Measurements of Higgs boson coupling properties to leptons with the ATLAS detector

Precision Higgs measurements and calculations IV
Higgs 2024 Uppsala

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on behalf of the ATLAS Collaboration

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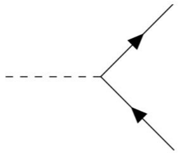
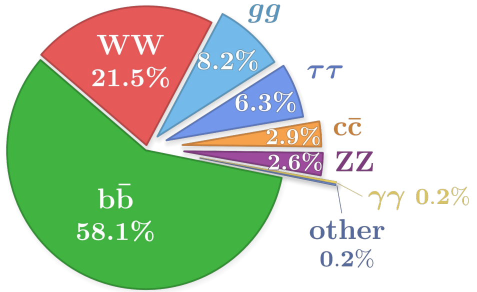
Introduction

- **The Higgs boson decays preferably to heavy particles** due to its coupling being **proportional to their mass** ($\propto m^2_V$, m_f)
- Coupling to bosons ($H\rightarrow\gamma\gamma$, $H\rightarrow ZZ^{(*)}\rightarrow 4\ell$) provides efficient balance between branching ratio and notable mass resolution for the Higgs boson candidate
- Coupling to fermions via **Yukawa mechanism:**
  - $H\rightarrow\tau\tau$, $H\rightarrow bb$: good mass resolution, challenging backgrounds
  - Other generations of fermions are limited by **lower branching ratios (BR)**
  - **Couplings of the Higgs boson to leptons at best possible precision**
    - provides tests of the Standard Model (SM) and offers stringent constraints on Beyond Standard Model (BSM) theories



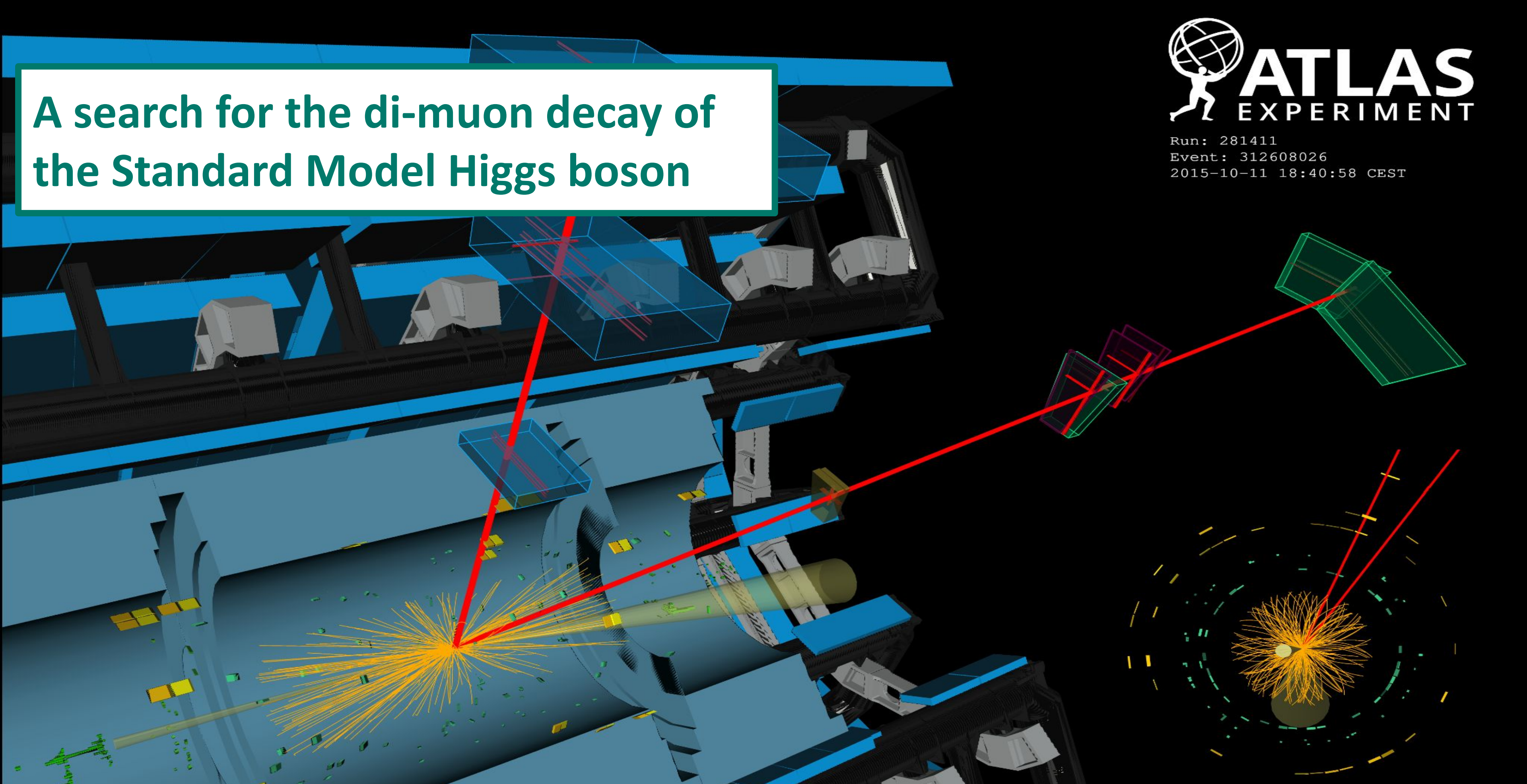
$$g_{Hf\bar{f}} = \frac{m_f}{\mathrm{vev}}$$



ATLAS Run-2 "precision era":

- Interaction with **third-generation leptons** (τ-leptons) **measured** (arXiv:2407.16320, Phys. Lett. B 855 (2024) 138817)
- **Indications** of interactions with **second-generation leptons** (muons, μ) are emerging (Phys. Lett. B 812 (2021) 135980)
- Other relevant analyses using H→leptons final states relying on their clean signatures:
  - **Searches for Lepton Flavour Violation (LFV)** (JHEP 07 (2023) 166)

A search for the di-muon decay of the Standard Model Higgs boson

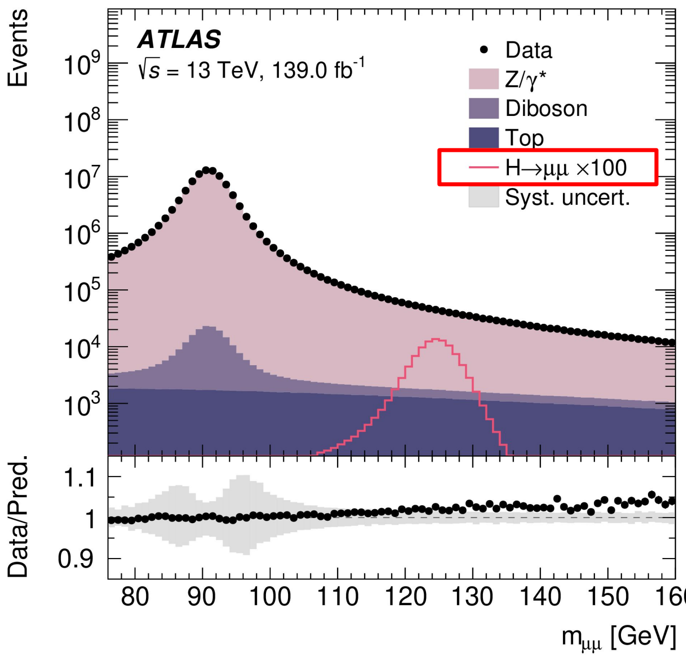


VBF($H \rightarrow \mu\mu$): Higgs boson candidate decaying to two muons (in red) + two forward jets (yellow cones)

H→$\mu\mu$ search: motivation

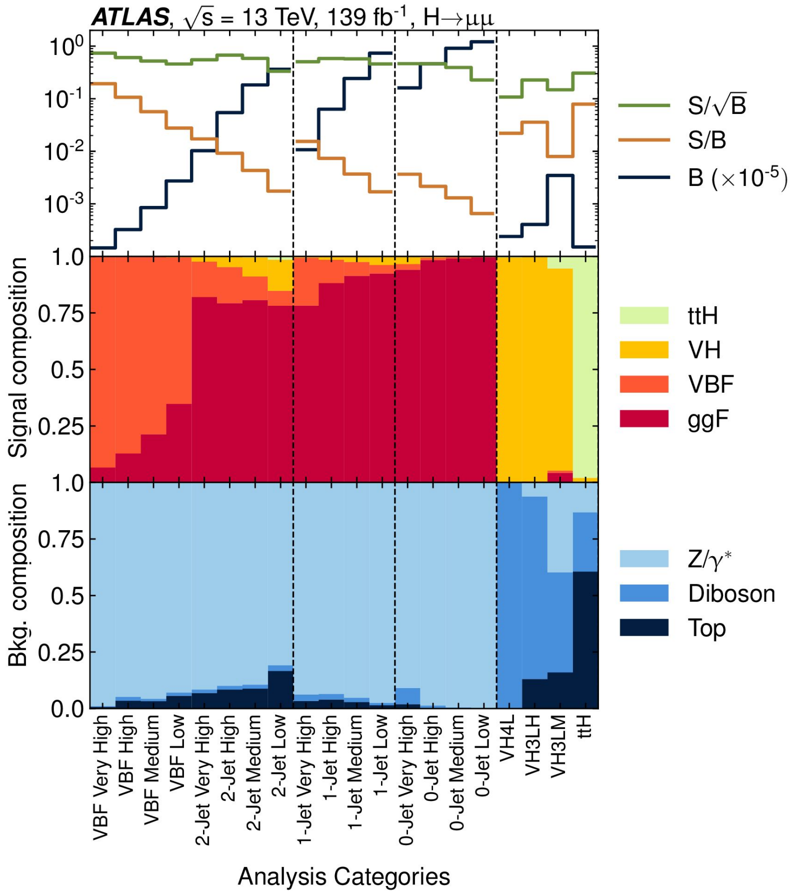
- *H→μμ* could provide the first measurement of Higgs boson interactions with second-generation fermions at LHC
- Very **clean final state**, but poor signal-to-background ratio
  - **Large irreducible background** from Drell-Yan (DY) production
  - **Small *H→μμ* branching fraction**: $(2.17 \pm 0.04)\times10^{-4}$
    - Signal/background ratio typically at **0.1% level**
- New round aiming to improve the previous preliminary results at 139 fb^{-1} (ATLAS-CONF-2019-028)
  - Observed significance: **0.8σ** (expected **1.5σ**)
  - Signal strength: $$\mu = \frac{N_{observed}}{N^{SM}_{expected}} = 0.5 \pm 0.7$$

Phys. Lett. B 812 (2021) 135980



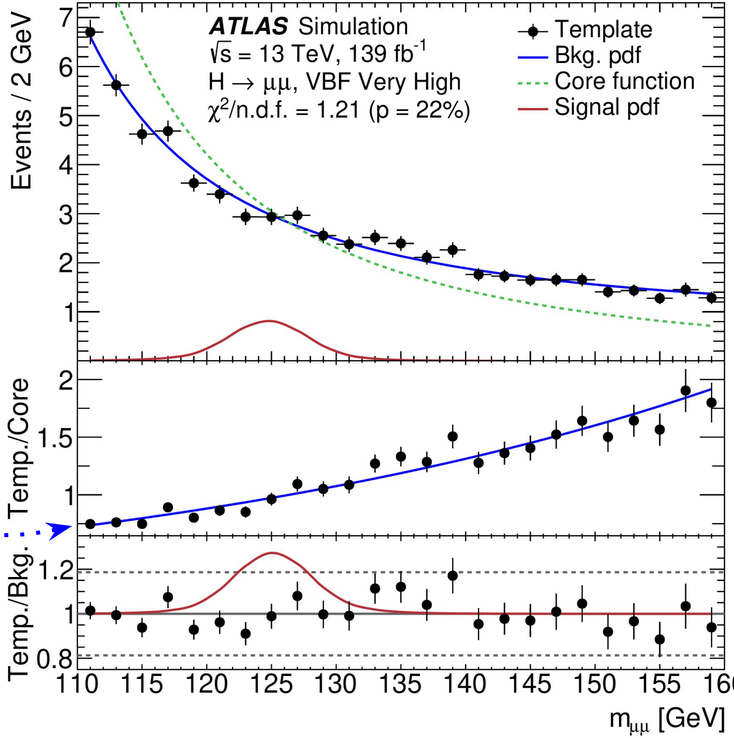
H→$\mu\mu$ search: analysis strategy

- Two oppositely charged, isolated and well identified muons
- Events classified into **20 mutually exclusive categories** defined to maximise sensitivity using **BDT discriminants**
  - First test for ttH category (b-jet + extra lepton)
  - If not, test for VH categories (1+ extra leptons + b-jet veto)
    - 3-leptons targeting WH and 4-lepton for ZH
  - Otherwise, **split according to jet multiplicity (0, 1, 2+) and target ggF/VBF productions** explicitly against Drell-Yan production sources



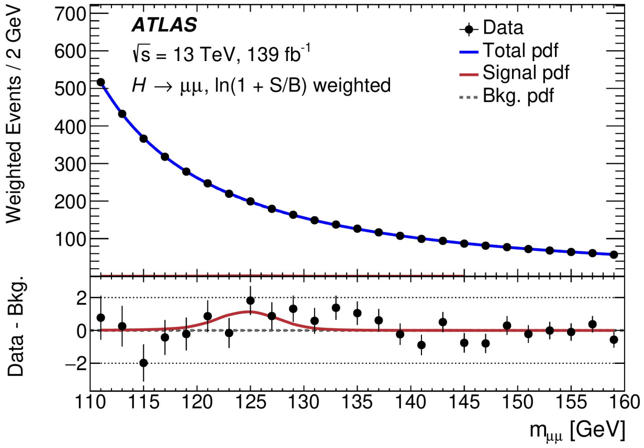
H→$\mu\mu$ search: background modelling

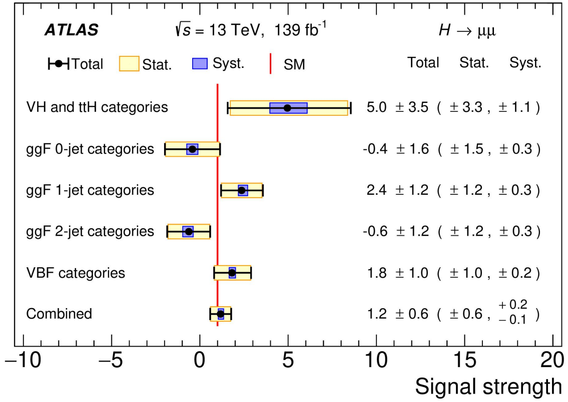
- **Given the small S/B (~0.2% inclusively in the 120-130 GeV window) an accurate description of the background is required**
  - Using a combination of **core** function **x** **empirical** one
    - Leading-order (DY) **line-shape ⊗ detector effects**
      - Describes DY mass shape
      - Inclusive and without free parameters
    - **Power law functions or exponential of polynomials,** used to account for $m_{\mu\mu}$ distortions in each category
      - Flexible: due to selection, categorisation…



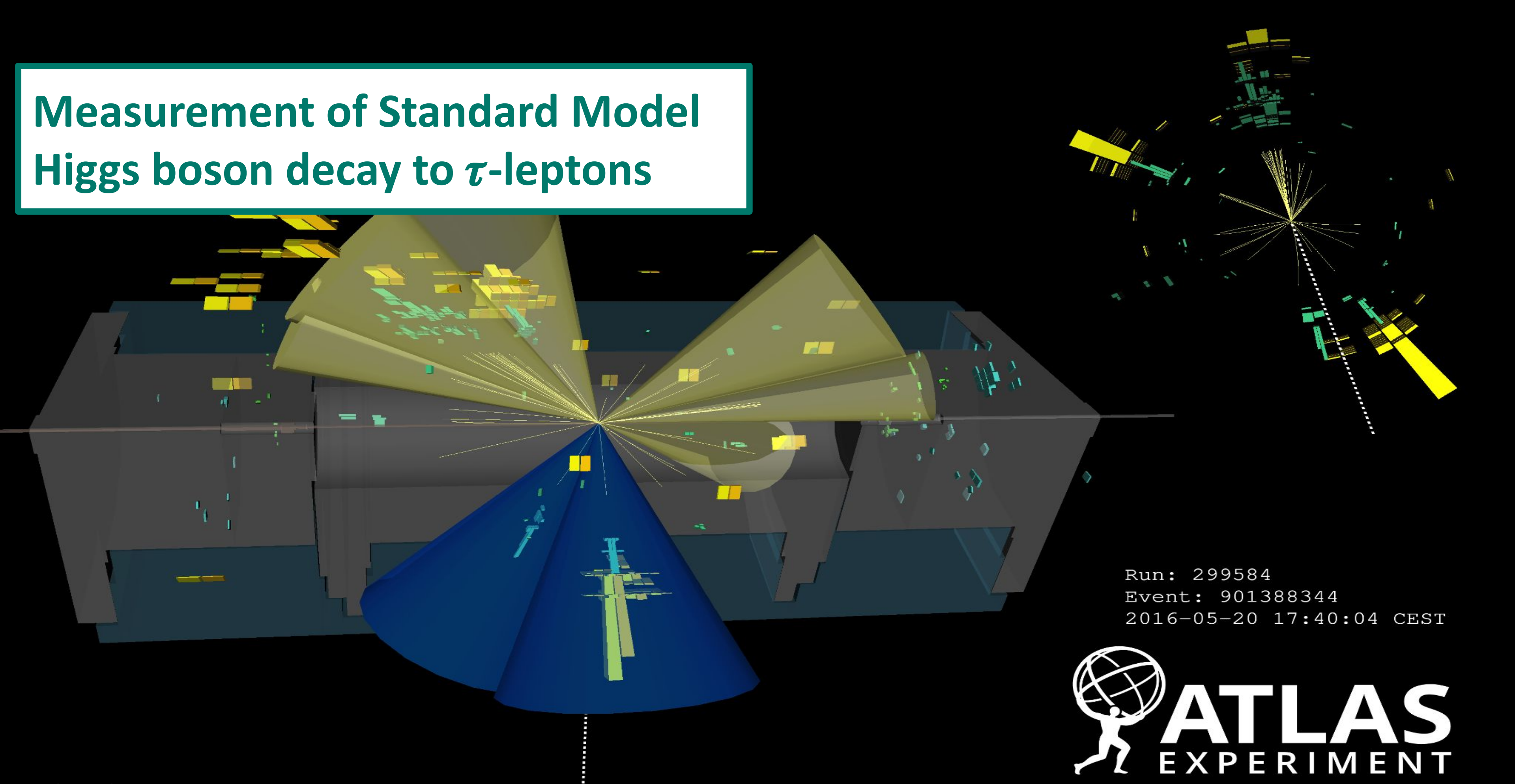
$H\to\mu\mu$ search: results

- **Signal yields** extracted from a simultaneous binned maximum likelihood fit to the $m_{\mu\mu}$ distributions in the 20 categories
- **Signal strength μ = 1.2 ± 0.6**
  - **Observed significance: 2.0σ** (expected 1.7σ)
  - Dominated by the **statistical** component (~0.58 in $\Delta\mu$)
    - signal systematics ~0.1 in $\Delta\mu$
    - experimental uncertainties ~0.05 in $\Delta\mu$
- **Upper limit on BR($H\to\mu\mu$) < 4.7 × 10^{-4}**
  - $BR_{SM}(H\to\mu\mu) = 2.18\times10^{-4}$
  - ~25% improvement with respect to previous result





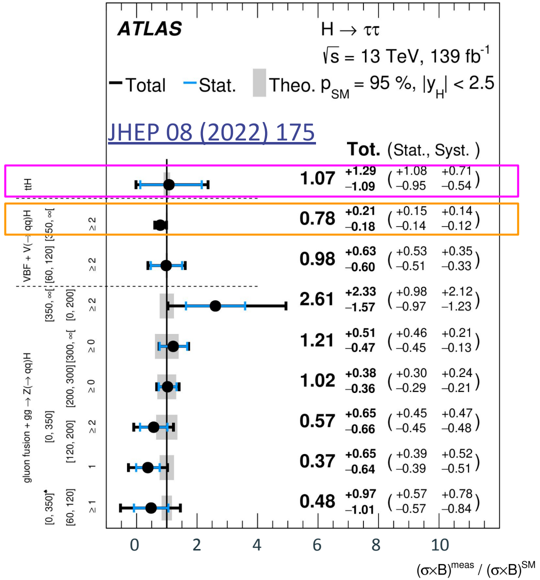
Measurement of Standard Model Higgs boson decay to τ-leptons

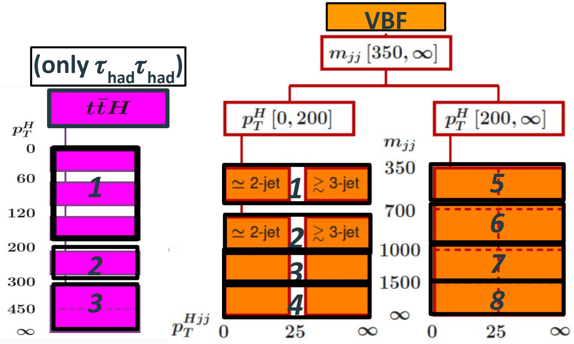


ttH($\rightarrow\tau\tau$): Higgs boson candidate decaying to two hadronically decaying taus (in blue) + six jets produced by top decays (yellow cones)

H→ττ measurement: motivation

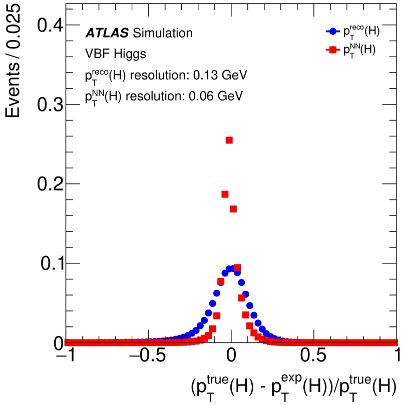
- Largest leptonic BR(H) of 6.3%
- Three di-τ system decay channels: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$
- $H\rightarrow\tau\tau$ provided the **most precise single measurement for VBF** production in the **first round of this analysis** (JHEP 08 (2022) 175)
- **New measurement performed:** re-analysis of full Run 2 dataset to further exploit ttH and VBF sensitivity (arXiv:2407.16320)
  - **STXS** $H\rightarrow\tau\tau$ measurements: improved phase space **granularity** for VBF (as function of $p_T(H)$ and m_{jj}) and ttH (as a function of $p_T(H)$)
  - **First fiducial differential cross section measurements** of $H\rightarrow\tau\tau$ in a VBF enhanced phase space
    - In bins of unfolded $p_T(j_0)$, $p_T(H)$, $\Delta\phi_{jj}^{signed}$, $\Delta\phi_{jj}^{signed}$ vs. $p_T(H)$
    - Results interpreted in SMEFT framework

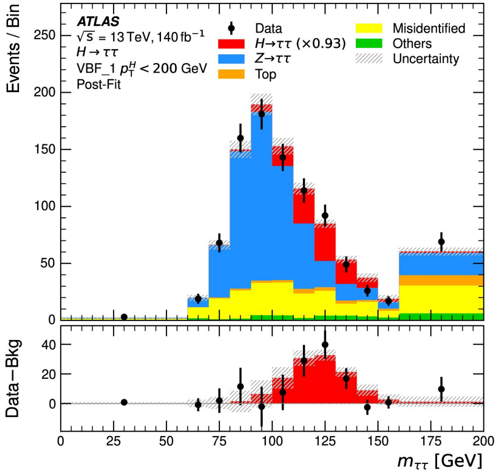




H→$\tau\tau$: analysis strategy

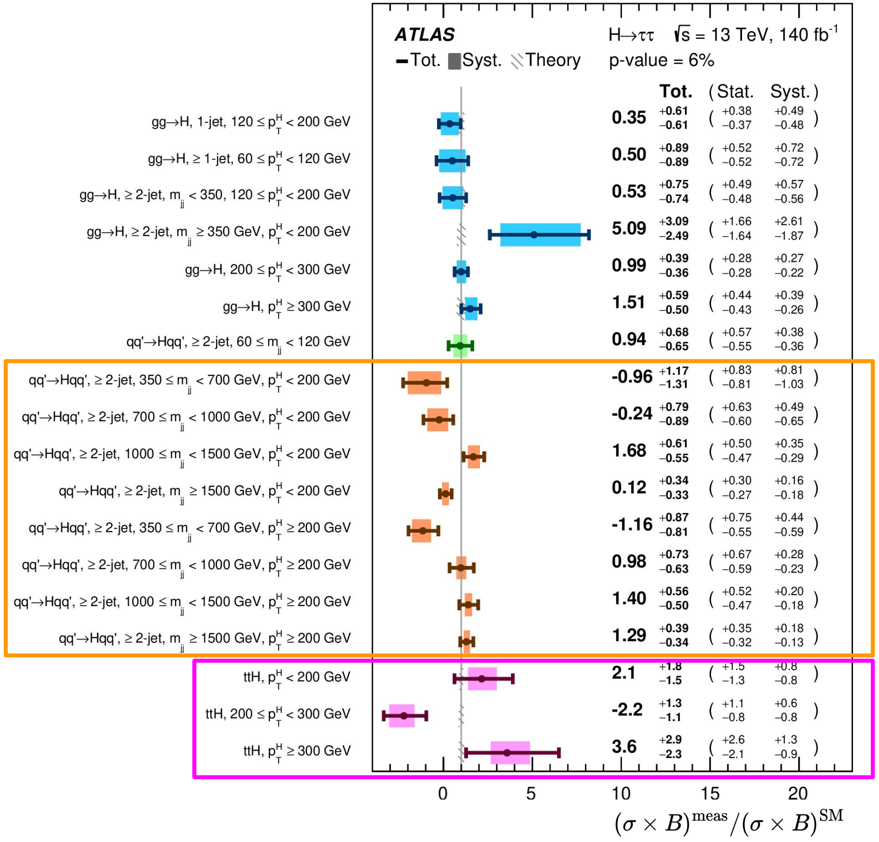
- **Event categorization** also mainly based on BDT discriminants
  - Separation of VBF from ggH/ Z →$\tau\tau$: dedicated BDT targeting VBF + optimized cuts on the score for each STXS VBF bins
  - Separation of ttH from tt/Z→$\tau\tau$: two Multiclass BDTs (p_T(H) < 200 GeV and p_T(H) > 200 GeV)
- **p_T(H) reconstruction approach**
  - VBF and ttH categorisation rely on a **novel NN regression** exploiting E_T^{miss} and di-τ system variables
- **Higgs boson candidate mass** reconstruction via **Missing Mass Calculator (MMC)**
  - $m_{\tau\tau}^{MMC}$ used as input for binned maximum likelihood fit used to extract the cross sections
- **Background estimation:** same strategy as in the previous round



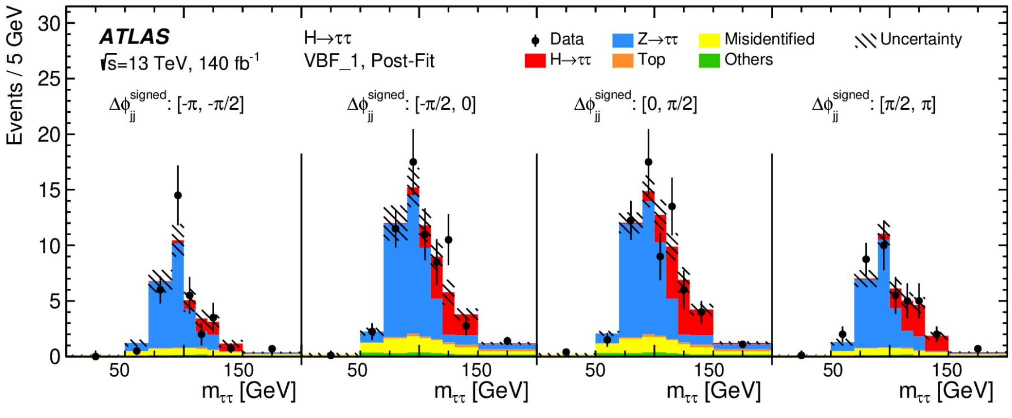


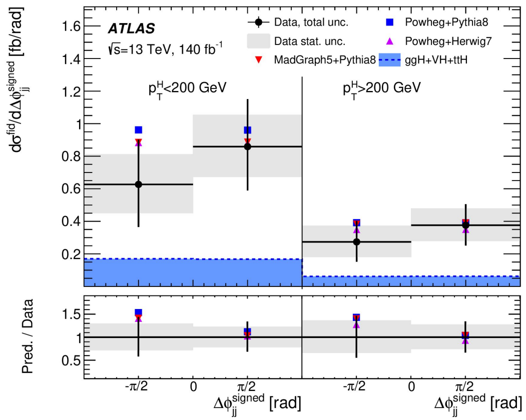
H→ττ measurement: results (STXS)

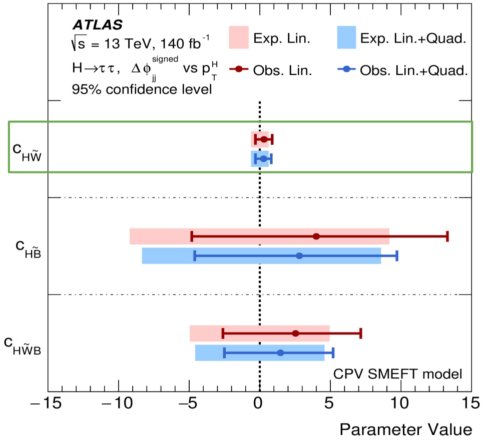
- No significant deviations observed from SM predictions
- STXS VBF 8 bins:
  - **p_T(H) > 200 GeV and m_{jj} > 1500 GeV**
    - $(\sigma \times B)^{\mathrm{meas}}/(\sigma \times B)^{\mathrm{SM}} = 1.29^{+0.39}_{-0.34}$
    - First measurement for higher p_T(H)
  - **p_T(H) < 200 GeV and m_{jj} > 1500 GeV**
    - $(\sigma \times B)^{\mathrm{meas}}/(\sigma \times B)^{\mathrm{SM}} = 0.12^{+0.34}_{-0.33}$
    - Most precise measurement for lower p_T(H)
- STXS ttH 3 bins: statistically limited→ upper limits
  - ~25% improvement on ttH **inclusive** measurement in the signal strength



H→ττ measurement: results (differential)







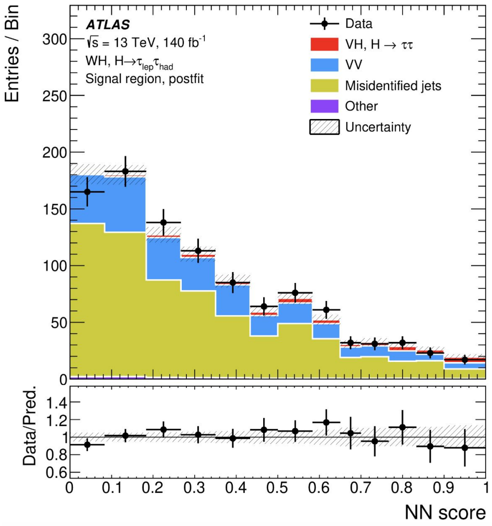
- Fitted $m_{\tau\tau}^{MMC}$ in all bins of the differential distributions
- Results of all bins in **differential fiducial phase space** in good agreement with the SM expectations
- **SMEFT interpretation**:

$$\sigma_{\text{SM+EFT}} \propto |\mathcal{M}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{M}_i|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2\sum_i \frac{c_i}{\Lambda^2}\mathcal{R}(\mathcal{M}_{\text{SM}}^*\mathcal{M}_i) + \sum_{i,j}\frac{c_i c_j}{\Lambda^4}\mathcal{R}(\mathcal{M}_i^*\mathcal{M}_j)$$

  - $C_{H\tilde{W}}: [-0.31, +0.88]$ for Λ = 1 TeV ⟶ tightest to the date from any channel

V(lep)H→$\tau\tau$ measurement

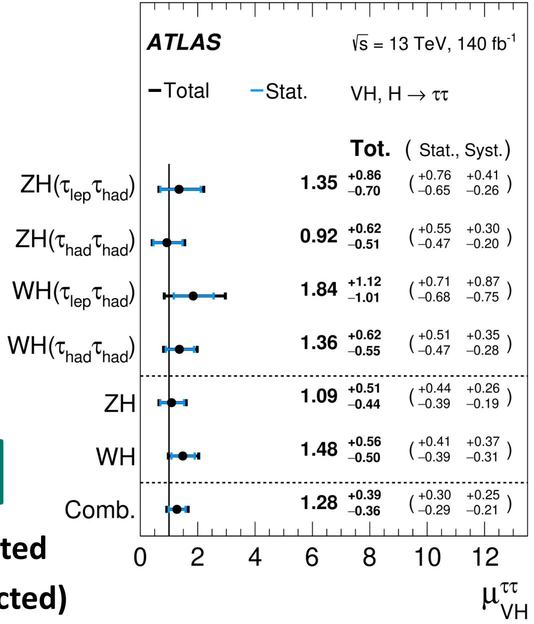
- Aim to **measure** cross-section of Higgs boson production in association with a **vector boson that decays leptonically,** with ***H→ττ* decaying into $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$** using the full Run-2 dataset (Phys. Lett. B 855 (2024) 138817)
  - VH and *H→ττ* processes already measured separately using Run-2 data
- Four final states: **ZH($\tau_{lep}\tau_{had}$), ZH($\tau_{had}\tau_{had}$), WH($\tau_{lep}\tau_{had}$)** and **WH($\tau_{had}\tau_{had}$):**
  - **WH($\tau_{lep}\tau_{had}$)** further split depending on: **ee, e*μ*, *μμ***
  - $H\to\tau_{lep}\tau_{lep}$ excluded to preserve orthogonality with other analyses



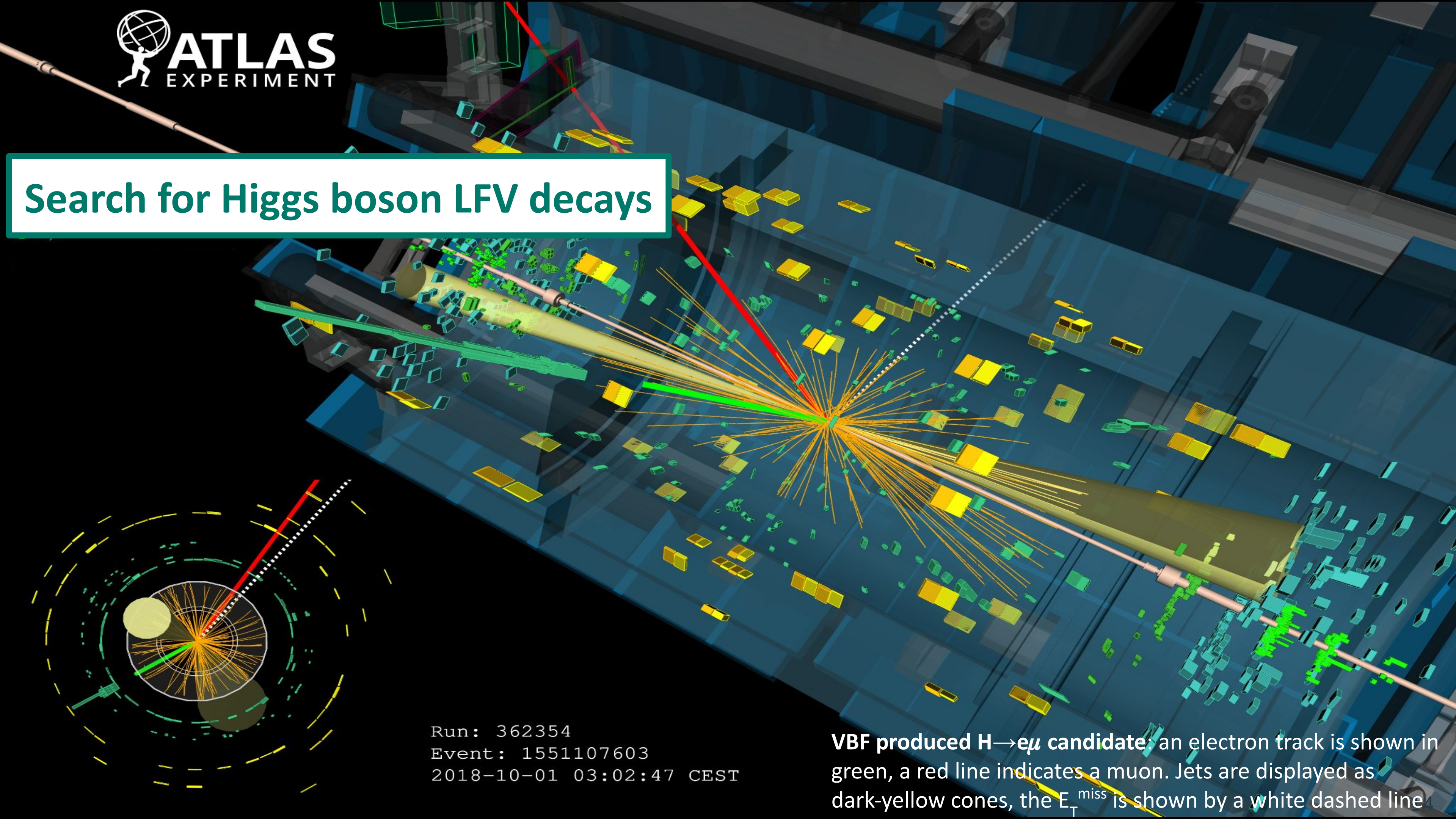
- Signal yields extracted from binned maximum likelihood fit to **NN classifier score distributions**
  - **Measured signal strength** relative to the SM prediction:

$$\mu_{VH}^{\tau\tau} = 1.28\,^{+0.39}_{-0.36} = 1.28\,^{+0.30}_{-0.29}\,(\text{stat.})\,^{+0.25}_{-0.21}\,(\text{syst.})$$

- **NN-based** analysis shows an **excess over the expected background** with a **significance of 4.5*σ* (3.5*σ* expected)**

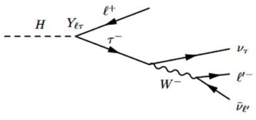


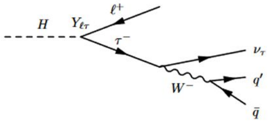
Search for Higgs boson LFV decays



VBF produced H→eμ candidate: an electron track is shown in green, a red line indicates a muon. Jets are displayed as dark-yellow cones, the E_T^{miss} is shown by a white dashed line

Search for H LFV decays





- Lepton flavour violation (LFV) **not allowed** in the **SM**
- In the charged sector one possibility are **LFV Higgs boson decays**: ***H→τe, H→τμ***
  - Separate searches for **eτ** and **μτ, with two channels each (**$\ell\tau_{\ell'}$ and $\ell\tau_{had}$)
- **MVA discriminants** (BDTs and NNs) used to further split signal and backgrounds (Z→ττ, Top and Misidentified objects)
- Statistical fit for signal strength extraction using binned maximum likelihood fit:
  - **1 POI fit**: independent fit for each signal, BR(H→eτ) = 0 when fitting BR(H→μτ) and viceversa
  - **2 POI fit**: simultaneous for BR(H→eτ) and BR(H→μτ)
    - **Compatibility is found to be within 2.3σ with the SM**

Observed(expected) 95% CL upper limits:

BR(H→eτ) = 0.230%($0.118^{+0.047}_{-0.033}$)

BR(H→μτ) = 0.163%($0.089^{+0.036}_{-0.025}$)

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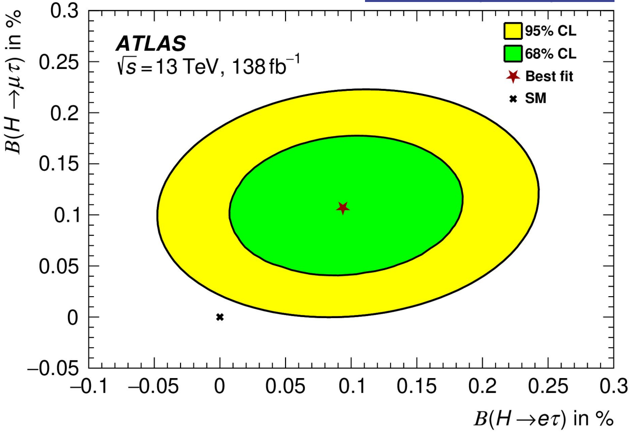

- **Observed limits are more stringent** by a factor of **2.4** and **1.5** in BR(H→eτ) and BR(H→μτ) respectively compared to JHEP 07 (2023) 166 (36 fb^{-1} previous analysis)
  - **Expected limits** improved by a factor of 3.1 and 4.1.

Summary

- Presented latest ATLAS analyses regarding the study of Higgs boson coupling properties to leptons
- **Full Run-2 (139 fb^{-1})** $H\rightarrow\mu\mu$ analysis improved expected sensitivity
  - More categories using BDT scores including specific VH and ttH production
- **"Legacy" Run-2 STXS/Differential** $H\rightarrow\tau\tau$ analysis improved by 8% the total signal strength and 25% ttH signal strength measurement. Provided again most precise VBF Higgs boson production cross-section measurement
  - Finer binning in the STXS strategy
  - New MVA machinery
  - First fiducial differential cross section measurements of $H\rightarrow\tau\tau$ in a VBF enhanced phase space
- **V(lep)**$H\rightarrow\tau\tau$ **measurement** forecasts an important observation of this process of 4.5σ (3.5 expected)
  - Room for further improvement
- No significant excess was observed from **searches for LFV Higgs boson decays**
  - Upper limits were significantly tightened

Acknowledgements

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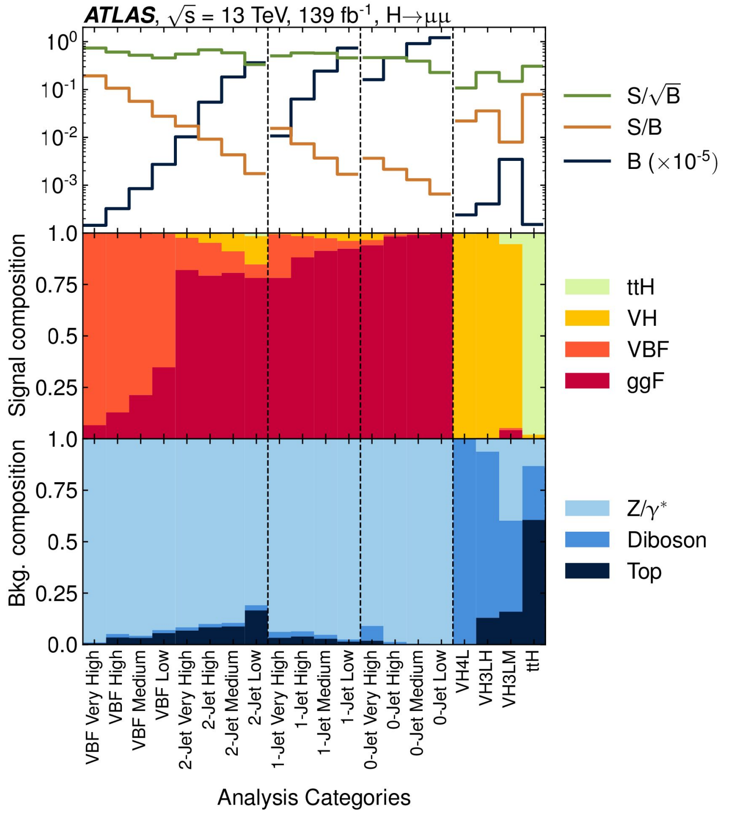
  - FPU2021 grant funded by MICIU/AEI /10.13039/501100011033 and by the FSE+
  - Grants PID2021-124912NB-I00 and PID2021-125069OB-100 funded by MCIN/AEI/10.13039/501100011033
  - Project ASFAE/2022/008 funded by MCIN, by the European Union NextGenerationEU (PRTR-C17.I01) and Generalitat Valenciana

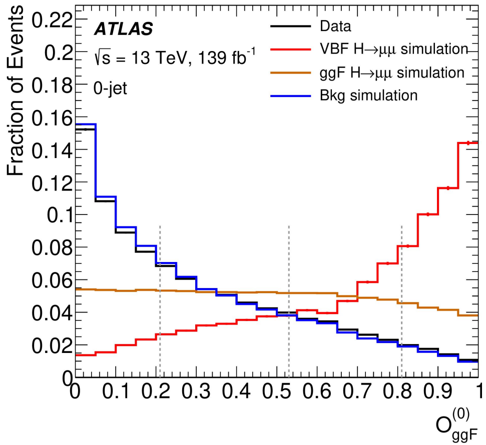
Additional material

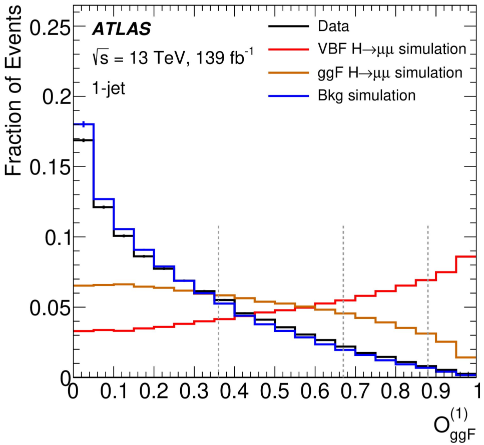
H→μμ search: analysis strategy

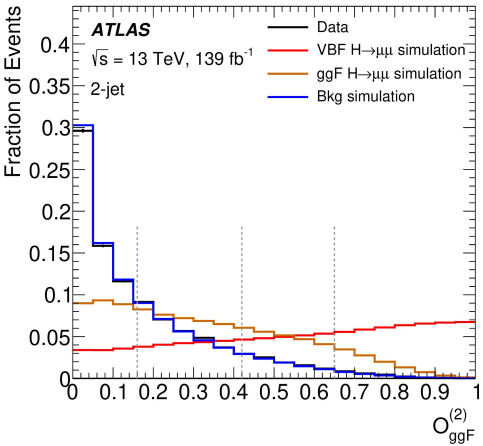
- Two oppositely charged, isolated and well identified muons
- Events classified into **20 mutually exclusive categories** defined to maximise sensitivity using **BDT discriminants**
  - First test for ttH category (b-jet + extra lepton)
    - 1 BDT: ttH vs. backgrounds
  - If not, test for VH categories (1+ extra leptons + b-jet veto)
    - 2 BDTs: 3-leptons targeting WH and 4-lepton targeting ZH
  - Otherwise, **split according to jet multiplicity (0, 1, 2+) and target ggF/VBF productions** explicitly against Drell-Yan production sources
    - 4 BDTs: +2-jets for VBF vs. backgrounds and +2/1/0-jets targeting ggF+VBF against backgrounds

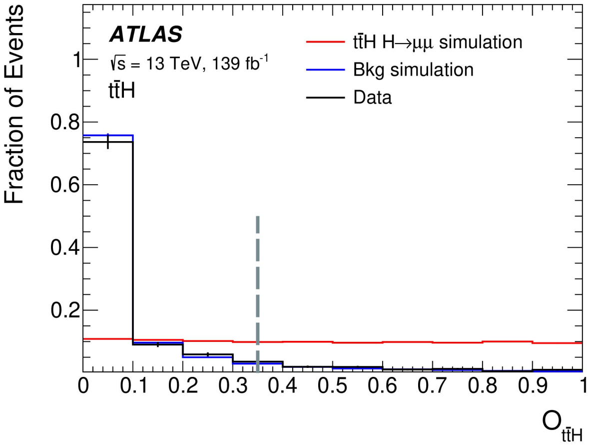


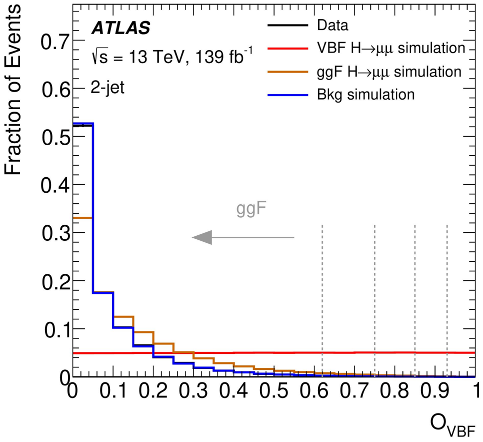
H→$\mu\mu$ search: BDT discriminants





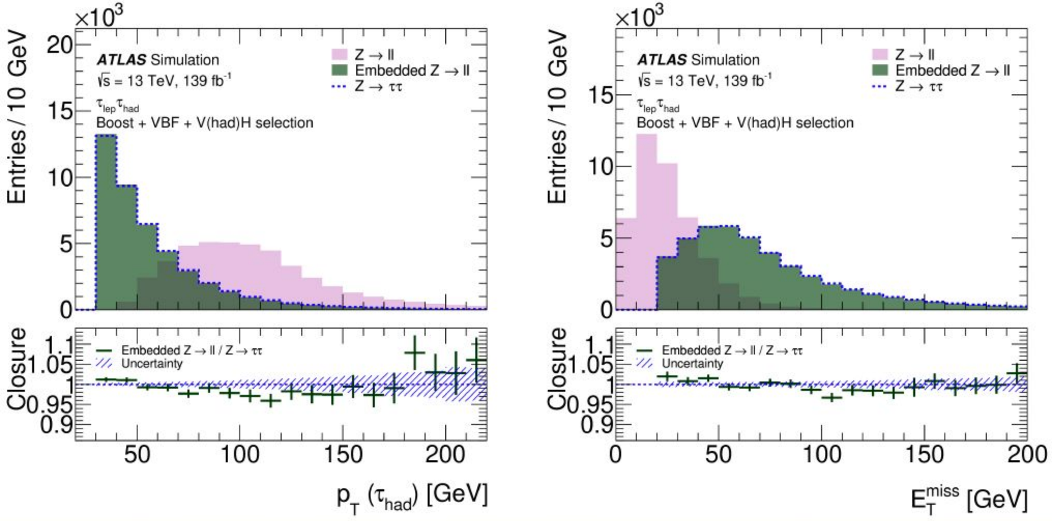






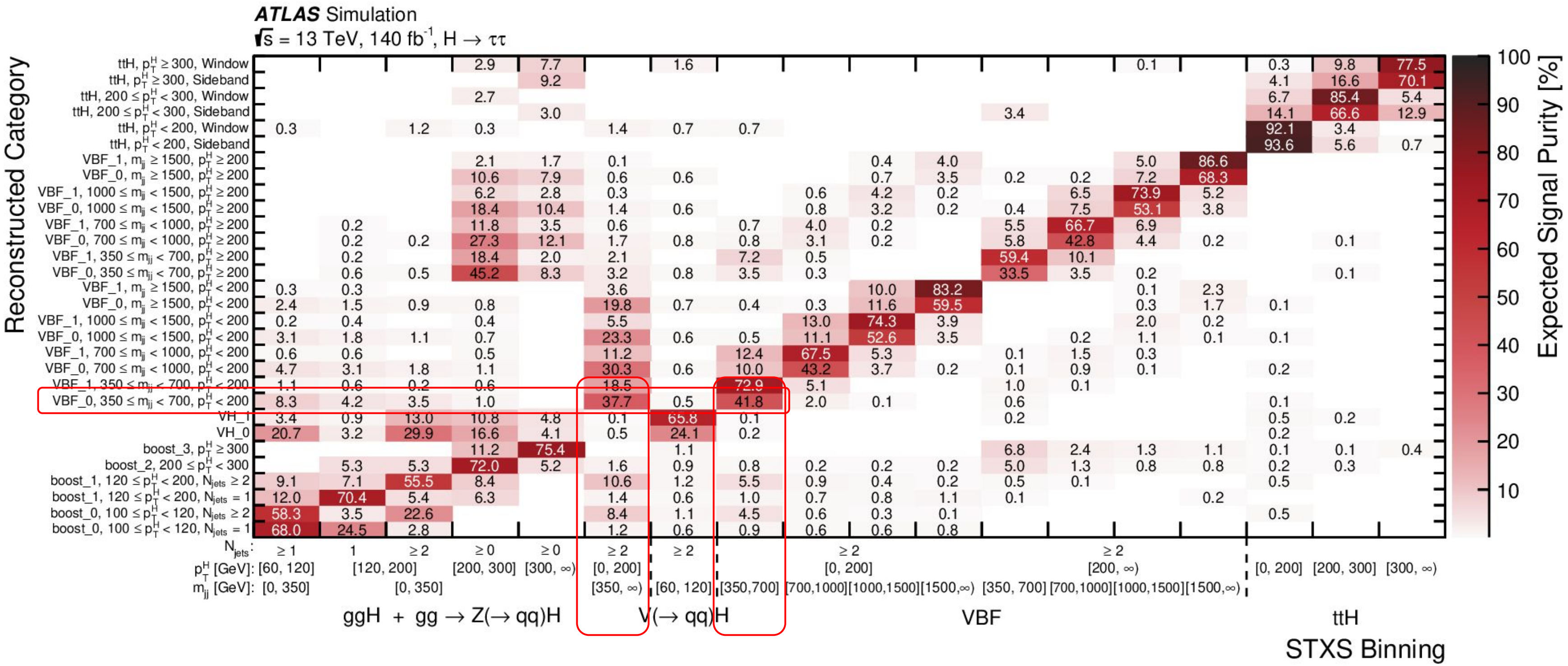
$H\to\tau\tau$ measurement: background estimation

- For this new round, background estimation strategy is mostly inherited from previous analysis
- **$Z\to\tau\tau$ is the largest background.** Object-level-embedding is employed to build control regions out of $Z\to\ell\ell$ events.
  - Kinematic cuts are applied on embedded τ objects that are created by splitting the ℓ into a visible and a neutrino component
  - Each signal region has single bin Z control region to constrain the Z contribution. MC is used to model the $m_{\tau\tau}$ contribution in the SR.
- **Fake leptons background** estimation: same Matrix Method (MM) in the $\tau_e\tau_\mu$ channel as before, and a fake factor derived for $\tau_\ell\tau_h$ and $\tau_h\tau_h$ channels.



H→ττ measurement: STXS - 18 PoI fit

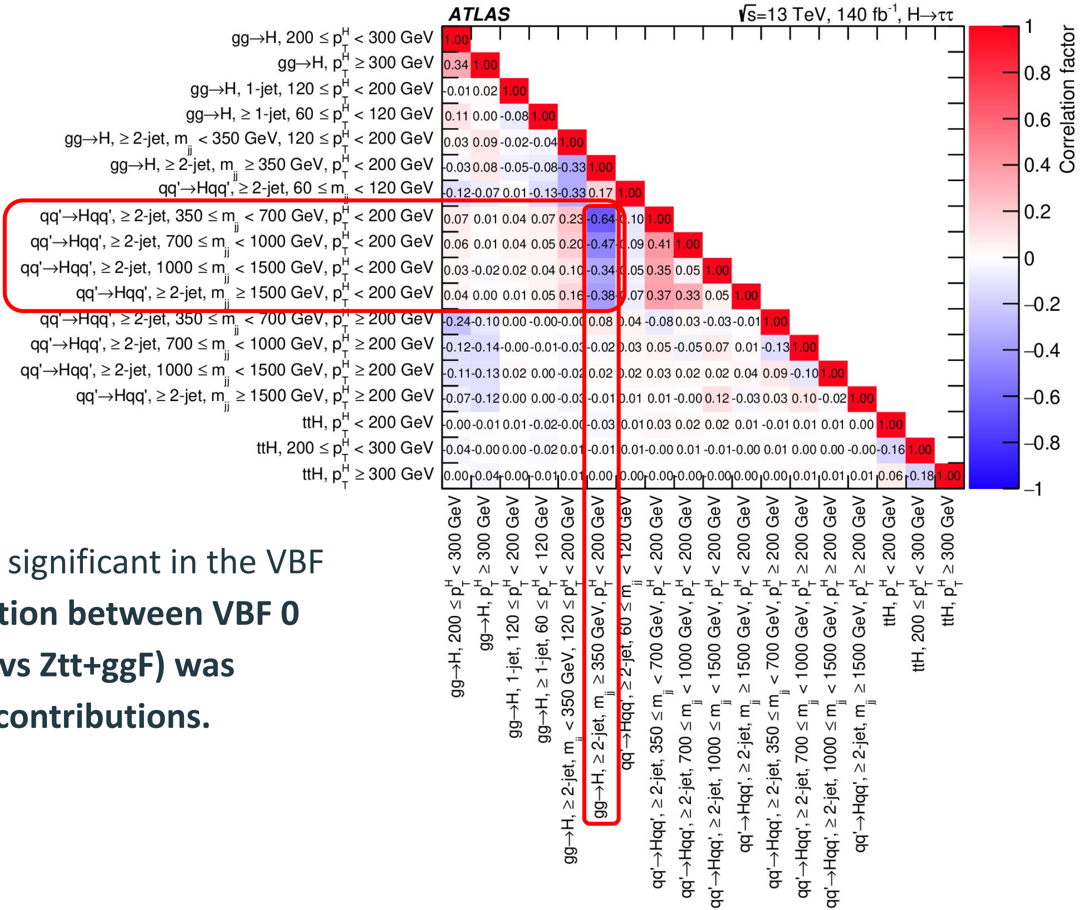
Pre-fit signal purity in each reconstructed category (per bin)



H→ττ measurement: STXS - 18 PoI fit

Correlations between PoIs

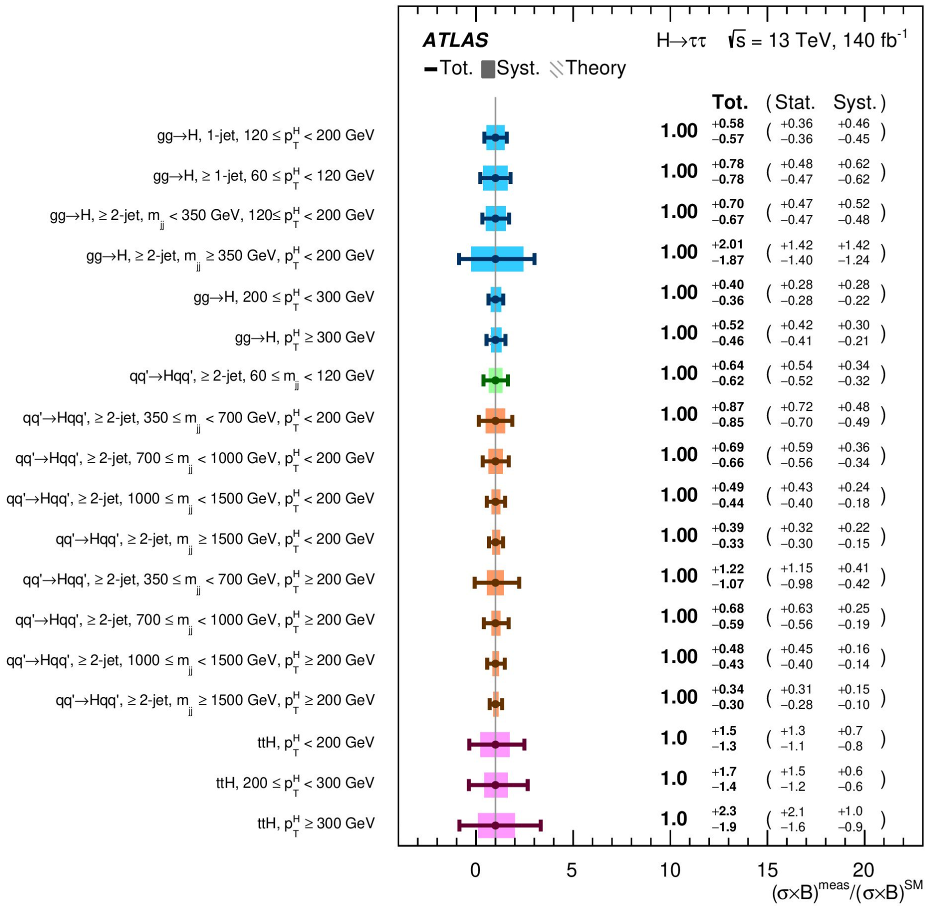
- Significant **VBF-like ggH contribution (ggH+2 jet production with m_{jj} > 350 GeV, p_T^H < 200 GeV)** in **reconstructed level** categories targeting VBF signal
  - Leads to **anti-correlation** in the measurements



- We knew that VBF-like ggH contribution was significant in the VBF 0 SRs. However, **we thought that the separation between VBF 0 and VBF 1 provided by the VBF tagger (VBF vs Ztt+ggF) was enough to isolate efficiently the VBF signal contributions.**

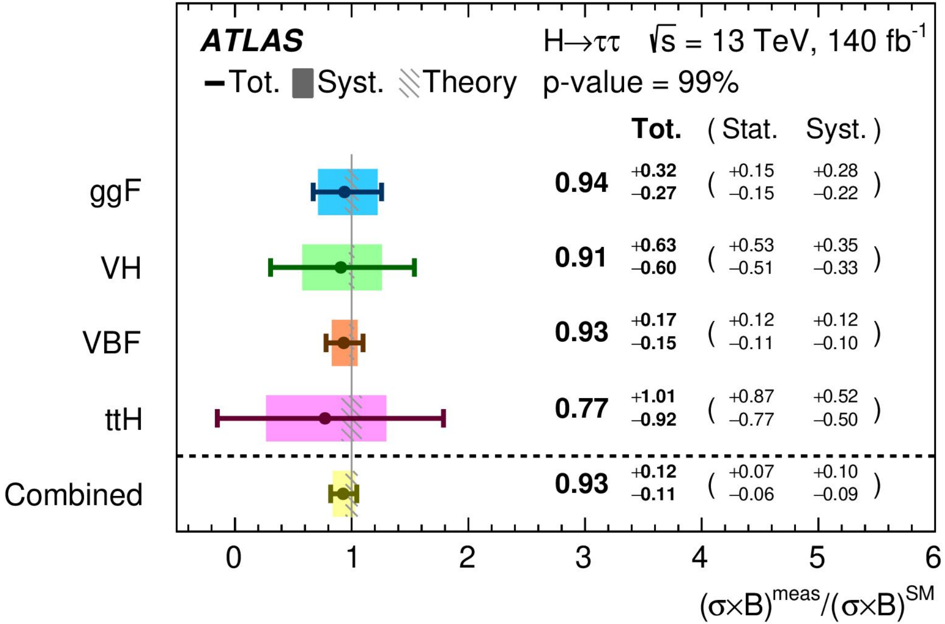
H→ττ measurement: STXS - 18 PoI fit

- **Expected values for the 18 POIs considered for the different STXS bins under study for each Higgs boson production mode**



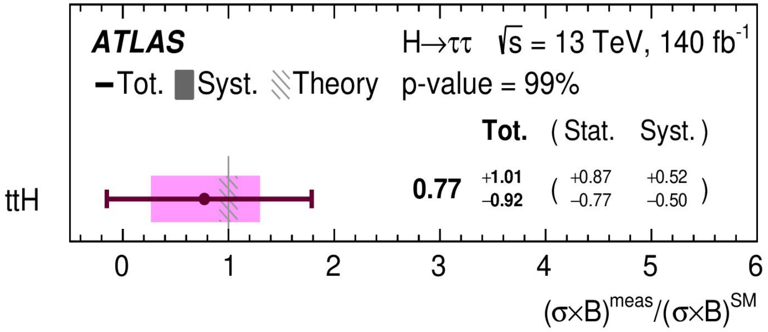
H→ττ measurement: STXS - 4 PoI fit

- **4-PoI fit results, considering a dedicated parameter for each of the four Higgs boson production modes**
- **The "Combined" results corresponds to the 1-PoI fit**

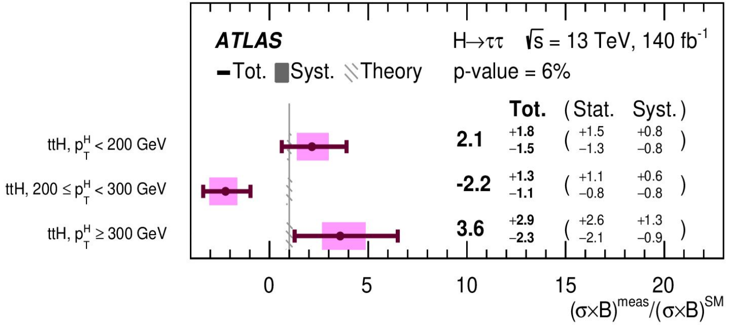


H→ττ measurement - Results for ttH

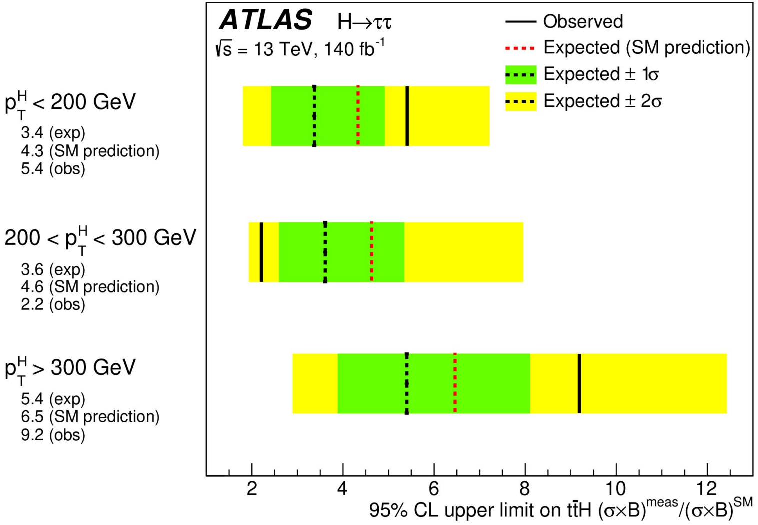
ttH measurement from 4-PoI fit



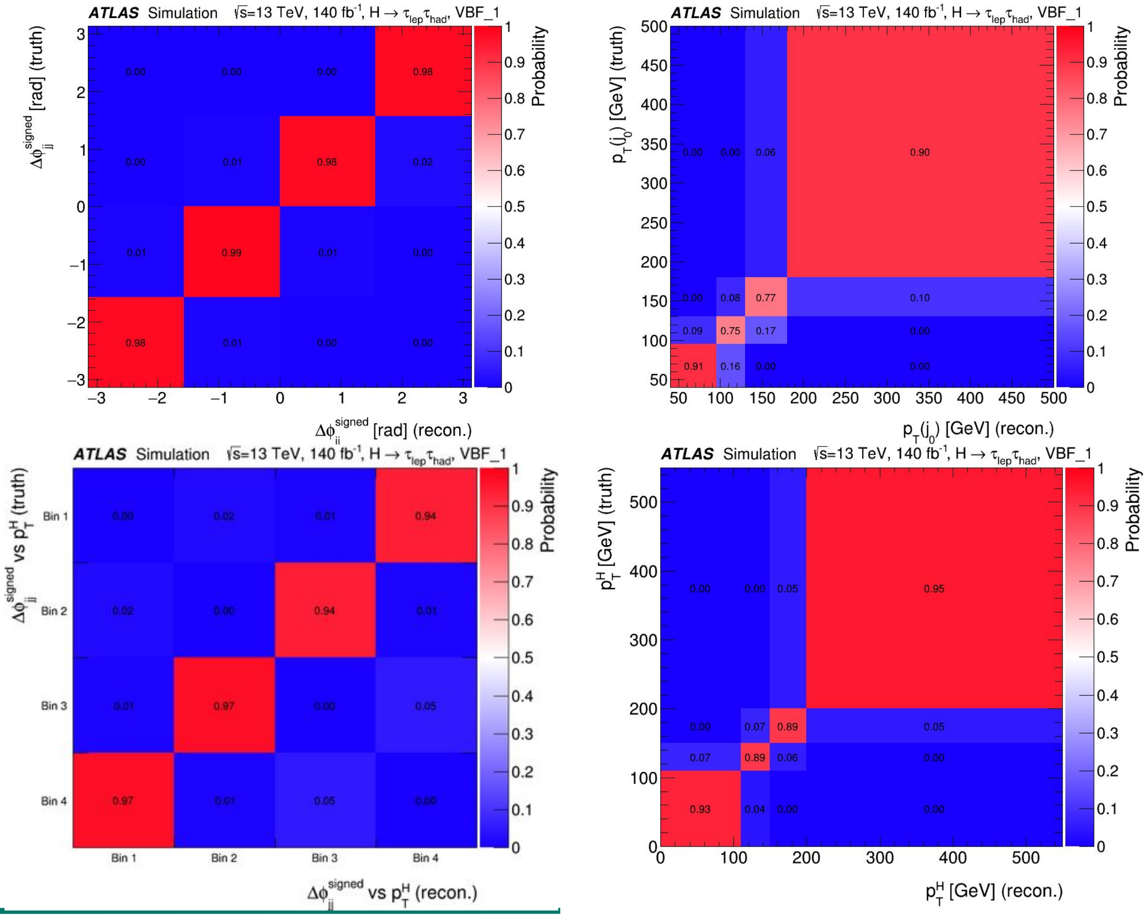
ttH measurement from 18-PoI fit



- **4-PoI fit:** dedicated PoI for each production mode
- **18-PoI fit**: no significant deviations from the SM in ttH STXS bins
  - Limited sensitivity obtained in the fit due to poor statistics.
  - **Upper exclusion limits at 95% CL** were computed:
    - Expected (μ=0): ranging between **~3-5xSM prediction**
    - Expected injecting μ=1: **~4-6xSM prediction**
    - Observed: **~2-9xSM prediction**



H→ττ measurement - Unfolded differential



- **Migration matrices** evaluated from MC simulations of Higgs bosons decaying to $\tau_{lep}\tau_{had}$
- Each matrix element is the probability for a signal event generated in a fiducial truth-bin to be selected in a VBF_1 reconstructed (recon.) bin in the $\tau_{lep}\tau_{had}$ channel

H→ττ measurement - Differential (SMEFT)

- Unfolded distributions are sensitive to BSM effects in VBF Higgs boson production
  - EFT framework parametrizes these potential BSM effects
  - Only dimension-six operators are considered in this analysis
  - Warsaw basis: 3 CP-even and 3 CP-odd operators contribute to Higgs boson interactions with vector bosons

Wilson Coefficient: Strength of the interaction

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_d \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)}, \text{ for } d > 4 .$$

- The change in the cross-section for each Wilson coefficient in each kinematic bin k:

Purely new physics

$$\sigma^k_{\rm SM+EFT} = \sigma^k_{\rm SM}\left(1 + \alpha_{ik}\frac{c_i}{\Lambda^2} + \beta_{ik}\left(\frac{c_i}{\Lambda^2}\right)^2\right)$$

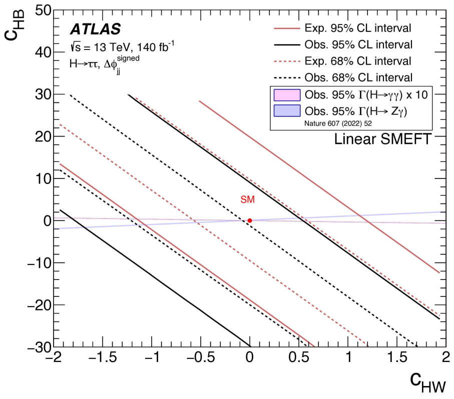
SM interference with new physics

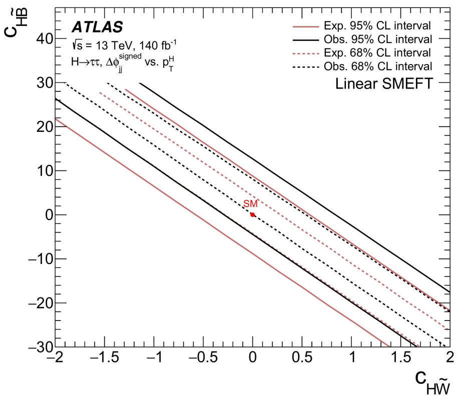
- Operators that directly affect the interactions between Higgs Boson and the vector bosons, in the Warsaw basis of the SMEFT formalism:

	CP-even		
Operator $O_i^{(d=6)}$	$H^\dagger H W^n_{\mu\nu} W^{n\mu\nu}$	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	$H^\dagger \tau^n H W^n_{\mu\nu} B^{\mu\nu}$
Wilson coefficient	c_{HW}	c_{HB}	c_{HWB}
	CP-odd		
Operator $O_i^{(d=6)}$	$H^\dagger H \tilde{W}^n_{\mu\nu} W^{n\mu\nu}$	$H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu}$	$H^\dagger \tau^n H \tilde{W}^n_{\mu\nu} B^{\mu\nu}$
Wilson coefficient	$c_{H\tilde{W}}$	$c_{H\tilde{B}}$	$c_{H\tilde{W}B}$

H→ττ measurement - Differential (SMEFT)

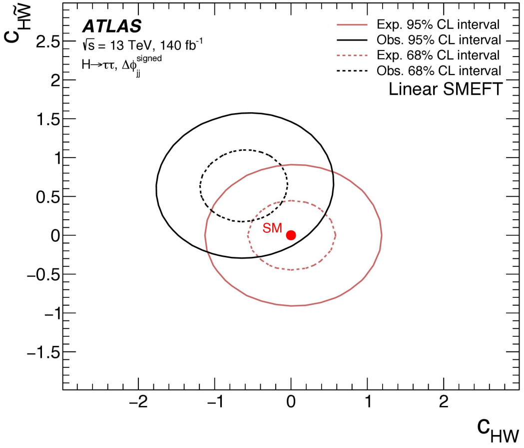
- In the case where two operators are non-zero, a plane of two Wilson coefficients is defined.





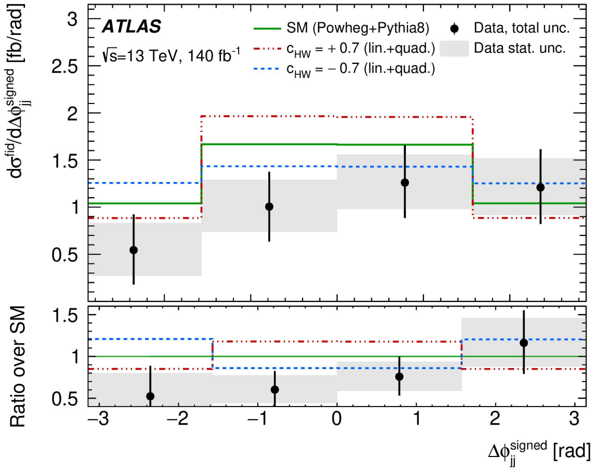
- The effect of the c_{HW} and c_{HB} coefficients is very similar, resulting in a "flat direction" where the two Wilson coefficients cancel each other out, leading to **no sensitivity from the analysis**

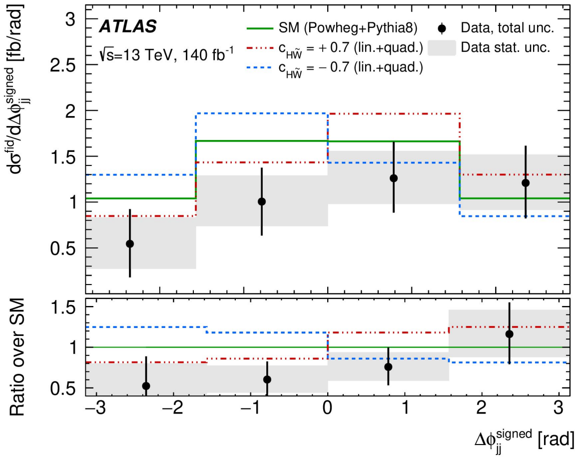
- In this case of $c_{H\hat{W}}$ vs c_{HW}, they introduce different shape differences to the $\Delta\phi_{jj}^{signed}$ distribution such that there are no flat directions.

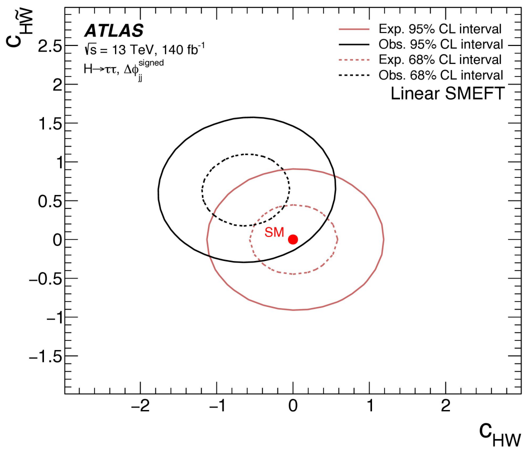


$H \to \tau\tau$ measurement - Differential (SMEFT)

- In this case of $c_{H\hat{W}}$ vs c_{HW}, **they introduce different shape differences to the $\Delta\phi_{jj}^{signed}$ distribution** such that there are no flat directions.







Search for H LFV decays: MVA categorization

symmetry-based leplep	MC-based leplep	MC-based lephad
Neural Networks, keras	Boosted Decision Trees, TMVA	
$e\tau$ and $\mu\tau$ trained together		separate BDT for $e\tau$ and $\mu\tau$
separate NN/BDT per region (nonVBF, VBF)		
# input vars: 18 (nonVBF), 27 (VBF)	# input vars: 15 (nonVBF), 23 (VBF)	# input vars: 12 (nonVBF), 14 (VBF)
1 NN for nonVBF w/ 3 classes: signal, symm.bkg., fakes, 3 NNs for VBF: sig vs $Z\rightarrow\tau\tau$+MCfakes+$H\rightarrow\tau\tau$, signal vs top+diboson+H→WW, signal vs fakes	3 BDTs for both regions: sig vs $Z\rightarrow\tau\tau + Z\rightarrow\ell\ell + H\rightarrow\tau\tau$, signal vs top+diboson+H→WW, signal vs fakes	3 BDTs for nonVBF $e\tau$: signal vs $Z\rightarrow\tau\tau$ signal vs fakes signal vs rest, 2 BDTS for rest: signal vs $Z\tau\tau$, signal vs rest
nonVBF: use sig node distr. in fit, VBF: combine 3 NNs linearly with coefficients c_i, use resulting distr. in fit	combine 3 BDTs linearly with coefficients c_i for each region, use resulting distr. in fit	combine 3/2 BDTs linearly(quadratically) with coefficients c_i for nonVBF(VBF), use resulting distr. in fit