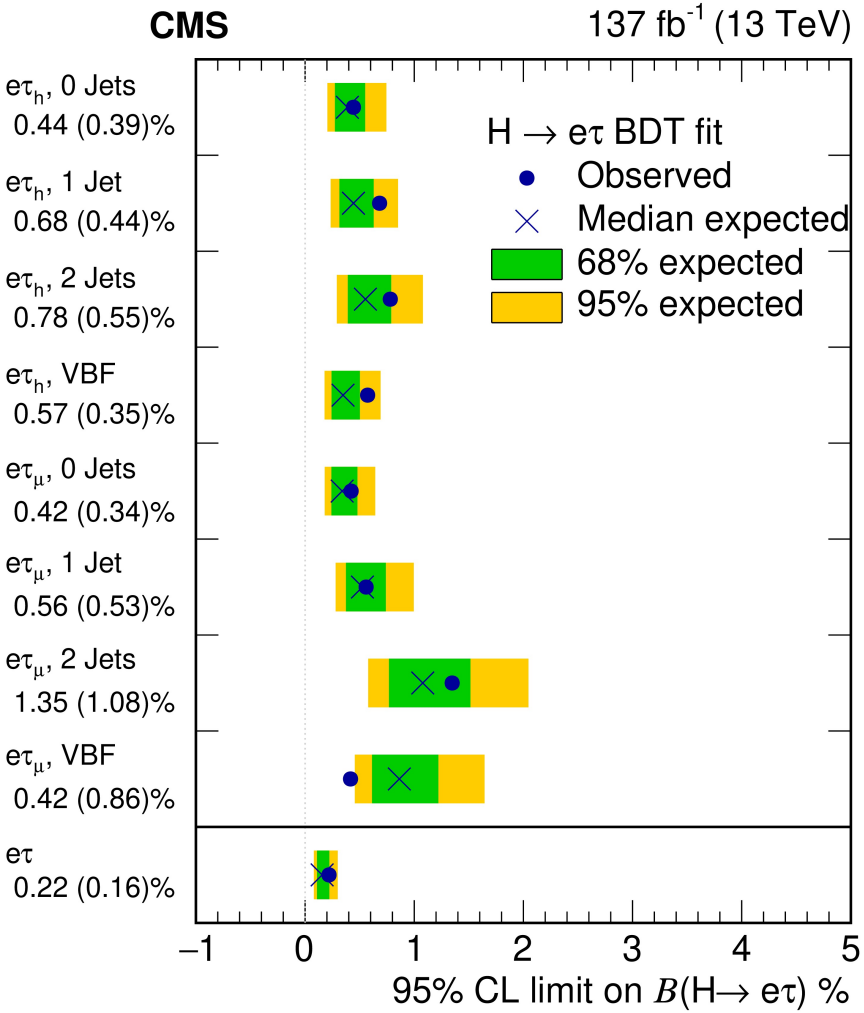
ATLAS Analysis:
Also makes use of BDT discriminants for two signal regions (exploiting VBFH and ggH production) Phys. Lett. B 800 (2020) 135069

LFV decays: H→eτ/μτ

Phys. Rev. D 104 (2021) 032013

- No significant excesses over the SM prediction are found
- Upper limits on LFV branching fractions at 95% CL:BR(H→μτ) < 0.15(0.15) %, BR(H→eτ) < 0.22(0.16) %





Previous results based on 36 fb^{-1}:

CMS: B(H → μτ) > 0.25(0.25) % and B(H→eτ) > 0.61%(0.37)% JHEP 06 (2018) 001

ATLAS: B(H → μτ) > 0.28(0.37) % and B(H→eτ) > 0.47(0.34)% Phys. Lett. B 800 (2020) 135069

LFV decays: H→eτ/μτ

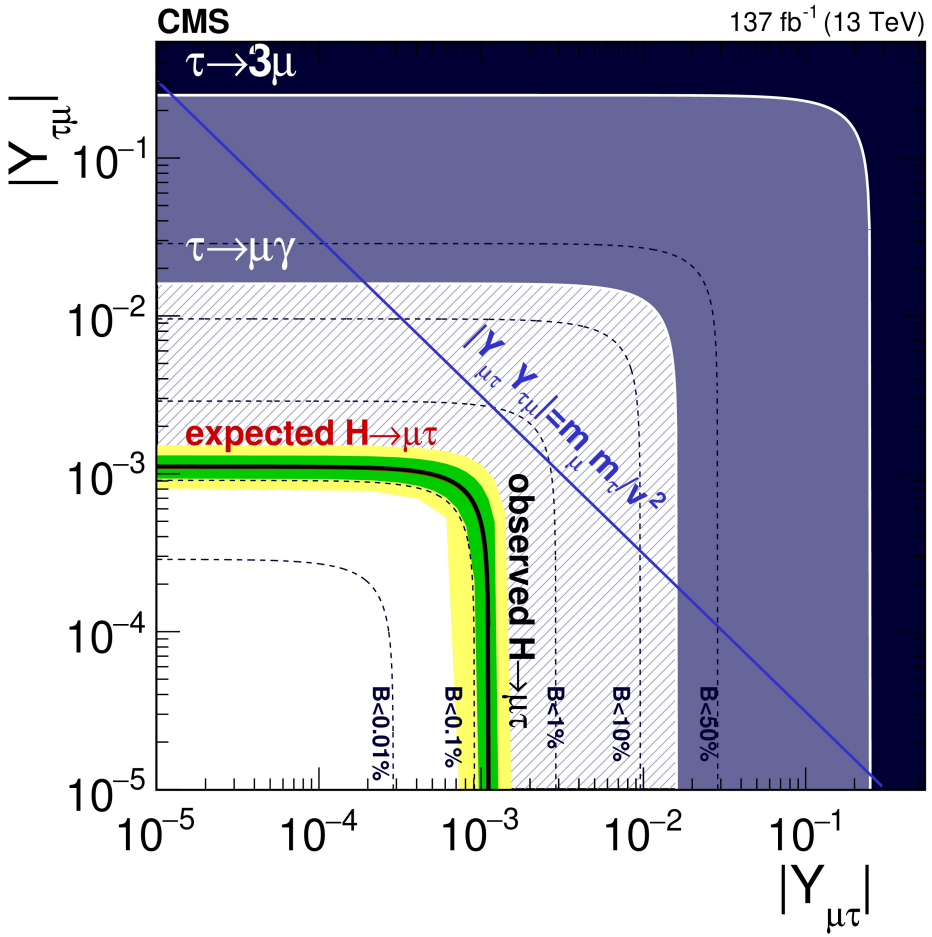
Phys. Rev. D 104 (2021) 032013

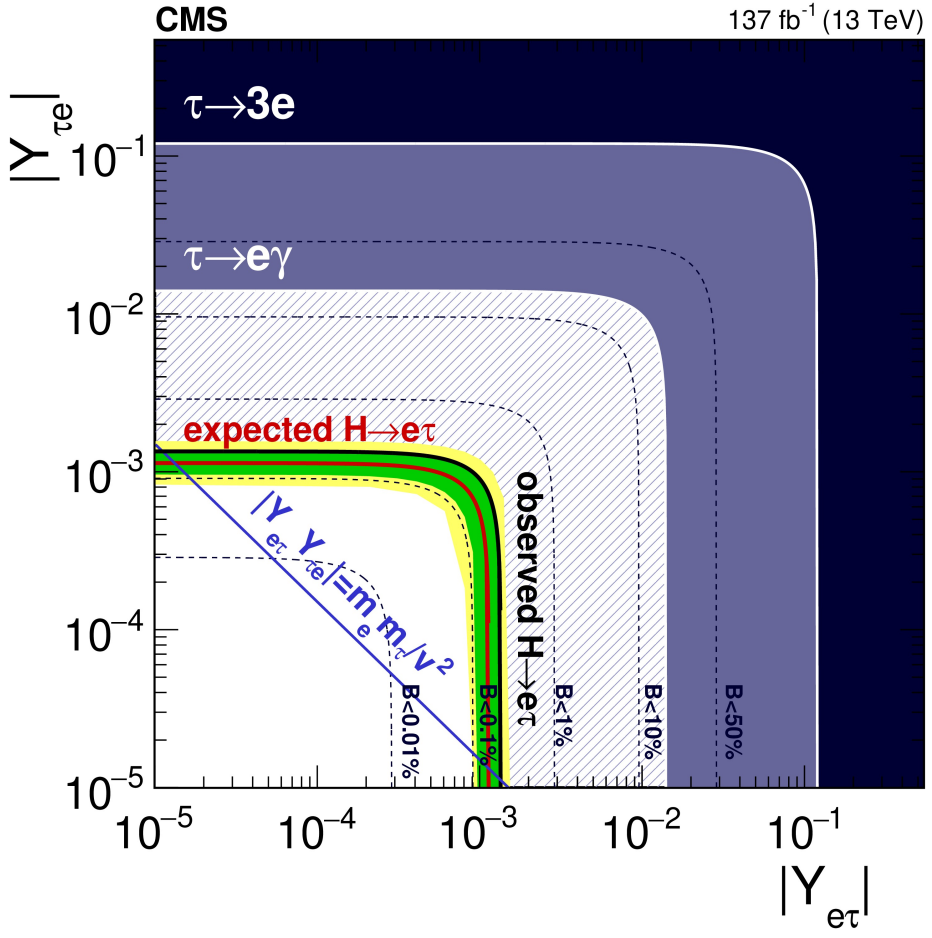
$$\Gamma\left(H \to \ell^{\alpha}\ell^{\beta}\right) = \frac{m_H}{8\pi}\left(\left|Y_{\ell^{\alpha}\ell^{\beta}}\right|^2 + \left|Y_{\ell^{\beta}\ell^{\alpha}}\right|^2\right)$$

$$\mathcal{B}\left(H \to \ell^{\alpha}\ell^{\beta}\right) = \frac{\Gamma\left(H \to \ell^{\alpha}\ell^{\beta}\right)}{\Gamma\left(H \to \ell^{\alpha}\ell^{\beta}\right) + \Gamma_{SM}}$$

here, $\ell^{\alpha}, \ell^{\beta}$ are different flavored leptons

- Branching fraction limits converted to limits on off-diagonal Yukawa couplings



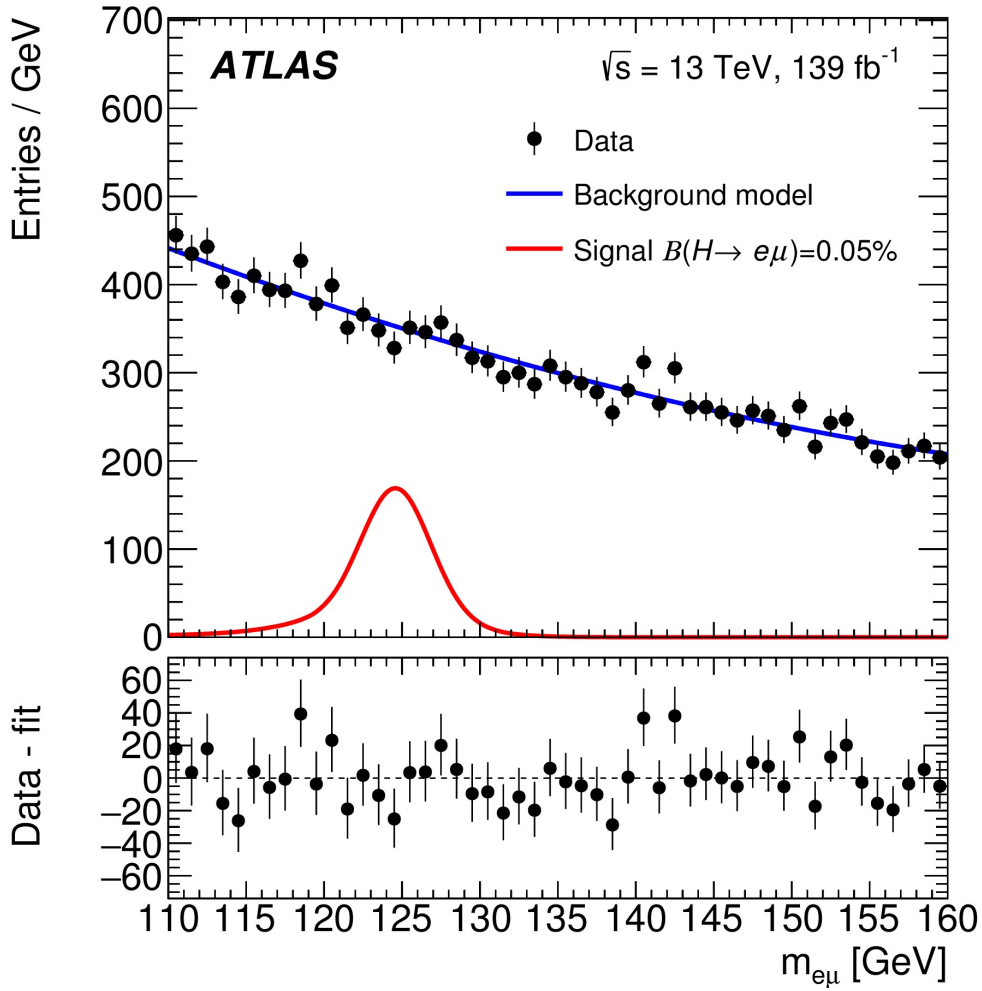


- Most stringent limits on branching fractions and couplings from LHC

LFV decays: H→eμ

- The H→eμ analysis follows a similar strategy to H→μμ analyses
- Events are selected with one electron and one muon and are categorized
- Eight categories are defined (S/B)
  - A low-p^{l}_{T} category in which one of the selected leptons has $p_T < 27$ GeV
  - A VBF category for events with two jets with $|\Delta\eta_{jj}| > 3$ and $m_{jj} > 500$ GeV
  - Remaining events are categorized as central if both leptons have $|\eta^{l}| < 1$, otherwise they are categorized as non-central
  - These events are then classified based on p^{ll}_{T} as low($p^{ll}_{T} \leq 15$), mid($15 < p^{ll}_{T} \leq 50$) or high-p_T ($p^{ll}_{T} > 50$)
- No excess above background only fit.
- Use to set limits on LFV branching ratio. Statistical uncertainties dominate

Phys. Lett. B 801 (2020) 135148



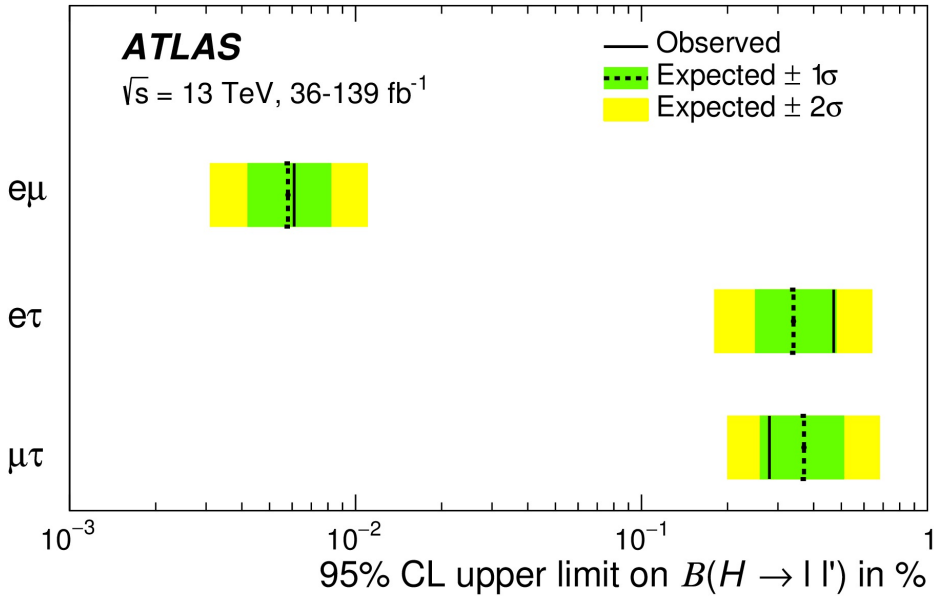
LFV Higgs Decays

- Upper limits on LFV branching fractions at 95% CL
  - B(H→μτ) < 0.28 %
  - B(H→eτ) < 0.47 %

Phys. Lett. B 800 (2020) 135069

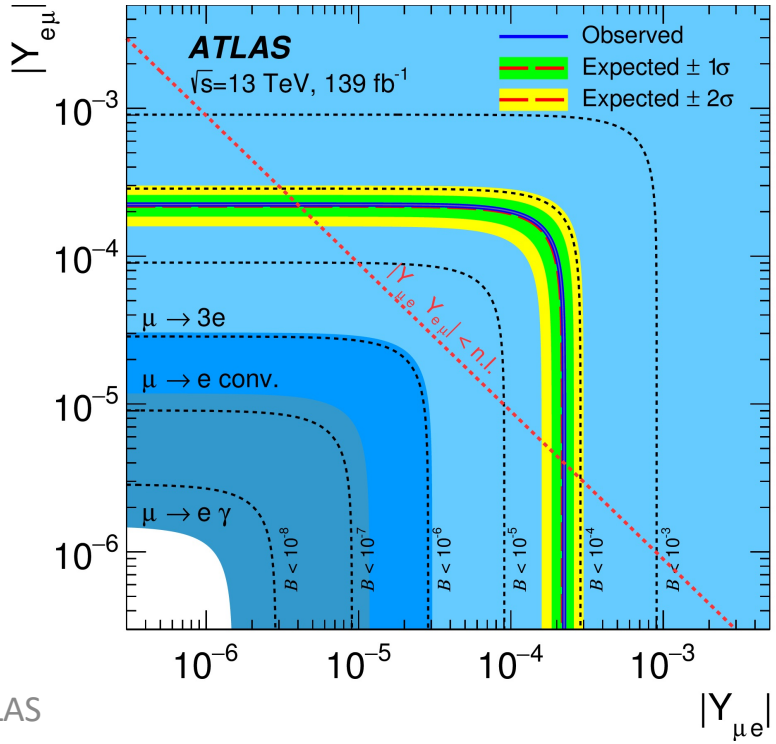
  - B(H→eμ) < 0.0062 (0.0059) %

Phys. Lett. B 801 (2020) 135148



- Branching fraction limits converted to limits on off-diagonal Yukawa couplings

Phys. Lett. B 801 (2020) 135148



Summary

- Searches by ATLAS and CMS for FCNC decays involving Higgs boson decays
- Searches have also been performed for LFV Higgs boson decays
- No evidence has yet been found and so limits have been set

- *Some analyses yet to exploit full Run 2 data*
- *The start of LHC Run 3 is in 2022*
- *Looking forward to more results from ATLAS and CMS on the search for Anomalous Higgs production…*

Back-up