Measurements and searches of Higgs boson decays to two fermions and of Higgs boson production in association with a ttbar pair at the ATLAS experiment

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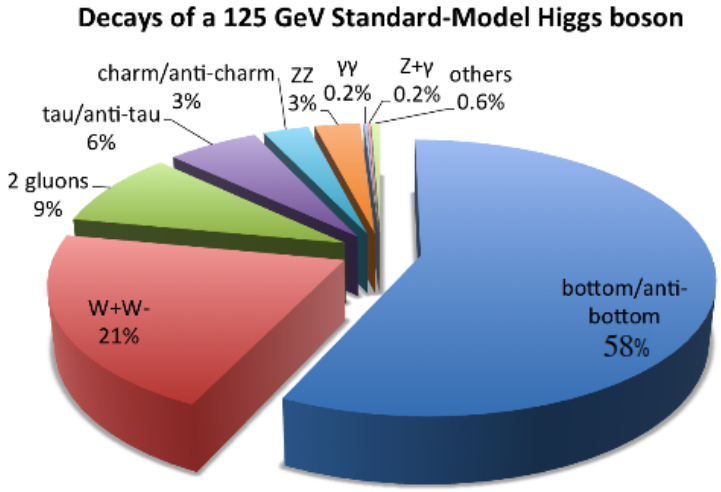
Testing the couplings of the Higgs boson to fermions

$H \to$ fermions represent $\sim 70\%$ of the Higgs decays.



Outline:

- coupling to third generation fermions:
  - $t\bar{t}H$, $H \to b\bar{b}$, $H \to \tau\tau$
- going beyond, simplified template cross section
  - reinterpretation of VH,$H \to b\bar{b}$ and $H \to \tau\tau$
- searches for couplings with second generation fermions
  - $H \to c\bar{c}$, $H \to \mu\mu$
- searches for lepton-flavour-violating decays

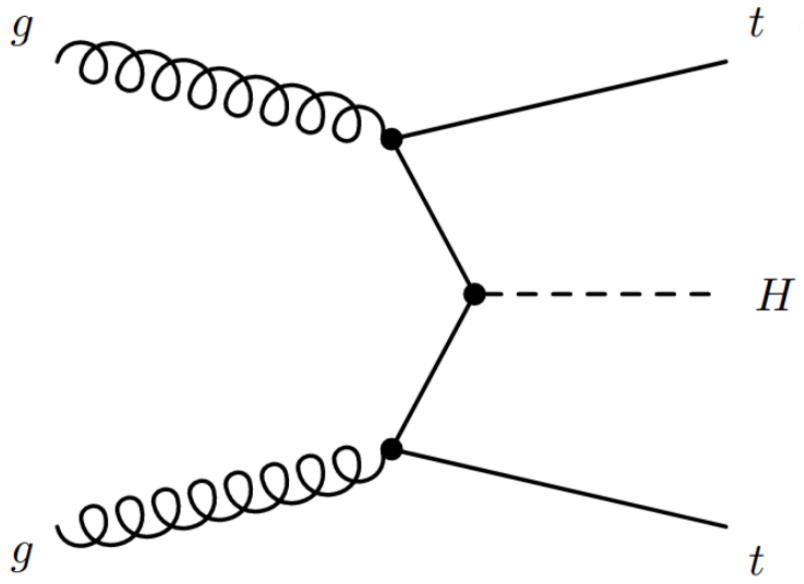
Couplings to third generation fermions

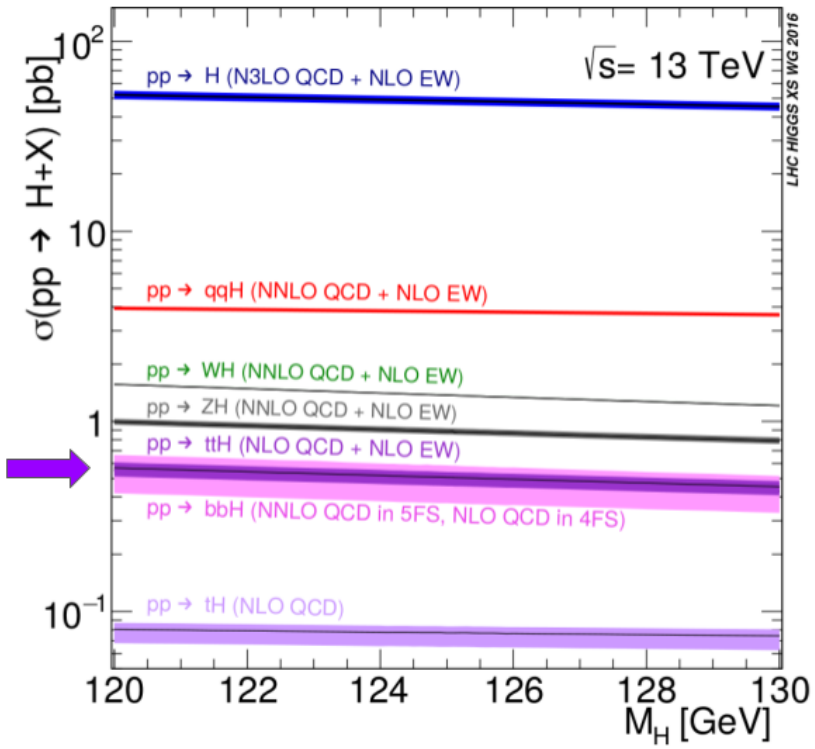
- Measurements of the Higgs coupling to fermions can provide stringent tests of the validity of the SM.
- only coupling to **third generation** fermions can be currently measured

First	Second	**Third**
u	c	**t**
d	s	**b**
e	μ	**τ**
ν_e	ν_μ	ν_τ

$t\bar{t}H$ production

$m_H = 125$ GeV $\Rightarrow$ Higgs to top coupling studied in the associated production





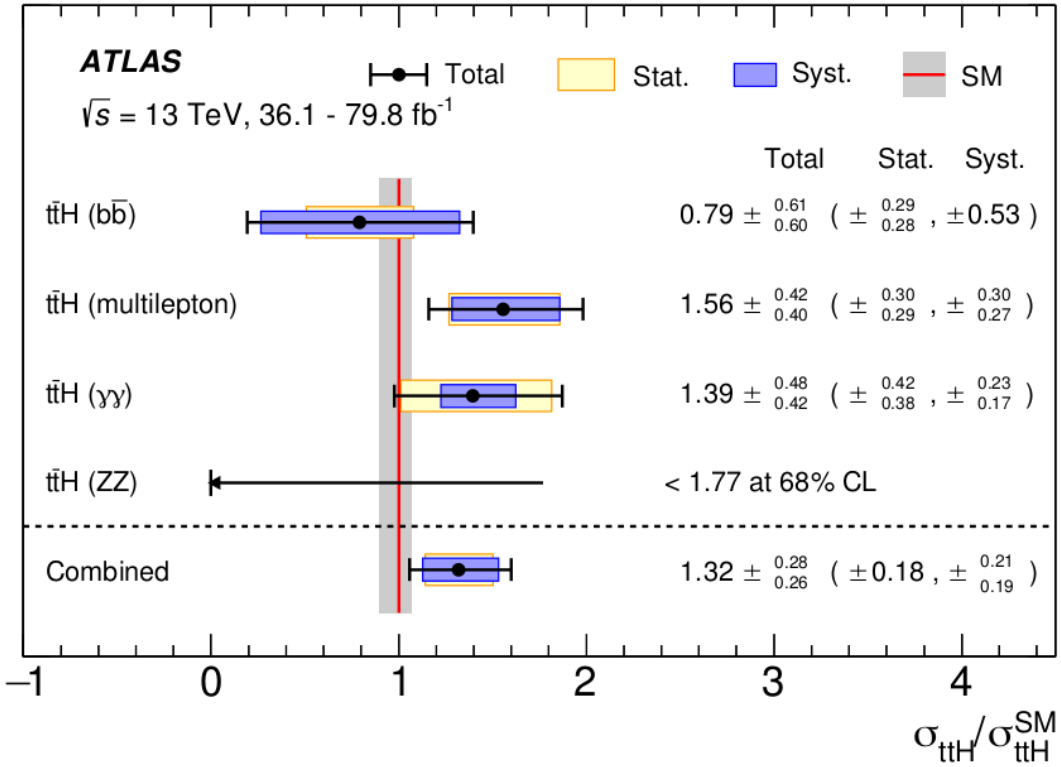
Most favorable production mode for **direct measurement** of top Yukawa coupling

- Complexity: $t\bar{t}H$ two orders of magnitude smaller than total Higgs cross section
- Advantage: distinctive top signature, access to many Higgs decays

Observation of $t\bar{t}H$ with up to 80 fb^{-1}

Combination of:

- $H \to b\bar{b}$ with 36 fb^{-1}
- H multilepton (WW^*, $\tau\tau$, ZZ^*) with 36 fb^{-1}
- $H \to \gamma\gamma$ with 80 fb^{-1}
- $H \to ZZ^* \to 4l$ with 80 fb^{-1}

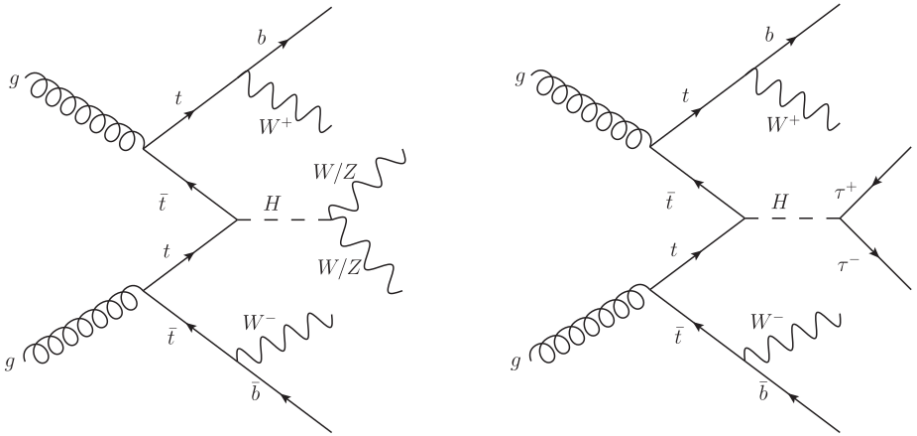


Combination with $t\bar{t}H$ searches at 7 TeV and 8 TeV: 6.3σ (5.1 expected)
$\to$ **direct observation** of Yukawa coupling between Higgs and top

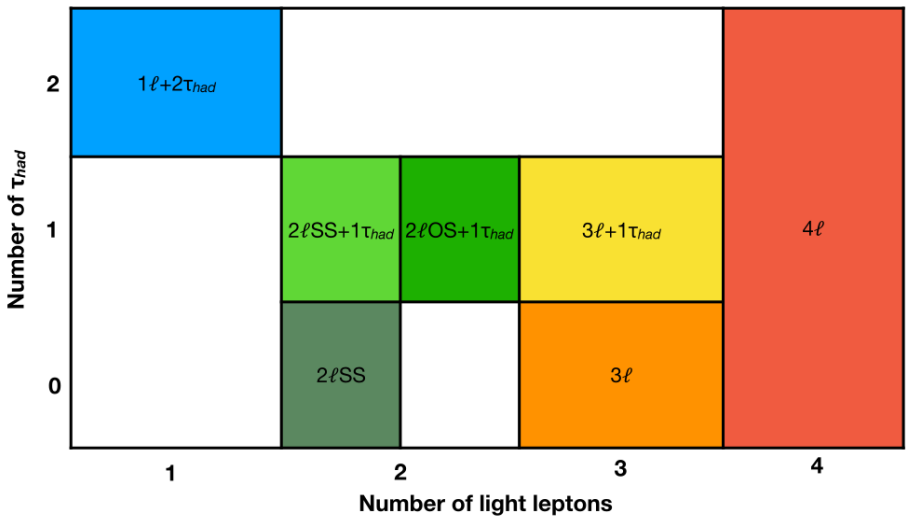
arXiv:1806.00425

$t\bar{t}H$ in multilepton final states with 36 fb^{-1}

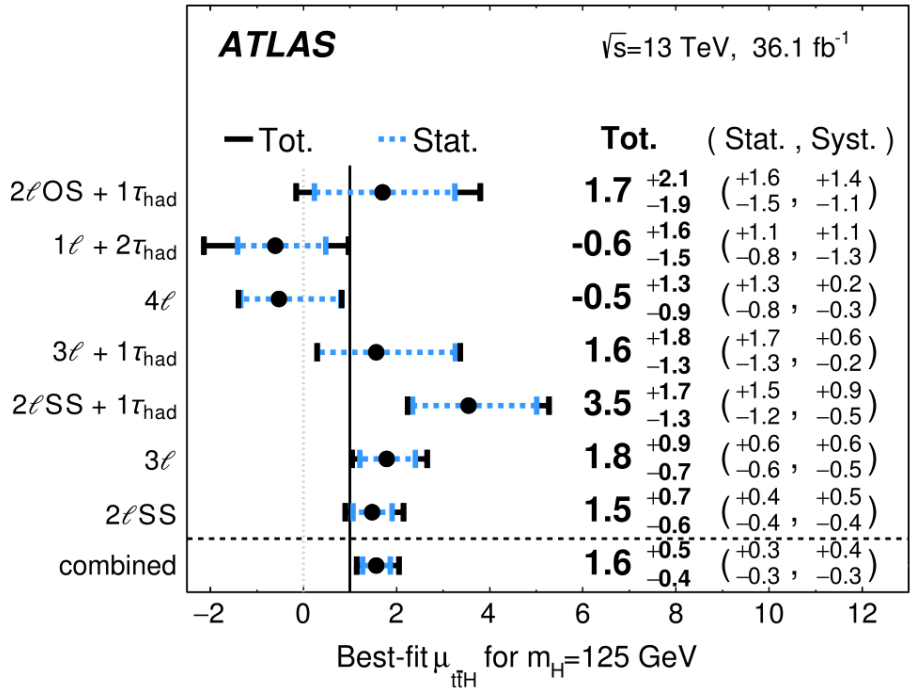
- $H \to WW^*$
- $H \to \tau\tau$
- $H \to ZZ^*$



Events split in seven channels according to the number of selected light leptons and τ_{had} candidates.



SS$\to$ same sign, OS$\to$ opposite sign



Significance: 4.1σ (expected 2.8σ)

arXiv:1712.08891

ttH, $H \to \gamma\gamma$ with 139 fb^{-1}, New!

- One of the first publications with full Run II dataset!
  Only 80 fb^{-1} result included in combination

BDT trained using the E_T^{miss}, photons, leptons and jets kinematic variables and the jets b-tag status.

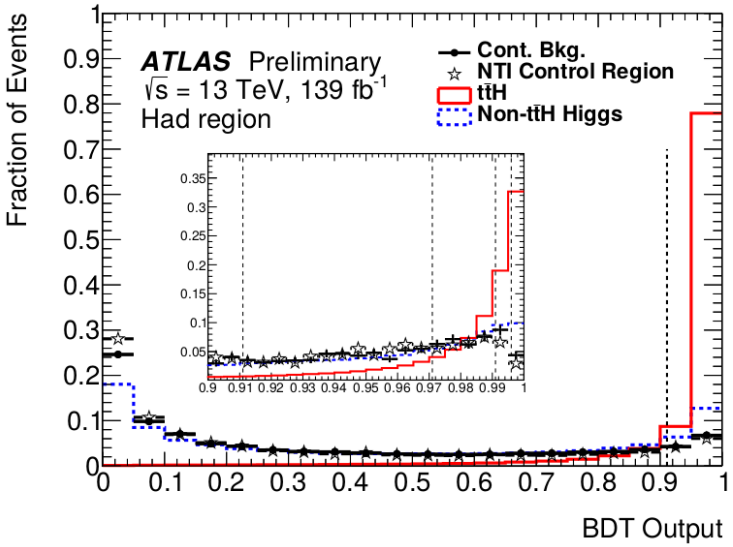
Two regions with dedicated BDT

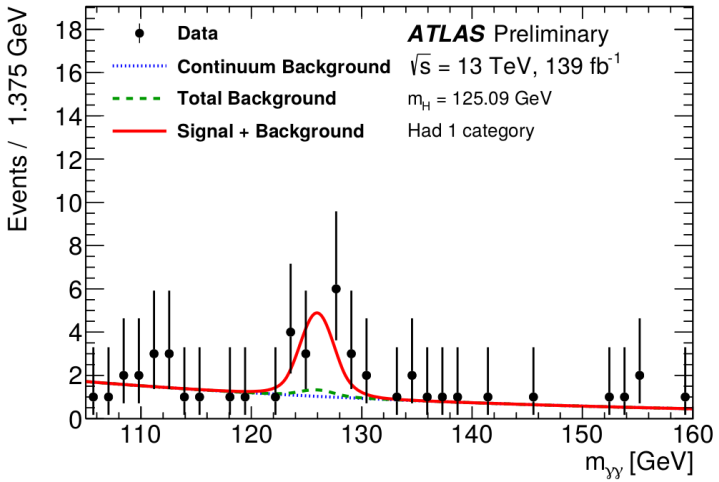
- "Lep" region with at least a W decaying leptonically
- "Had" region for hadronic top decays

Events are further categorised according to the BDT score

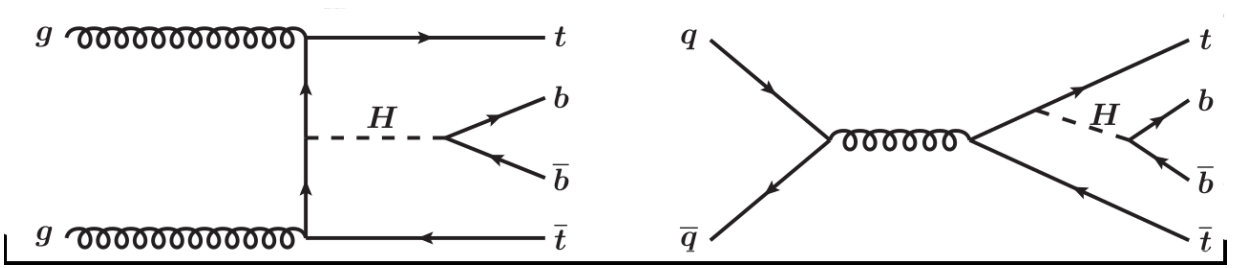
4.9σ observed (4.2σ expected)

▸ ATLAS-CONF-2019-004

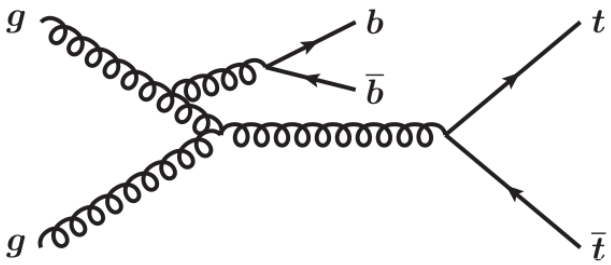




$t\bar{t}H$, $H \to b\bar{b}$ with 36 fb^{-1}



Signal

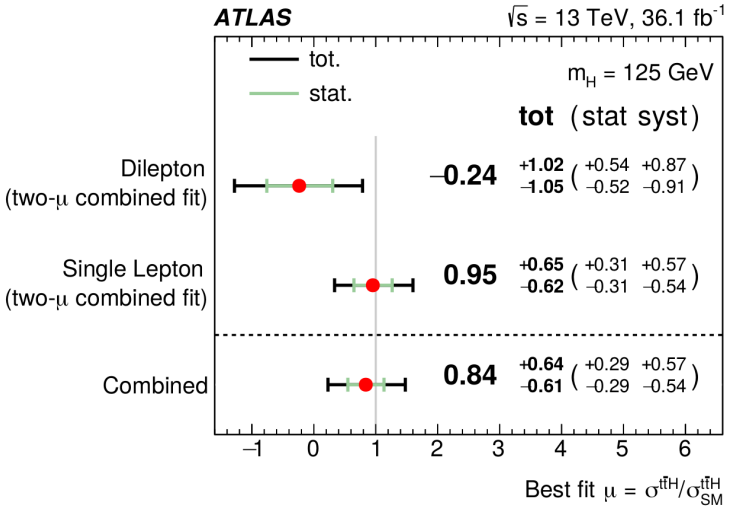


Main background

- one or both top decaying semi-leptonically
- multivariate techniques

Events categorisation:

- number of leptons (one or two)
- number of jets (3 to 6)
- number of b-jets at 4 working points



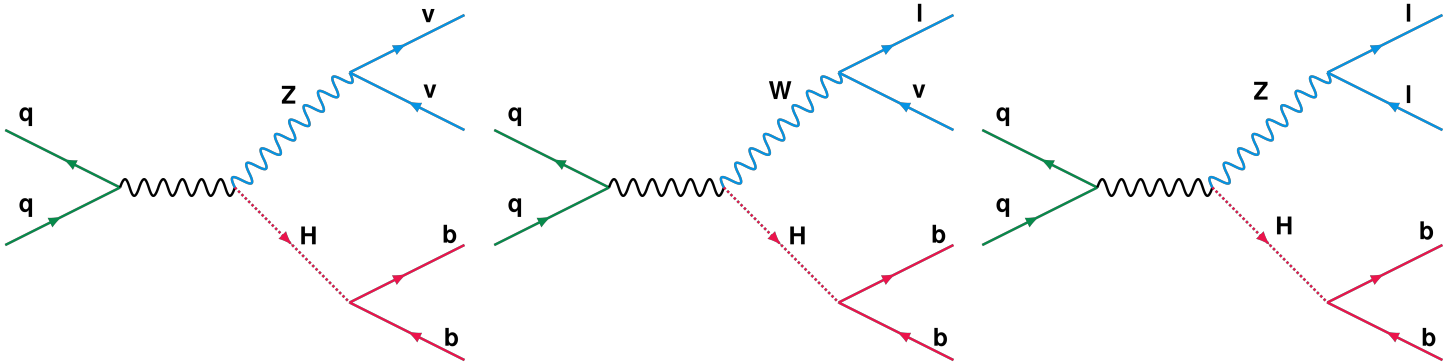
Dedicated "boosted" category for high energy events

1.4σ observed (1.6σ expected) arXiv:1712.08895

dominated by systematic uncertainties (theoretical knowledge of one of the main background, $t\bar{t}+ \geq 1b$)

VH, $H \to b\bar{b}$ with 80 fb^{-1}

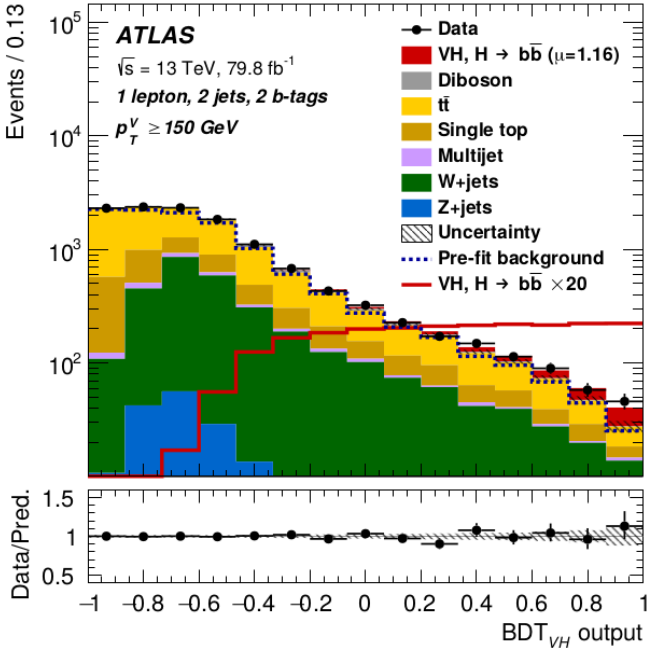
Large BR ($\sim$ 58%) but large multi-jet background $\Rightarrow$ study $H \to b\bar{b}$ decay in associated production $VH, H \to b\bar{b}$



Three selection channels

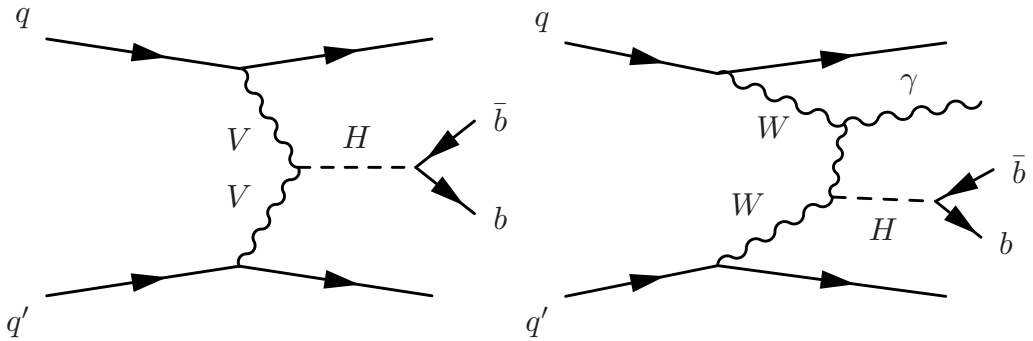
- 0 leptons: $ZH \to \nu\nu b\bar{b}$
- 1 lepton: $WH \to \ell\nu b\bar{b}$
- 2 leptons: $ZH \to \ell\ell b\bar{b}$

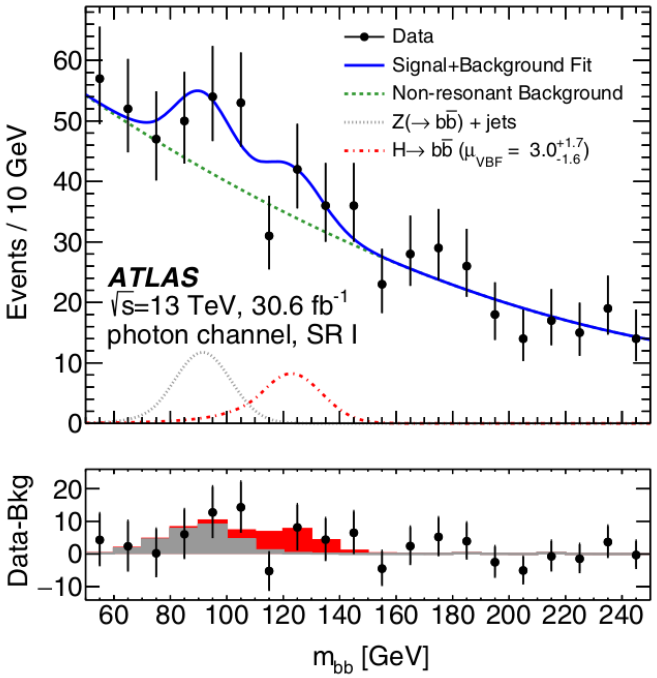
BDT trained in all signal regions and used as final discriminant ▸ arXiv:1808.08238



$H \to b\bar{b}$ in vector boson fusion production with 31 fb^{-1}

Complementary to VH production



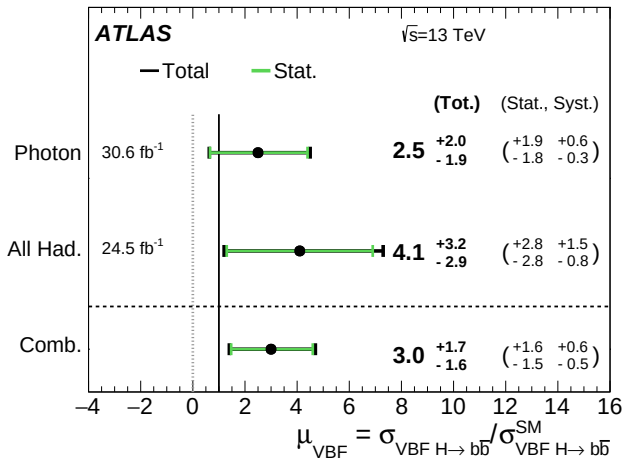


Three channels considered:

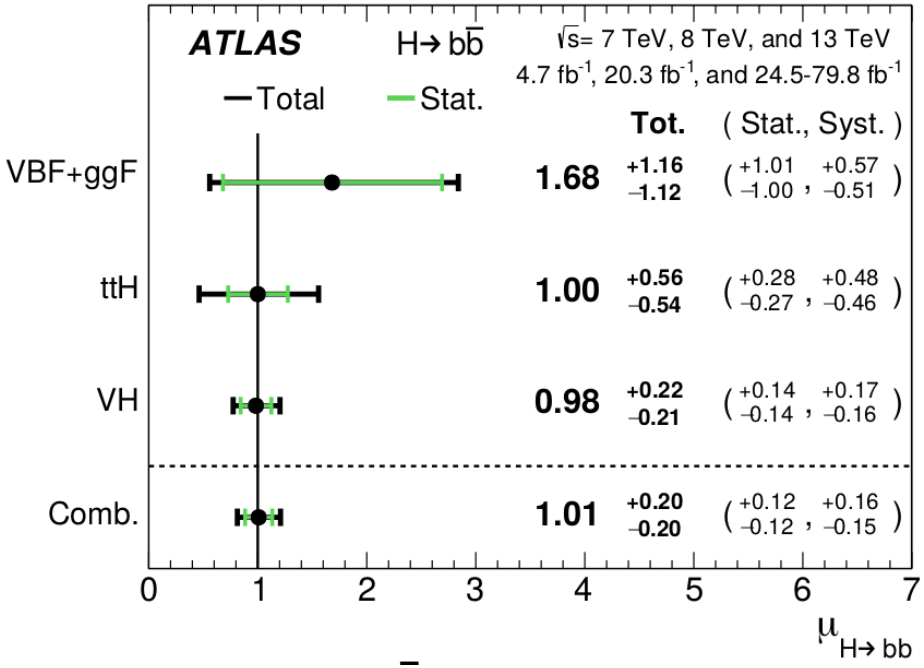
- all hadronic channels:
  - two central jets
  - four central jets
- a photon associated channel

Upper limit on $\sigma \times BR \Rightarrow$ 4.8 times the SM expectation for inclusive production ($2.5^{+1.0}_{-0.7}$ expected) and 5.9 for VBF ($3.0^{+1.3}_{-0.8}$ expected)

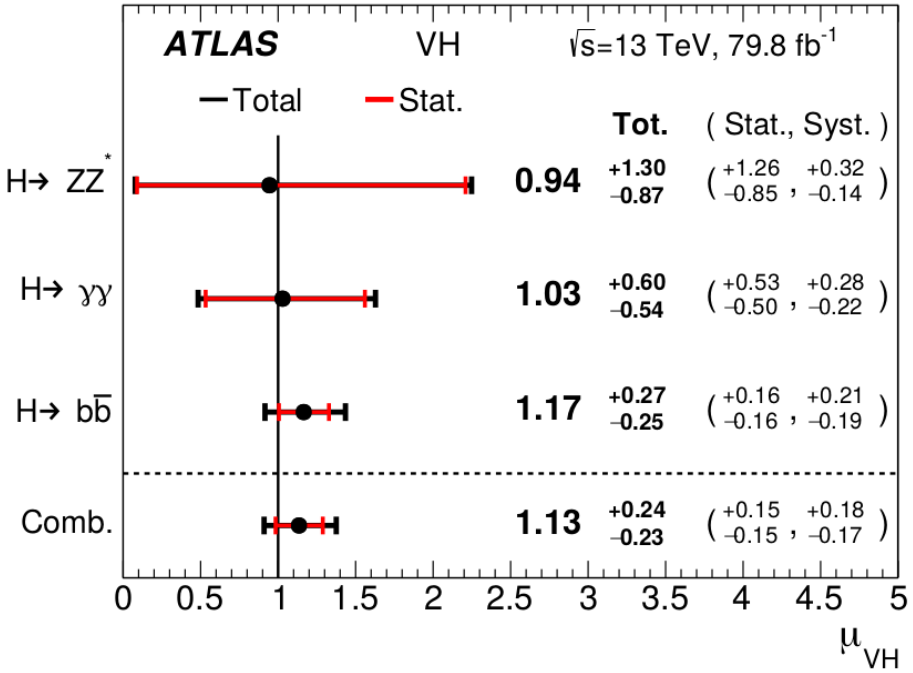
▸ arXiv:1807.08639



VH, $H \to b\bar{b}$ combination



$H \to b\bar{b}$ observation



VH observation

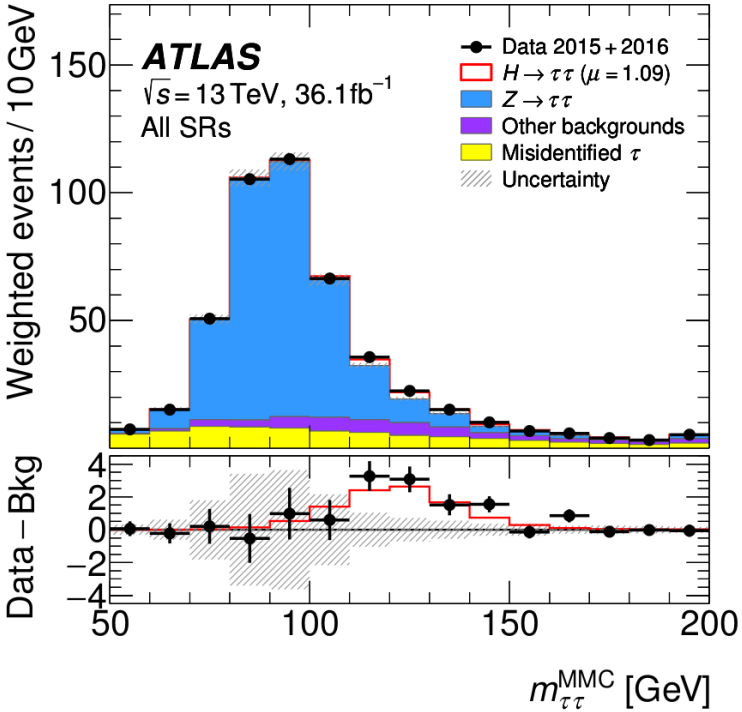
$$\mu = \frac{\sigma_{\text{measured}}}{\sigma_{\text{expected (SM)}}}$$

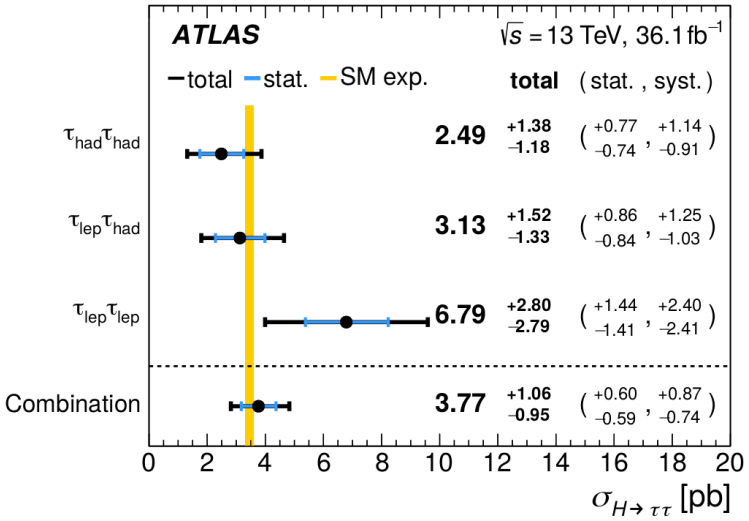
arXiv:1808.08238

$H \to \tau\tau$ with 36 fb^{-1}

- BR $\sim$ 6%
- only currently accessible leptonic decay mode

All combinations of leptonic and hadronic tau decays considered



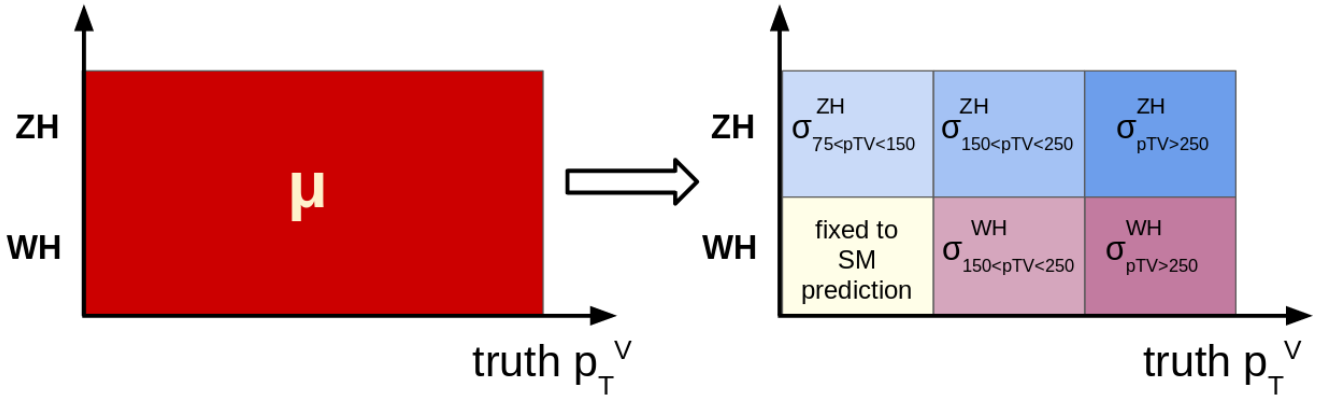


Combination of results at $\sqrt{s} = 13$ TeV with results at 7 and 8 TeV: 6.4σ observed (5.4σ expected) ▸ arXiv:1811.08856

Going beyond, Simplified Template Cross Sections

Proposed at Les Houches 2015 ▸ Proceedings ▸ YR4

Measure **production modes cross-sections** (ggF, VBF, VH, ttH) in exclusive regions defined in fiducial selection → reduced model dependency and maximised **sensitivity to BSM effects**

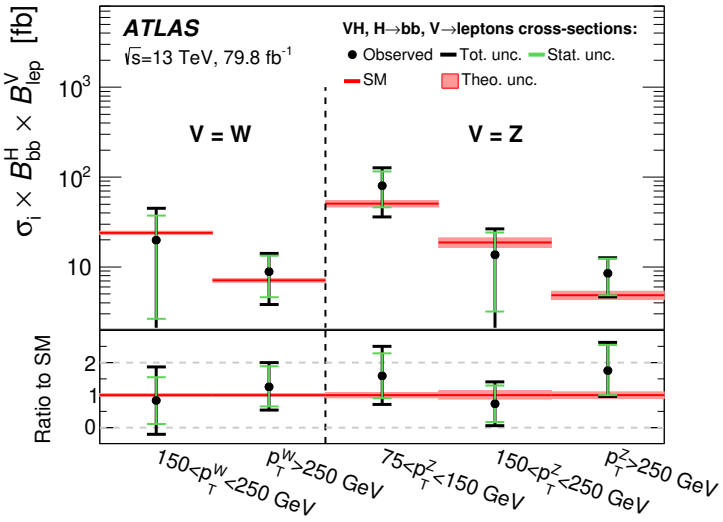


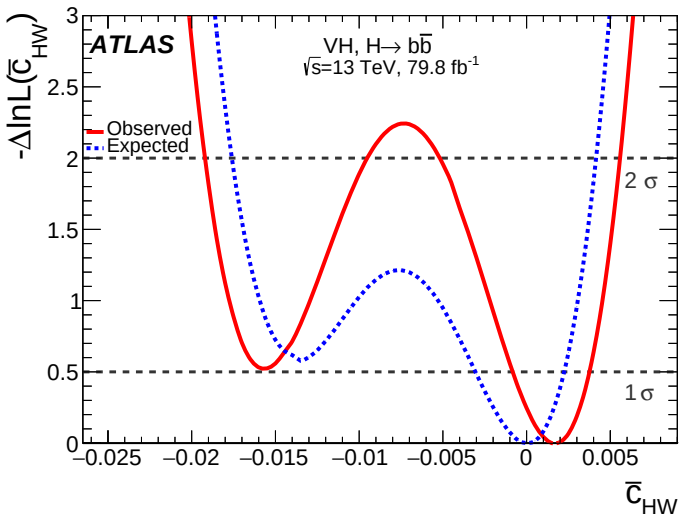
Goals

- probe Higgs properties in more detail
- reduced extrapolation from analysis selection phase space to measurement phase space
- easier to compare with future updated calculations
- easy combination of different decay channels→ increase sensitivity

$VH, H \to b\bar{b}$ in STXS framework with 80 fb^{-1}

Possibility to go beyond the signal strength measurement → STXS





$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \bar{c}_i^{(6)} O_i^{(6)}$$

Beyond the Standard Model (BSM) effects parameterised with an effective lagrangian. STXS measurements set limits on the lagrangian parameters

▸ arXiv:1903.04618 ▸ theoretical uncertainties evaluation

In $H \to \tau\tau$ a three-dimensional fit was performed in the STXS framework (VBF cross section in one region and ggF cross sections in two exclusive regions of phase space) ▸ arXiv:1811.08856

Couplings to second generation fermions

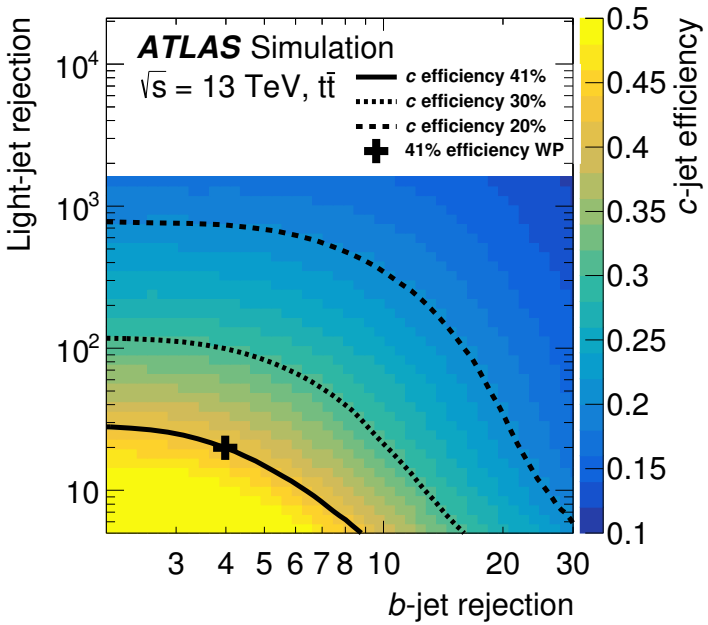
- couplings to **second generation** fermions expected to be much smaller w.r.t third generation fermions
- some BSM scenarios predict deviations of 2nd generation couplings **as** the Yukawa coupling is so small

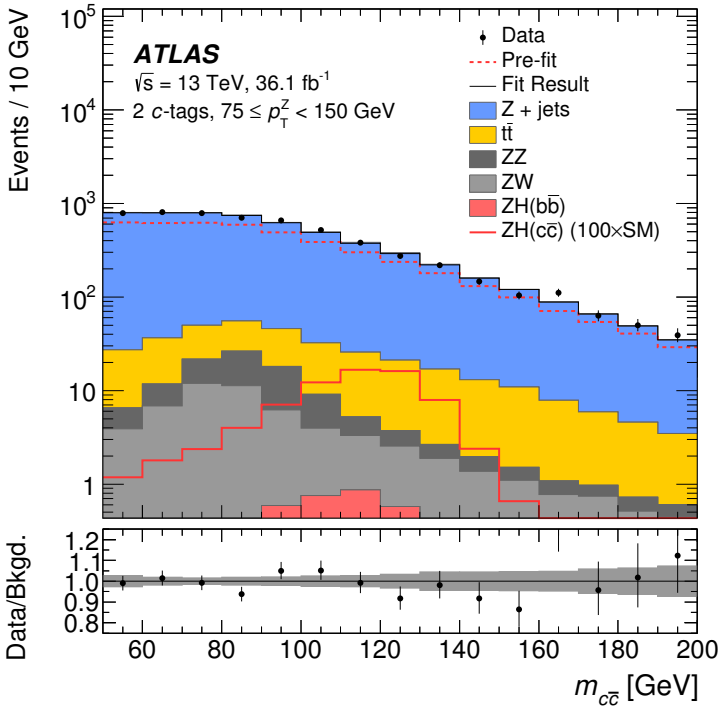
First	**Second**	Third
u	c	**t**
d	s	**b**
e	μ	**τ**
ν_e	ν_μ	ν_τ

$H \to c\bar{c}$ with 36 fb^{-1}

Challenging measurement at hadron colliders

- small branching fraction ($\sim 3\%$)
- large backgrounds $\to$ study the associated production $ZH \to l^+l^-c\bar{c}$
- challenging c-tagging



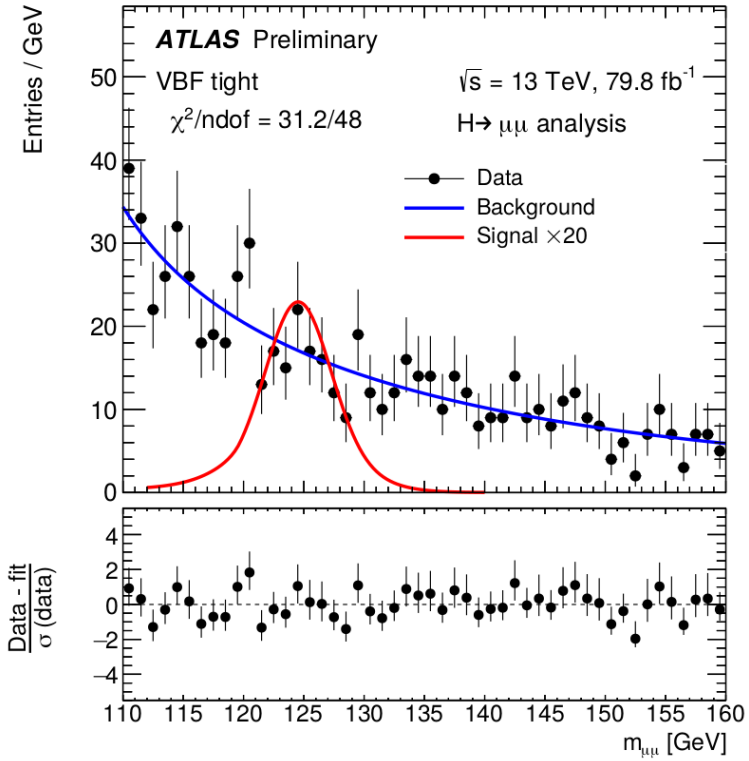


Observed upper limit on $\sigma(pp \to ZH) \times B(H \to c\bar{c})$ is 2.7 pb (expected SM value: 26 fb) ▸ arXiv:1802.04329

$H \to \mu\mu$ with 80 fb^{-1}

- BR($H \to \mu\mu$)$\sim 2.2 \times 10^{-4} \Rightarrow$ rare decay but clear signature
- Only way to directly measure couplings between a Higgs boson and second generation fermions at LHC

Events split with MVA discriminant to target VBF and ggF production



Observed upper limit on $\sigma \times BR \Rightarrow$ 2.1 times the SM prediction.
Dominated by statistical uncertainty ▸ ATLAS-CONF-2018-026

Higgs lepton-flavour-violating decays with 36 fb^{-1}, new!

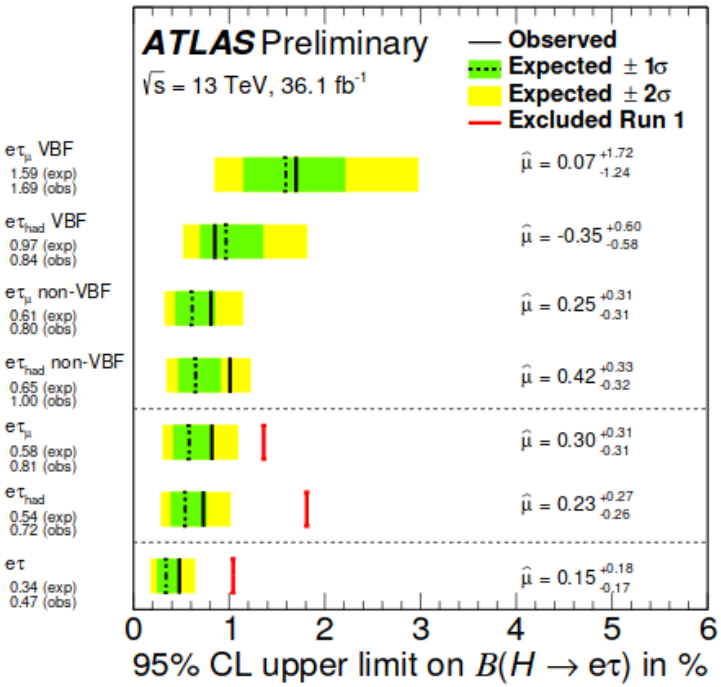
	e	μ	τ
e	SM	LFV	LFV
μ		SM	LFV
τ			SM

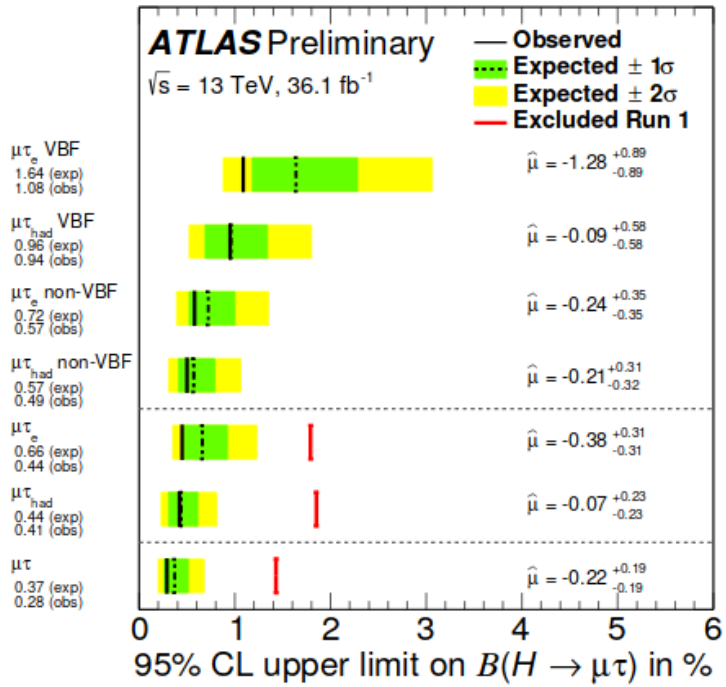
Serch for $H \to e\tau$ and $H \to \mu\tau$

No significant excesses over the SM predictions

observed (expected) 95% CL upper limits on the branching ratios

- $H \to e\tau$ 0.47% ($0.34^{+0.13}_{-0.10}$%)
- $H \to \mu\tau$ 0.28% ($0.37^{+0.14}_{-0.10}$%)





Conclusions

Many important results reached:

- observation of $H \to bb$
- observation of VH production
- observation of ttH production
- observation of $H \to \tau\tau$

First results within the simplified template cross section framework

- VH with $H \to bb$
- VBF and ggF with $H \to \tau\tau$

All results seem to agree to SM predictions
Many of the analysis presented are **statistically limited**
$\to$ stay tuned for the full Run II results (140 fb^{-1})!