# Search for Rare Processes and Lepton-flavor Violation Decays of Higgs Boson at ATLAS Experiment

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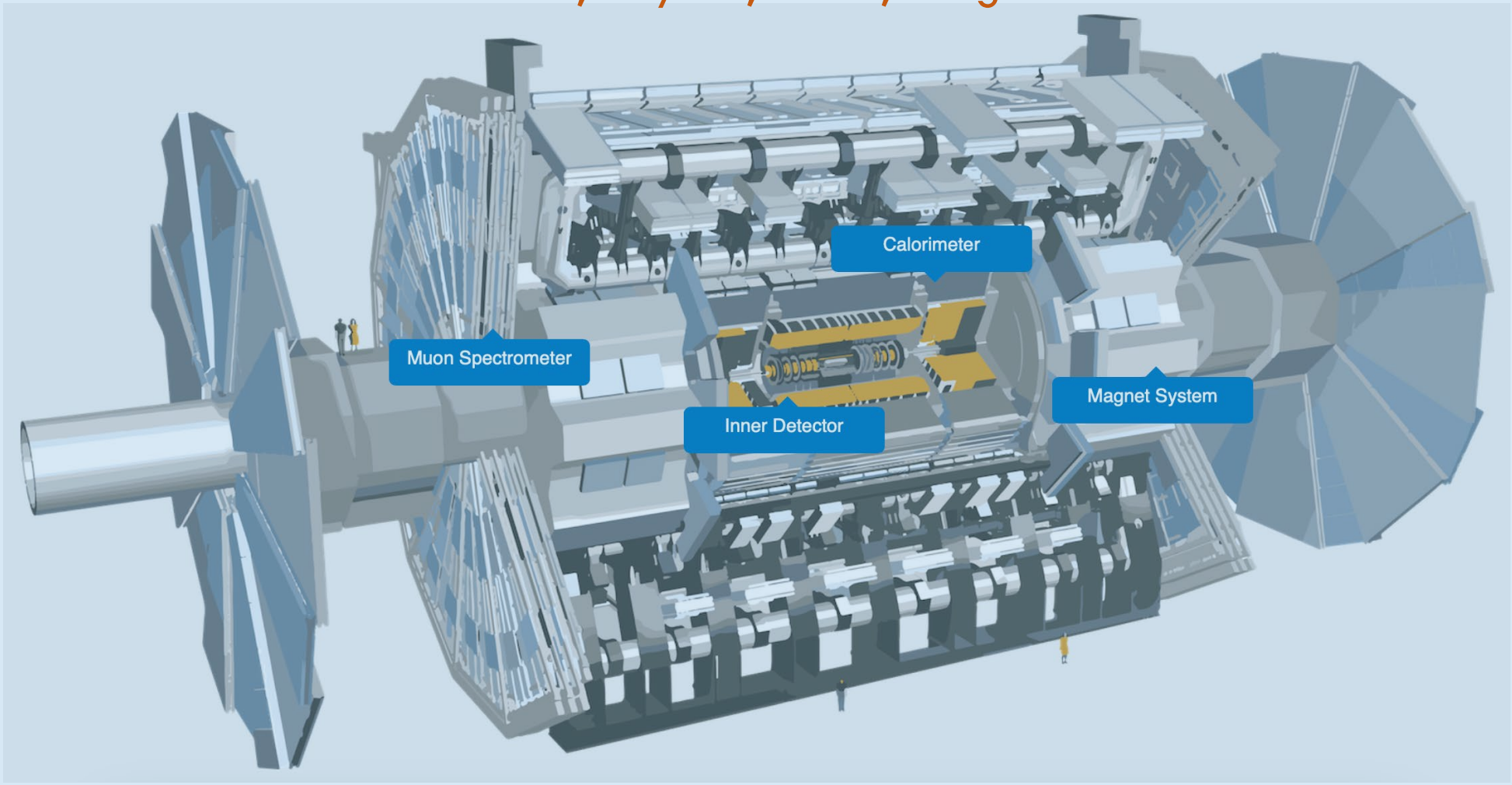
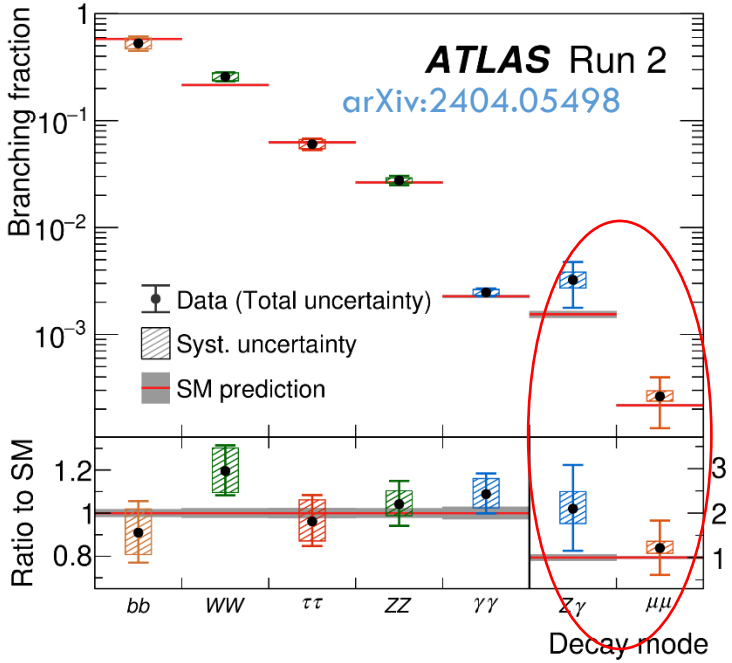
ICHEP, July 18, 2024, Prague



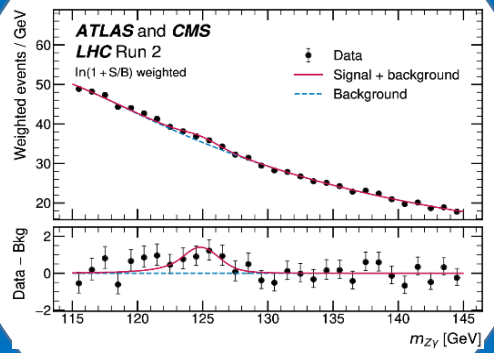
# Introduction

- Over 12M Higgs boson produced at the LHC opened a new research area for **discovery of rare processes** and searching for lepton-flavor violation decays of the Higgs boson
- Probing the Higgs boson couplings to the 2nd (& possible 1st) Fermion families become accessible, where there may be signs of new physics.
- Outline of the report will follow the topics shown in the pictures below




## The First Evidence

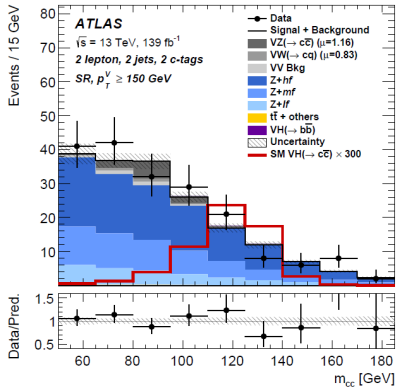
$H \to Z\gamma$




PRL 132(2024)021803

## Search for Higgs couplings to the 2nd generation fermions

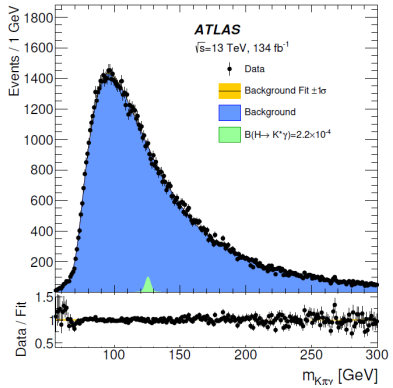
$H \to c\bar{c}$




EPJC (2022) 717

## Search for Higgs decays to meson + γ

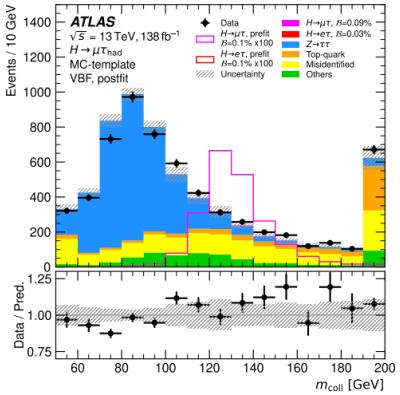
$H \to K^{*}\gamma$




PLB 847(2023)138292

## Search for LFV decays of Higgs boson

$H \to \tau e(\mu)$

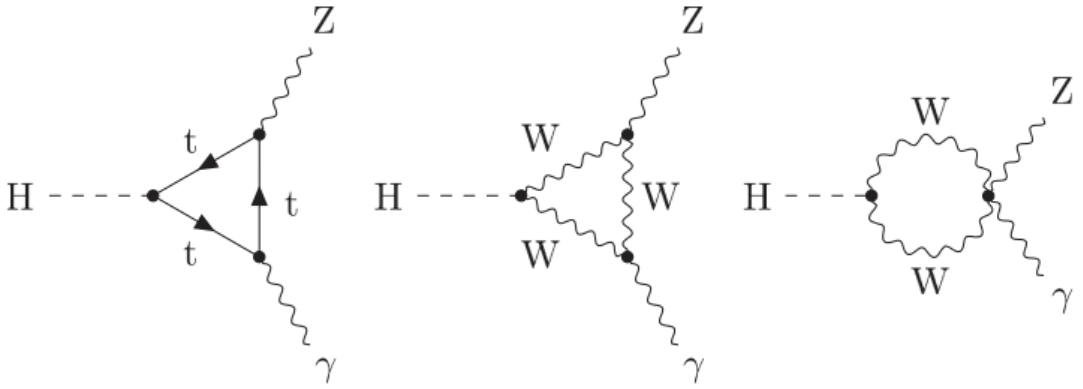


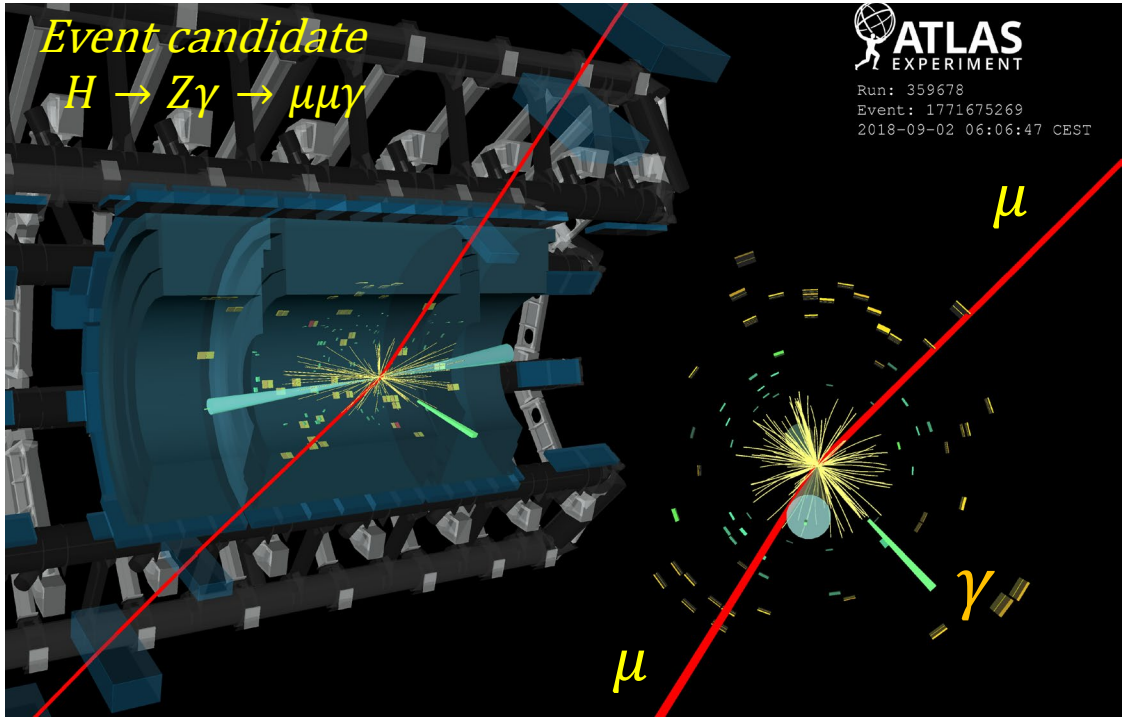

JHEP 07(2023) 166

# Search for H→Zγ

Phys. Lett. B 809 (2020) 135754 (arXiv:2005.05382v2 )

- **SM Br(H→Zγ):** $\sim 1.5 \times 10^{-3}$
- **Higgs decay to Zγ** through loops; **sensitive to new physics**
- **ATLAS Run 2 data:** 140 fb$^{-1}$, pp collision at $\sqrt{s} = 13\ TeV$
- **Final states: high mass resolution & clean signature:** an isolated high pT photon plus a pair of $e^+e^-$ *or* $\mu^+\mu^-$ decay from Z ($|m_{ll} - m_Z| < 10$ GeV)
- **Major background:** $l^+l^- + (fake)\gamma$ from DY+ISR, and DY+jets (estimated from data)
- **Analysis:** classify the events into **six exclusive categories.** Boosted-Decision-Trees is applied to separate the Higgs events from VBF production mode.
- **Final discriminant:** $m_{Z\gamma}$, simultaneous fit S+B to all categories to extract the signal. (Signal model is decided by MC and background is described by analytic functions.)



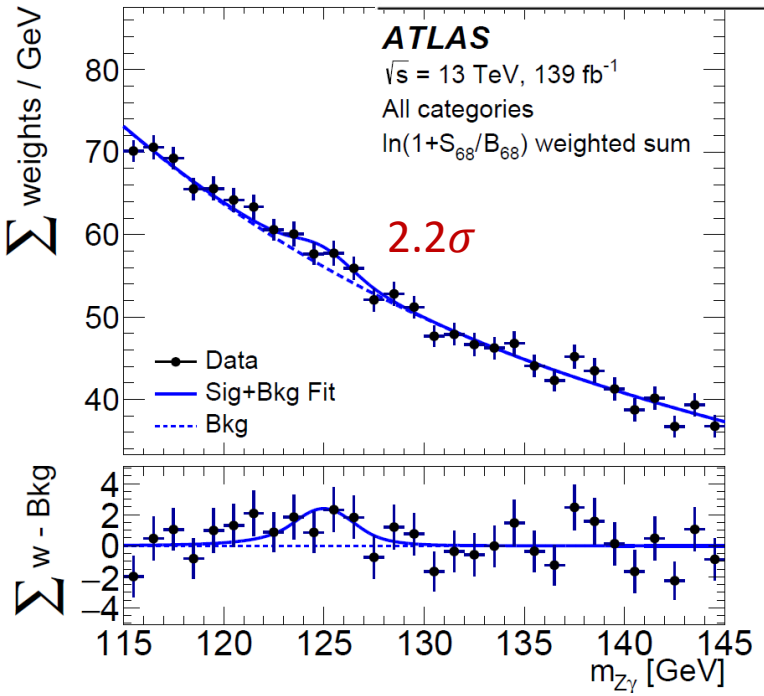



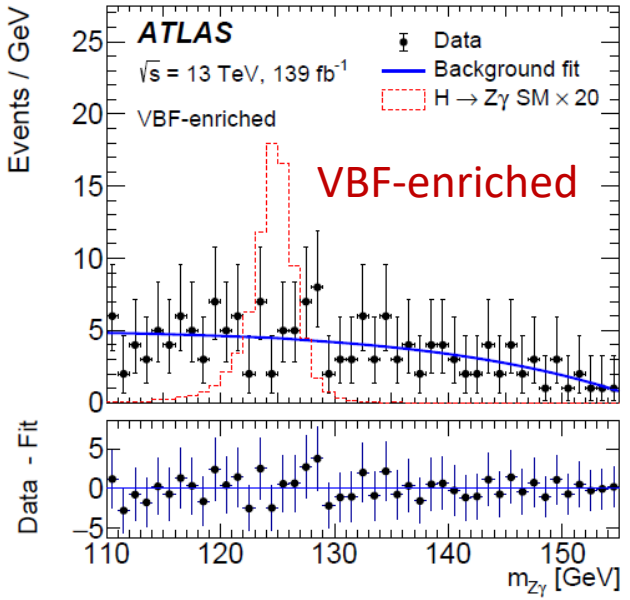
# Search for $H \to Z\gamma$

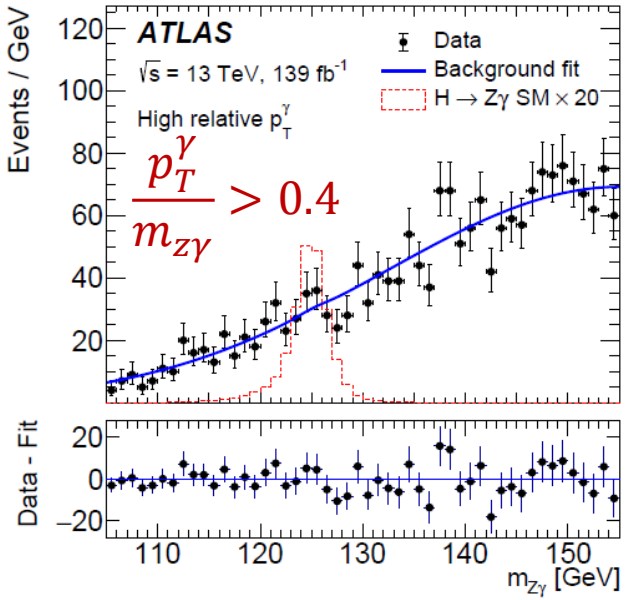
Phys. Lett. B 809 (2020) 135754 (arXiv:2005.05382v2 )

**The number of data events selected in six categories in $m_{Z\gamma}$ mass range [105, 160] GeV**

| Category | Events |
|---|---|
| VBF-enriched | 194 |
| High relative $p_T$ | 2276 |
| High $p_{Tt}$ $ee$ | 5567 |
| Low $p_{Tt}$ $ee$ | 76 679 |
| High $p_{Tt}$ $\mu\mu$ | 6979 |
| Low $p_{Tt}$ $\mu\mu$ | 100 876 |
| Inclusive | 192 571 |



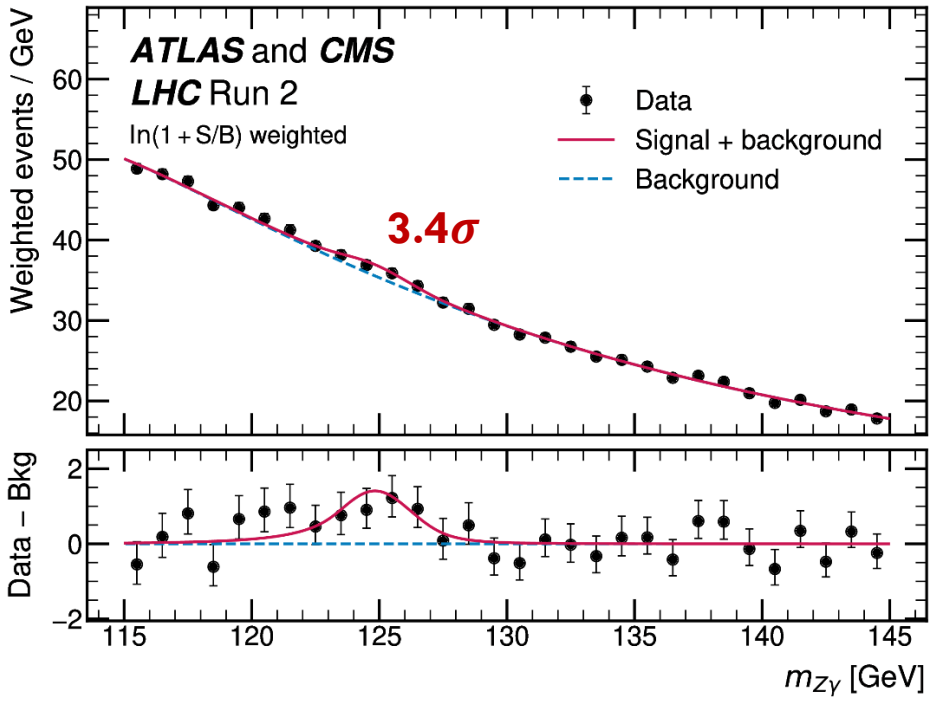

- Observed (expected) upper limit on the $\sigma \times \mathcal{B}$ for $pp \to H \to z\gamma$: 3.6 (2.6) × *SM prediction* at 95% CL
- The observed (expected) significance: $2.2\sigma$ $(1.2\sigma)$
- The best-fit signal strength: $\mu \equiv \frac{\sigma_{measured}}{\sigma_{SM}} = \mathbf{2.0^{+1.0}_{-0.9}}$

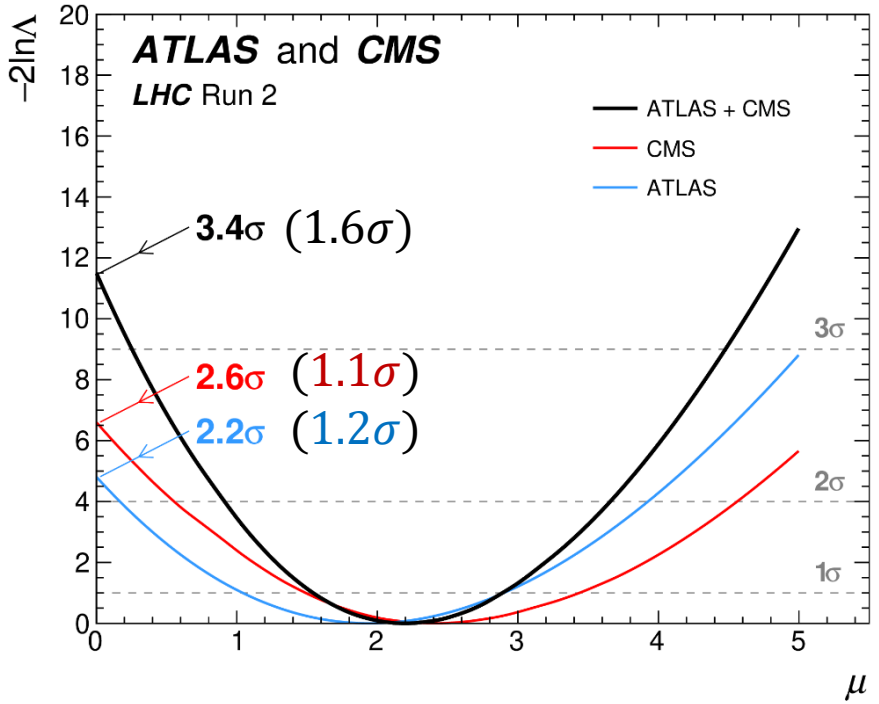
# The 1st Evidence for H→Zγ

## ATLAS + CMS Combined search for H→Zγ

Phys. Rev. Lett. 132 (2024) 021803

- The CMS analysis classify the events into **eight** exclusive categories based on BDT and kinematic distributions; having similar search sensitivity as ATLAS.
- The experimental uncertainties from the ATLAS and CMS are treated as uncorrelated; the theoretical QCD uncertainty and the ones in the H→Zγ branching fraction prediction are treated as correlated.



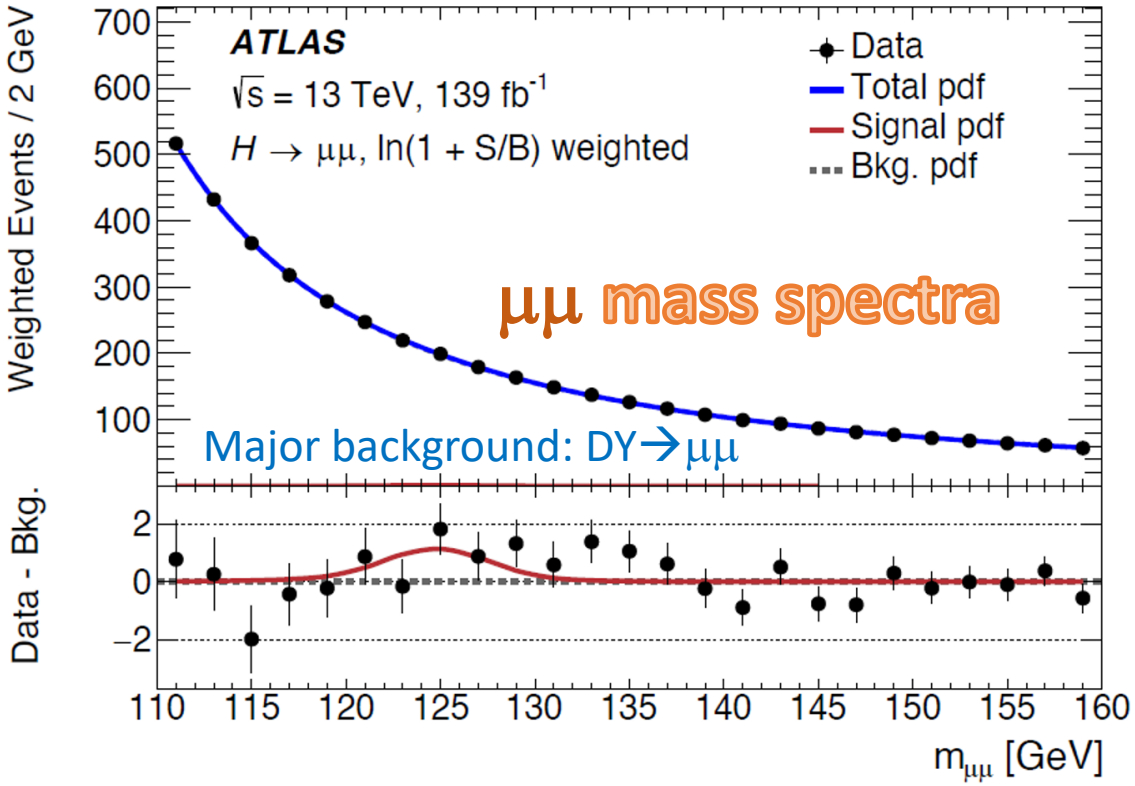



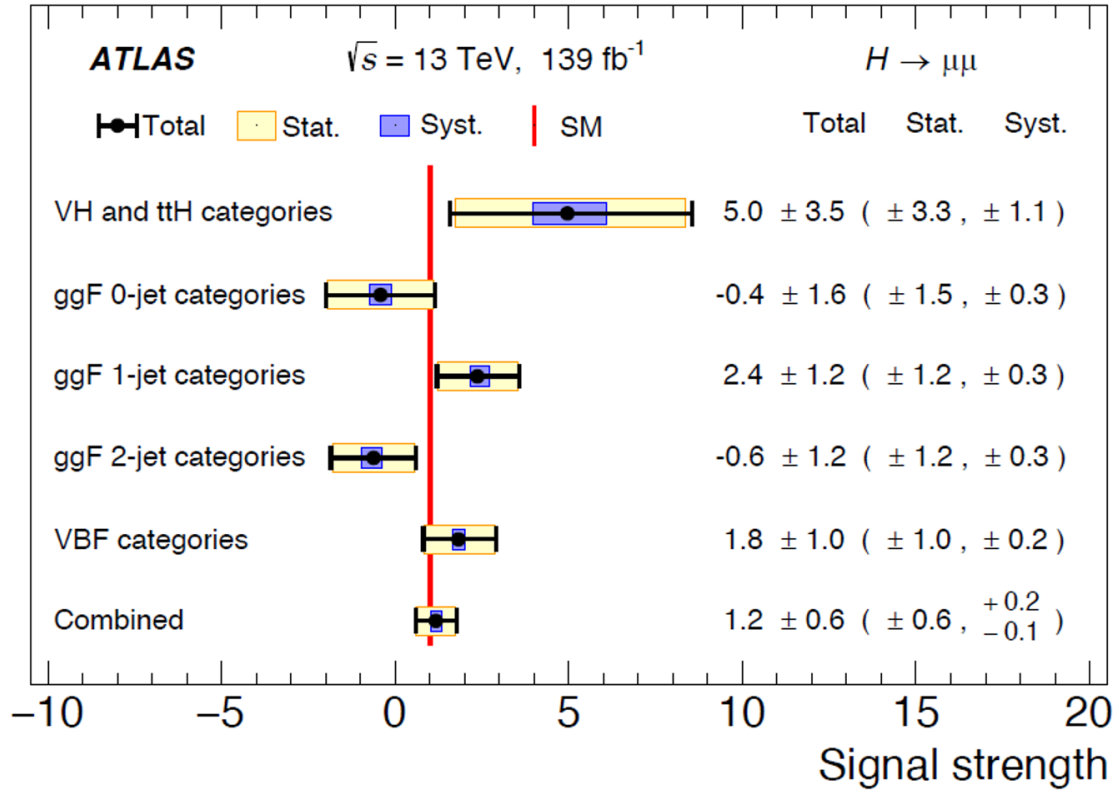

**The measured (predicted) signal strength (yield) is $2.2 \pm 0.7\ (1.0 \pm 0.6)$ × SM prediction, and agrees with the theoretical expectation within 1.9σ**

# Search for H→μμ

PLB 812 (2021) 135980 (arXiv:2007.07830v2)

## Probing the Higgs Boson Yukawa couplings to the 2nd generation fermions



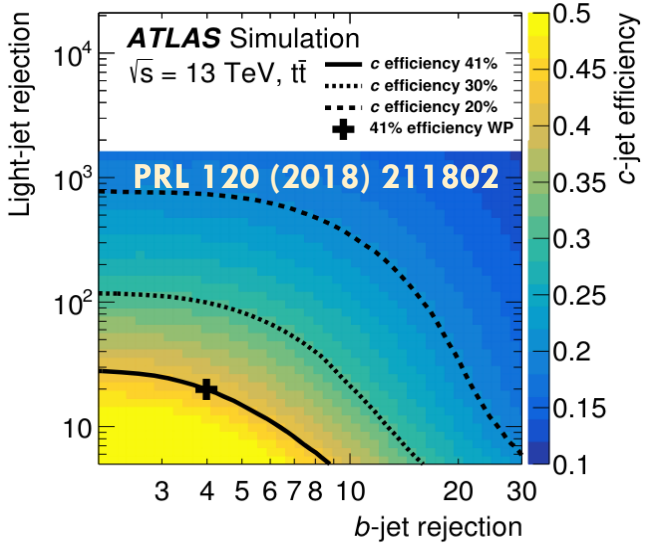

- Observed upper limit on the $\sigma \times \mathcal{B}$ ($2.18 \times 10^{-4}$) for $pp \to H \to \mu\mu$: $2.2 \times SM\ prediction$ at 95% CL
- The best-fit signal strength: $\mu \equiv \frac{\sigma_{measured}}{\sigma_{SM}} = 1.2 \pm 0.6$
- The observed (expected) significance: $2.0\sigma$ $(1.7\sigma)$

# Search for H→cc

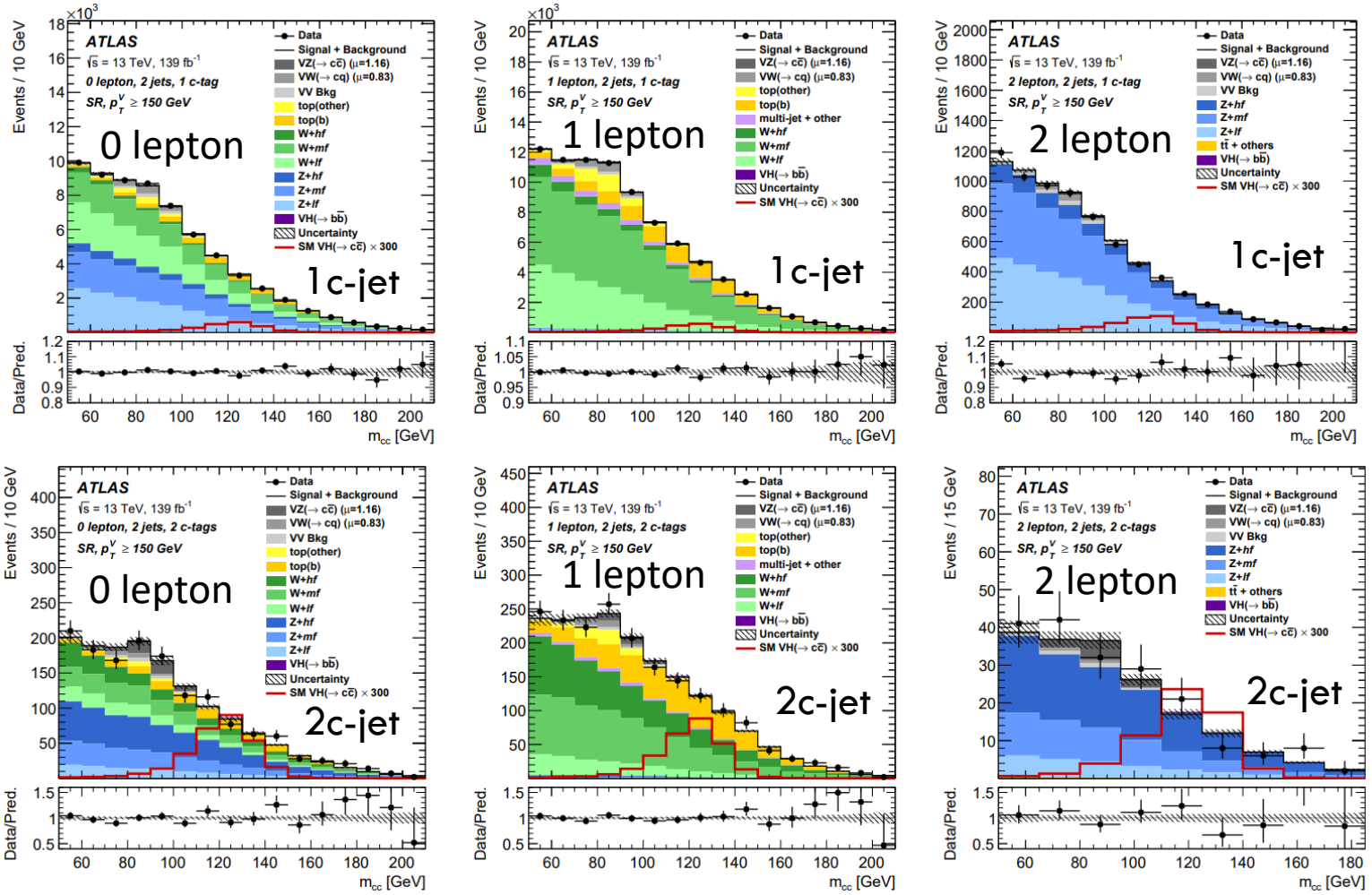
## Probing the Higgs Boson Yukawa couplings to the 2nd generation fermions

Eur. Phys. J. C 82 (2022) 717

- Higgs production associating with a vector boson Z, or W ($\mathcal{B}$(H→cc)=3%)
- $H \to c\bar{c}$, Z and W decay leptonically:
  - $ZH \to \nu\bar{\nu}\, c\bar{c},\ l^+l^-c\bar{c}$
  - $W^{\pm}H \to l^{\pm}\nu\, c\bar{c}$
  - events contain 0, 1, 2 charged leptons, tag 1c-jet and 2 c-jets
- Major background from Z/W+jets, top, and VZ($\to c\bar{c}$)
- Exploits specific c-tagging techniques



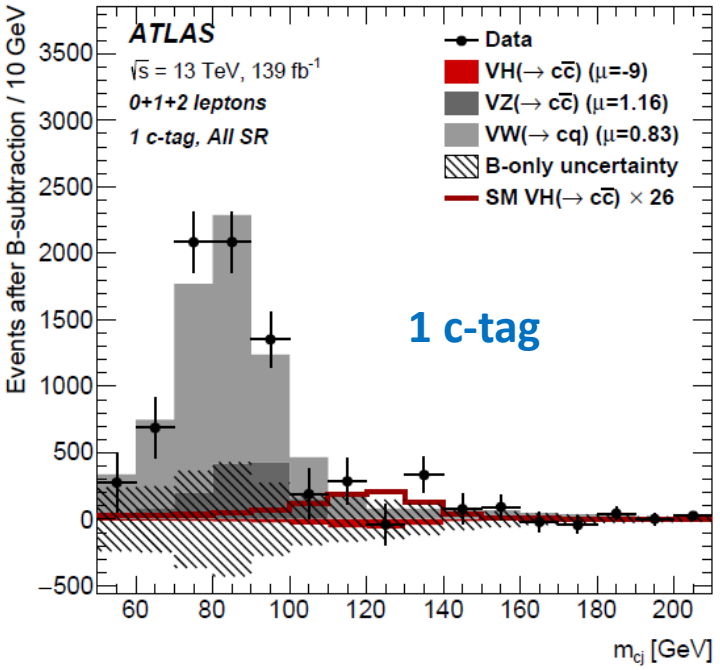

### $m_{cc}$ spectra with different $l$, and c − jet final states

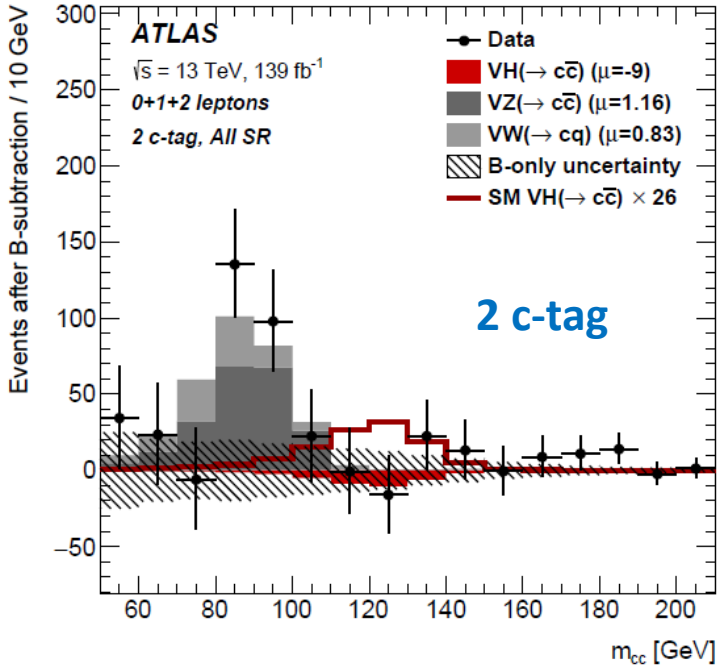


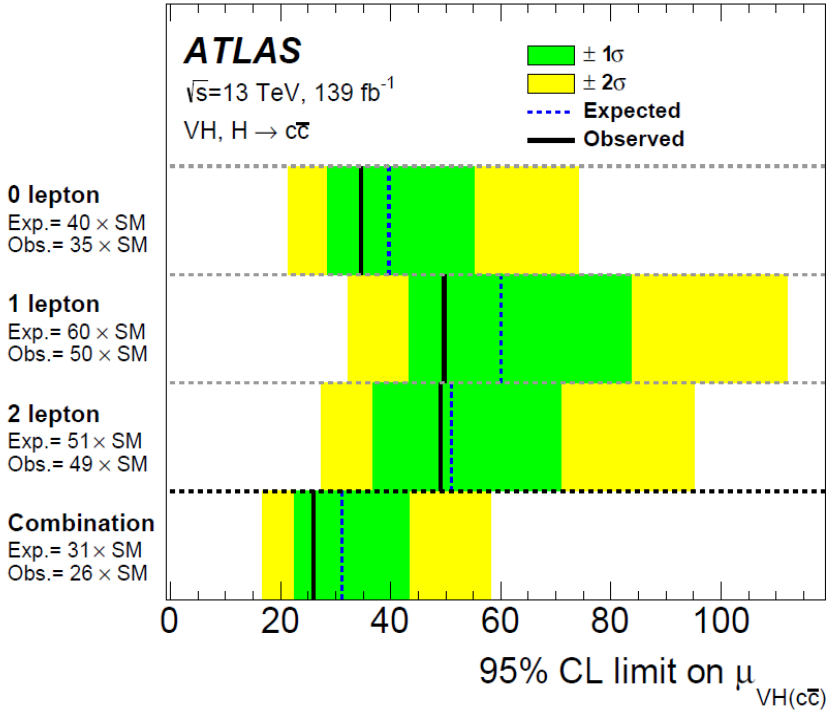
# Search for H→cc

- Validated with simultaneous measurements of WW, WZ, ZZ events with $Z \to c\bar{c}$, and W→ $cq$.
- Observed (expected) upper limit on (W/Z)Z(→ $c\bar{c}$) is 2.6 (2.2) standard deviations above background-only prediction for (W/Z)W(→ $cq$) 3.8(4.6)
- Upper limit of observed (expected) of (W/Z)H(→ $c\bar{c}$) is 26 (31)× $SM$ prediction

Eur. Phys. J. C 82 (2022) 717



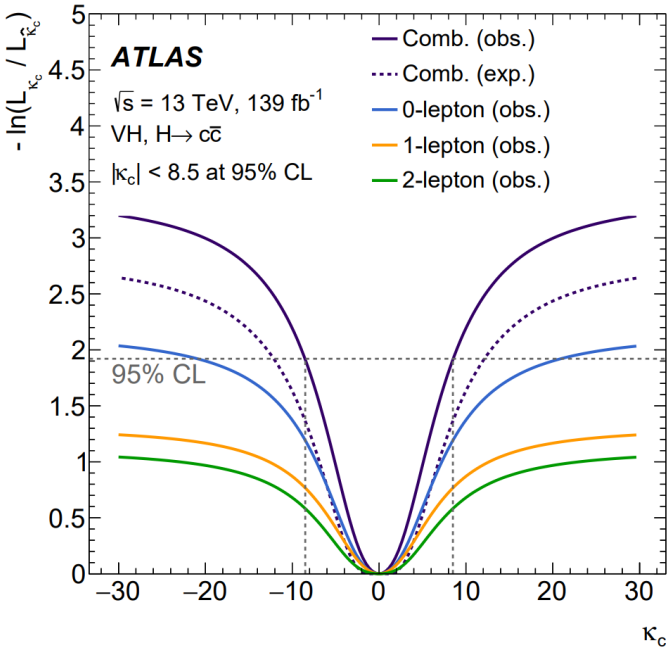




**Post-fit $m_{cc}$ distribution summed over all signal regions after subtracting backgrounds, leaving events from VH(→cc),VZ(→cc), VW(→cq), with 1 c-tag (left) and 2 c-tags (right).**

# Higgs-charm Yukawa Coupling

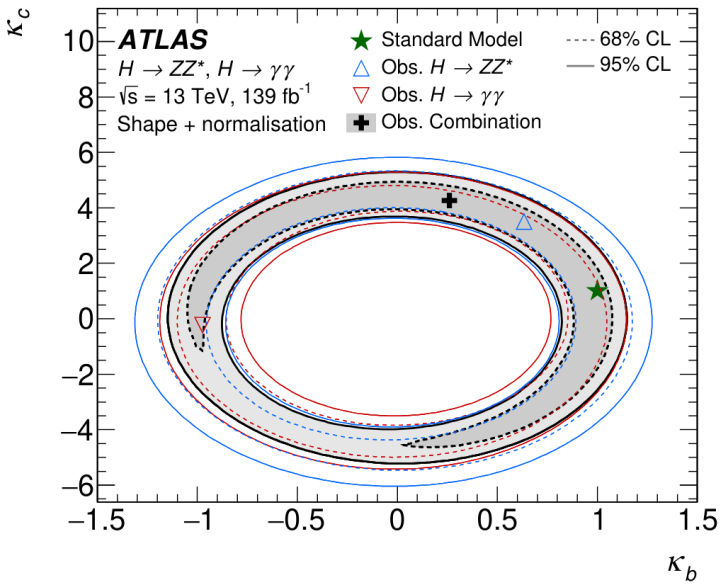
Eur. Phys. J. C 82 (2022) 717




$VH, H \rightarrow cc$ (direct search)

The observed (expected) Higgs-charm Yukawa coupling modifier $|\kappa_c| < 8.5\ (12.4)$ at 95% CL

JHEP 05 (2023) 028 arXiv:2207.08615v2



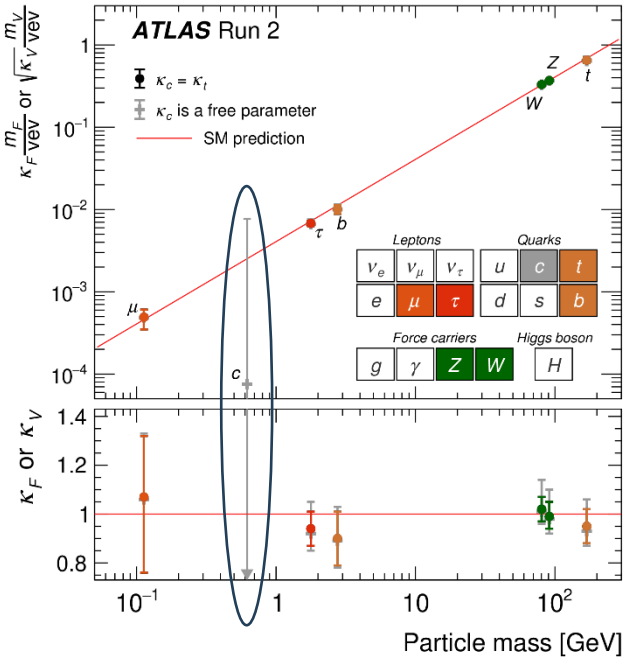

The limit on the $\kappa_c$ can be improved by combining **VH(→cc, bb)** with the interpretation $p_T^H(H \rightarrow 4l, \gamma\gamma)$

$|\kappa_c| < 2.5$

Combined with VH(→bb):

Ratio: |κc/κb| < 4.5 (5.1 expected) at 95% CL, smaller than the ratio of b- and c-quark masses

Nature-Phys 607 pages 52-59 (2022)




arXiv:2207.00092v2

Combined coupling fitting

When the coupling strength modifier κc is left unconstrained in the fit, an upper limit of $|\kappa_c| < 5.7\ (7.6)$ at 95% C.L.

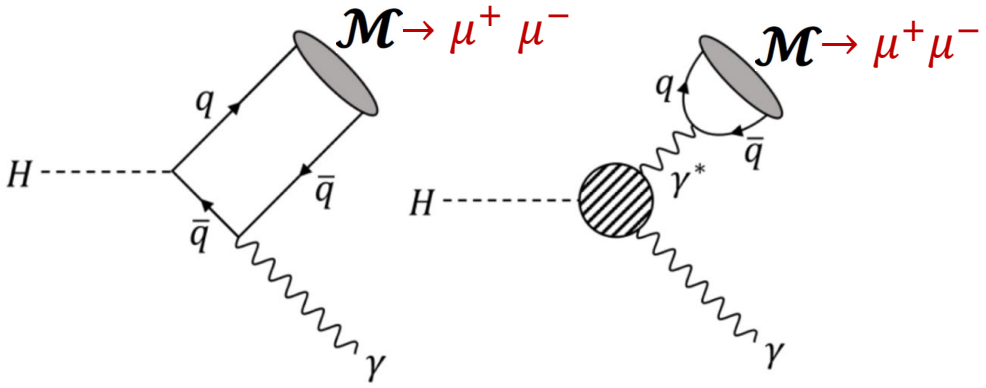
# Search for H→J/$\psi$ /$\psi(2S)$/$\Upsilon(nS)$ + $\gamma$

Eur. Phys. J. C 83 (2023) 781 (arXiv:2208.03122v3)

H→ $\mathcal{M}$ +$\gamma$ offer an alternative way to probe the quark Yukawa couplings to Higgs boson

- **H→J/$\psi$ /$\psi(2S)$+ $\gamma$** allow access to the **c-quark Yukawa coupling**
- **H→ $\Upsilon(1S, 2S, 3S)$+ $\gamma$** allow access to the **b-quark Yukawa coupling**

| Vector quarkonium state | SM branching fraction, $\mathcal{B}(H \to Q\gamma)$ | | |
|---|---|---|---|
| | Ref. [31] (2015) | Refs. [33, 34] (2017) | Ref. [36] (2019) |
| $J/\psi$ | $2.95^{+0.17}_{-0.17} \times 10^{-6}$ | $2.99^{+0.16}_{-0.15} \times 10^{-6}$ | $3.01^{+0.15}_{-0.15} \times 10^{-6}$ |
| $\Upsilon(1S)$ | $4.61^{+1.76}_{-1.23} \times 10^{-9}$ | $5.22^{+2.02}_{-1.70} \times 10^{-9}$ | $9.97^{+4.04}_{-3.03} \times 10^{-9}$ |
| $\Upsilon(2S)$ | $2.34^{+0.76}_{-1.00} \times 10^{-9}$ | $1.42^{+0.72}_{-0.57} \times 10^{-9}$ | $2.62^{+1.39}_{-0.91} \times 10^{-9}$ |
| $\Upsilon(3S)$ | $2.13^{+0.76}_{-1.13} \times 10^{-9}$ | $0.91^{+0.48}_{-0.38} \times 10^{-9}$ | $1.87^{+1.05}_{-0.69} \times 10^{-9}$ |



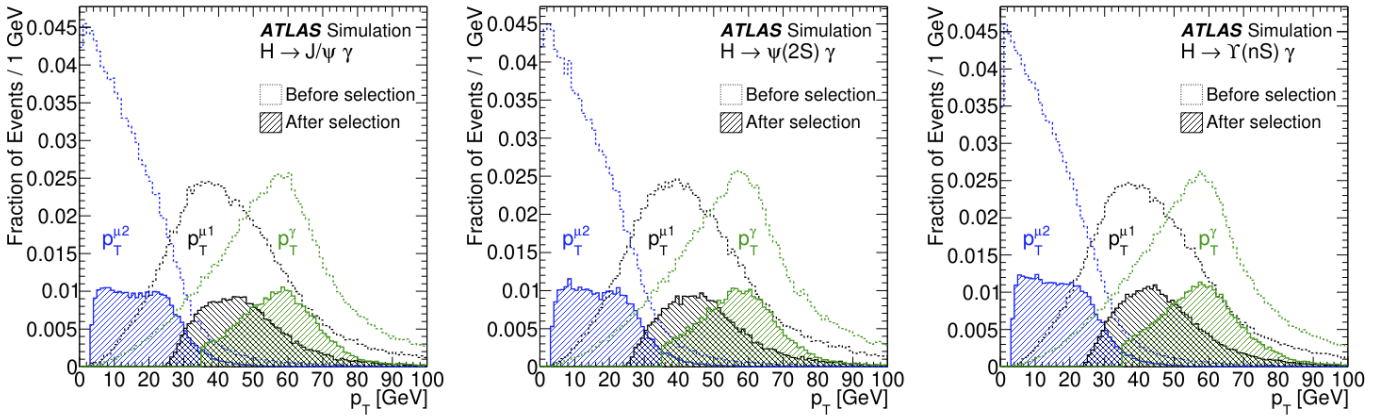

$p_T^{\mu} > 3\ GeV$ $p_T^{\gamma} > 35$ GeV

❖ Trigger: a high pT $\gamma$ and 1 or 2 muons in the event

❖ These radiative decays have a distinct signature, $\mathcal{M}(\to \mu^+\mu^-) + \gamma$, which helps suppress the large multi-jet background that affect direct $H \to q\bar{q}$ searches.

❖ Signal event selection efficiencies 19% – 21%

❖ Background: inclusive production $q\bar{q} \to \mu^+\mu^- \gamma$ from DY, QCD jets with real or fake $\gamma$, estimated from data



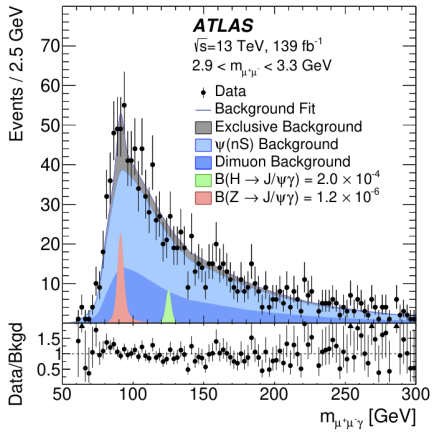

(a) $H \to J/\psi\,\gamma$ (b) $H \to \psi(2S)\,\gamma$ (c) $H \to \Upsilon(nS)\,\gamma$

# Search for H→J/$\psi$ /$\psi(2S)$/$\Upsilon(nS)$ + $\gamma$

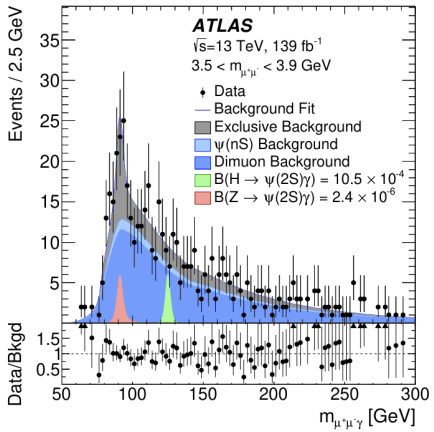
## Mass spectra

Eur. Phys. J. C 83 (2023) 781 (arXiv:2208.03122v3)

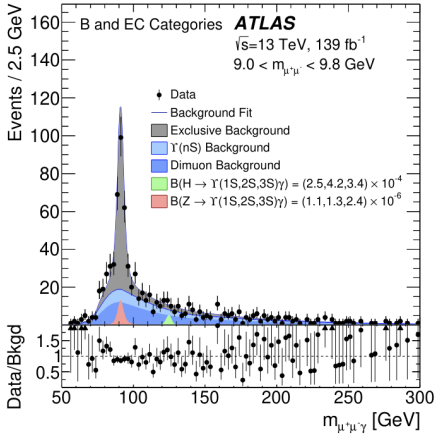
### H→J/$\psi$ + $\gamma$

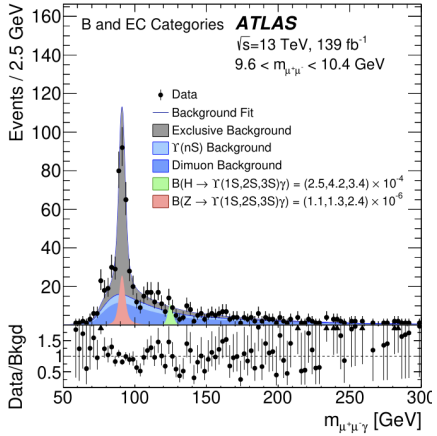


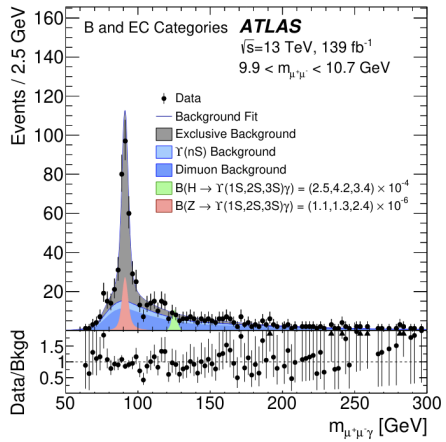

### H→$\psi(2S)$+ $\gamma$



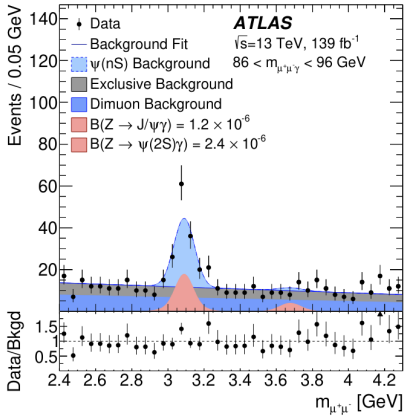

### H→$\Upsilon(1S, 2S, 3S)$ + $\gamma$



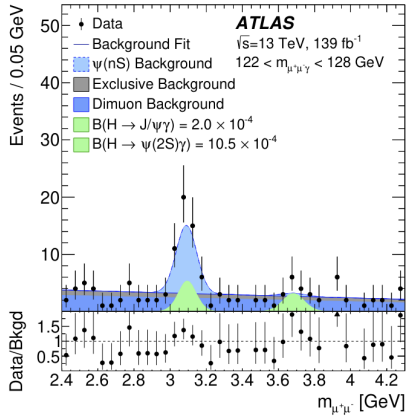




### J/$\psi\to\mu^+\mu^-$




### $\psi(2S)\to\mu^+\mu^-$




## Results

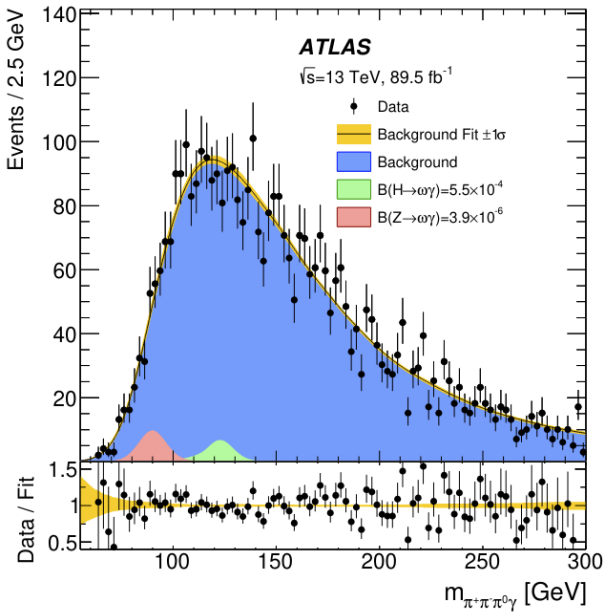
| Decay channel | 95% CL upper limits: Branching fraction, Higgs boson [ $10^{-4}$ ] Expected | Observed | $Z$ boson [ $10^{-6}$ ] Expected | Observed | $\sigma \times \mathcal{B}$, Higgs boson [fb] Observed | $Z$ boson [fb] Observed |
|---|---|---|---|---|---|---|
| $J/\psi\,\gamma$ | $1.8^{+0.8}_{-0.5}$ | 2.0 | $0.7^{+0.3}_{-0.2}$ | 1.2 | 11 | 69 |
| $\psi(2S)\,\gamma$ | $8.1^{+3.6}_{-2.3}$ | 10.5 | $3.0^{+1.3}_{-0.8}$ | 2.4 | 58 | 142 |
| $\Upsilon(1S)\,\gamma$ | $2.7^{+1.2}_{-0.8}$ | 2.5 | $1.6^{+0.6}_{-0.4}$ | 1.1 | 14 | 62 |
| $\Upsilon(2S)\,\gamma$ | $3.4^{+1.5}_{-1.0}$ | 4.2 | $2.1^{+0.8}_{-0.6}$ | 1.3 | 24 | 74 |
| $\Upsilon(3S)\,\gamma$ | $3.0^{+1.3}_{-0.8}$ | 3.4 | $1.9^{+0.8}_{-0.5}$ | 2.4 | 19 | 143 |

# Search for $H \to \omega\gamma$, or $H \to k^* \gamma$

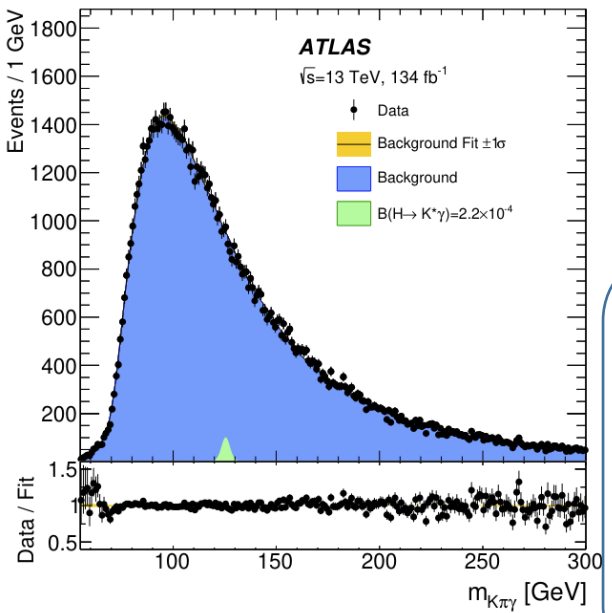
Phys. Lett. B. 847 (2023) 138292 (arXiv:2301.09938v2)

- Search for $H \to \omega\gamma \to \pi^+\pi^-\pi^0\gamma$ to **probe flavour-conserving Higgs boson couplings to light quarks** ($\mathcal{B}(H \to \omega\gamma) = (1.48 \pm 0.08) \times 10^{-6}$); the search is performed along with the analogous $Z \to \omega\gamma$ ($\mathcal{B}(Z \to \omega\gamma) = (2.82 \pm 0.40) \times 10{-}8$). Upper limit from previous search at LEP: $\mathcal{B}(Z \to \omega\gamma) < 6.5 \times 10^{-4}$.
- **Search for $H \to k^* \gamma \to k^+\pi^-\gamma$ can probe flavour-violating Higgs boson couplings to light quarks**
- The main sources of background in the searches are events involving inclusive $\gamma$ + jet or multi-jet processes, where a Meson system is reconstructed from Inner Detector tracks originating from a jet.

$H \to \omega\gamma \to \pi^+\pi^-\pi^0\gamma$




$H \to k^* \gamma \to k^+\pi^-\gamma$




Mass spectra

**Selected number of events: data (MC), and expected signals**

| Channel | Mass range [GeV ] | Observed (Expected) background | $H$ signal $\mathcal{B} = 10^{-4}$ | $Z$ signal $\mathcal{B} = 10^{-6}$ |
|---|---|---|---|---|
| $H \to \omega\gamma$ | 115–135 | 686 (730 ± 17) | 9 ± 1 | – |
| $Z \to \omega\gamma$ | 80–100 | 388 (386 ± 16) | – | 18 ± 2 |
| $H \to K^*\gamma$ | 120–130 | 9526 (9630 ± 50) | 53 ± 4 | – |

| Channel | 95% CL upper limit Expected | Observed |
|---|---|---|
| $H \to \omega\gamma$ [$10^{-4}$] | $10.4^{+3.8}_{-2.9}$ | 5.5 |
| $Z \to \omega\gamma$ [$10^{-6}$] | $4.7^{+2.0}_{-1.3}$ | 3.9 |
| $H \to K^*\gamma$ [$10^{-4}$] | $3.7^{+1.5}_{-1.0}$ | 2.2 |

**$\mathcal{B}$ Limits**

a two-orders-of-magnitude improvement

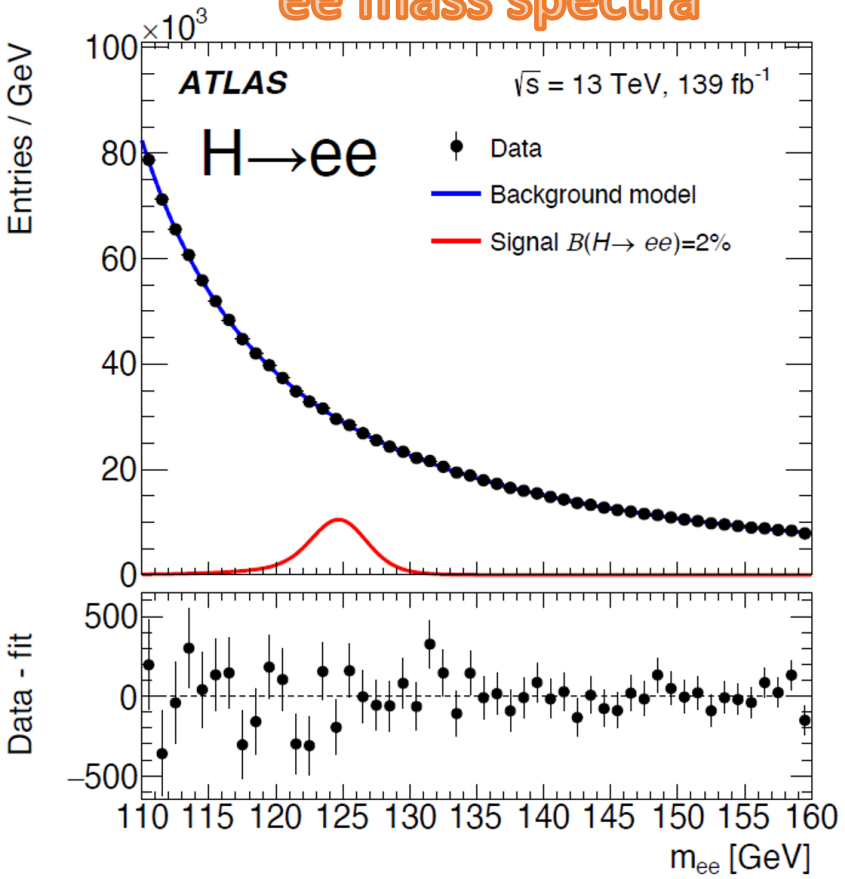
# Search for $H \to ee$, and $H \to e\mu$ (LFV)

PLB 801 (2020) 135148

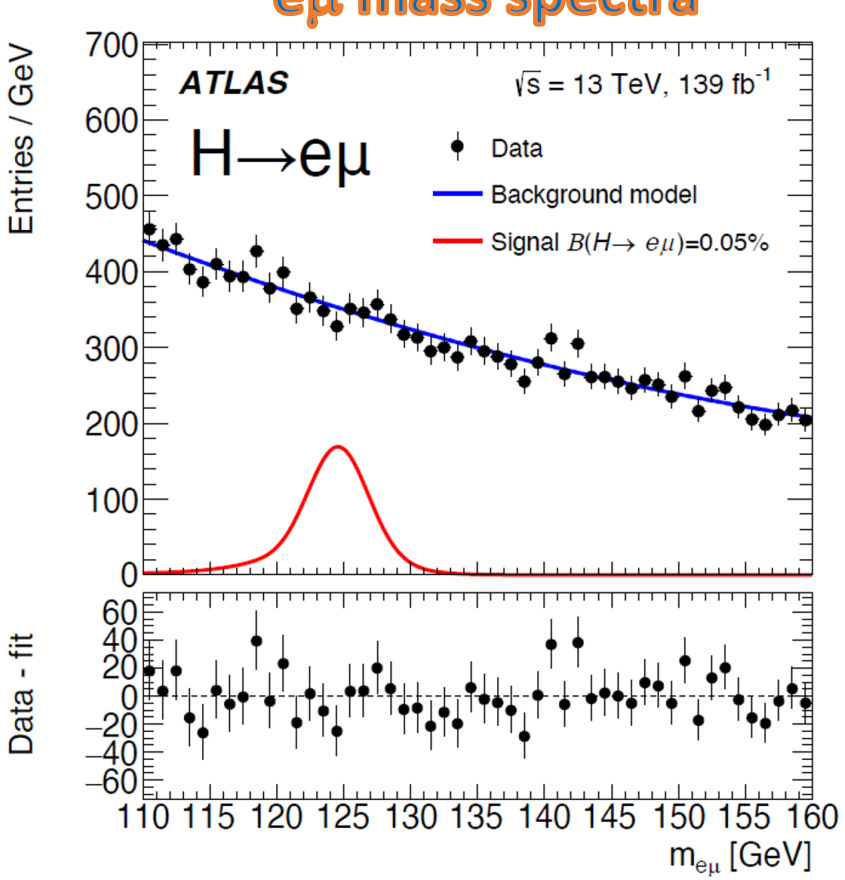
(2304.13757)

- $\mathcal{B}(H \to ee) \sim 5 \times 10^{-9}$; Major background: DY→ee
- **A possible sign of new physics would be the observation of lepton flavour violation (LFV) in decays of the Higgs boson into a pair of leptons with different flavours.**

## ee mass spectra




## eμ mass spectra




## Fit

- Signal (MC): Crystal ball & Gaussian
- Background: 2nd order Polynomial
- Mass window [110, 160] GeV

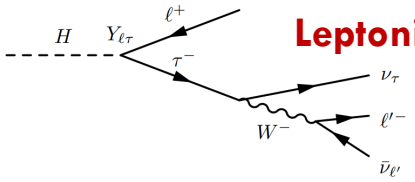
## Results

The observed (expected) $\mathcal{B}$ upper limits at 95% C.L.

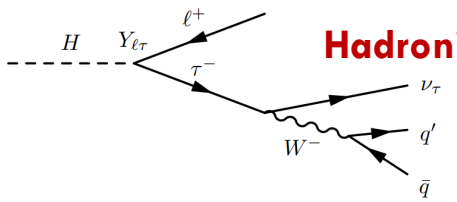
- $\mathcal{B}(H \to ee)$: $\mathbf{3.6 \times 10^{-4}}$ $(3.5 \times 10^{-4})$
- $\mathcal{B}(H \to e\mu)$: $\mathbf{6.2 \times 10^{-5}}$ $(5.8 \times 10^{-5})$

# Search for LFV Higgs Boson Decays

## Directly search for $H \to e\tau$ and $H \to \mu\tau$




Leptonic decay

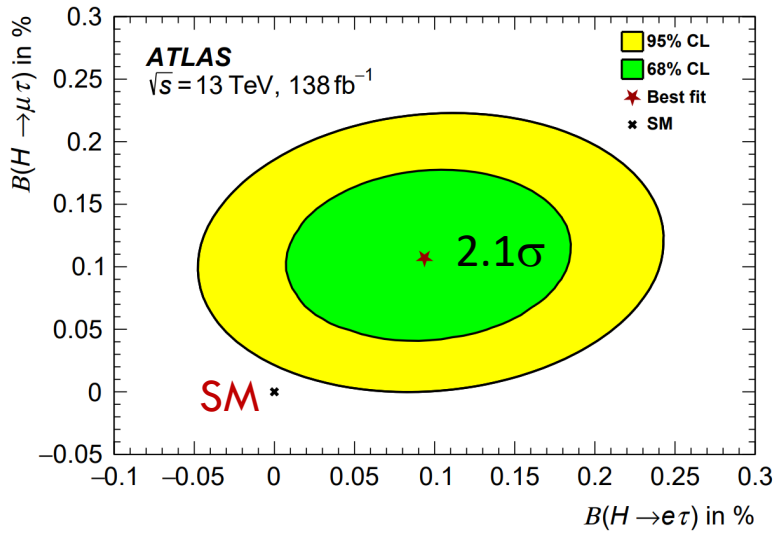



Hadronic decay

Use Multi-variant-Analysis (Neutral Networks & Boosted Decision Trees) discriminants to enhance signal over background, extract results

**Obs. (exp) limits at 95% CL come from a simultaneous fit**

$$\mathcal{B}(H \to \mu\tau) < 0.18\%\ (0.09\%)$$
$$\mathcal{B}(H \to e\tau) < 0.20\%\ (0.12\%)$$

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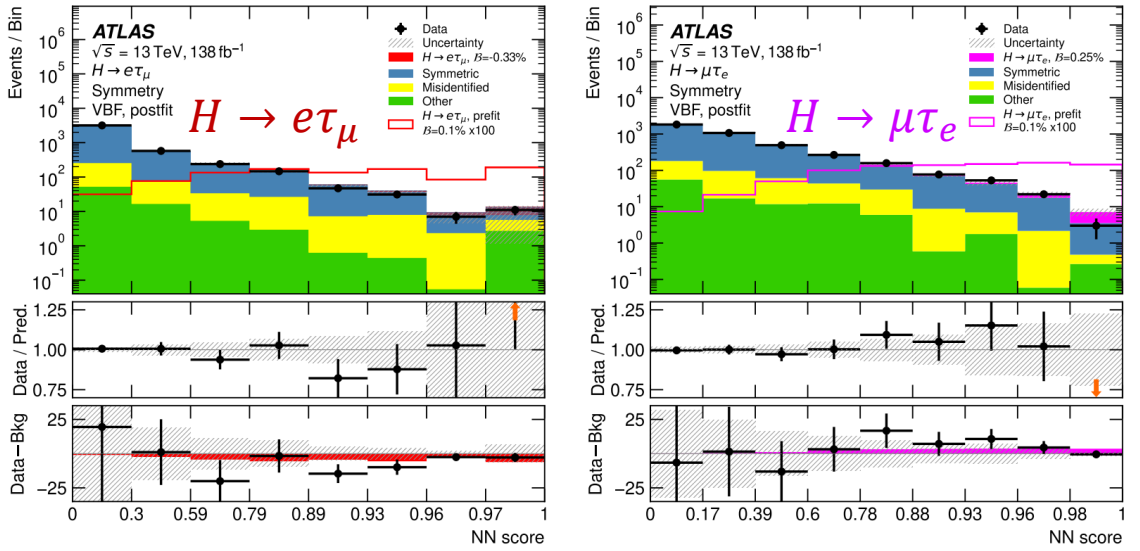





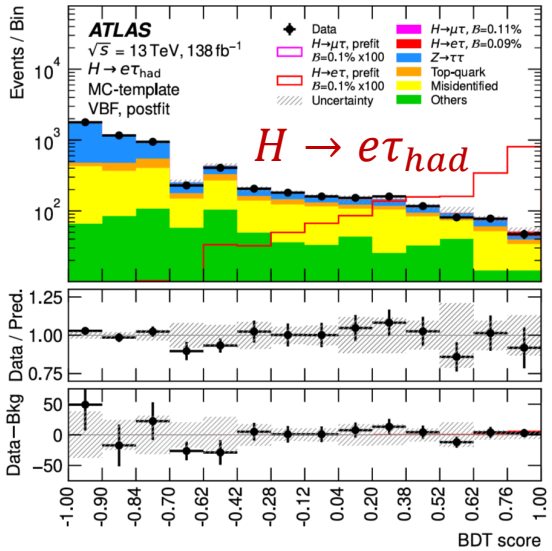


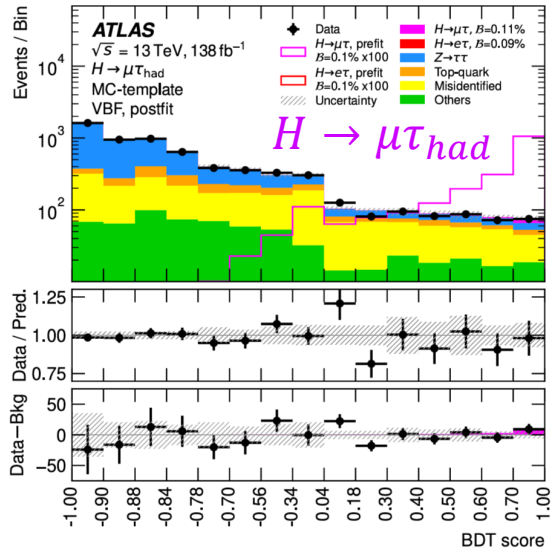

# Summary

**ATLAS has searched for rare processes and Lepton-flavor Violation decays of Higgs Boson**

- The first evidence of **$H \to Z\gamma$ is observed with $3.4\sigma$ significance by** combining ATLAS and CMS results
- Probing the Higgs boson Yukawa couplings to the 2nd generation fermions,
  - The observed (expected) **$H \to \mu\mu$** significance: $2.0\sigma$ $(1.7\sigma)$
  - **$H \to cc$,** Higgs boson to charm-quark quark coupling: $|\kappa_c| < 5.7$ $(7.6)$ at 95% C.L.
- Search for $H \to \mathcal{M}\gamma$ to probe the Higgs boson couplings to the light quarks is performed in different channels
- Search for $H \to e\mu, \tau\mu, \tau e$ have reached sensitivities of $10^{-5} - 10^{-3}$
- **With much improved analysis techniques, and increased integrated luminosity in Run3 and HL-LHC, we have great potential to observe many rare Higgs boson decay modes to probe new physics**

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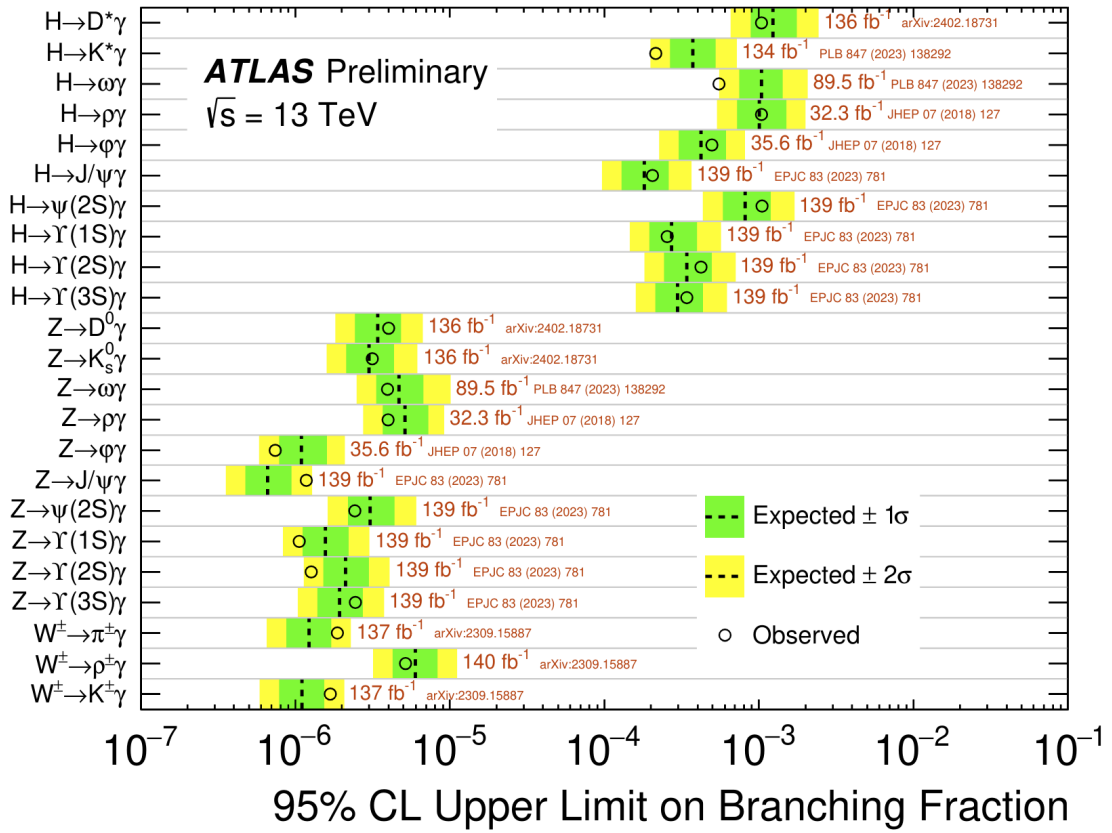


**Thanks!**