Observation of Higgs boson production in association with a ttbar pair

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on behalf of the ATLAS Collaboration
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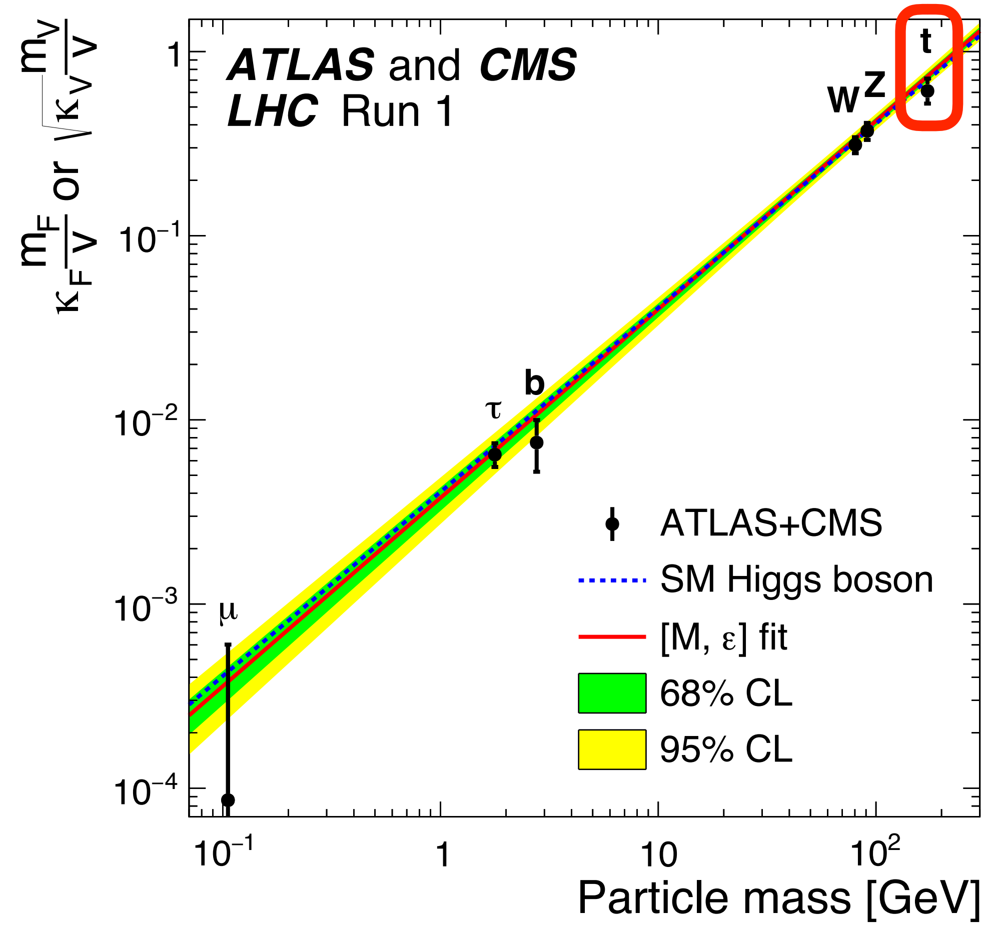
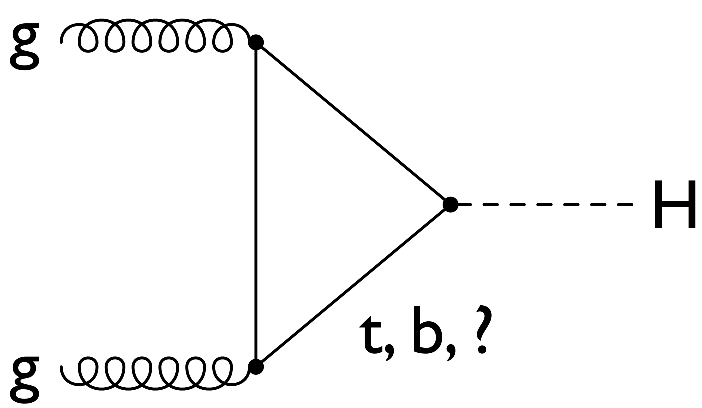
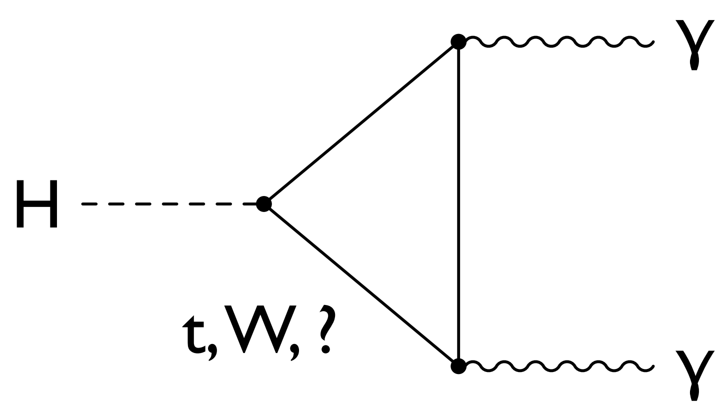
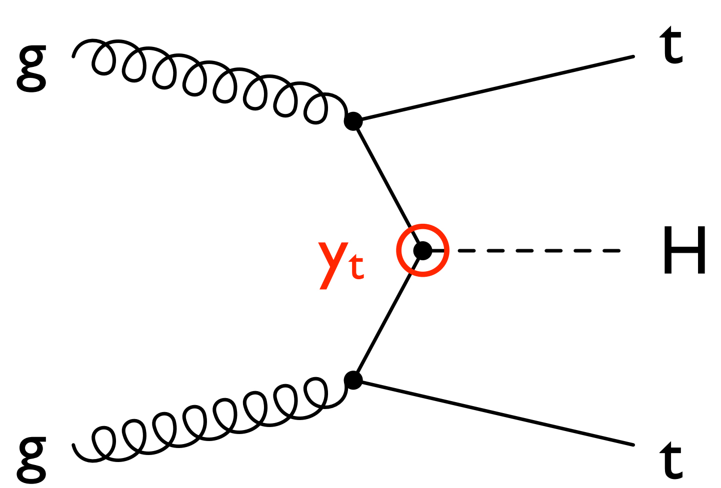
Introduction

- Top Yukawa coupling (y_t) contributes to the following quantum loops.
  - Higgs gluon fusion production
  - Higgs diphoton decay
- Run 1 ATLAS+CMS result: 20% precision in y_t but assuming no BSM contributions in the loops.
- ttH cross section measurement allows direct constraint on top Yukawa coupling.





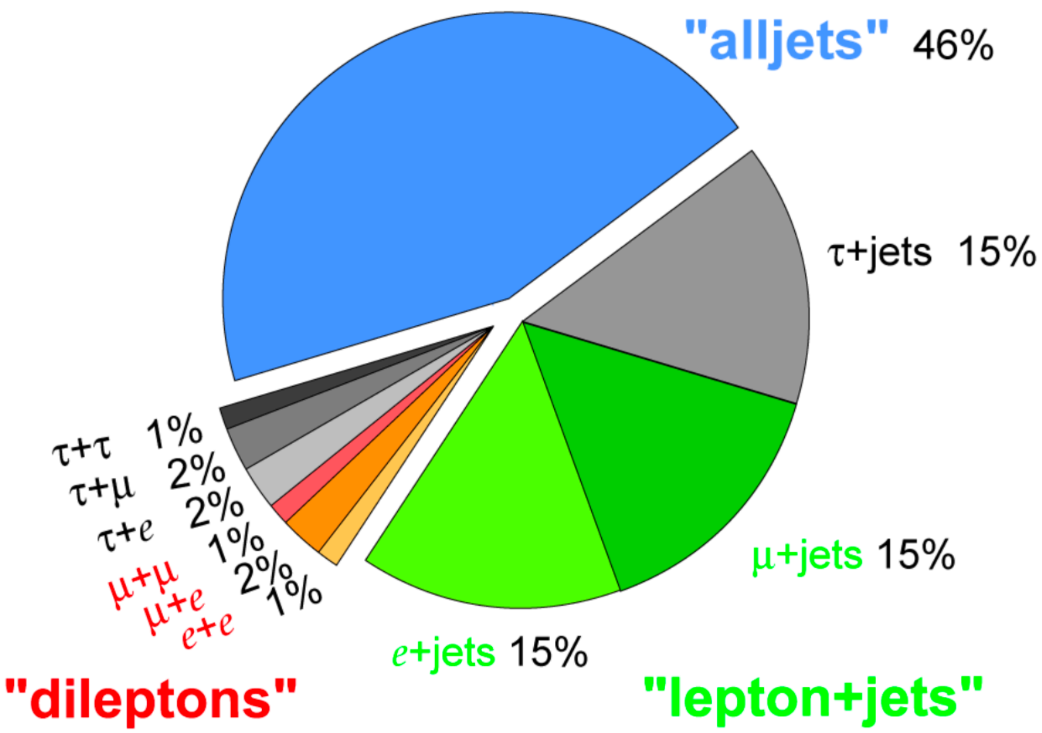




Experimental Signatures for ttH

- Signature depends on
  - ttbar system decay:

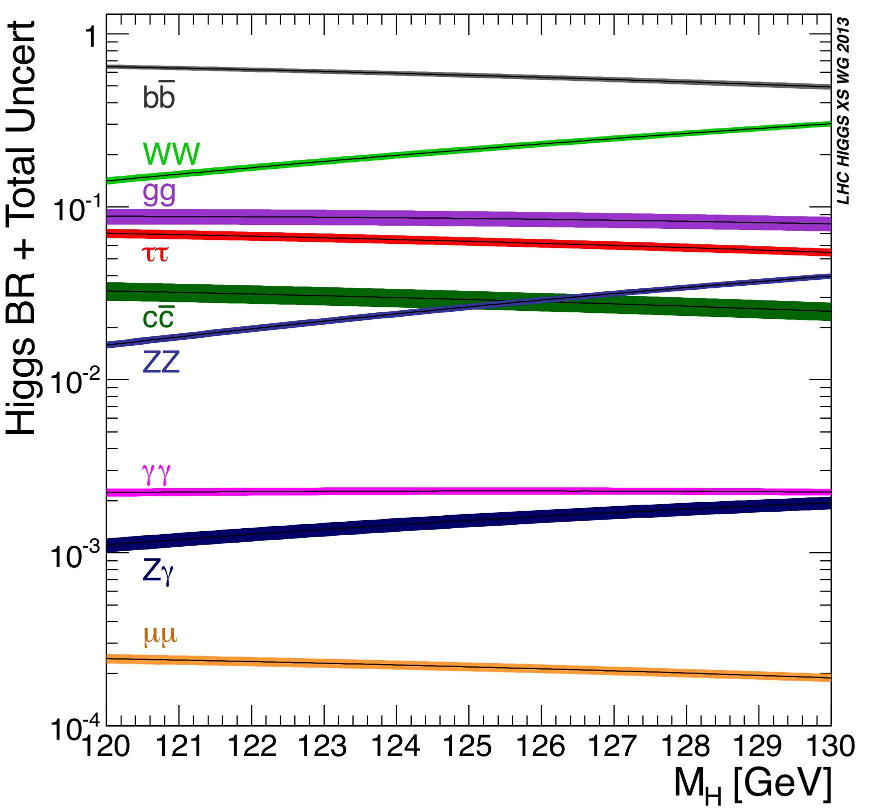
    0, 1, and 2 charged leptons
  - Higgs decay: bb, WW*, ττ, ZZ*, γγ



- Four different analyses:
  - ttH with H→bb (0, 1, or 2 e/μ)
  - ttH to multilepton

    targetting mostly H→WW* and ττ
  - ttH with H→γγ (0 or ≥1 e/μ)
  - ttH with H→ZZ*→ 4 e/μ

Smaller BR, larger S/B



Latest Results on ttH at ATLAS

Channel	Data ($\sqrt{s}$, $\int \mathcal{L}dt$)	Reference
ttH, H→bb	13 TeV, 36.1 fb^{-1}	Phys. Rev. D 97, 072016 (2018)
ttH, multilepton	13 TeV, 36.1 fb^{-1}	Phys. Rev. D 97, 072003 (2018)
ttH, H→γγ	13 TeV, 79.8 fb^{-1}	arXiv:1806.00425, submitted to Phys. Lett. B
ttH, H→ZZ*→4l (l=e/μ)	13 TeV, 79.8 fb^{-1}	arXiv:1806.00425, submitted to Phys. Lett. B

Combination of all analyses with 36.1 fb^{-1} led to 4.2σ (3.8σ expected) evidence.

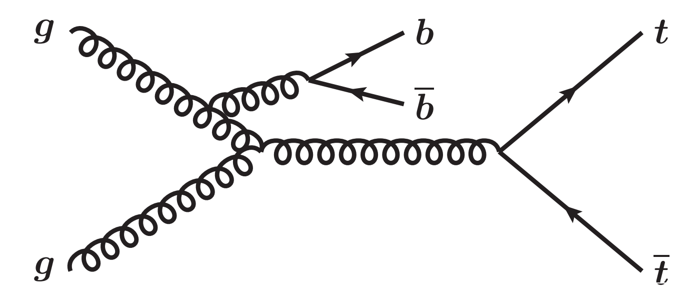
New results on H→γγ and H→ZZ*→4l with 79.8 fb^{-1} improve the significance.

36.1 fb^{-1}: data taken in 2015-2016

79.8 fb^{-1}: data taken in 2015-2017

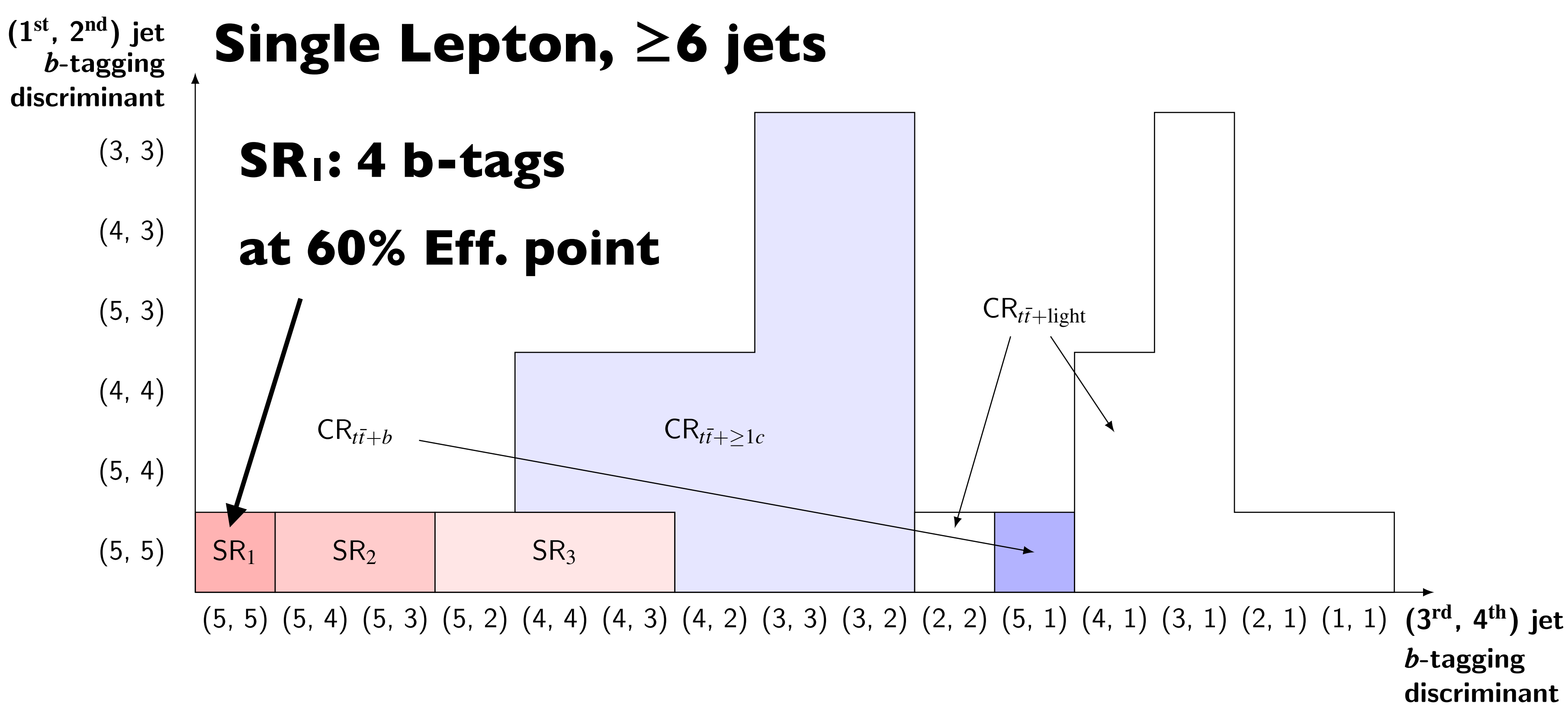
ttH, H→bb: Analysis Strategy

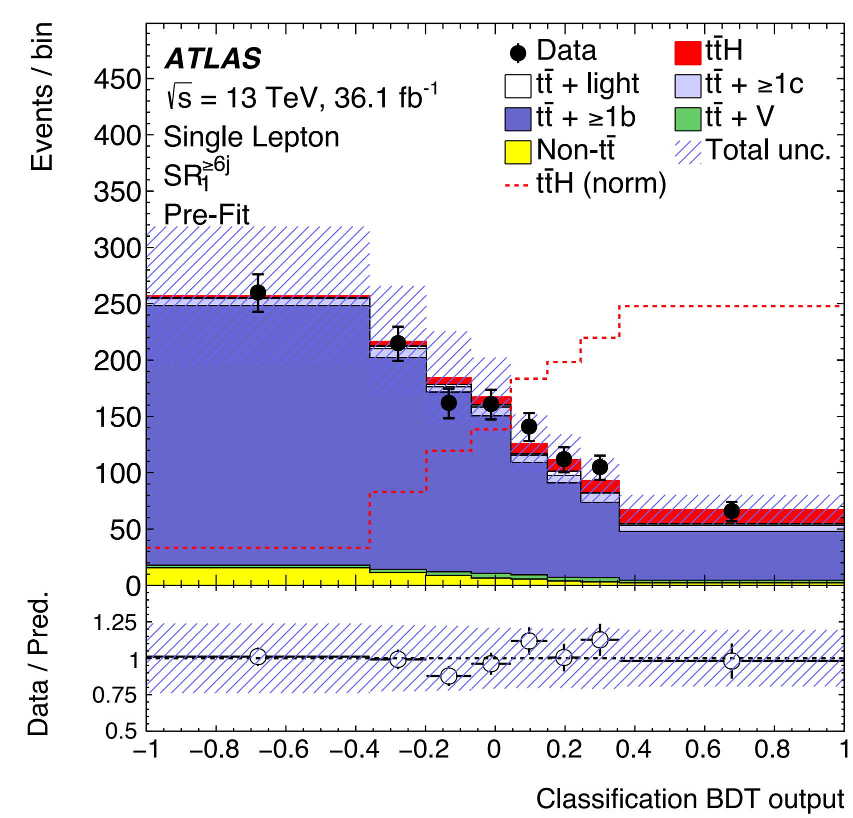
Largest Higgs branching ratio, but tt + heavy flavour production has large cross section and the modelling is challenging.



1 lepton and 2 lepton channels split into 9 signal regions and 10 control regions based on jet and b-jet multiplicity/quality. Pseudo-continuous b-tagging introduced; b-tagging discriminant defined for efficiency points 60%, 70%, 77%, 85%, and 100%.

Boosted Decision Tree (BDT) in each signal region used as the final discriminants for signal extraction.



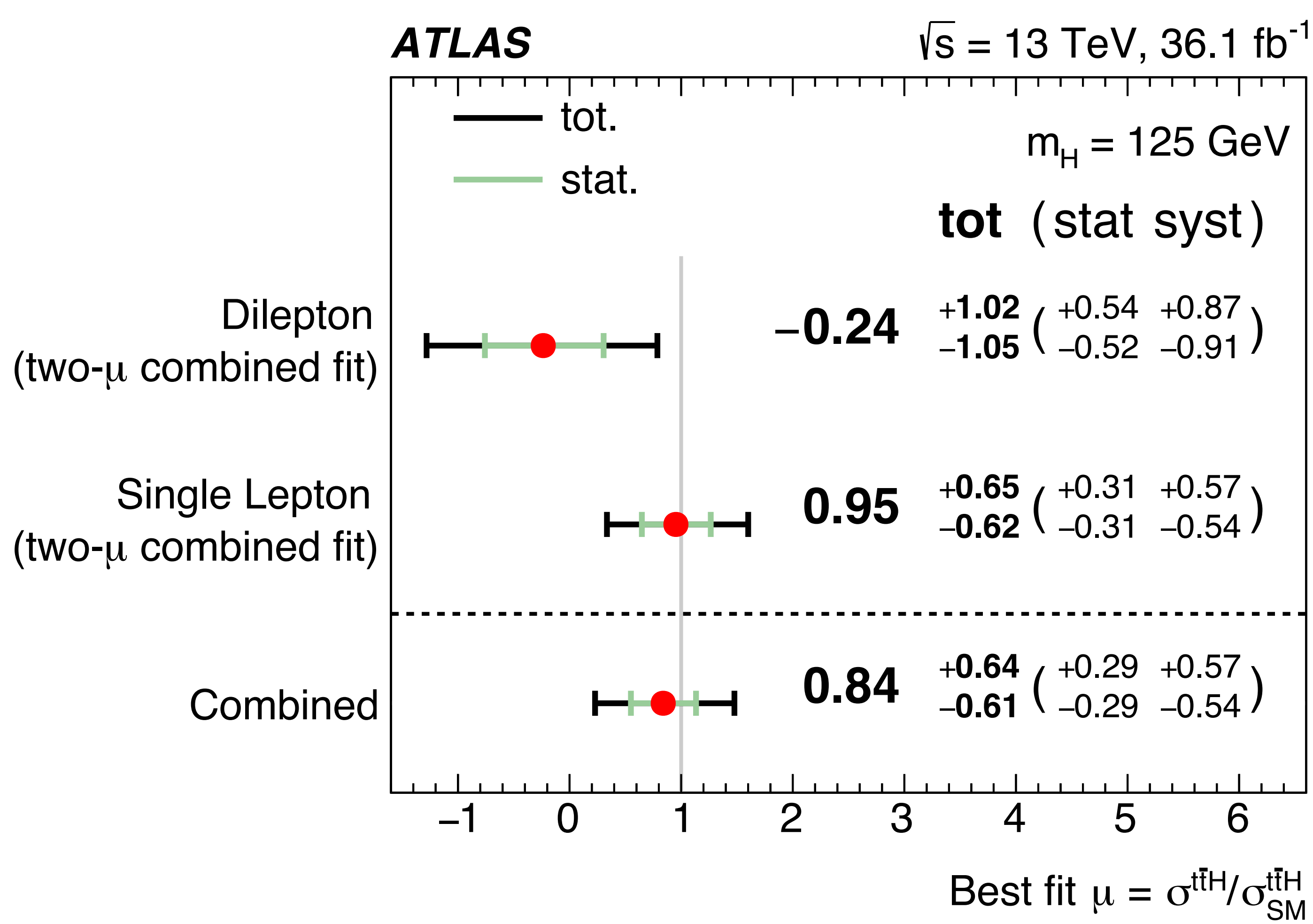


ttH, H→bb: Result

Signal is extracted with binned profile likelihood fit to all signal and control regions.

Normalisations of tt + ≥1b and tt + ≥1c are allowed to float in the fit.

Signal strength $\mu = \sigma/\sigma_{SM}$



$\mu = 0.84 \pm 0.29\ (\text{stat.})\ ^{+0.57}_{-0.54}\ (\text{syst.})$

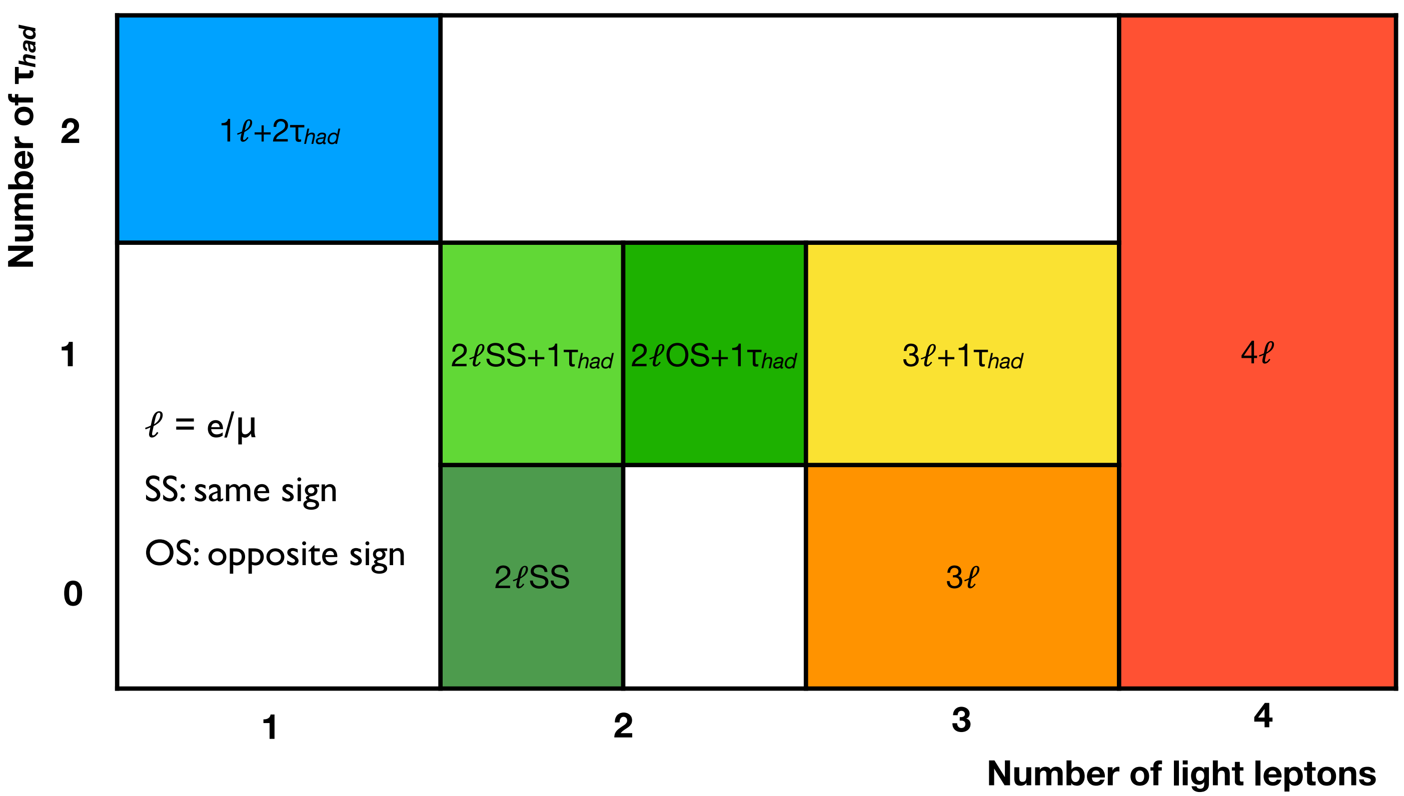
Significance: 1.4σ (1.6σ expected)

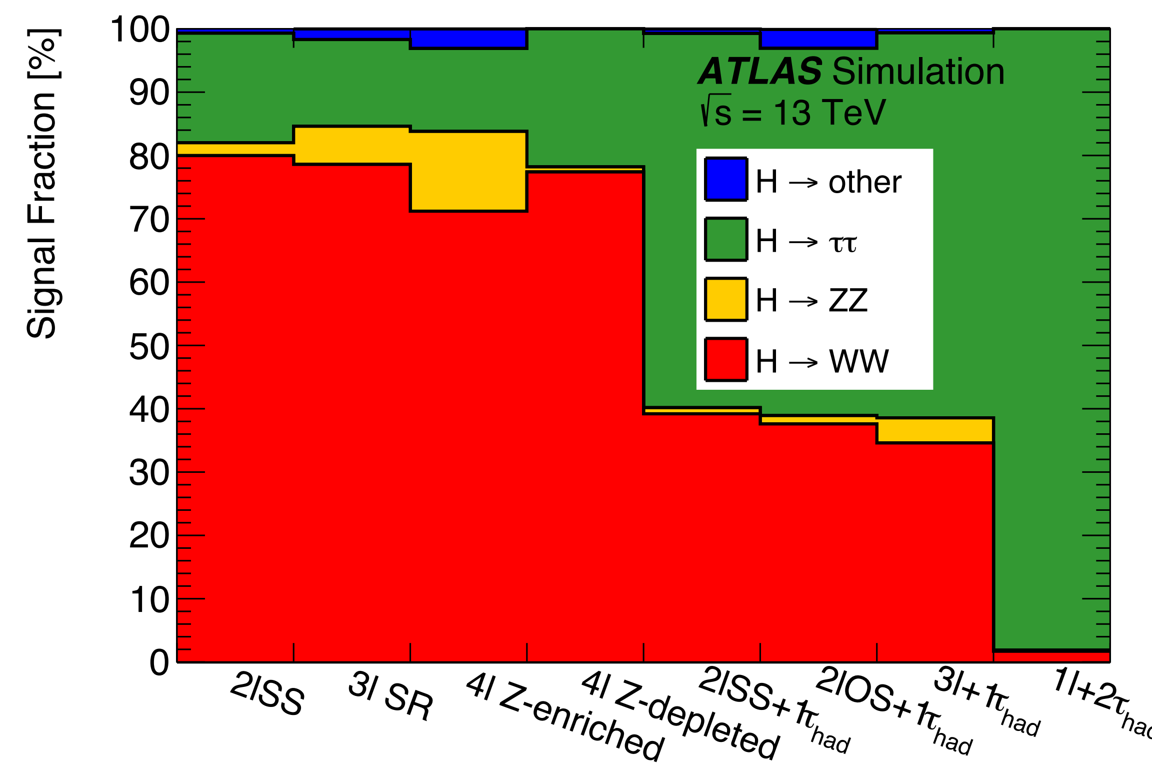
Main systematic uncertainties

- tt + ≥1b background modelling (generator comparison Syst.): ±0.46
- Background-model Stat. Unc.: $^{+0.29}_{-0.31}$

ttH, Multilepton: Analysis Strategy

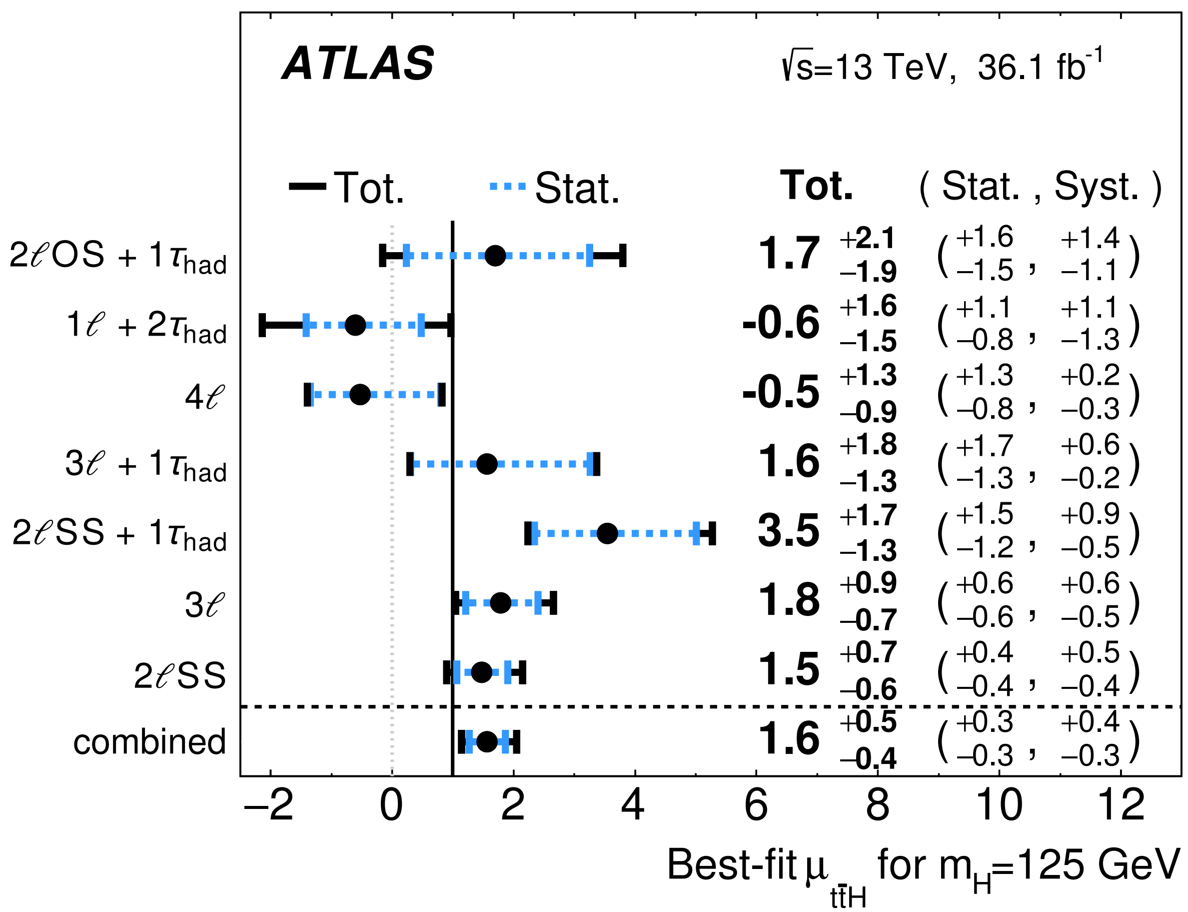
- Combination of seven channels with different e/μ and τ lepton multiplicity
- BDT-based prompt e/μ selection: ~20 rejection for e/μ from b hadrons
- Irreducible backgrounds (ttW, ttZ, ...): estimated from MC and validated in data
- Reducible backgrounds (non-prompt e/μ and fake τ_{had}): estimated from data
- Multivariate techniques applied in most channels

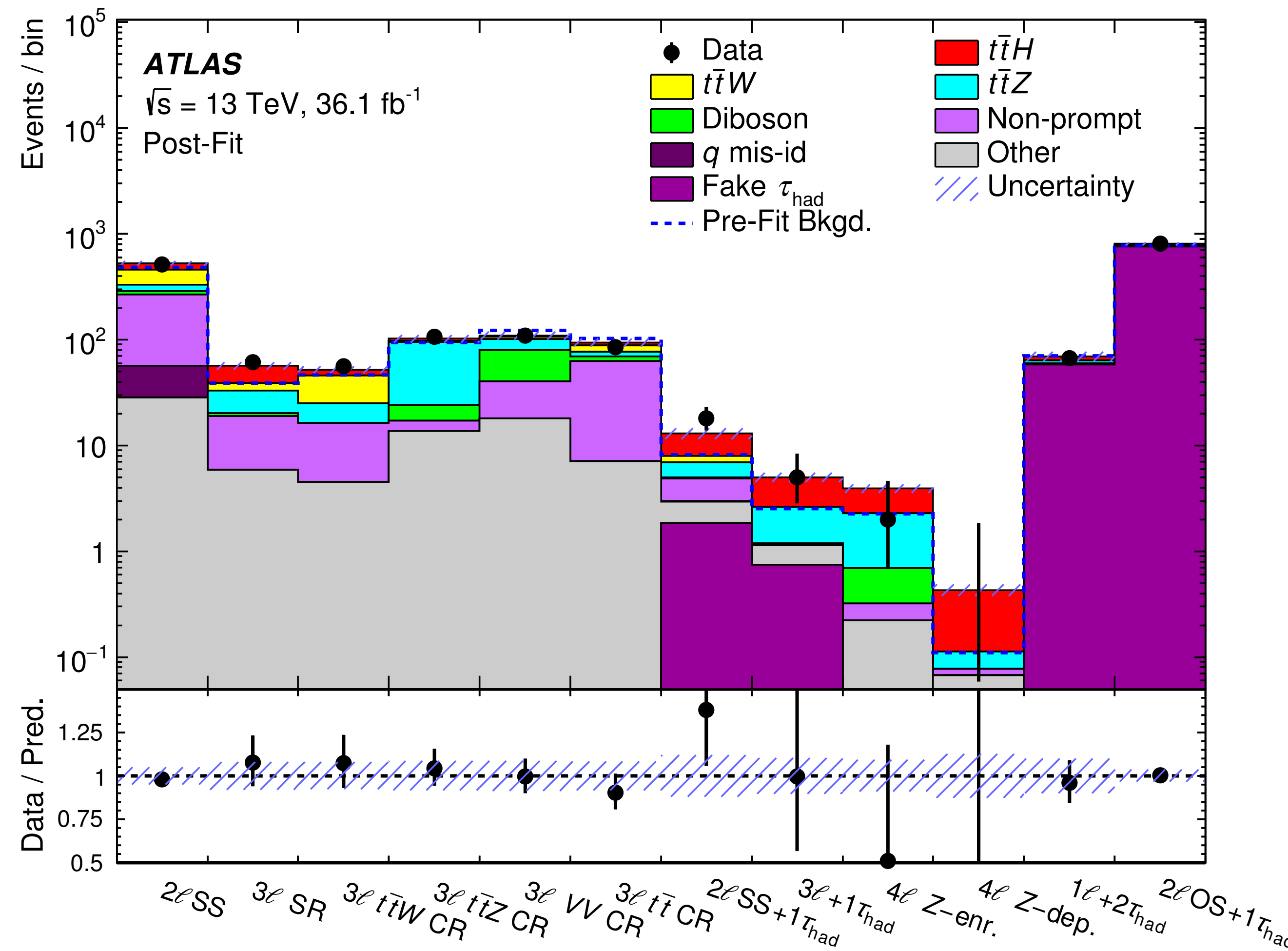




ttH, Multilepton: Result

Signal is extracted with a binned profile likelihood fit across all categories including main background control region.





Main systematic uncertainties

- ttH modelling (cross section): $^{+0.20}_{-0.09}$
- Jet energy scale/resolution: $^{+0.18}_{-0.15}$
- Non-prompt e/μ estimates: $^{+0.15}_{-0.13}$

$\mu = 1.6 \pm 0.3\ (\text{stat.})\ ^{+0.4}_{-0.3}\ (\text{syst.})$

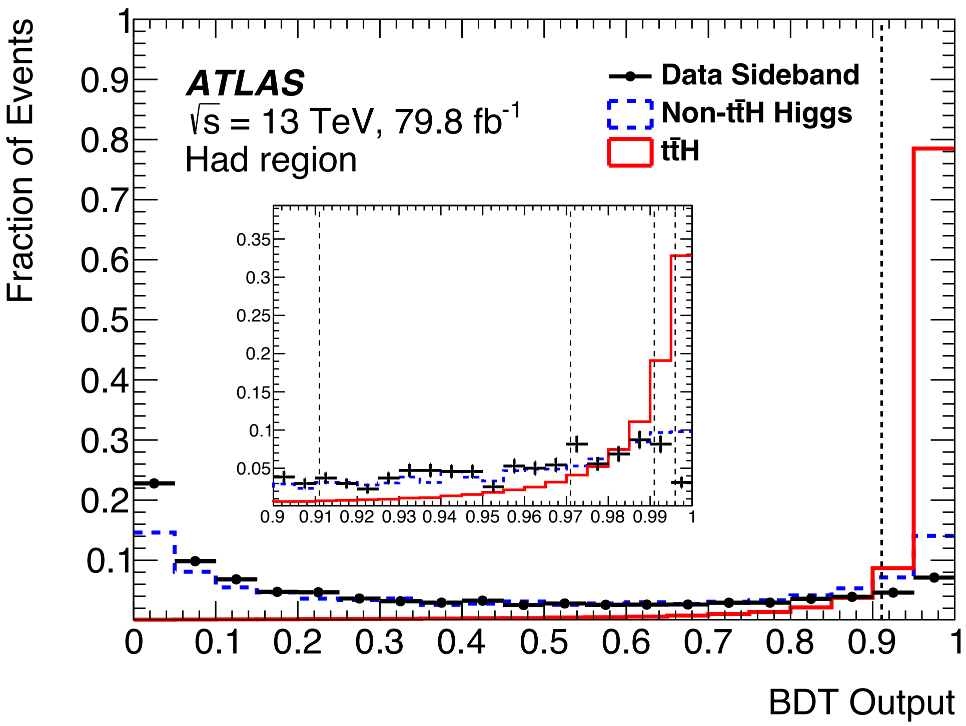
Significance: 4.1σ (2.8σ expected)

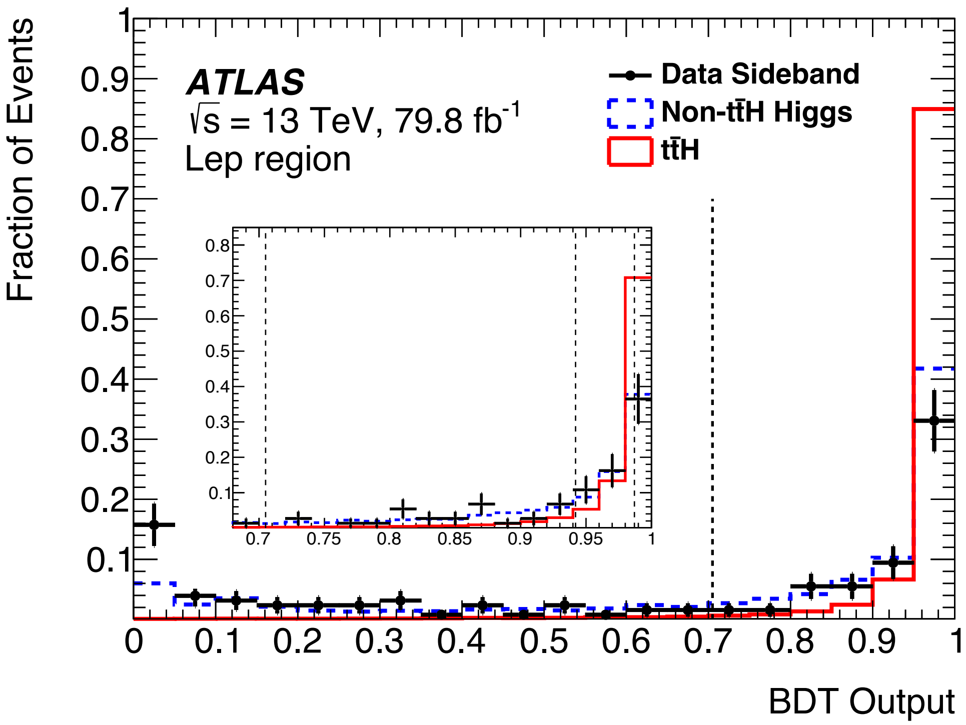
ttH, H→γγ: Analysis Strategy

50% improvement in the sensitivity:

new analysis method and new reconstruction software

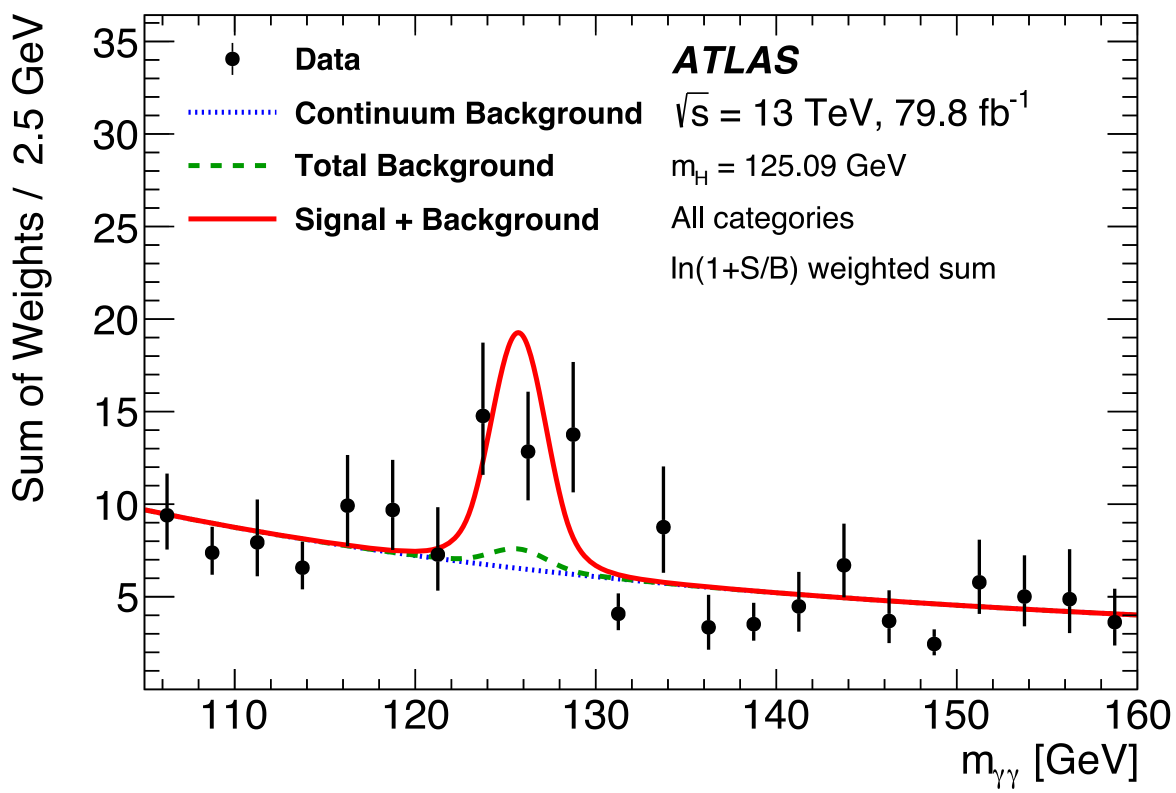
- Categorisation based on 0/≥1 lepton events — hadronic and leptonic categories
- Further categorisation with XGBoost BDT
    - Inputs: 4-vector information of photons ($p_T/m_{\gamma\gamma}$), jets, E_T^{miss}, lepton(s) (lep cat), and b-tag (had cat)
    - Training: ttH MC vs main background (γγ, ttγγ) from data control region and other background from simulation
    - 4 hadronic and 3 leptonic categories based on the BDT output

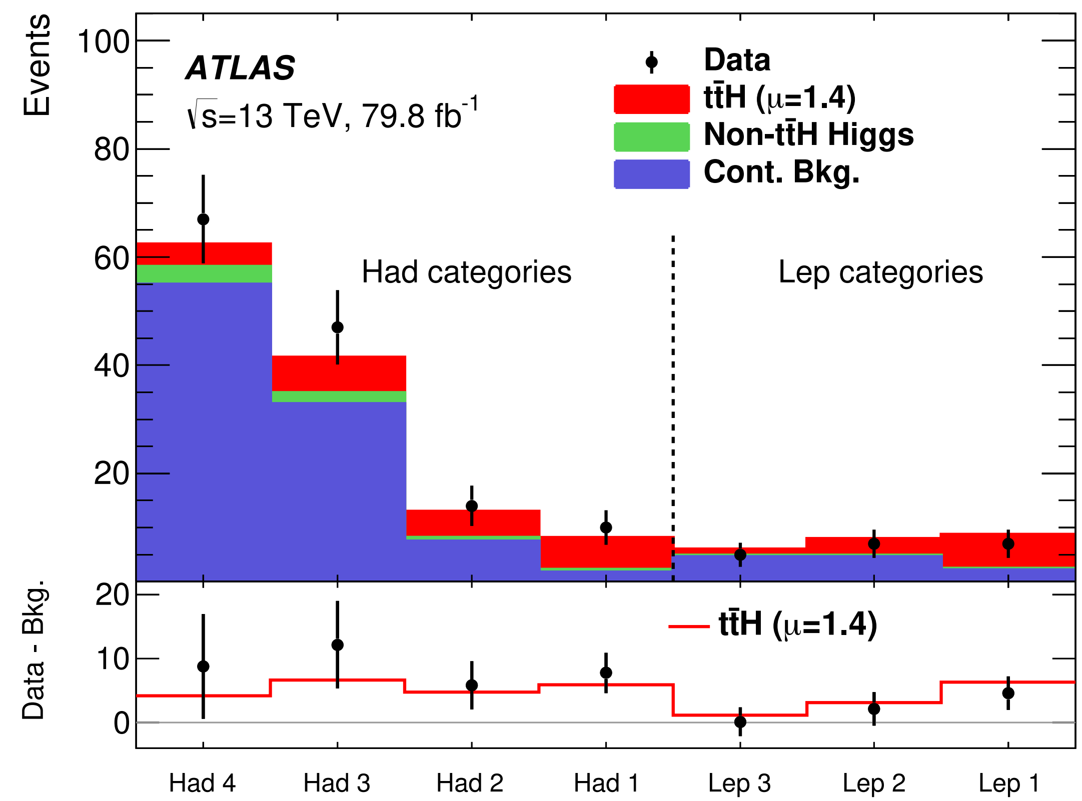




ttH, H→γγ: Result

Combined unbinned fit is applied for the seven $m_{\gamma\gamma}$ distributions to extract signal (double-sided Crystal Ball function) and background (exponential or power-law)





For mass window that contains 90% of ttH signal

Number of fitted ttH events: 36^{+12}_{-11}

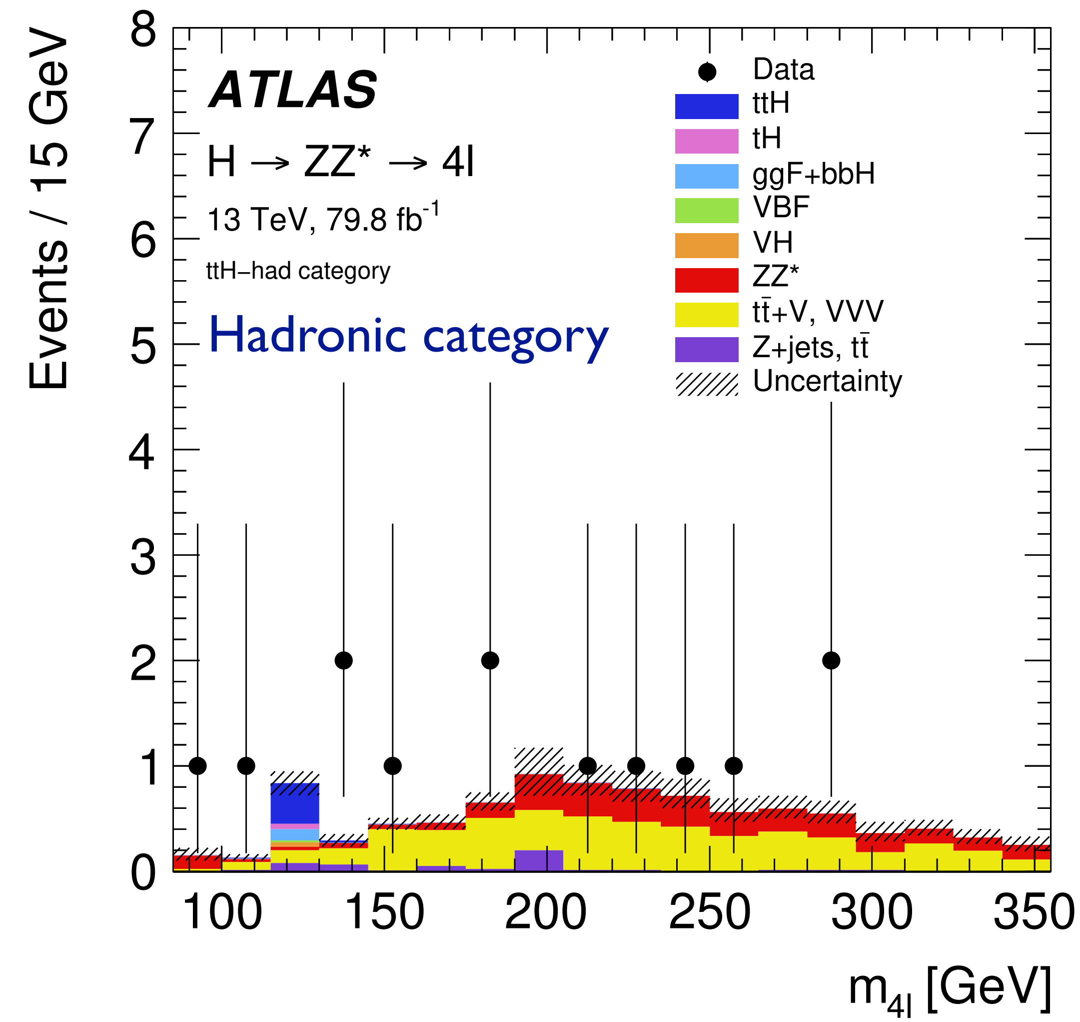
Significance: 4.1σ (3.7σ expected)

$\mu = 1.39^{+0.42}_{-0.38}$ (stat.) $^{+0.23}_{-0.17}$ (syst.)

Systematic uncertainties:
ttH parton shower model (8%),
photon energy resolution (6%), …

ttH, H→ZZ*→4l (l = e or μ)

- Extremely low rate but clean final state with high S/B rate (> 5)
- Select H→ZZ*→4l candidates and define ttH-enriched category:
  - ≥1 b-tagged jet
  - ≥4 jets (hadronic ttbar) or 1 lepton + ≥2 jets (leptonic ttbar)
- BDT in hadronic category
  - Inputs: kinematic variables including matrix element discriminant (ttH vs ttV)
- Expected significance: 1.2σ



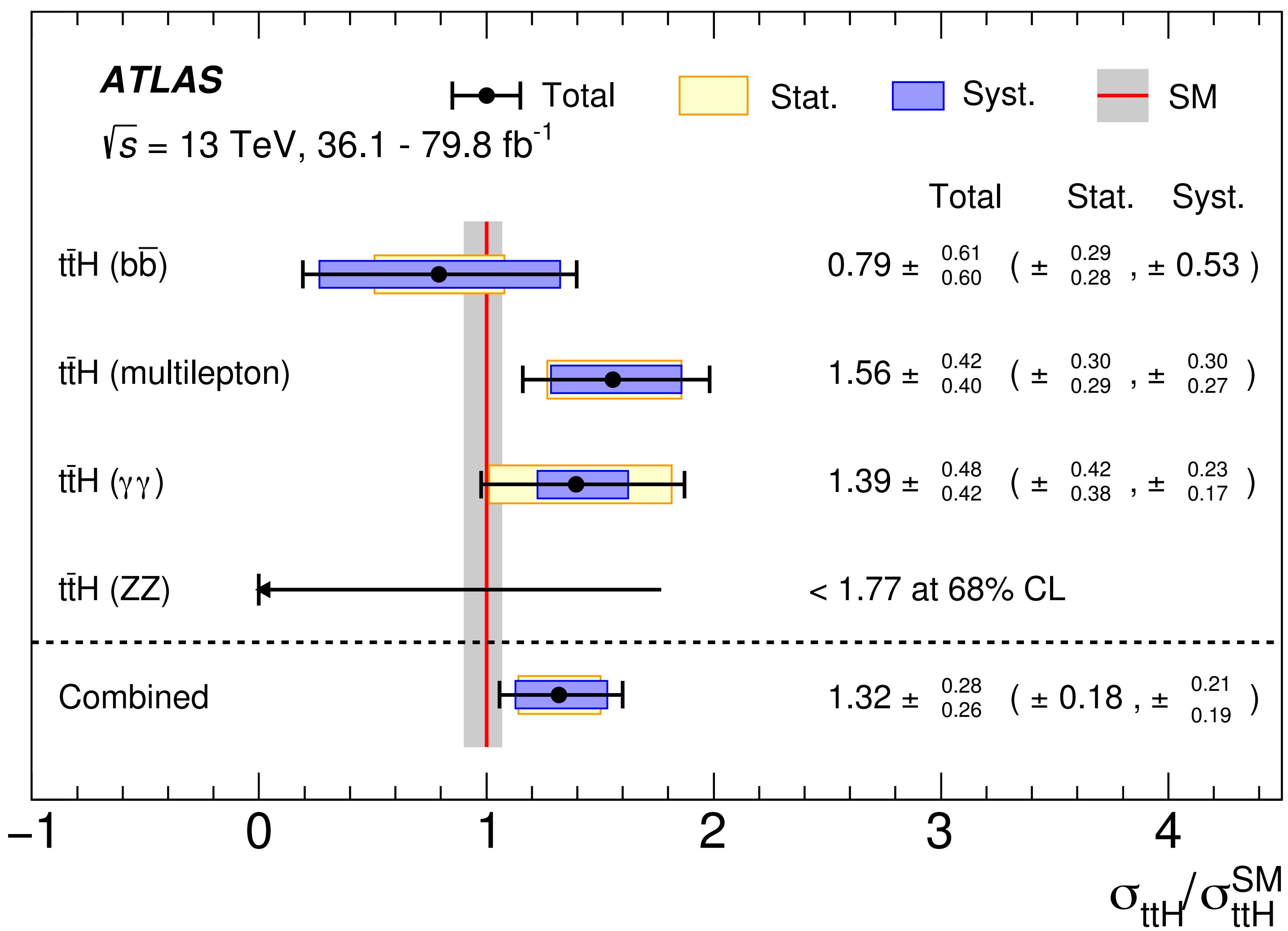
Expect 0.6 ttH events in 115 GeV < m_{4l} < 130 GeV, but observe 0 events

ttH Combination

Simultaneous fits applied to signal regions and control regions of the individual analyses.

Contributions from non-ttH Higgs production fixed to the SM prediction.

Correlation scheme of systematic uncertainties studied in detail.



Significance Obs. (Exp.)	
1.4σ (1.6σ)	
4.1σ (2.8σ)	
4.1σ (3.7σ)	
0σ (1.2σ)	
5.8σ (4.9σ)	**6.3σ (5.1σ)**
13 TeV only	7, 8, and 13 TeV

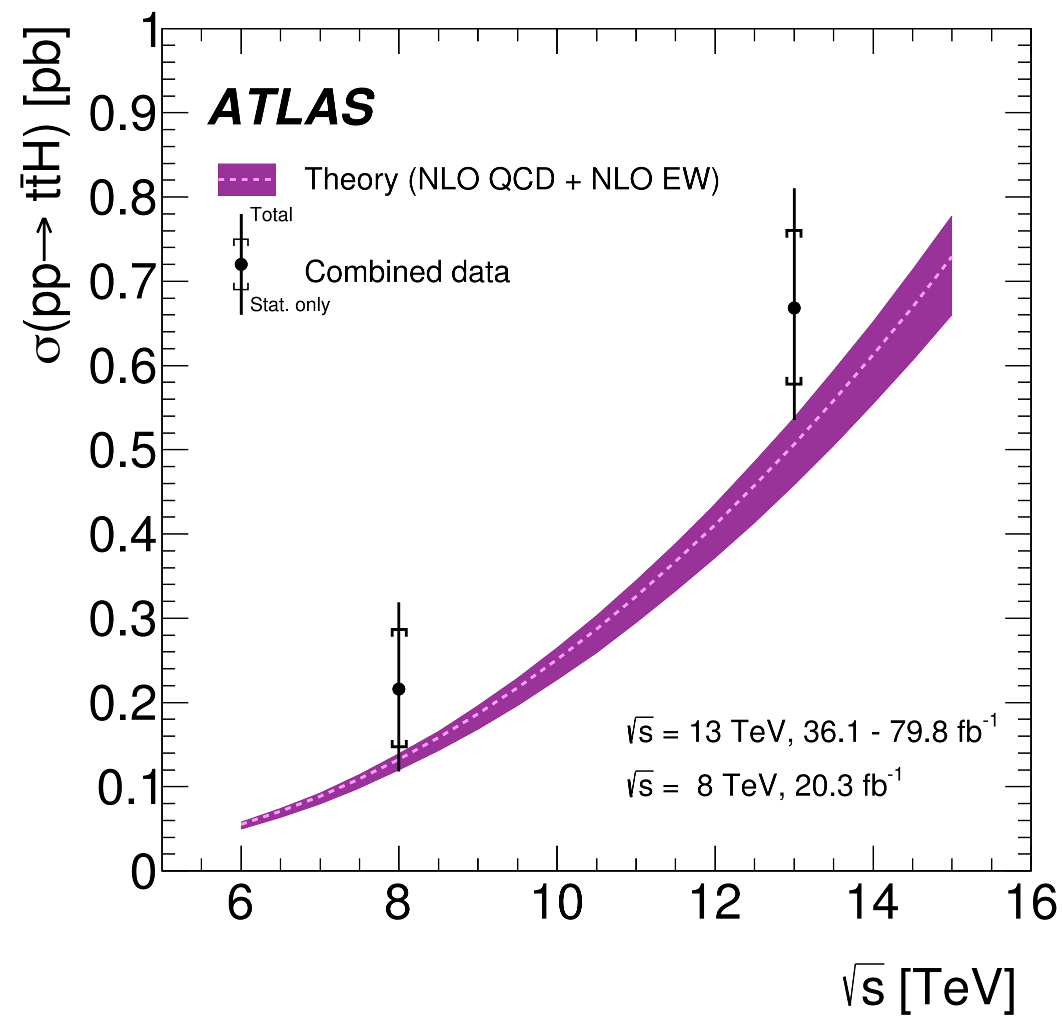
Observation of ttH production!

ttH Cross Section

Cross section for pp→ttH is extracted

assuming SM branching ratios.

Analysis	$t\bar{t}H$ cross section [fb]
$H \to \gamma\gamma$	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)
$H \to$ multilepton	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)
$H \to b\bar{b}$	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)
$H \to ZZ^* \to 4\ell$	<900 (68% CL)



Combined (13 TeV): 670 ± 90 (stat.) $^{+110}_{-100}$ (syst.) fb

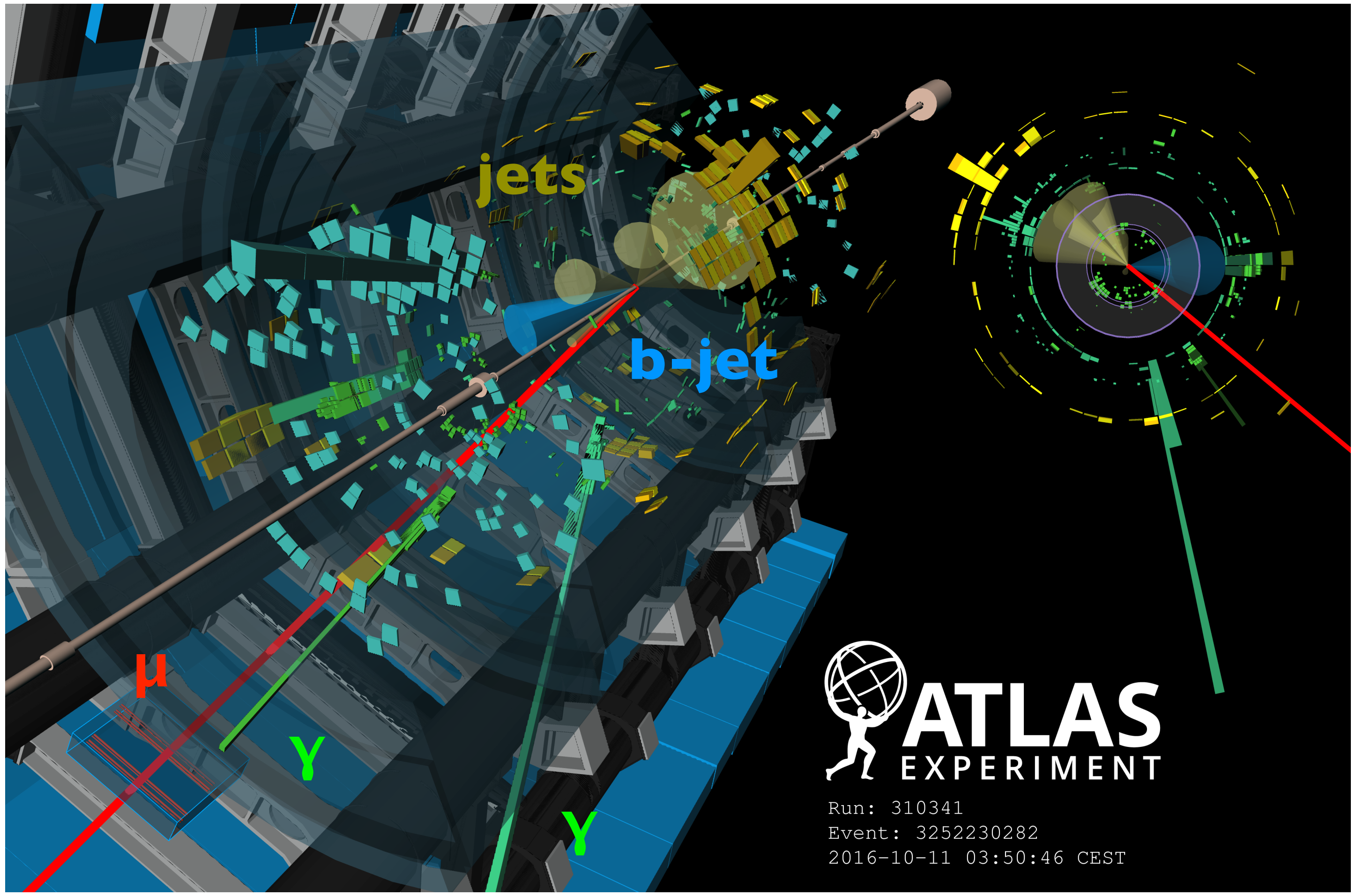
Compatible with the SM prediction: 507 $^{+35}_{-50}$ fb

Dominant systematic uncertainties:

- tt + heavy flavour modelling (9.9%)
- ttH modelling (6.0%)
- Non-prompt leptons (5.2%)
- Jets/E_T^{miss} (4.9%)

Conclusion

- We have observed the ttH process.
  - Run 2: 5.8σ (4.9σ exp.)
  - Run 2 + Run 1: 6.3σ (5.1σ exp.)
- Cross section measurements are in agreement with SM prediction.
  - Measurement for 13 TeV: $670 \pm 90\ (\text{stat.})\ ^{+110}_{-100}\ (\text{syst.})$ fb
  - SM prediction: $507\ ^{+35}_{-50}$ fb



A data event from the ttH, H→γγ Lep BDT bin with the highest S/B ratio

Establishment of the tree-level coupling of the Higgs boson and the top quark!