



Lepton Yukawa *Interactions*

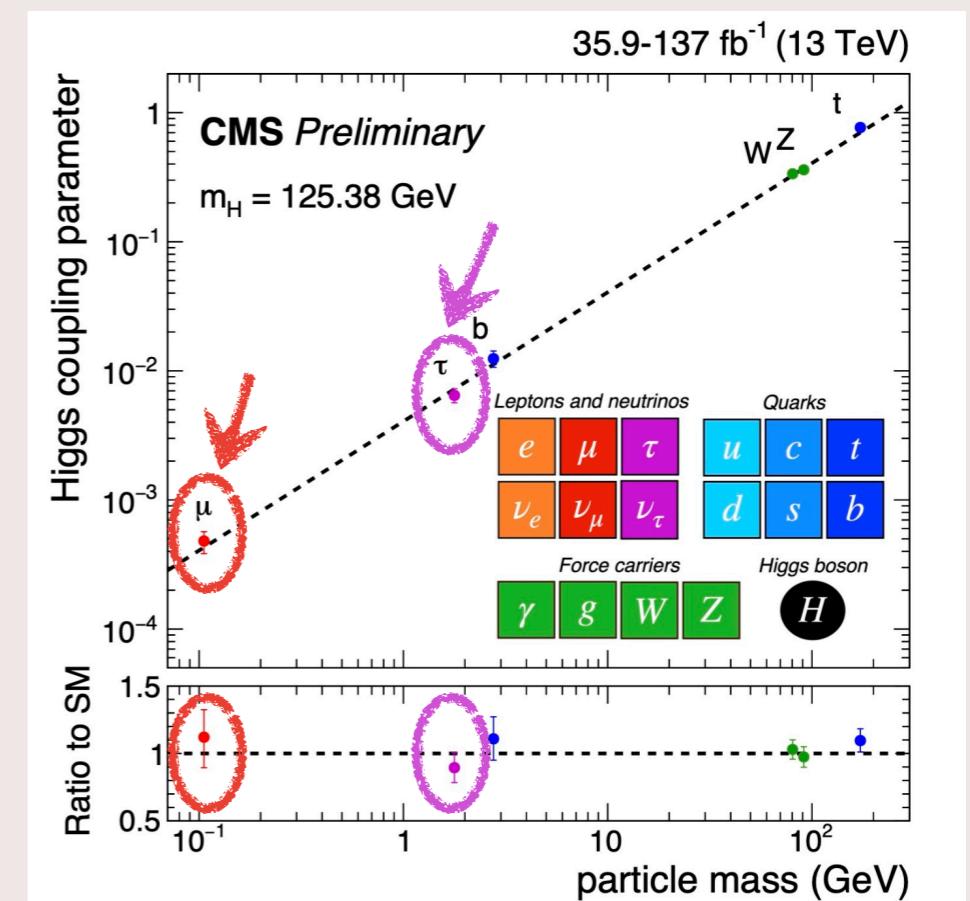
Tina Ojeda
on behalf of the ATLAS and CMS Collaborations

HIGGS 2021
October 19th, 2021

Motivation

- Higgs interactions proportional to particle masses
 - Fermion masses obtained via Yukawa interactions
 - Only interaction in the SM that distinguishes between fermion generations!
 - Mass ratios ($\tau : \mu : e$) $3477 : 207 : 1$
- Interactions between Higgs bosons and other particles studied in detail over the ~ 10 years since the Higgs discovery
 - In this talk:
 - Measurements of couplings to **3rd generation fermions ($H \rightarrow \tau\tau$)**
 - Searches for couplings to **2nd generation fermions ($H \rightarrow \mu\mu$)** and a note about $H \rightarrow ee$
 - Searches for **lepton flavour violation** in $H \rightarrow e\mu, e\tau, \mu\tau$

Observed in ATLAS+CMS combination in 2016
[CERN-EP-2016-100](#)



3rd generation: $H \rightarrow \tau\tau$

- Analyses sensitive to main production modes at the LHC (ggH , VBF, VH , $t\bar{t}H$) and exploit the various τ decay modes ($\tau_{\text{had}}\tau_{\text{had}}$, $\tau_{\text{had}}\tau_\mu$, $\tau_{\text{had}}\tau_e$, $\tau_\mu\tau_e$)
 - Complex final states due to decay of the τ
 - Poor mass resolution due to presence of ν in the τ decays
 - Large background from $Z \rightarrow \tau\tau$ that is difficult to separate from $H \rightarrow \tau\tau$
- Measurements now available with the **full Run 2 dataset**
 - Increased statistical power allows exploration of **differential measurements**
 - Significant improvements to the reconstruction/identification/calibration of τ , jets, ...
 - Systematic uncertainties significantly reduced
- High branching ratio for $H \rightarrow \tau\tau$ makes it possible to study a **wide range of phase space**
 - Particular sensitivity to high Higgs p_T and VBF topologies

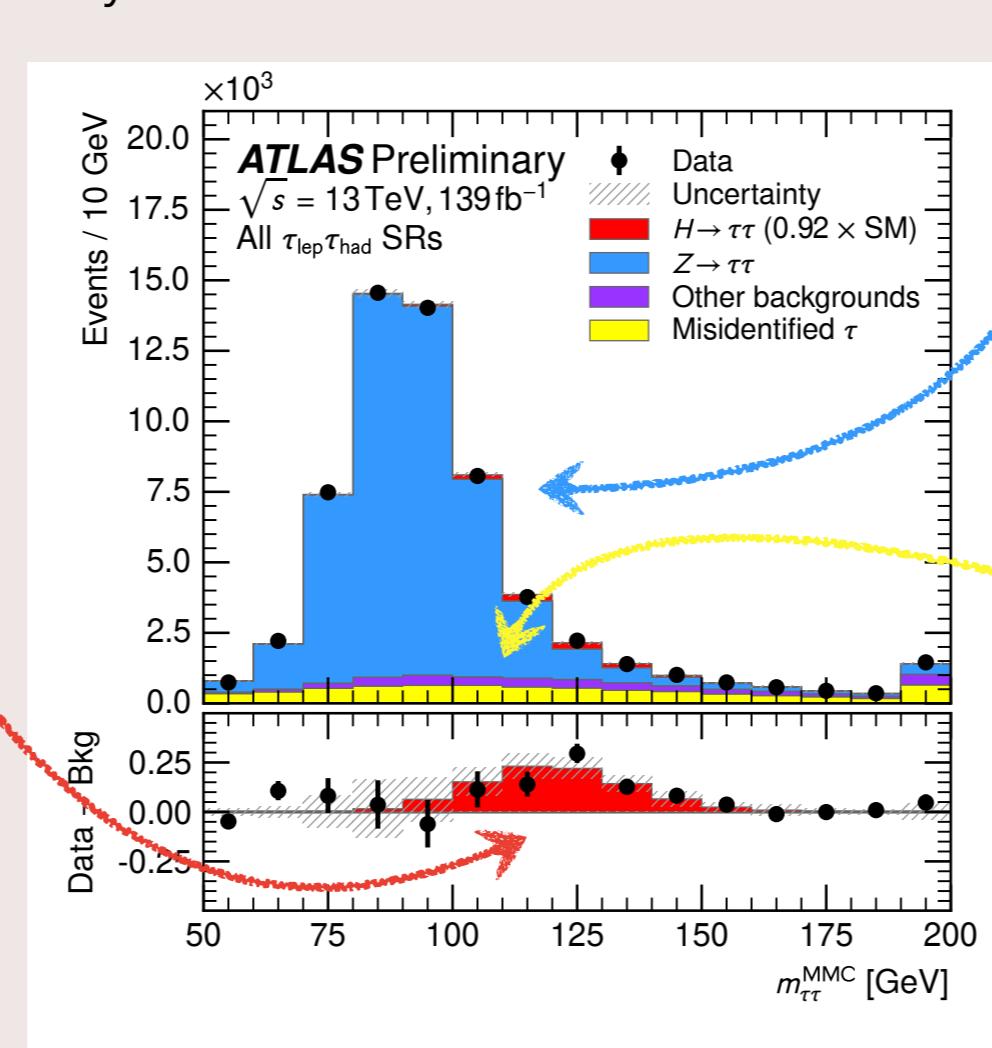
3rd generation: $H \rightarrow \tau\tau$ (ATLAS)

- Targets measurement of $\sigma \times \mathcal{B}$ for the four main production modes
 - Measurements performed within the Simplified Template Cross Section (STXS) framework *
 - Missing mass calculator (MMC) used to reconstruct the di- τ mass *
- Characteristics of the analysis:

Signal

Contributions from VBF, VH, $t\bar{t}H$ enhanced via multivariate discriminants

For ggH : phase space studied as a function of p_T^H and N_{jets}

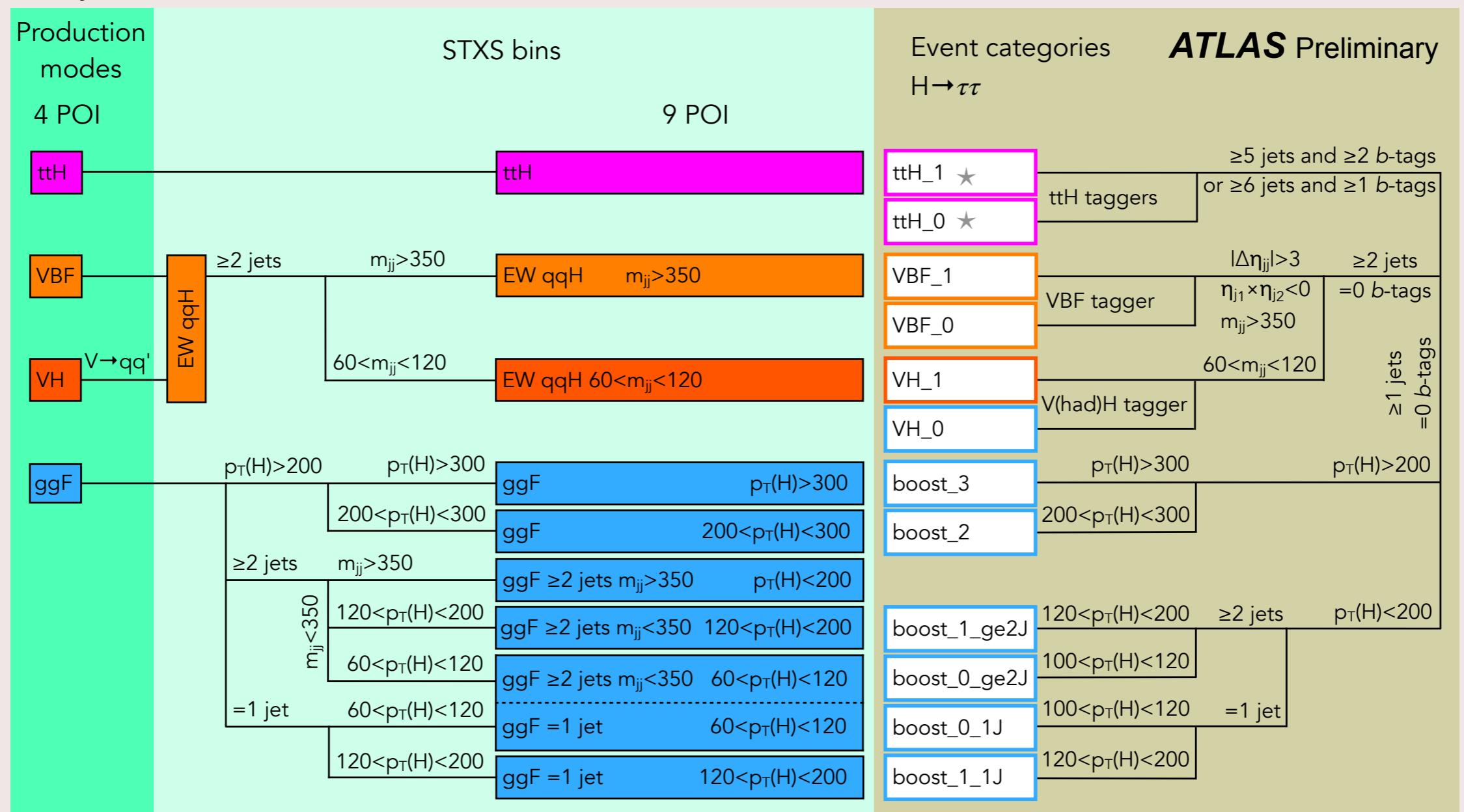


$Z \rightarrow \tau\tau$
Validated + normalised using a parametrised version of embedding in $Z \rightarrow \ell\ell$ CRs

Misid. leptons (e, μ, τ)
Consolidated estimates in the $\tau_{\text{had}}\tau_{\text{had}}$ and $\tau_e\tau_\mu$ SRs

3rd generation: $H \rightarrow \tau\tau$ (ATLAS)

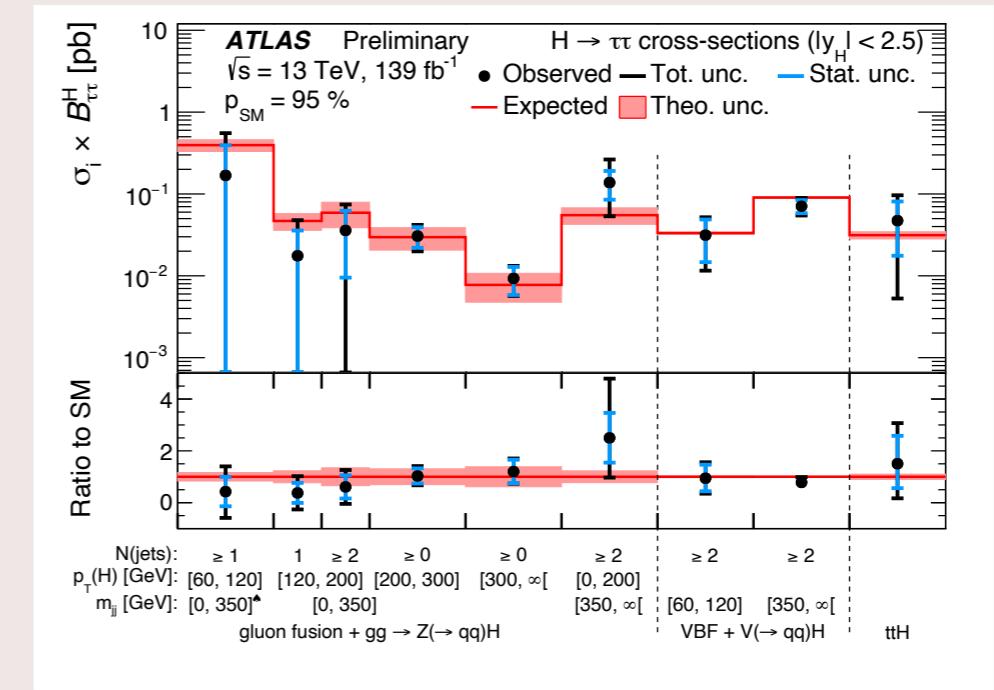
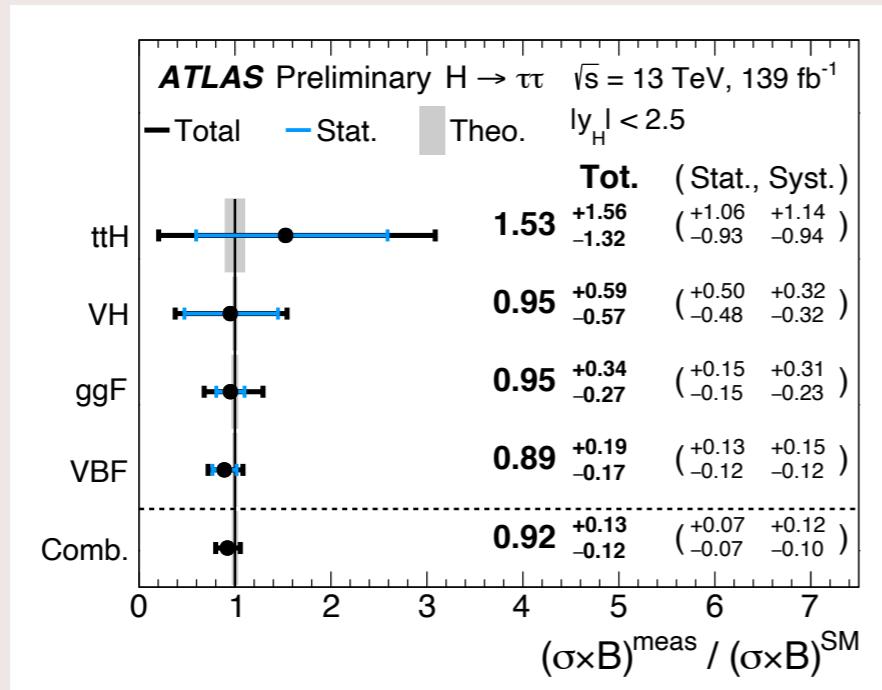
- Event categorisation vs STXS Stage 1.2 bins targeted: the dominant STXS bin contributing to each event category is indicated by the colour of the category box or the STXS bin adjacent to it.



3rd generation: $H \rightarrow \tau\tau$ (ATLAS)

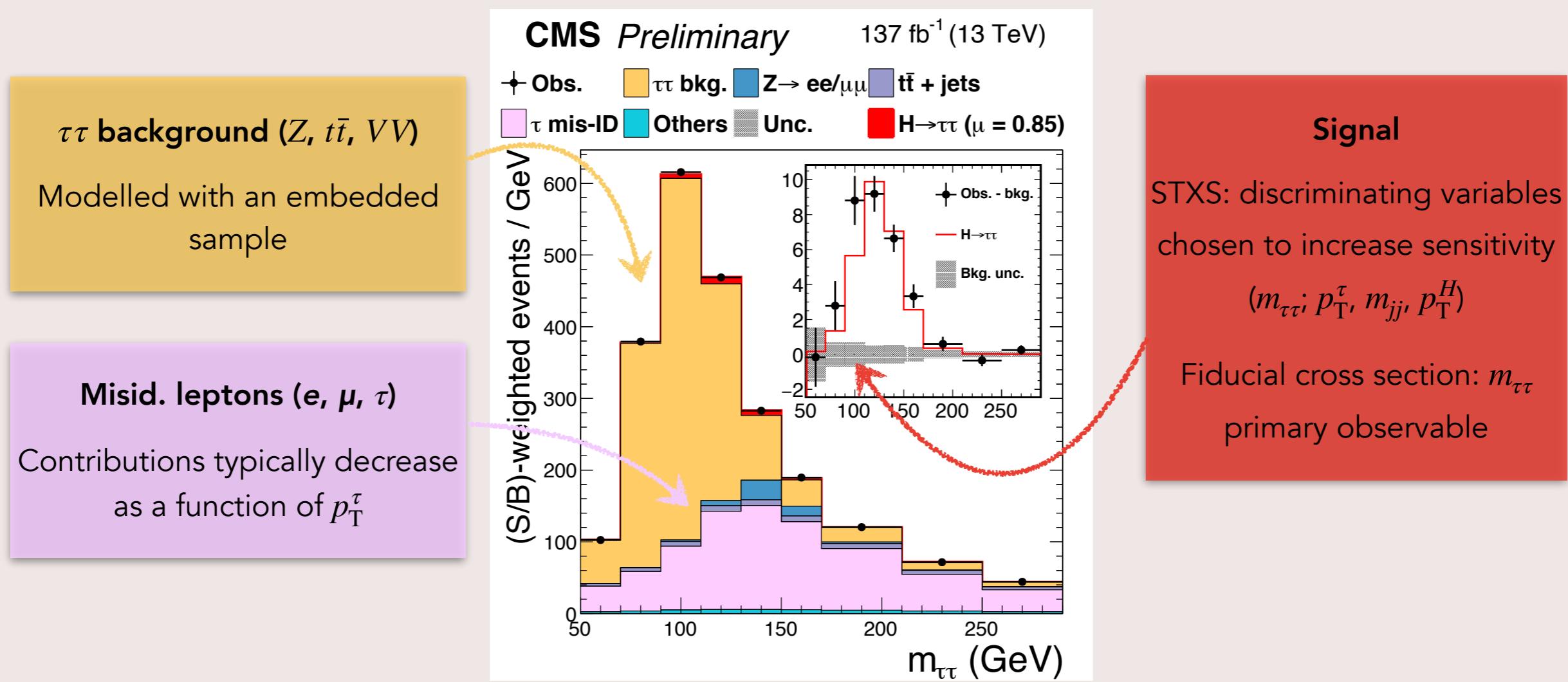
- $pp \rightarrow H \rightarrow \tau\tau$ cross section measured to be $2.90 \pm 0.21(\text{stat})^{+0.37}_{-0.32}(\text{syst}) \text{ pb}$ for $|y_H| < 2.5$
 - In agreement with SM prediction of $3.15 \pm 0.09 \text{ pb}$
- Measurement of **production cross sections** for the four main production modes and in kinematic STXS bins also in agreement with SM predictions (p -values of 88% and 95%)

Source of uncertainty	Impact on $\Delta\sigma / \sigma(pp \rightarrow H \rightarrow \tau\tau) [\%]$	
	Observed	Expected
Theoretical uncertainty in signal	8.1	8.6
Jet and \vec{E}_T^{miss}	4.2	4.1
Background sample size	3.7	3.4
Hadronic τ decays	2.0	2.1
Misidentified τ	1.9	1.8
Luminosity	1.7	1.8
Theoretical uncertainty in Top processes	1.4	1.2
Theoretical uncertainty in Z+jets processes	1.1	1.1
Flavor tagging	0.5	0.5
Electrons and muons	0.4	0.3
Total systematic uncertainty	11.1	11.0
Data sample size	6.6	6.3
Total	12.8	12.5



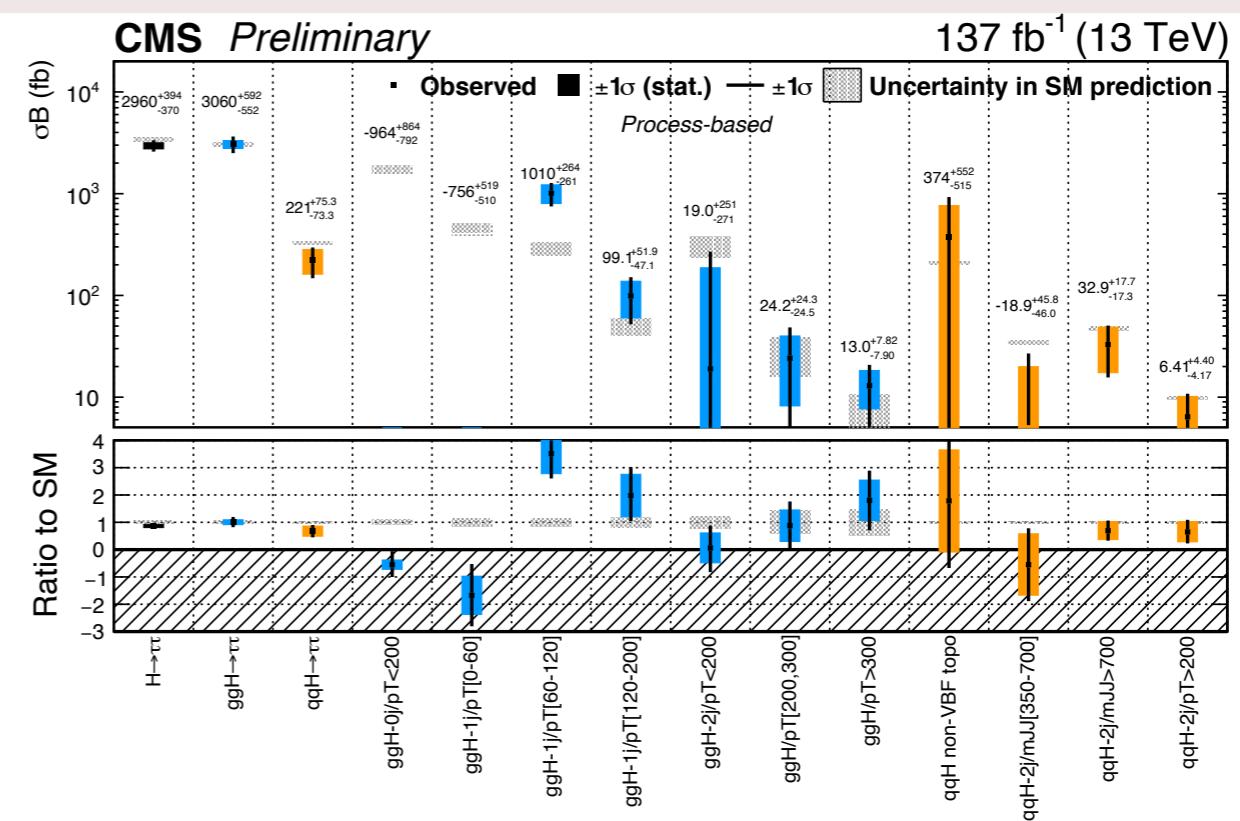
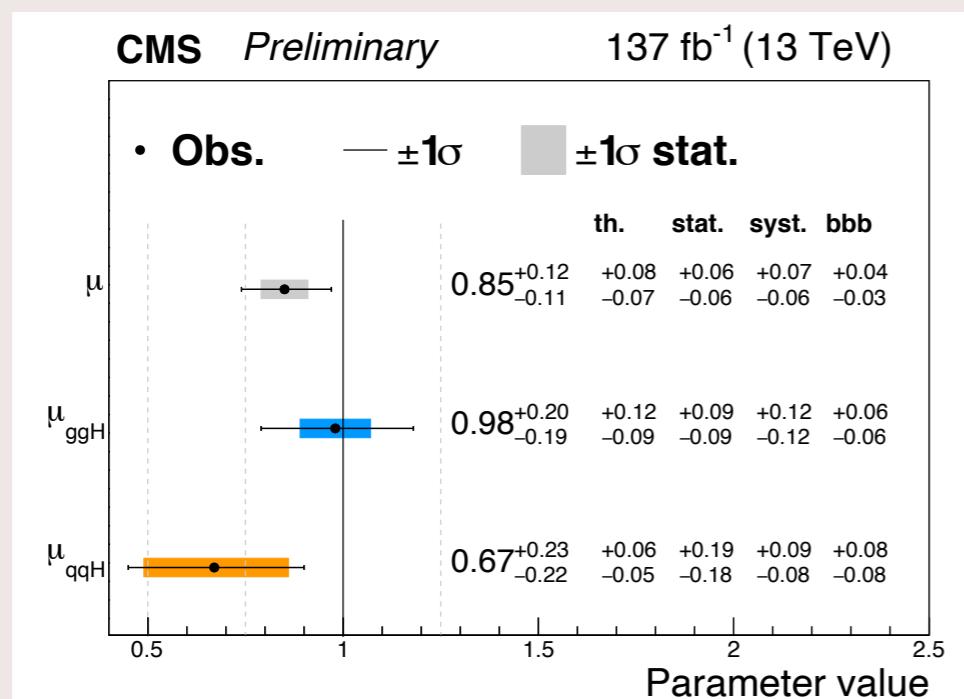
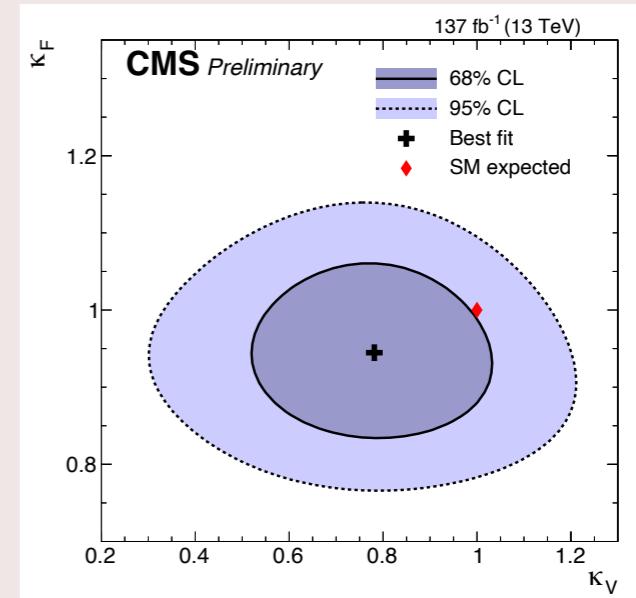
3rd generation: $H \rightarrow \tau\tau$ (CMS)

- Targets measurement of inclusive and differential fiducial cross sections as well as STXS
 - Variables studied for fiducial cross sections: p_T^H , N_{jets} and $p_T^{\text{leading jet}}$
 - Simplified matrix element algorithm used to reconstruct the di- τ mass $\underline{*}$
- Characteristics of the analysis:



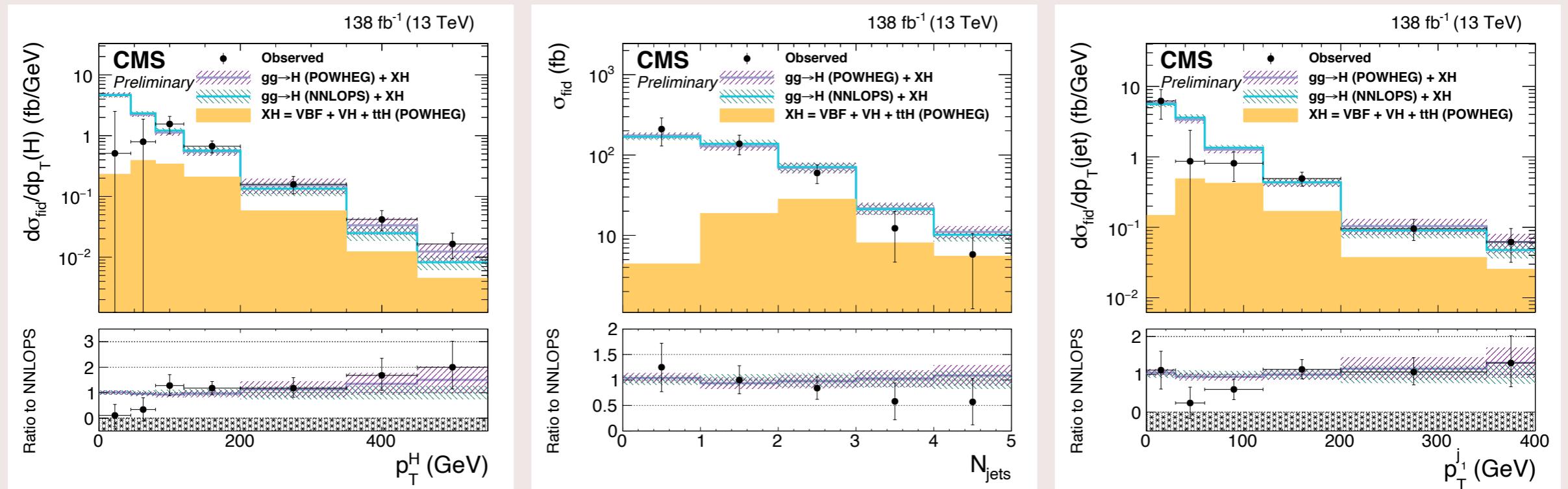
3rd generation: $H \rightarrow \tau\tau$ (CMS)

- $pp \rightarrow H \rightarrow \tau\tau$ cross section measured to be $0.85^{+0.12}_{-0.11} \times \text{SM}$
 - Reminder: result from ATLAS is $0.92^{+0.13}_{-0.12} \times \text{SM}$
- Measurement of **production cross sections** for the main production modes and in STXS kinematic bins, as well as in the **kappa framework** * also in agreement with SM predictions



3rd generation: $H \rightarrow \tau\tau$ (CMS)

- **Inclusive fiducial cross section** (summing N_{jets} bins) measured to be 426 ± 102 fb
 - In agreement with SM prediction of 408 ± 27 fb
 - Fiducial volume defined by the visible τ decay products
- **Differential fiducial cross section measurements** in $H \rightarrow \tau\tau$ performed for the first time!
 - Also shows good agreement with SM predictions (p -values of 17% for p_T^H , 71% for N_{jets} and 45% for p_T^{j1})



2nd generation: $H \rightarrow \mu\mu$

- Analyses target all four main production modes at the LHC (ggH , VBF , VH , $t\bar{t}H$)
 - Helps to increase sensitivity to this low-statistics process
- Good signal resolution but small branching ratio ($\approx 2.2 \times 10^{-4}$) and large irreducible background from $Z \rightarrow \mu\mu$
- Measurements now available with the **full Run 2 dataset**
 - First **evidence** for Higgs couplings to 2nd generation!

2nd generation: $H \rightarrow \mu\mu$ (CMS)

- Categories corresponding to four main production modes:
 - Contributions enhanced via multivariate discriminants for ggH , VBF, VH , $t\bar{t}H$
 - Score used to split into sub-categories

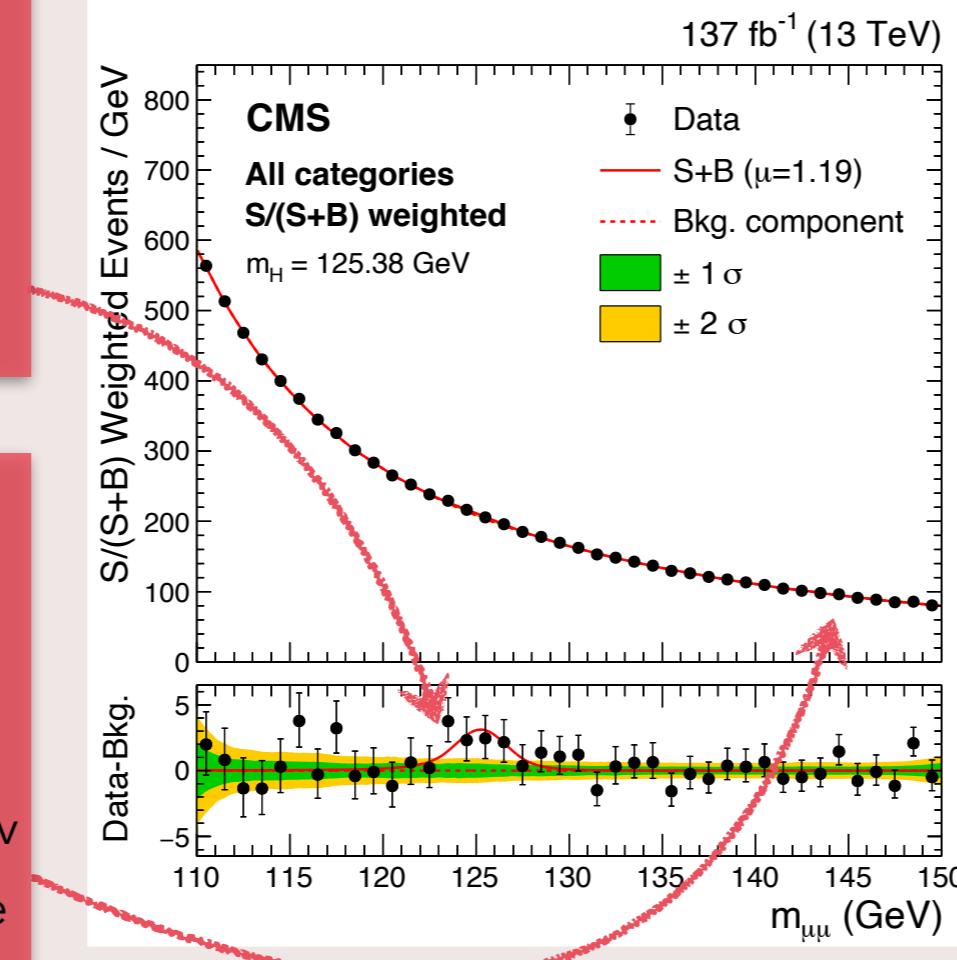
Signal

Extracted from $m_{\mu\mu}$

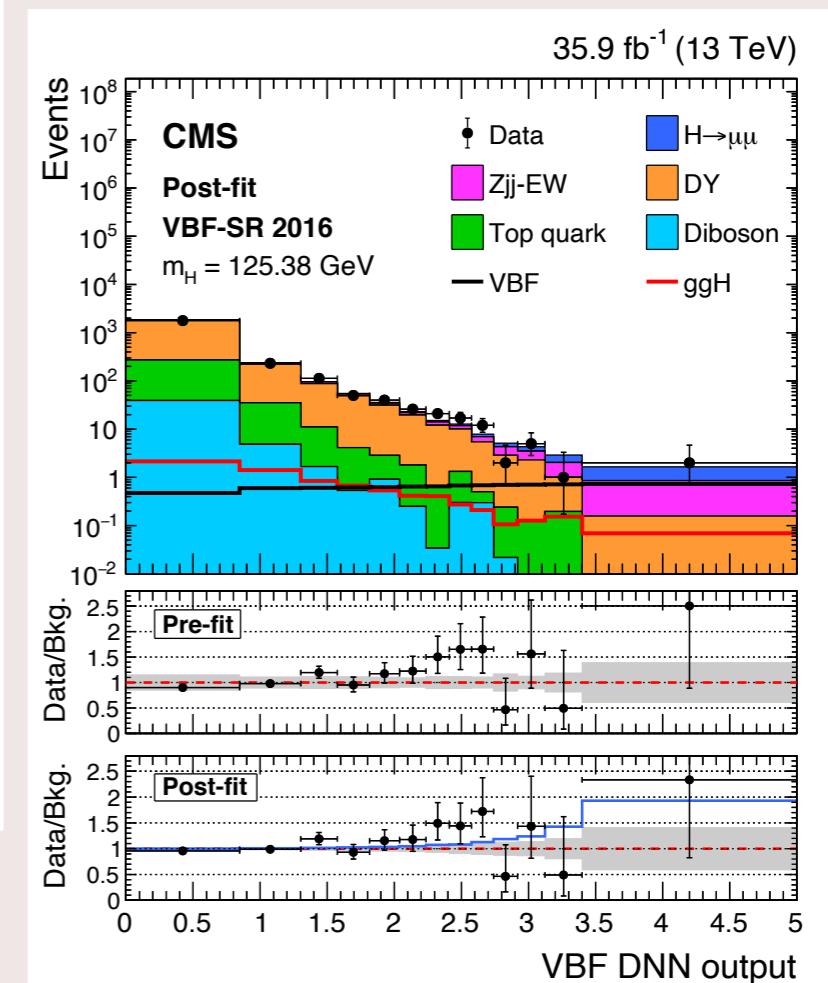
Parametrised with double-sided Crystal-Ball function

Background

Parametrised using a core function (shared between categories) and a Chebyshev polynomial function (unique to each category)

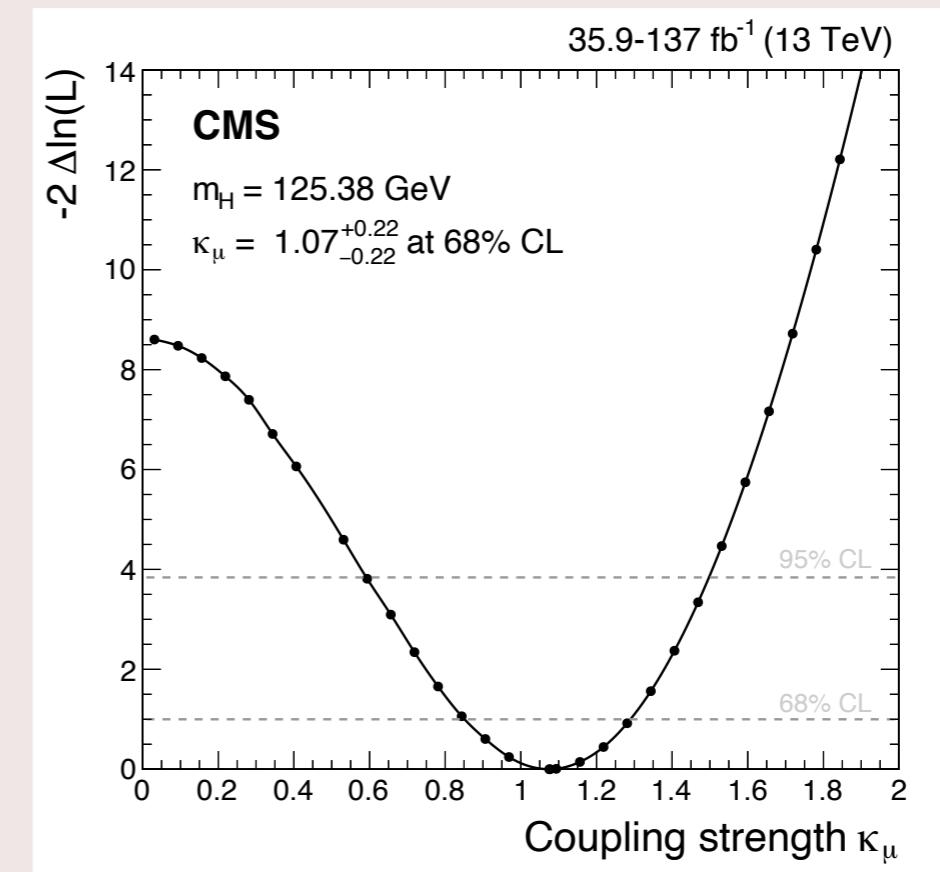
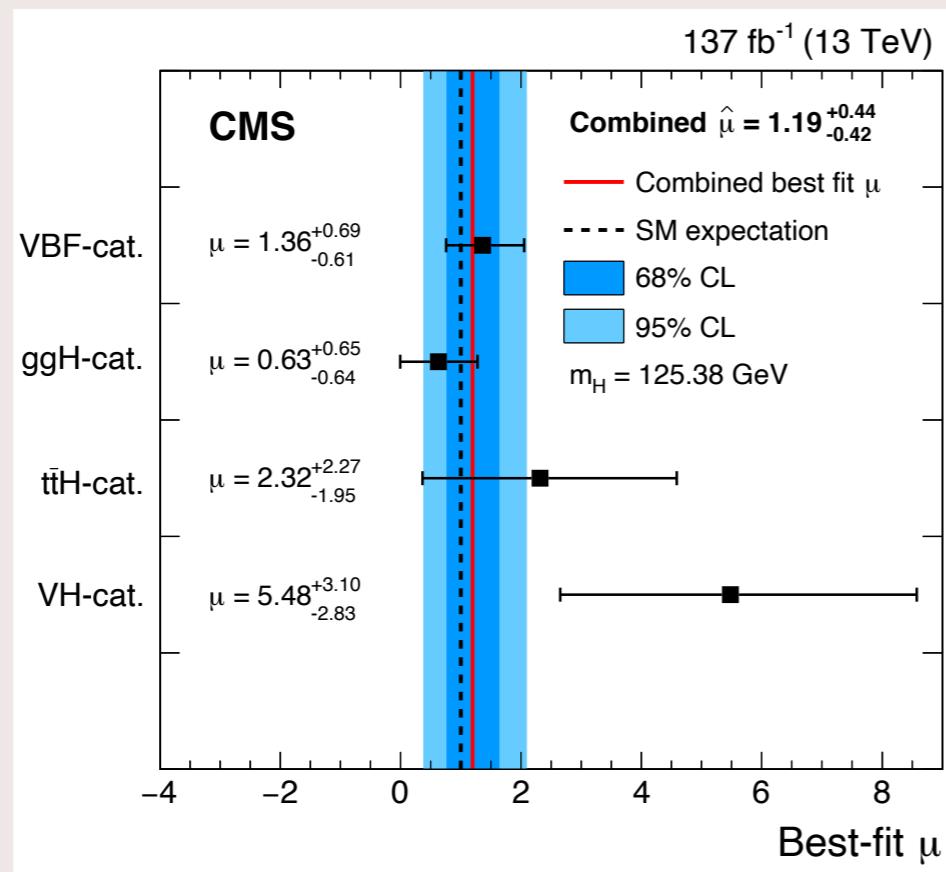
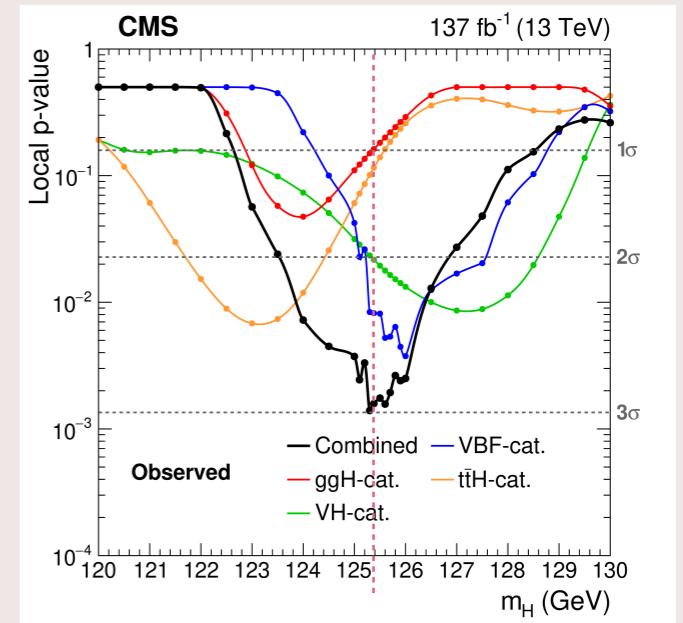


... except in the VBF categories, where the shape of the DNN output is fitted



2nd generation: $H \rightarrow \mu\mu$ (CMS)

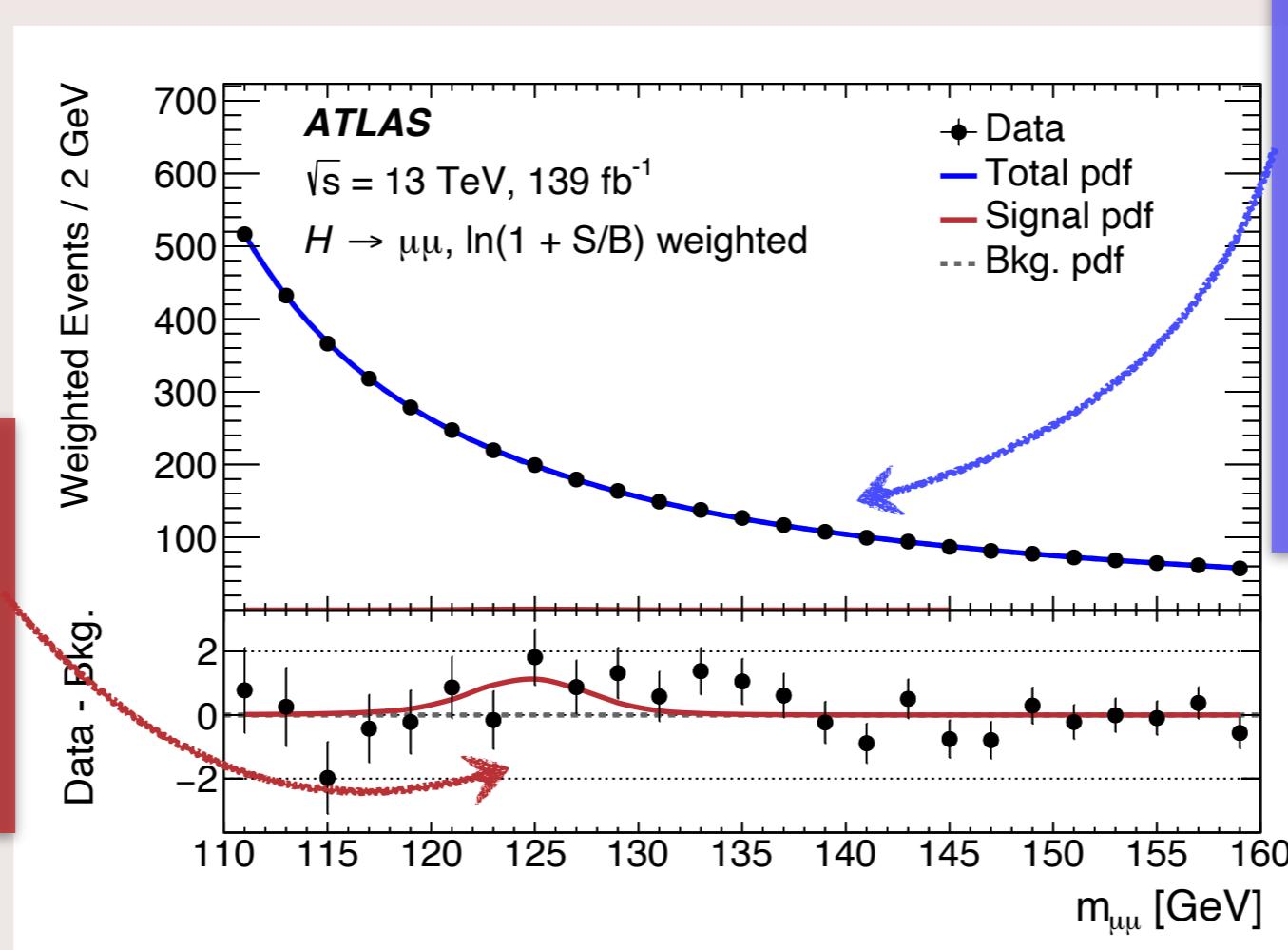
- All results at best measured value of $m_H = 125.38$ GeV ^{*}
 - Best-fit value for $pp \rightarrow H \rightarrow \mu\mu$ cross section with respect to the SM is $\mu = \frac{\sigma}{\sigma_{SM}} = 1.19^{+0.40}_{-0.39}$ (stat) $^{+0.15}_{-0.14}$ (syst)
 - Observed (expected) significance of 3.0σ (2.5σ) — **Evidence!**
 - Observed upper limit of $1.9 \times \text{SM}$ at 95% CL
 - Measurement of coupling strength in **kappa framework**



2nd generation: $H \rightarrow \mu\mu$ (ATLAS)

- Categories corresponding to four main production modes:
 - Contributions enhanced via multivariate discriminants for VBF, VH, $t\bar{t}H$
 - Split in jet multiplicity for ggH , with discriminants in each sub-category

Signal
 Extracted from $m_{\mu\mu}$
 Parametrised with double-sided Crystal-Ball function

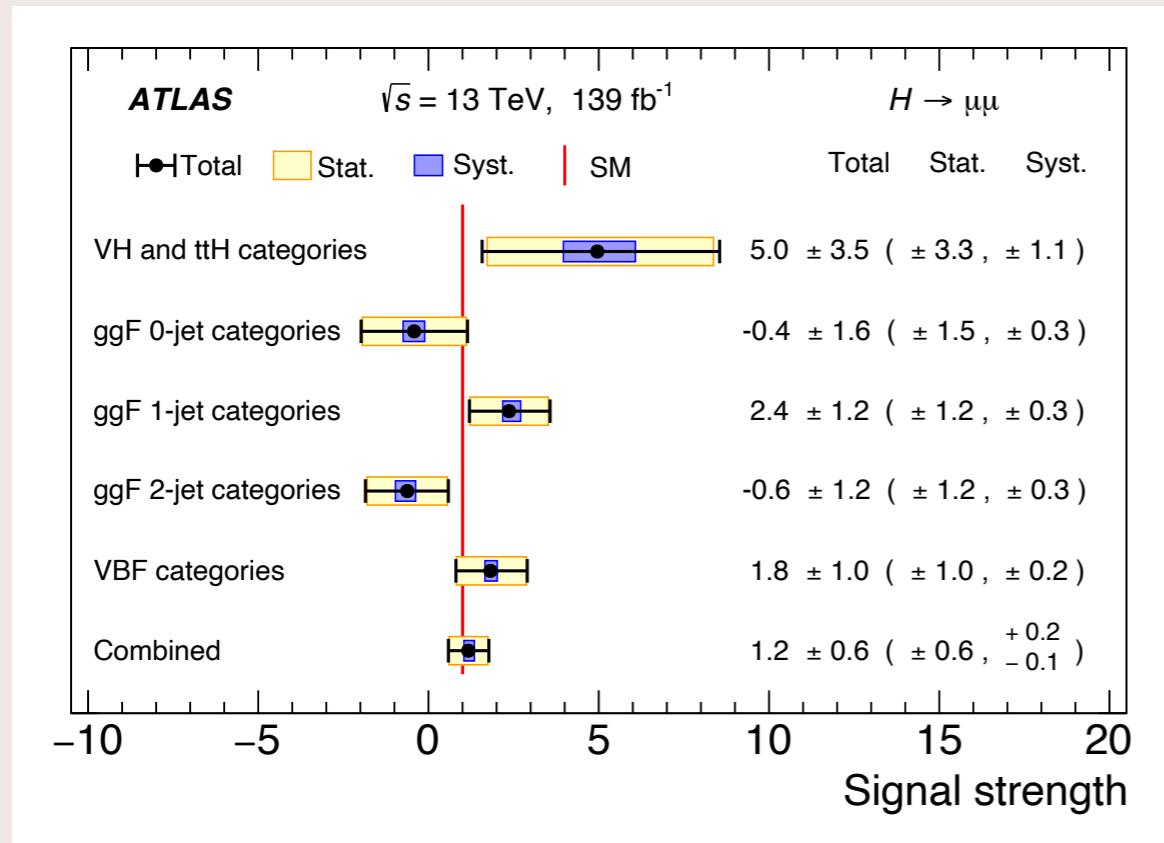


Background

Parametrised using a core function (based on LO DY shape, shared between category) and an empirical function (unique to each category)

2nd generation: $H \rightarrow \mu\mu$ (ATLAS)

- All results at $m_H = 125.09$ GeV ^{*}
 - Best-fit value for $pp \rightarrow H \rightarrow \mu\mu$ cross section with respect to the SM is $\mu = \frac{\sigma}{\sigma_{SM}} = 1.2 \pm 0.6$
 - Reminder: result from CMS is $\mu = \frac{\sigma}{\sigma_{SM}} = 1.19^{+0.44}_{-0.42}$
- Observed (expected) significance of 2.0σ (1.7σ)
- Observed upper limit of $2.2 \times \text{SM}$ at 95% CL



Bonus: $H \rightarrow ee$ ^{*} at 139 fb^{-1}
Follows closely $H \rightarrow \mu\mu$ analysis strategy

Observed (expected) upper limit on branching fraction
 3.6×10^{-4} (3.5×10^{-4}) at 95% CL

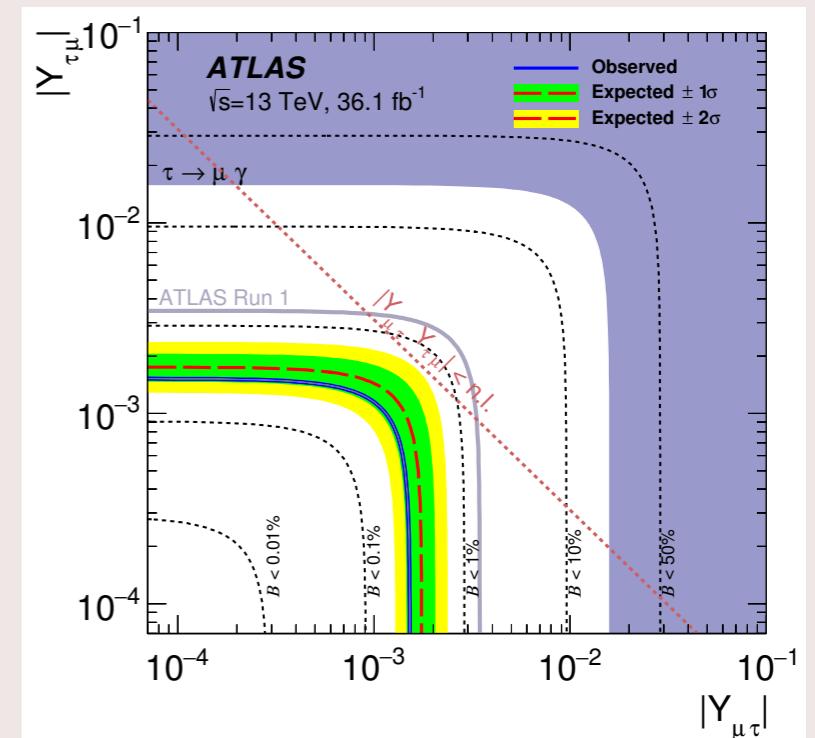
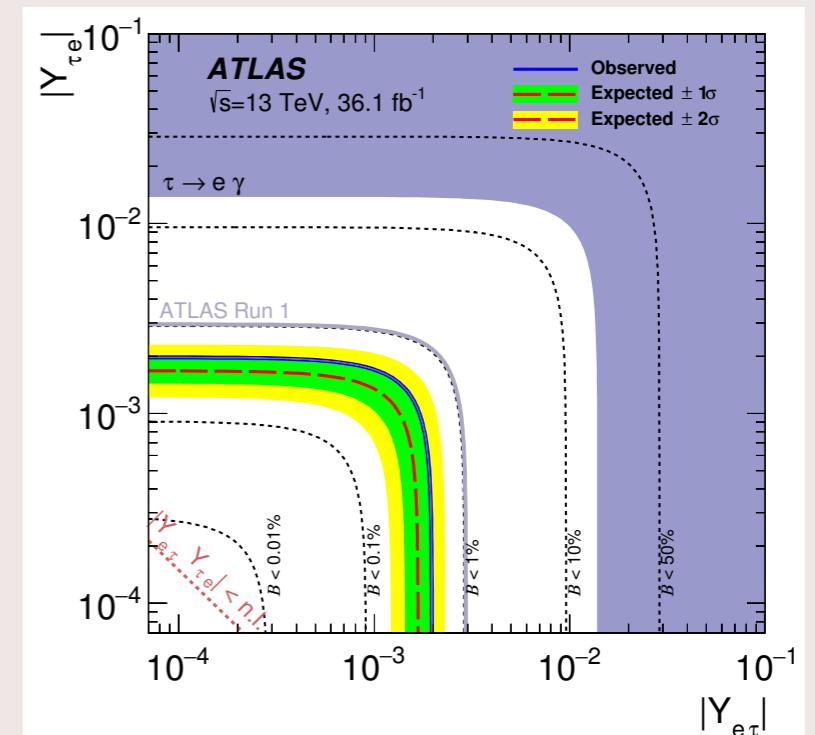
CMS result form Run 1: upper limit on branching
fraction of 0.0019 at 95% CL ^{*}

LFV: $H \rightarrow e\mu, e\tau, \mu\tau$

- So far, all properties of the Higgs boson are compatible with the SM predictions
- Still some space available to probe other models with Higgs decays that don't conserve lepton flavour
 - E.g. models with Higgs doublets, SUSY models, composite Higgs models, ...
 - **LFV Yukawa couplings** $Y_{e\mu}$, $Y_{e\tau}$, $Y_{\mu\tau}$
 - Constraints exist from other measurements:
 - Searches for $\mu \rightarrow e\gamma$ constrain $\mathcal{B}(H \rightarrow e\mu)$ to $< 10^{-8}$ or 0.000001 %
 - Searches for $\tau \rightarrow e\gamma$ and $\tau \rightarrow \mu\gamma$ as well as measurements of e and μ magnetic and dipole moments constrain $\mathcal{B}(H \rightarrow e\tau)$ and $\mathcal{B}(H \rightarrow \mu\tau)$ to $\approx 10\%$
 - **Potential for improvement** here!
- Results translated into **constraints on branching fractions** and into **limits on the LFV Yukawa couplings**

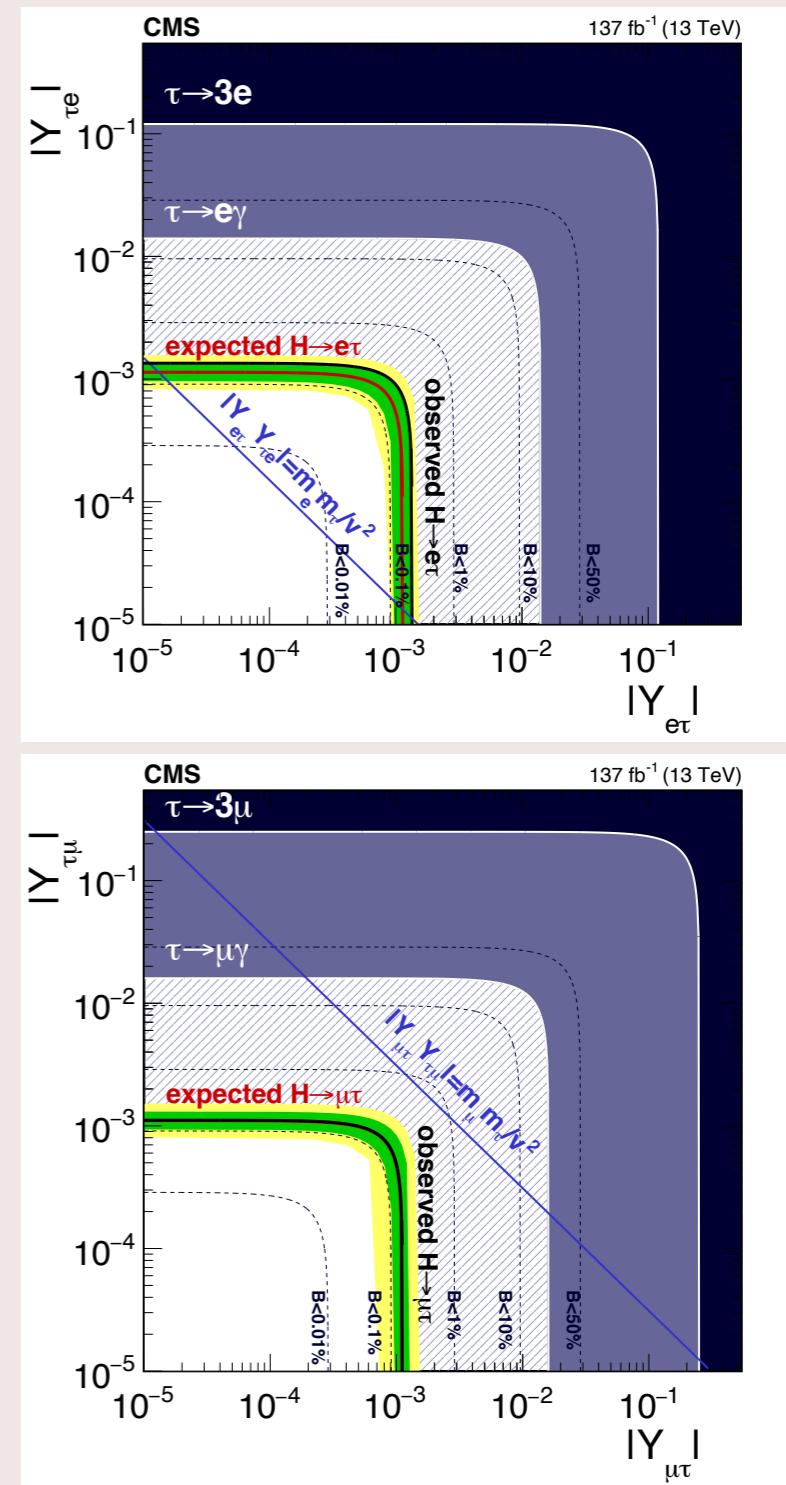
LFV: $H \rightarrow e\mu, e\tau, \mu\tau$ (ATLAS)

- $H \rightarrow e\tau, \mu\tau$: targets $e\tau_{\text{had}}, e\tau_\mu, \mu\tau_{\text{had}}, \mu\tau_e$ decay modes
 - Many similarities to the $SM H \rightarrow \tau\tau$ analysis
 - Regions split into VBF and non-VBF categories
 - Split based on $p_T^{j1}, p_T^{j2}, |\Delta\eta(j1, j2)|, m_{j1j2}$
 - Multivariate discriminants trained in each decay channel and production category
 - Signal extracted from **fit to discriminant**
- $H \rightarrow e\mu$
 - Full Run 2 dataset!
 - Strategy closely follows analysis strategy of $H \rightarrow \mu\mu$ & ee , with signal and background templates used in the fit
- Observed (expected) upper limits:
 - 0.47 % ($0.34^{+0.13\%}_{-0.10\%}$) on $\mathcal{B}(H \rightarrow e\tau)$
 - 0.28 % ($0.37^{+0.14\%}_{-0.10\%}$) on $\mathcal{B}(H \rightarrow \mu\tau)$
 - 0.0062 % (0.0059%) on $\mathcal{B}(H \rightarrow e\mu)$



LFV: $H \rightarrow e\mu, e\tau, \mu\tau$ (CMS)

- $H \rightarrow e\tau, \mu\tau$: targets $e\tau_{\text{had}}, e\tau_\mu, \mu\tau_{\text{had}}, \mu\tau_e$ decay modes
 - Full Run 2 dataset!
 - Categorized by jet multiplicity, with a high- m_{jj} region in the 2-jet category enriched in VBF events
 - Each with its own multivariate discriminant
 - Signal extracted from **fit to discriminant**
 - $H \rightarrow e\mu$
 - Strategy also closely follows analysis strategy of $H \rightarrow \mu\mu$ & ee , with signal and background templates used in the fit
 - Observed (expected) upper limits:
 - 0.22 % (0.16%) on $\mathcal{B}(H \rightarrow e\tau)$
 - 0.15 % (0.15%) on $\mathcal{B}(H \rightarrow \mu\tau)$
 - 0.035 % (0.048%) on $\mathcal{B}(H \rightarrow e\mu)$



Conclusion

- Many interesting results from ATLAS and CMS with full Run 2 dataset(s)!
- $H \rightarrow \tau\tau$ measurements becoming much more precise
 - Limited by systematic uncertainties now
 - Moving more and more towards **differential measurements**
- **Evidence** for Higgs couplings to second generation with $H \rightarrow \mu\mu$
 - Sensitivity continues to increase with larger datasets and more advanced analysis techniques
- No deviations from the SM predictions found... (yet?)
- Searches for LFV in $H \rightarrow e\mu, e\tau, \mu\tau$ are becoming more sensitive, and nicely complement existing constraints

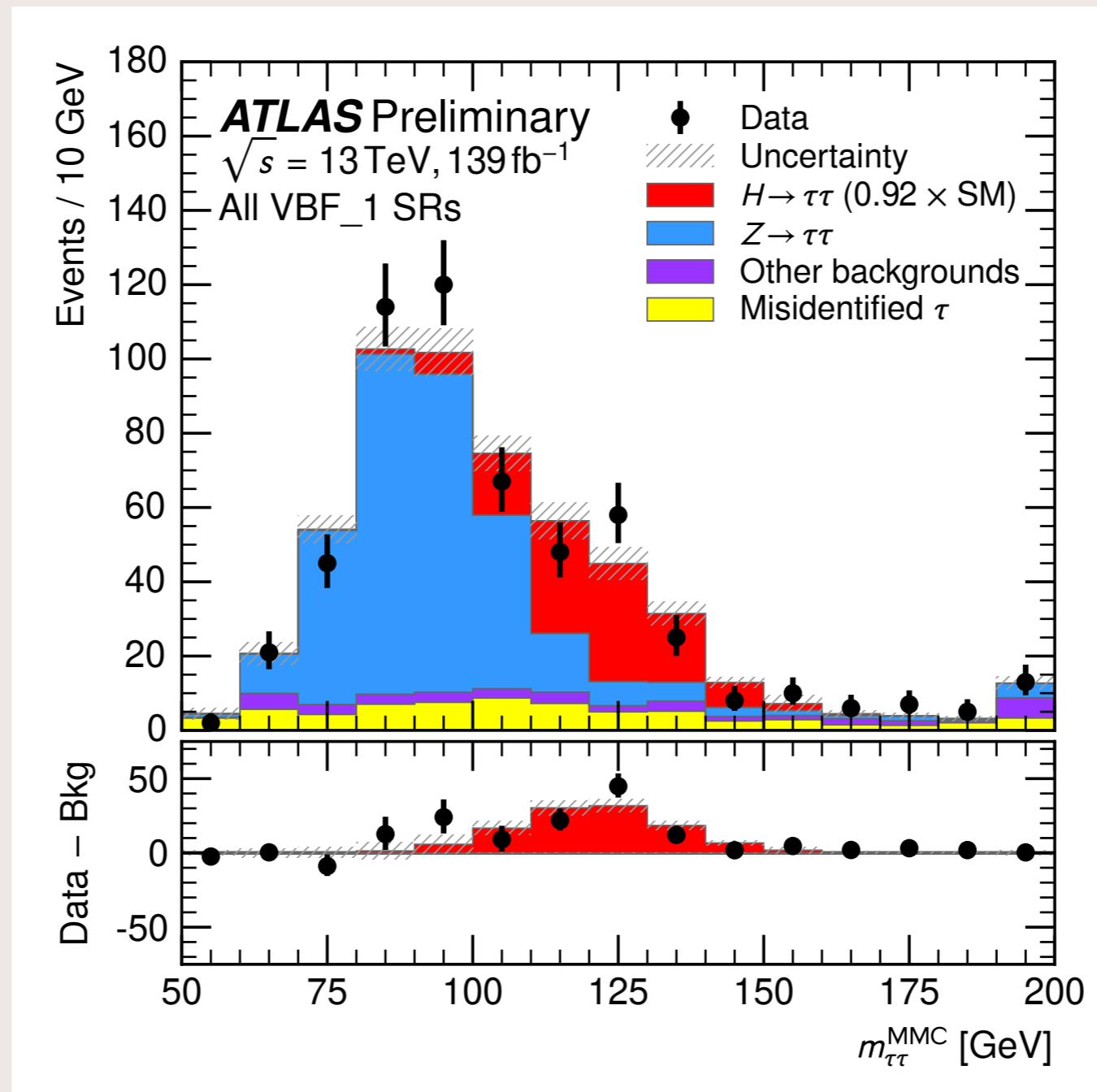
Other talks on this topic...

- Exotic Higgs decays at CMS — Wednesday
- Measurements of Higgs boson production cross sections in the **H → ττ decay channel** in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector — Thursday
- Higgs boson coupling to **second generation fermions** with the ATLAS detector — Thursday
- Rare Higgs decays at CMS — Thursday
- Search for rare and **lepton flavor violating decays** of the Higgs boson with the ATLAS detector — Thursday
- Measurements of Higgs boson production in **decays to two tau leptons** with the ATLAS detector — Thursday
- Measurements of Higgs cross sections and differential distributions in the **H->tautau** final state from CMS — Thursday

- SM Higgs-boson properties: mass, width, **CP** — Tuesday
- Higgs **CP and anomalous coupling** measurements in the **H->tautau** and H->ZZ final states from CMS — Tuesday
- Studies of the **CP properties** of the Higgs boson at the ATLAS experiment — Wednesday
- Analysis of the **CP structure** of the Higgs boson in **tau tau decays** at CMS — Thursday

Backup

3rd generation: $H \rightarrow \tau\tau$ (ATLAS)



2nd generation: $H \rightarrow \mu\mu$ (ATLAS)

