Observation of the ttH production at √s=13 TeV in ATLAS

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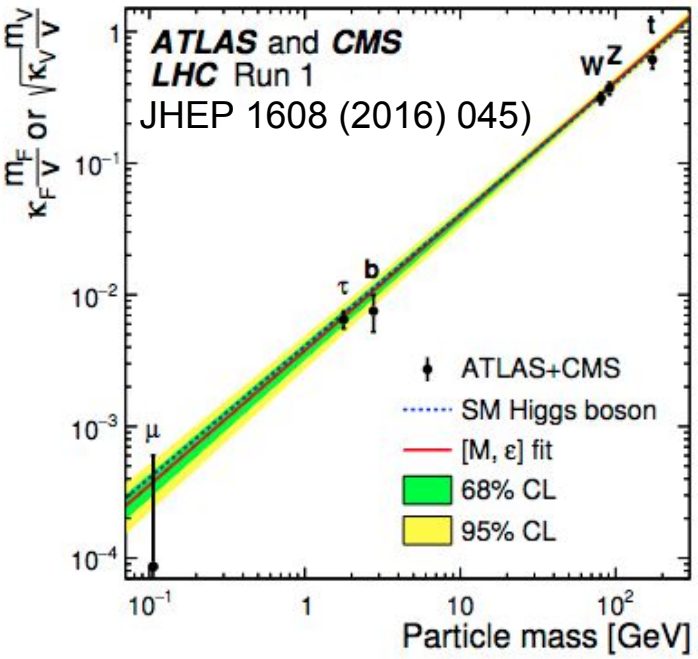
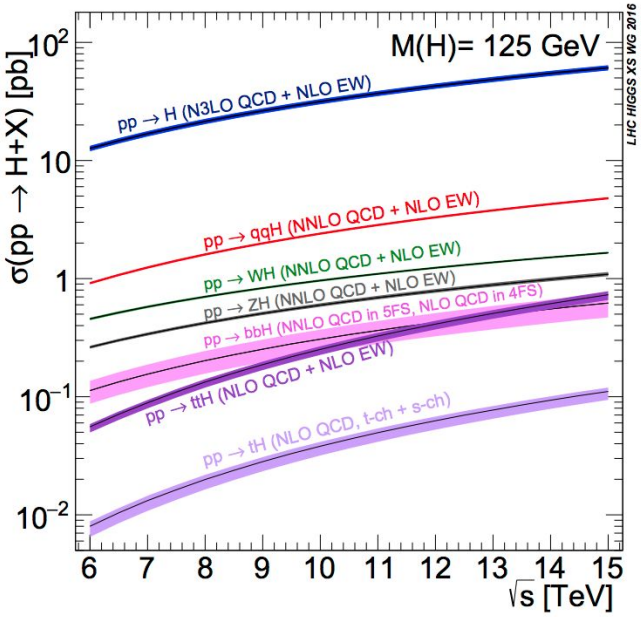
Introduction

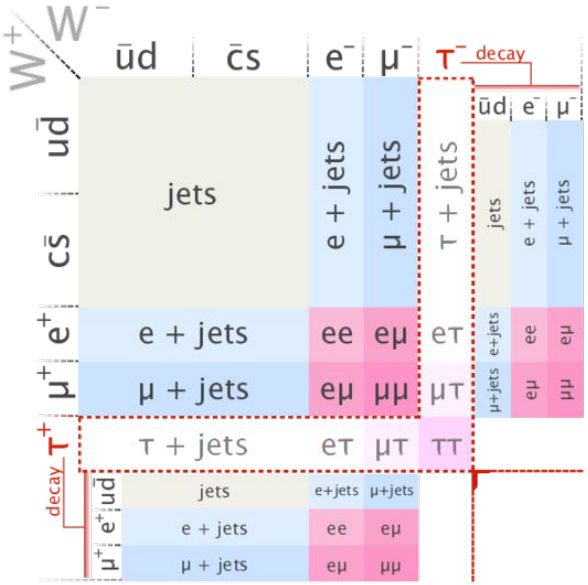
- Discovery of the Higgs boson in 2012
- Properties compatible with SM hypothesis
- key role of the Yukawa interaction describing the coupling between the Higgs field and quarks/leptons
- top quark Yukawa coupling $\lambda_{top} = \sqrt{2}\, m_t/v \sim 1$
  - largest coupling of Higgs boson to fermion and a key parameter of SM





- λ_{top} probed indirectly though loops in gg→H and H→γγ
- λ_{top} can be probed directly in ttH production
  - process at tree level
  - Large increase in the expected signal cross section from 8 to 13 TeV

Experimental signatures for ttH production

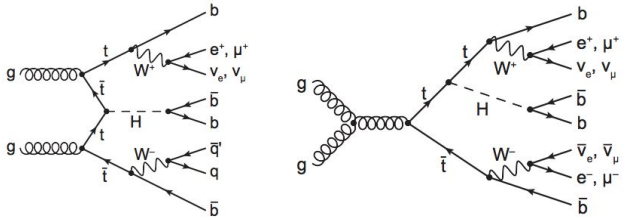


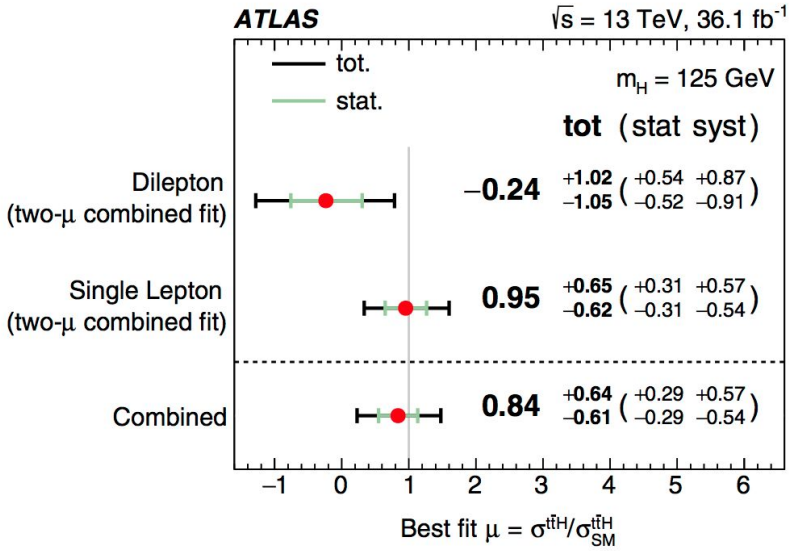
Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

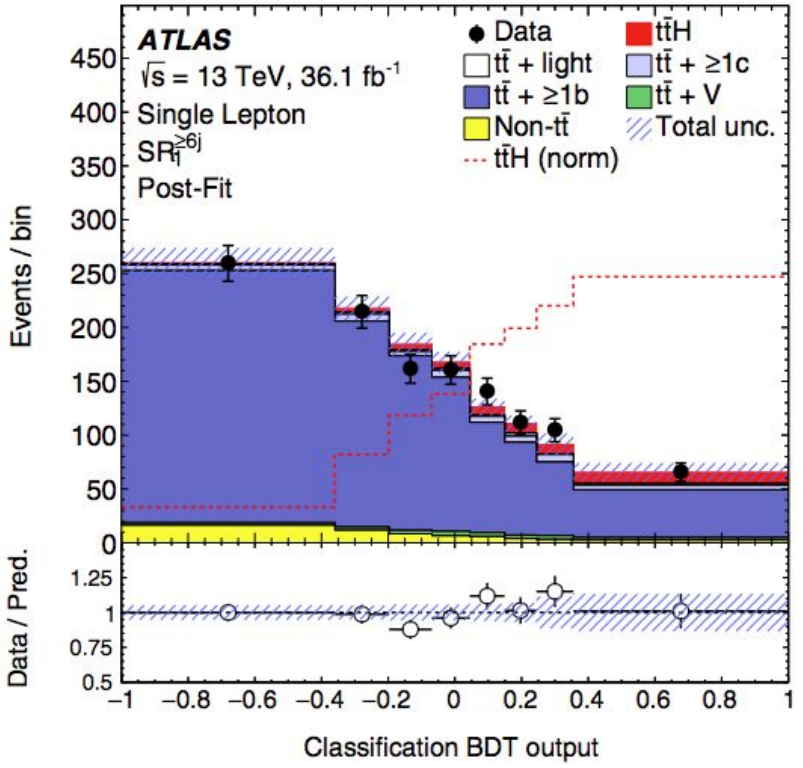
- Several final states probed:
  - **ttH H→bb** : large BR, but limited sensitivity due to high bkg
    - at least one of the W from top with leptonic decay
  - **ttH multilepton** (H→WW,ττ,ZZ) : smaller rate but also reduced background
  - **ttH H→γγ** : final state clean very small rate
  - **ttH H→ZZ→4l** : extremely low rate (~0.01 ev/fb) but highest S/B
- The challenge: large backgrounds (tt+jets, tt+bb, ttW, ttZ)

ttH (H→bb)

- H→bb most abundant ttH event sample
  - focus on single lepton and dilepton final states
  - main bkg contribution from tt+HF jets
- Events categorized according to N_l, N_j, b-tagged jets
- CR used in the fit to estimate them and constrain modeling uncertainties
  - tt+≥1b, tt+≥1c, tt+≥light flavour
- One BDT in each SR, with several inputs
  - general kin. variables, b-tag discriminant
  - top and Higgs kinematic variables reconstructed with dedicated BDTs
  - 1D likelihood discriminants, MEM (1lep)



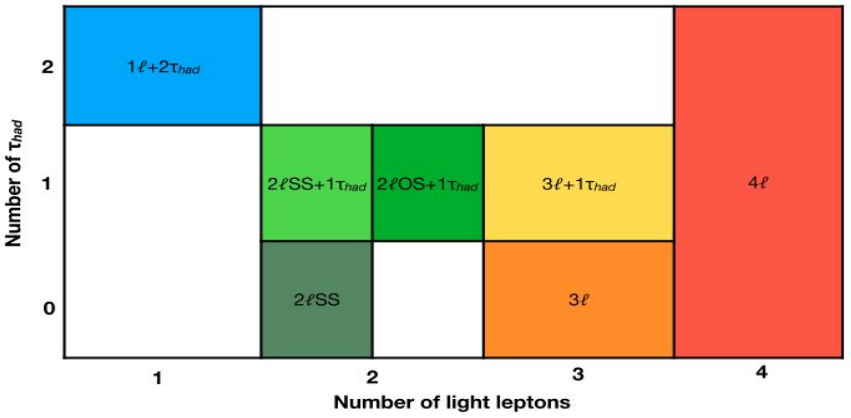


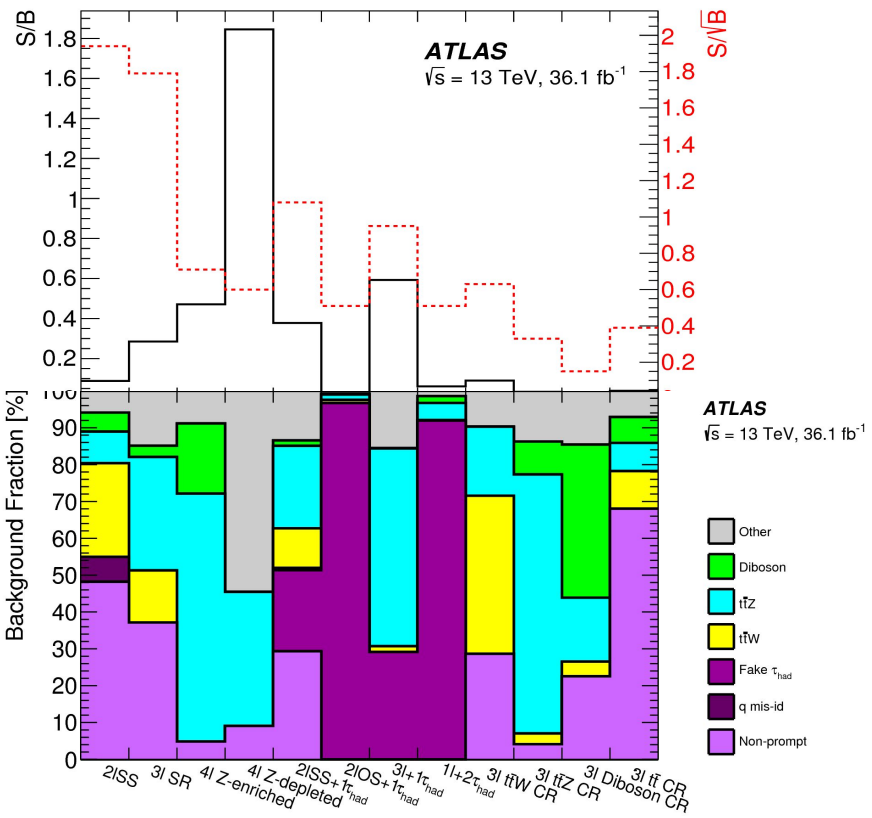


Observed significance:1.4σ (1.6σ expected)

ttH multilepton

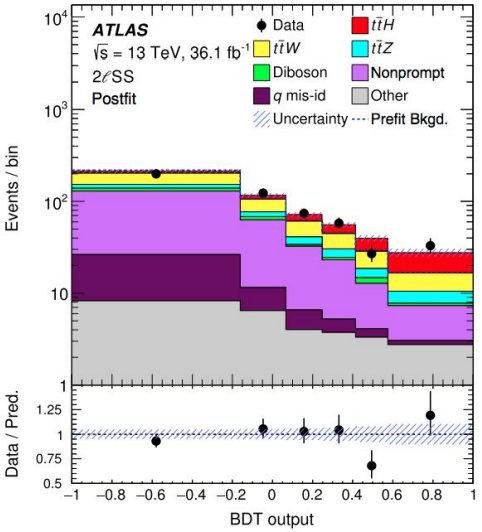
- 7 Orthogonal analysis channels
  - overlap with H->ZZ*->4l removed in the 4l category
- jet requirements: $N_{jet} \geq 2$, $N_{b\text{-}tag} \geq 1$
  - 2ℓSS, 2ℓSS+1τhad: Njet ≥ 4
  - 2ℓOS+1τhad, 1ℓ+2τhad: Njet ≥ 3
- tt suppressed by requirement of at least two SS or additional leptons
- Different bkg composition in the various SR
- **Irreducible bkg.**
  - estimates rely on MC prediction + validation region
- **Reducible bkg**
  - Non-prompt light leptons: from b-hadron decays (tt) and photon conversions
  - Electron charge mis-identification (q mis-id): from 2ℓOS tt events
  - Fake τhad: from light flavour jets and mis-identified electrons

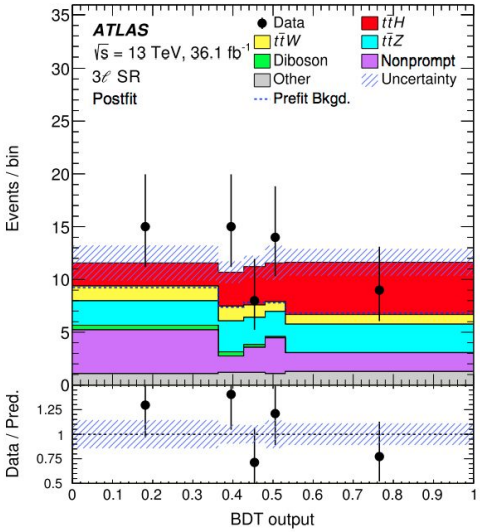




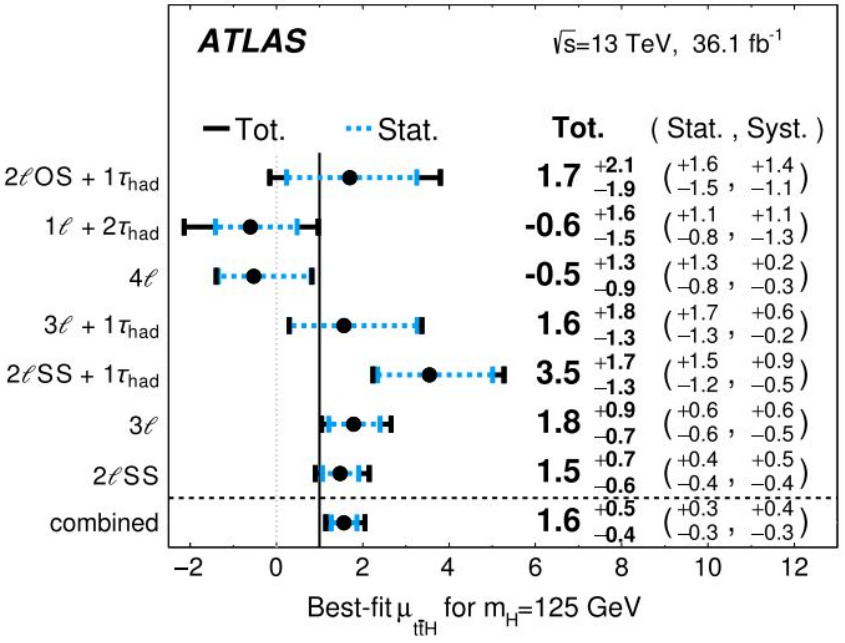
ttH multilepton

- BDTs employed in 5/7 channels
  - trained against different bkg according to the different SR
- 3l and 2lSS most sensitive channels
- Systematic uncertainties with largest impact on errors on μ_{ttH} are
  - ttH cross section uncertainty
  - Jet energy scale (JES) and resolution (JER)
  - Non-prompt light lepton estimates, large contribution of CR statistics





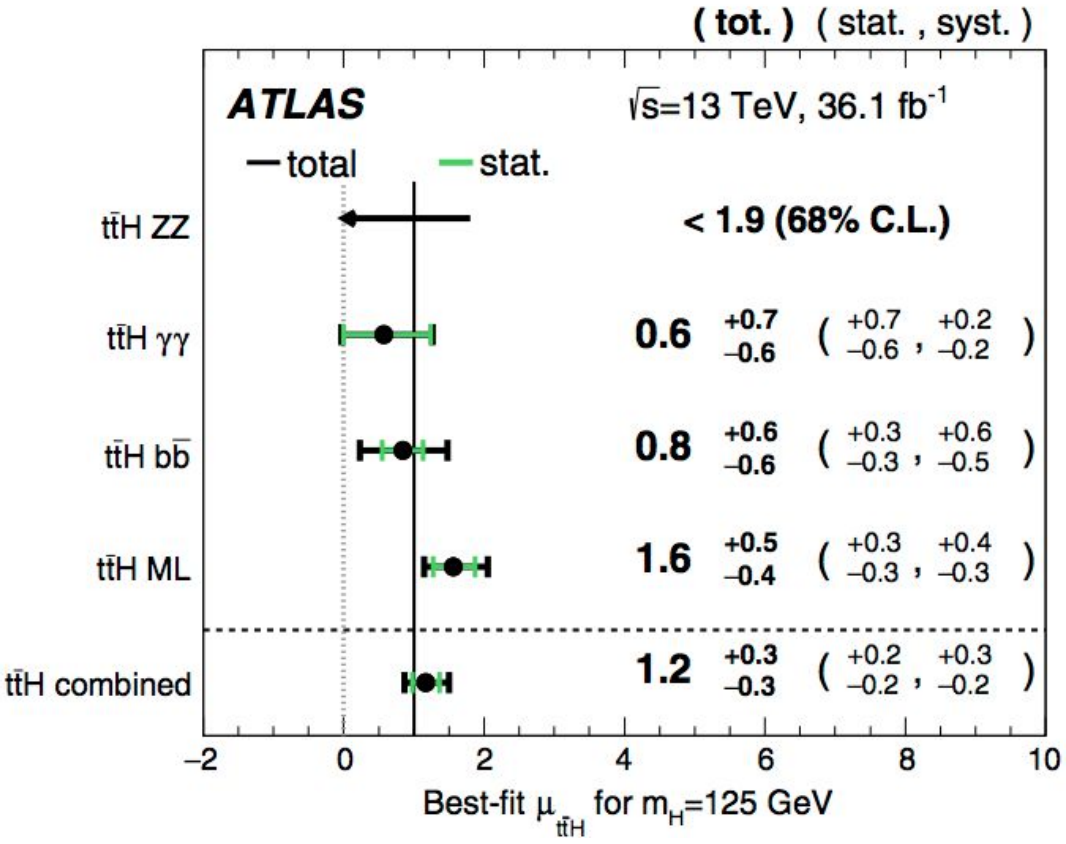
- Observed (expected) significance at 4.1σ (2.8σ) over SM background
- Alternative fit with free floating normalisation for ttV
  - Same central μ value for signal (degradation in sensitivity)
    - $\mu_{ttZ} = 1.17^{+0.25}_{-0.22}$
    - $\mu_{ttW} = 0.92 \pm 0.32$



L = 36 fb^{-1} : Phys. Rev. D 97, 072003

ttH combination with 36 fb^{-1}

- Combination of **ttH Hbb** and **multilepton** together with **ZZ*→4l** and **H→γγ**
- Assumptions:
  - tH production treated as background (fixed to SM expectations within theory uncertainties)
  - BR of Higgs decays fixed to SM values
- **Observed** (expected) significance: **4.2 (3.8)σ**
- **Evidence of ttH production!**



- Cross-section measured: $\sigma_{ttH} = 590^{+160}_{-150}\,\text{fb}$ (SM: 507^{+35}_{-50} fb)

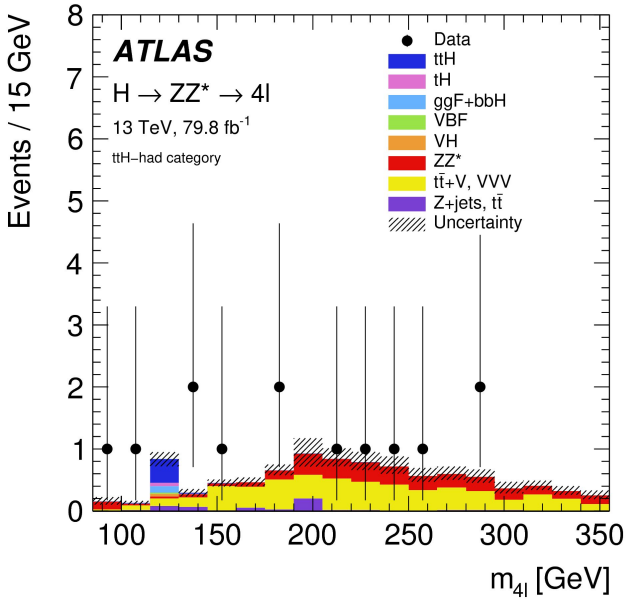
ttH (H→ZZ*→4l and H→γγ) statistically limited

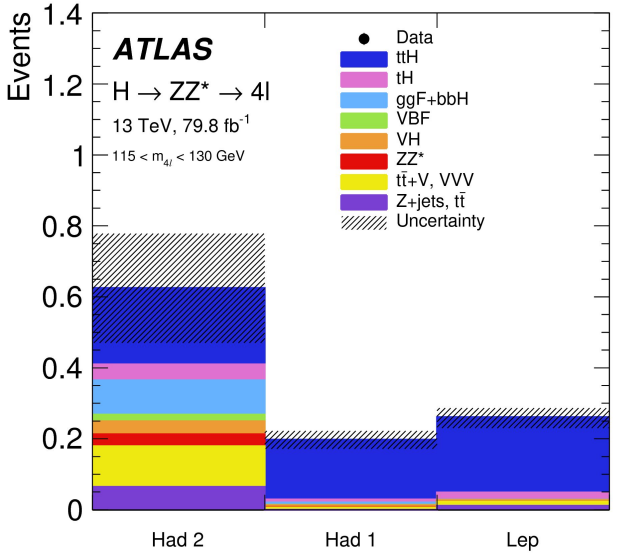
Analyses updated and improved using **80 fb^{-1}**

NEW!! L = 80 fb^{-1} : arXiv:1806.00425

ttH (H→ZZ*→4l)

- Analysis updated wrt the evidence paper selection
- H→ZZ*→4l candidates selected first
  - follow the standard 4l couplings analysis
- ttH enriched events selected requiring >0 b-jet and ≥4 leptons
- "Leptonic" category: ≥1 extra lepton and ≥2j
  - cut and count S/B~10
- "Hadronic" category: ≥ 4jets
  - BDT exploiting jet, Zs and ME(H→4l) information to separated ttH against mainly ttZ and ggH
- improvement of ~30% wrt the previous categorization
- expected significance: 1.2σ
- no events observed (1 total expected)

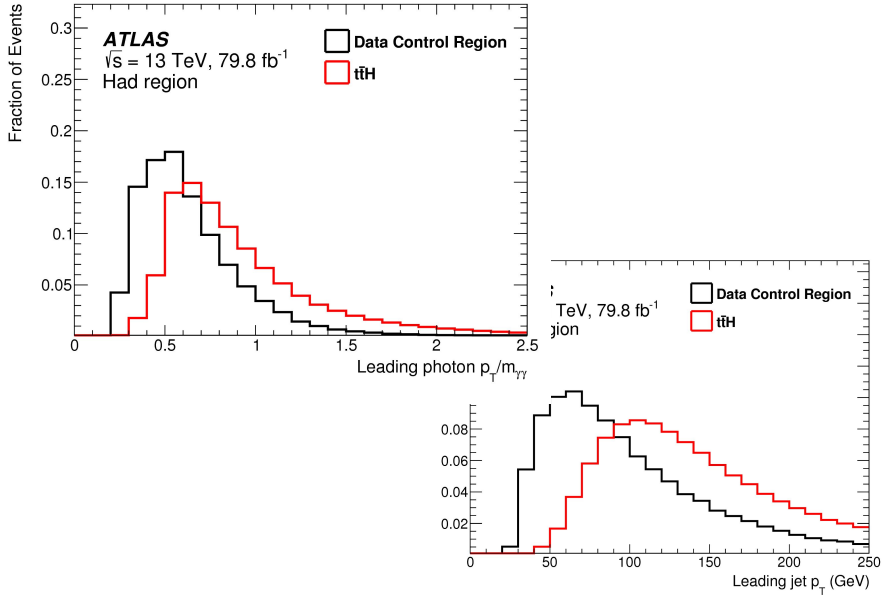


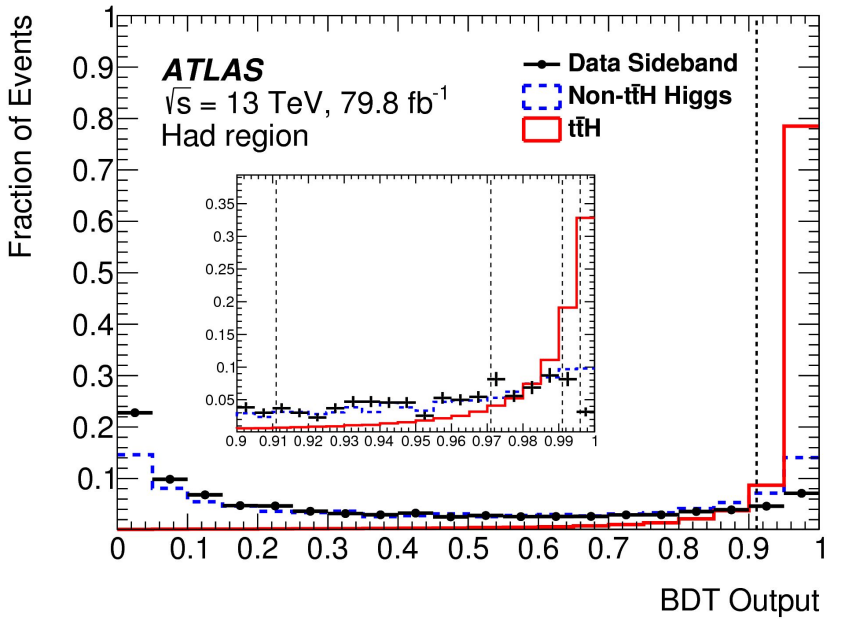


NEW!! L = 80 fb^{-1} : arXiv:1806.00425

ttH (H→γγ)

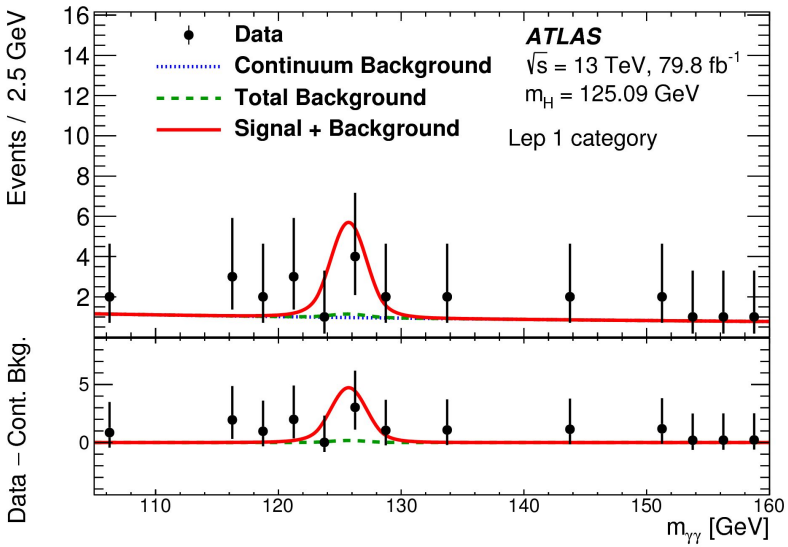
- 2 isolated photons, p_T > 35, 25 GeV
- At least one jet with p_T > 25 GeV
- Specific ttH categories
  - **leptonic** (>0 b-jet, >0 leptons)
  - **hadronic** (>0 b-jet, > 2 jets, 0 leptons)
- Events are then further divided into categories based on an XGBoost BDT discriminant score
  - Training uses energy and direction of photons, jets, leptons, b-tag flag, MET and MET_φ
- Simultaneously fit to $m_{\gamma\gamma}$ spectrum across 7 categories to extract the signal

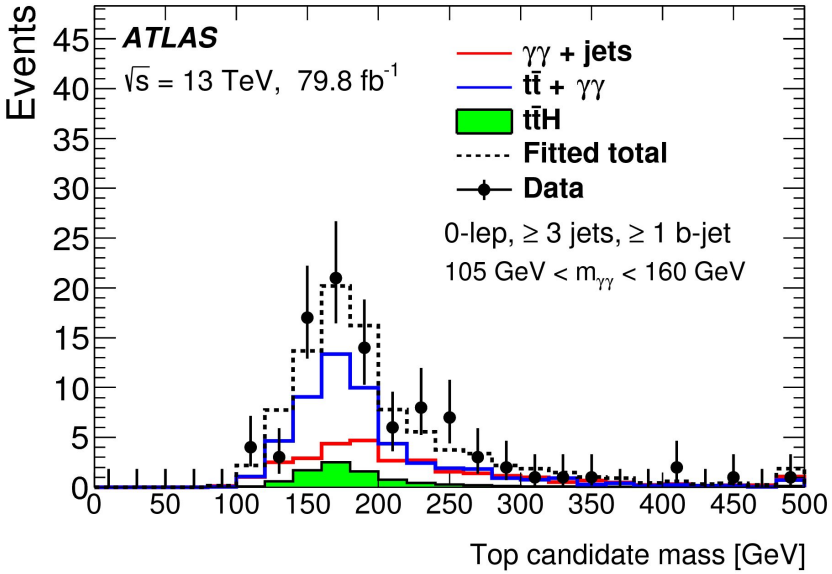




ttH (H→γγ)

- Higgs signal modeled as a double-sided Crystal Ball function (m_H = 125.09 GeV)
- Background modeled by a smooth falling function
  - functional form from simulated bkg(Lep) or CR (had)
  - Non-ttH Higgs processes are fixed to the SM
    - 100% unc. - negligible impact





- had-BDT selects clearly events with top candidates

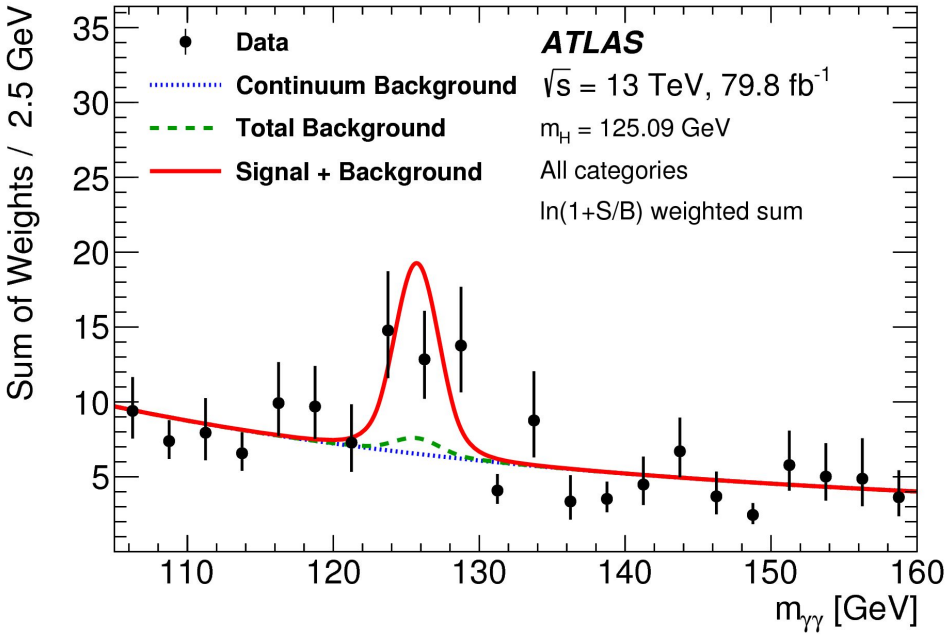
Main Systematics:

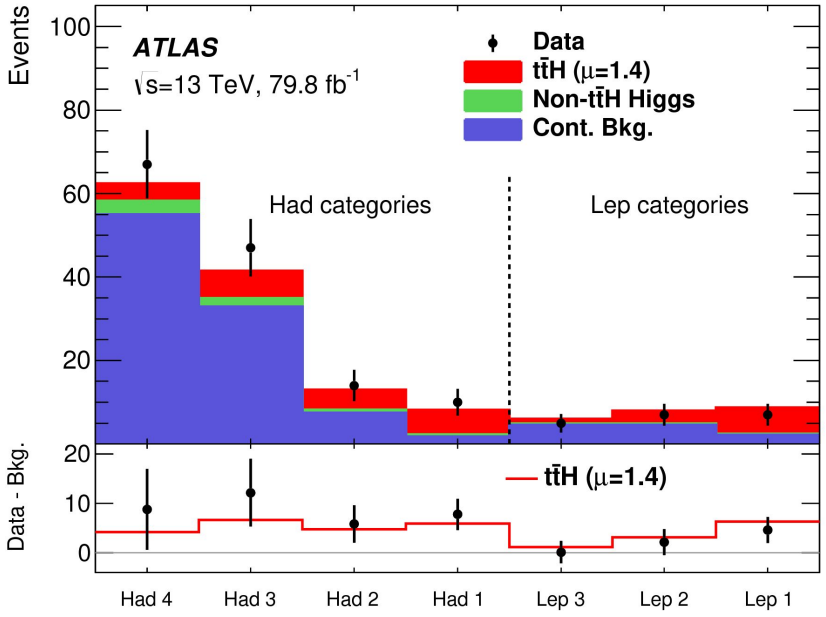
- Exp syst: γ/jet energy scale and resolution, γ isolation efficiency (~5%)
- TH syst: Shower uncertainty for ttH signal (8%)

ttH (H→γγ)

- **Observed ttH significance** : **4.1σ**
  - expected 3.7σ
- Measured cross section at 13 TeV:

$$\sigma_{ttH} = 710^{+210}_{-190}\,(stat)\,^{120}_{-90}\,(syst)\,\text{fb} \qquad (\text{SM} = 507^{+35}_{-50}\,\text{fb})$$





- considering same statistics as for the previous analysis with 36 fb^{-1} ~50% improvement

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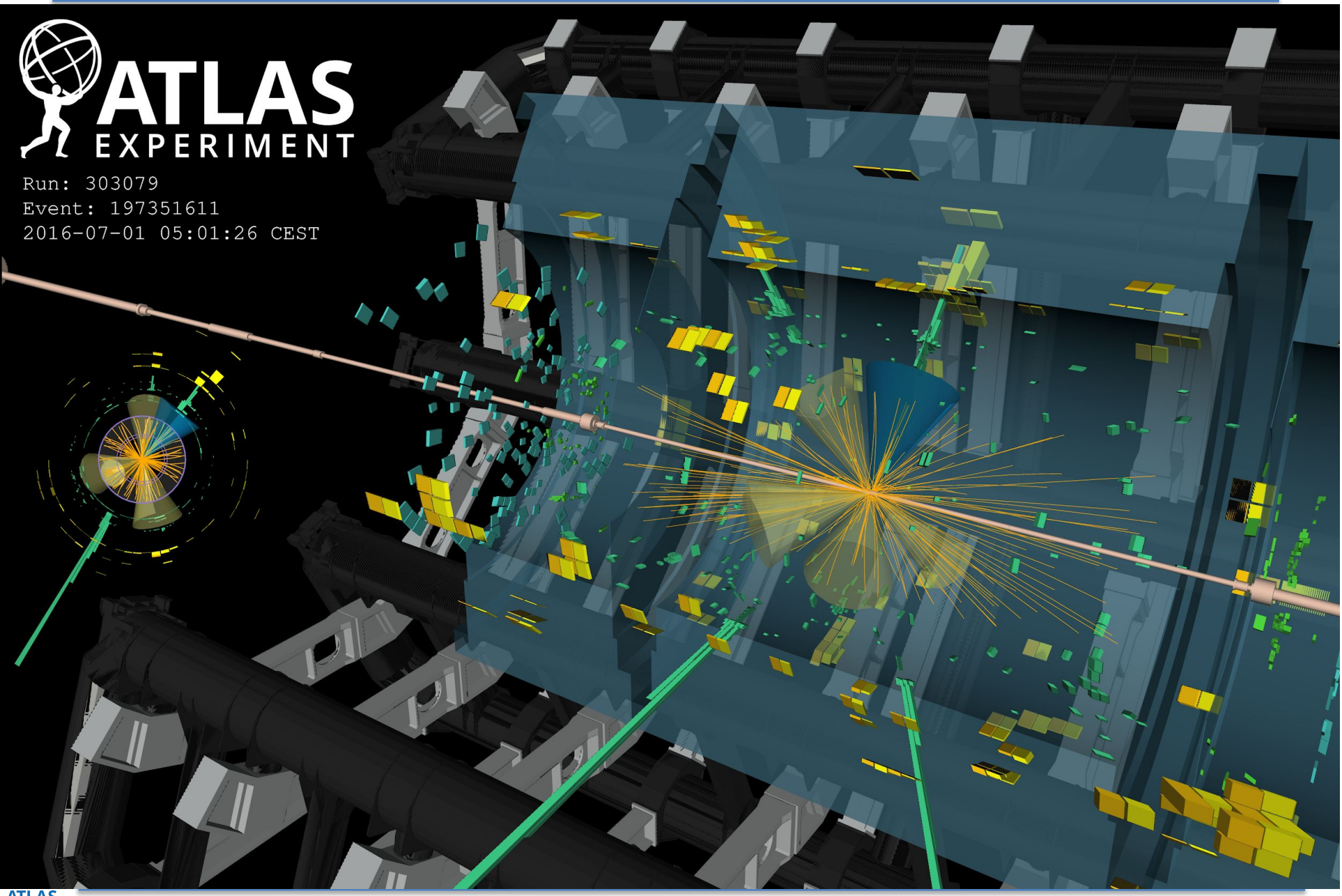
ttH (H→γγ)



NEW!! L = 80 fb^{-1} : arXiv:1806.00425

Combination

- **Run2 combination**
  - updated yy and ZZ→4l (80fb^{-1}) combined with ML and H→bb (36 fb^{-1})
  - event overlap negligible
  - some syst components on lumi, JES, e/y E scale/resolution and ID efficiency correlated
  - Theory uncertainties correlated between channels
  - SM Branching Ratio assumed

Observed ttH significance: 5.8σ

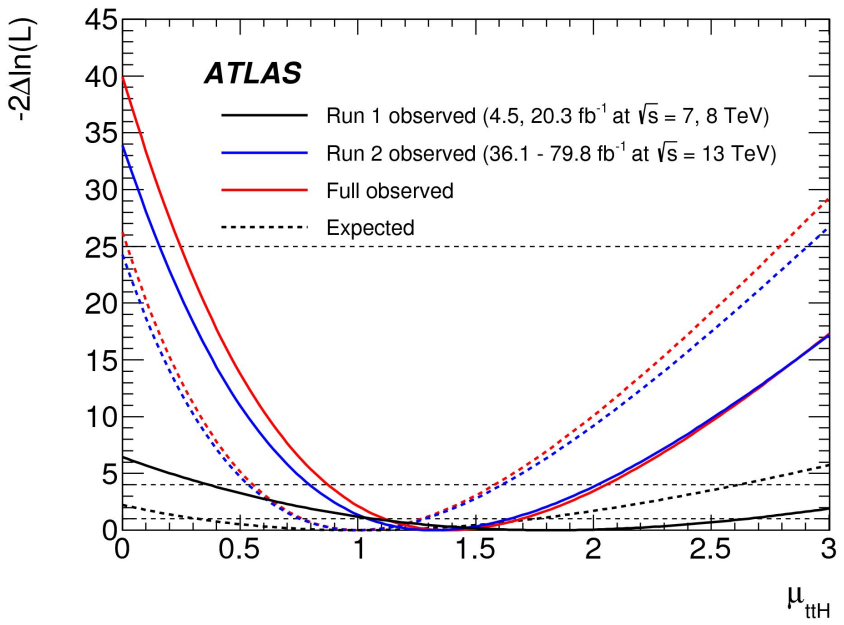
  - expected 4.9σ

- **Run1+Run2 combination**
  - Run1 channels: bb,ML,yy

Observed ttH significance : **6.3σ**

  - expected: 5.1 σ

Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-$t\bar{t}H$ Higgs boson production modes	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-lepton	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4



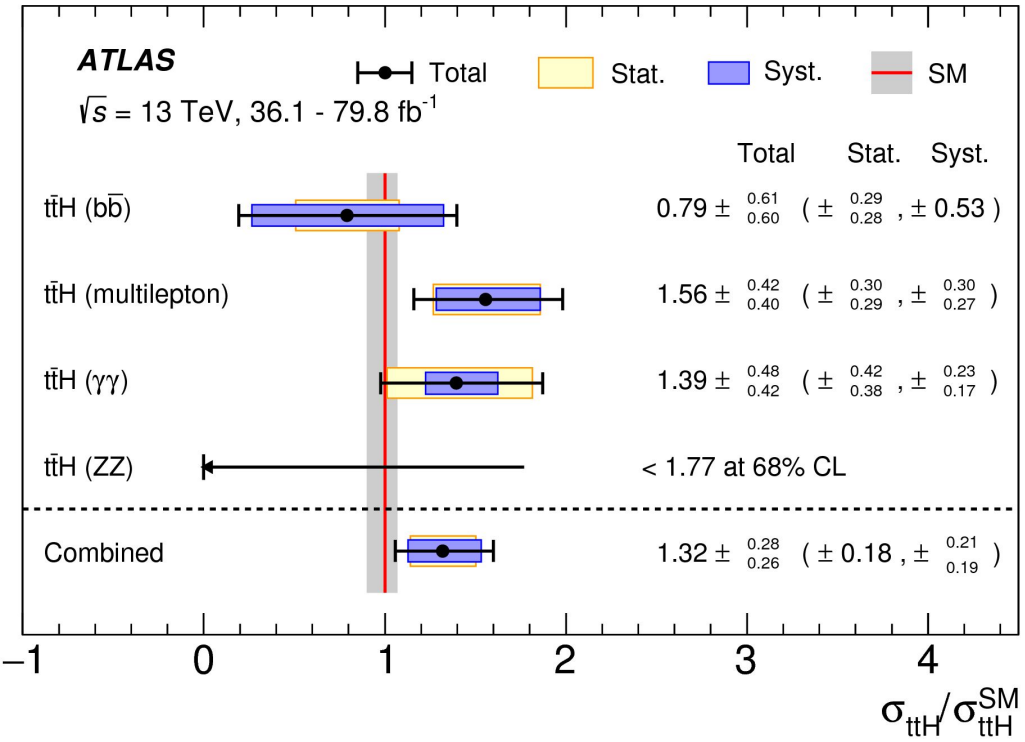
Combination

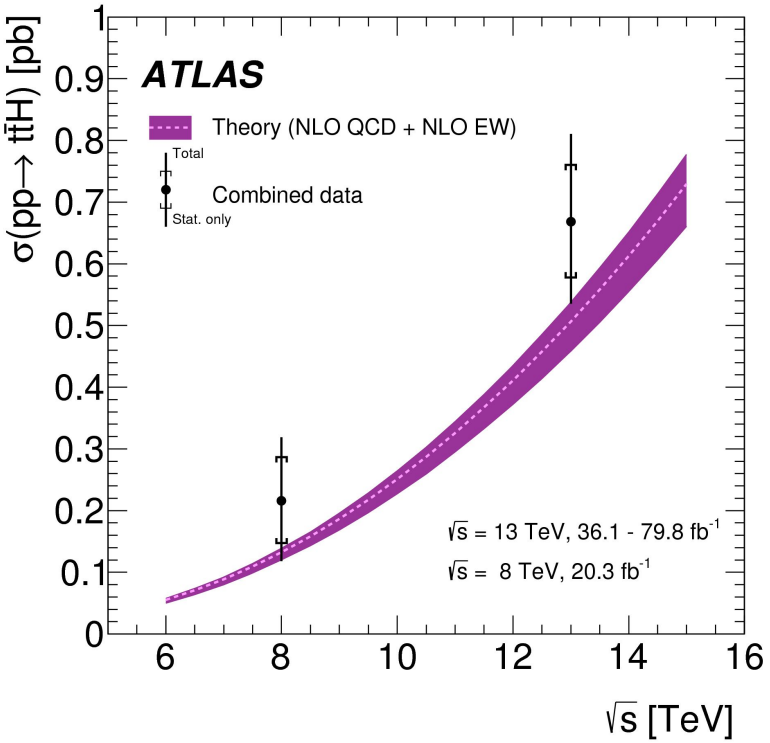
- Measured total cross section of ttH production at $\sqrt{s}$=13 TeV :

$$\sigma_{ttH} = 670 \pm 90\,(stat)\,^{+110}_{-100}\,(syst)\,\text{fb} \qquad (\text{SM} = 507^{+35}_{-50}\,\text{fb})$$

- Measured total cross section of ttH production at $\sqrt{s}$=8 TeV :

$$\sigma_{ttH} = 220 \pm 100\,(stat)\ \pm 70\,(syst)\,\text{fb} \qquad (\text{SM} = 133^{+6}_{-13}\,\text{fb})$$





Conclusions

- Results presented for ttH searches with 36 and 80 fb^{-1} of pp collision data
- Improved techniques compared to Run1 for ttH bb ML and yy
- ttH, H→yy and H→ZZ→4l improved sensitivities allowed the observation of the ttH process at 13 TeV
- Observed ttH significance of **6.3 σ**
  - direct observation of the Higgs boson Yukawa coupling to the top quark
  - constraint on the λ_{top} coupling at 10-15% level with direct measurement
- Cross section measurement for this process at 13 TeV

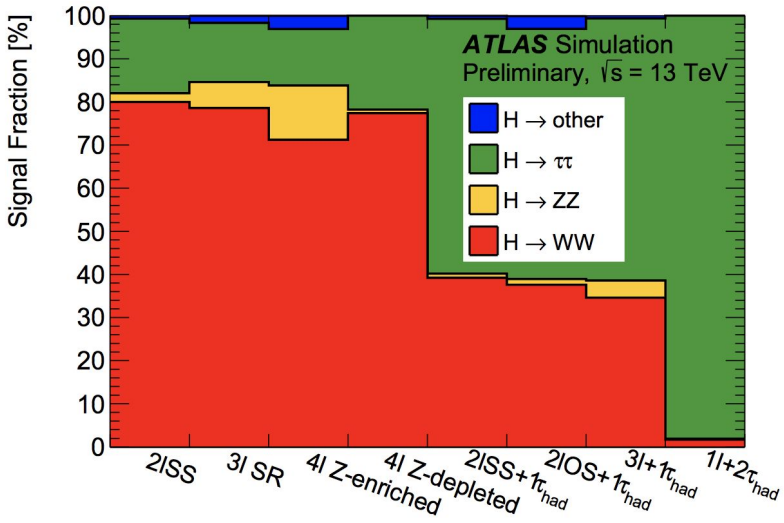
$$\sigma_{ttH} = 670 \pm 90\,(stat)\,^{+110}_{-100}\,(syst)\,\text{fb} \qquad (\text{SM} = 507^{+35}_{-50}\,\text{fb})$$

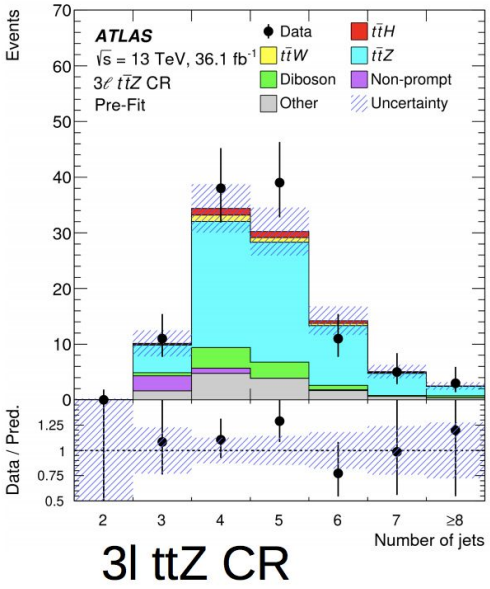
- Working on further improvements and analysis of Run2 data
  - increase sensitivity on λ_{top} to find possible NP effects

Backup

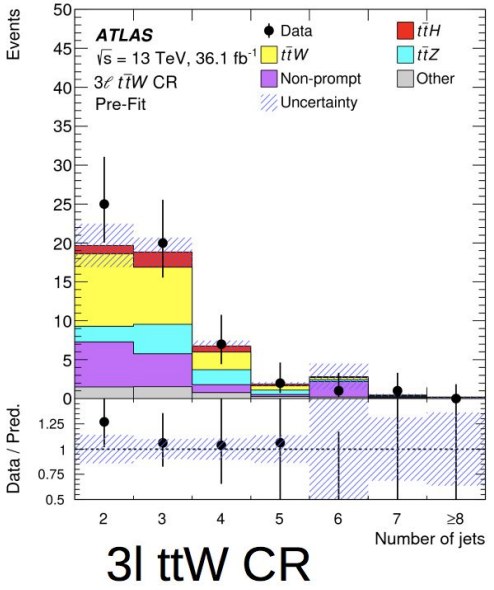
- Four b-tagging working points calibrated on data:
  - Loose – Medium – Tight – Very Tight corresponding to: 85% - 77% - 70% - 60% eff. to tag a b-jet
  - Assign a b-tagging score from 1 to 5 (from not-tagged to 60%)
- b-jets calibrated with ttbar events (2-10% uncertainty, dominated by ttbar modelling)
- c-jets calibrated with ttbar events (W→cs) and W+c events (5-20% uncertainty) light-jets calibrated with dijets events (10-50% uncertainty)

Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modeling	+0.46	−0.46
Background-model stat. unc.	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
$t\bar{t} + \geq 1c$ modeling	+0.09	−0.11
JVT, pileup modeling	+0.03	−0.05
Other background modeling	+0.08	−0.08
$t\bar{t}$ + light modeling	+0.06	−0.03
Luminosity	+0.03	−0.02
Light lepton (e, μ) id., isolation, trigger	+0.03	−0.04
Total systematic uncertainty	+0.57	−0.54
$t\bar{t} + \geq 1b$ normalization	+0.09	−0.10
$t\bar{t} + \geq 1c$ normalization	+0.02	−0.03
Intrinsic statistical uncertainty	+0.21	−0.20
Total statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61





3l ttZ CR

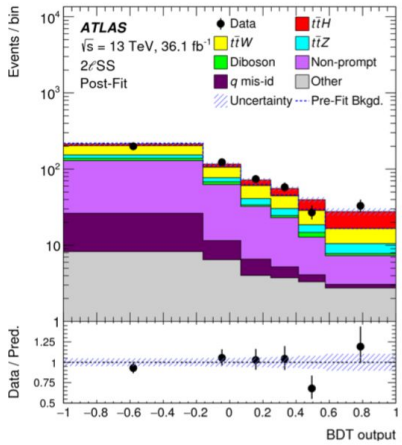


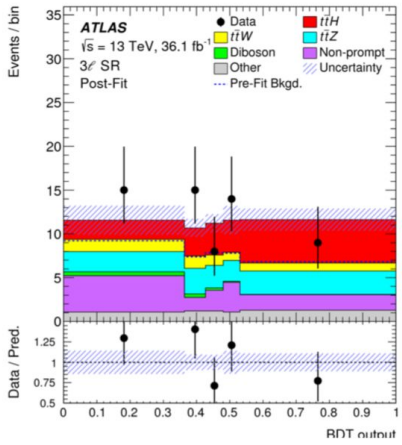
3l ttW CR

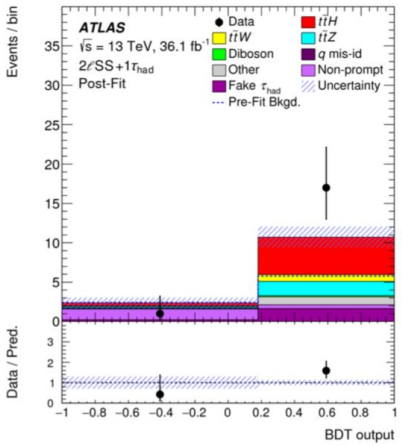
	2ℓSS	3ℓ	4ℓ	1ℓ+2τ_{had}	2ℓSS+1τ_{had}	2ℓOS+1τ_{had}	3ℓ+1τ_{had}
BDT trained against	Fakes and $t\bar{t}V$	$t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, VV	$t\bar{t}Z$ / -	$t\bar{t}$	all	$t\bar{t}$	-
Discriminant	2×1D BDT	5D BDT	Event count	BDT	BDT	BDT	Event count
Number of bins	6	5	1 / 1	2	2	10	1
Control regions	-	4	-	-	-	-	-

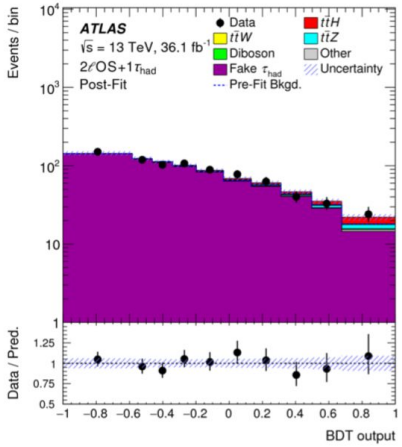
Systematic uncertainty	Type	Components
Luminosity	N	1
Pileup reweighting	SN	1
Physics Objects		
Electron	SN	6
Muon	SN	15
τ_{had}	SN	10
Jet energy scale and resolution	SN	28
Jet vertex fraction	SN	1
Jet flavor tagging	SN	126
E_T^{miss}	SN	3
Total (Experimental)	–	191
Data-driven non-prompt/fake leptons and charge misassignment		
Control region statistics	SN	38
Light-lepton efficiencies	SN	22
Non-prompt light-lepton estimates: non-closure	N	5
γ-conversion fraction	N	5
Fake τ_{had} estimates	N/SN	12
Electron charge misassignment	SN	1
Total (Data-driven reducible background)	–	83
$t\bar{t}H$ **modeling**		
Cross section	N	2
Renormalization and factorization scales	S	3
Parton shower and hadronization model	SN	1
Higgs boson branching fraction	N	4
Shower tune	SN	1
$t\bar{t}W$ **modeling**		
Cross section	N	2
Renormalization and factorization scales	S	3
Matrix-element MC event generator	SN	1
Shower tune	SN	1
$t\bar{t}Z$ **modeling**		
Cross section	N	2
Renormalization and factorization scales	S	3
Matrix-element MC event generator	SN	1
Shower tune	SN	1
Other background modeling		
Cross section	N	15
Shower tune	SN	1
Total (Signal and background modeling)	–	41
Total (Overall)	–	315

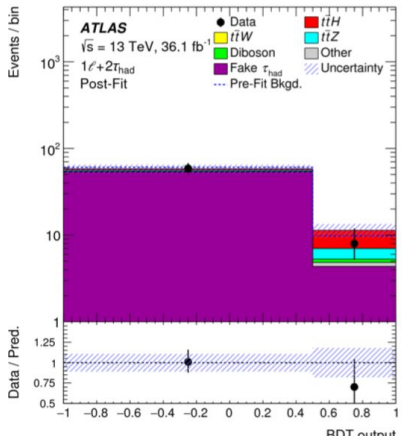
	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{\text{had}}$	$2\ell\text{SS}+1\tau_{\text{had}}$	$2\ell\text{OS}+1\tau_{\text{had}}$	$3\ell+1\tau_{\text{had}}$
BDT trained against	Fakes and $t\bar{t}V$	$t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, VV	$t\bar{t}Z$ / -	$t\bar{t}$	all	$t\bar{t}$	-
Discriminant	2×1D BDT	5D BDT	Event count	BDT	BDT	BDT	Event count
Number of bins	6	5	1 / 1	2	2	10	1
Control regions	-	4	-	-	-	-	-

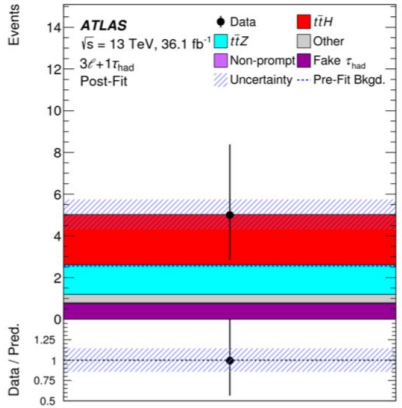


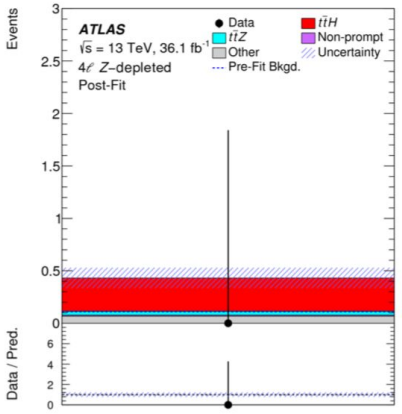


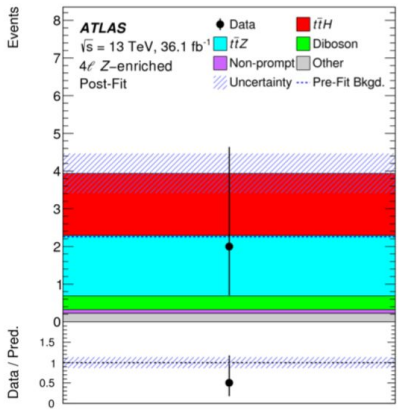


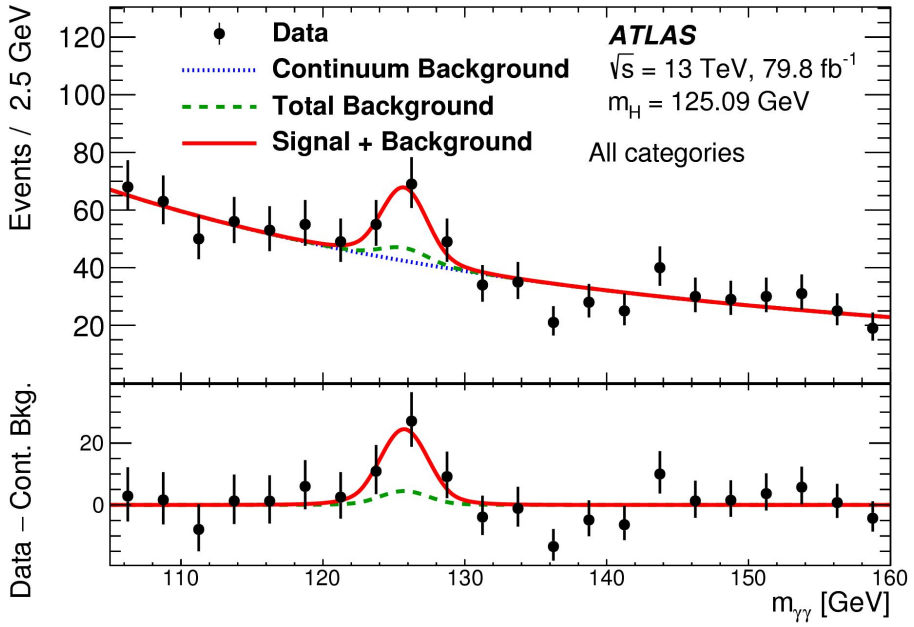




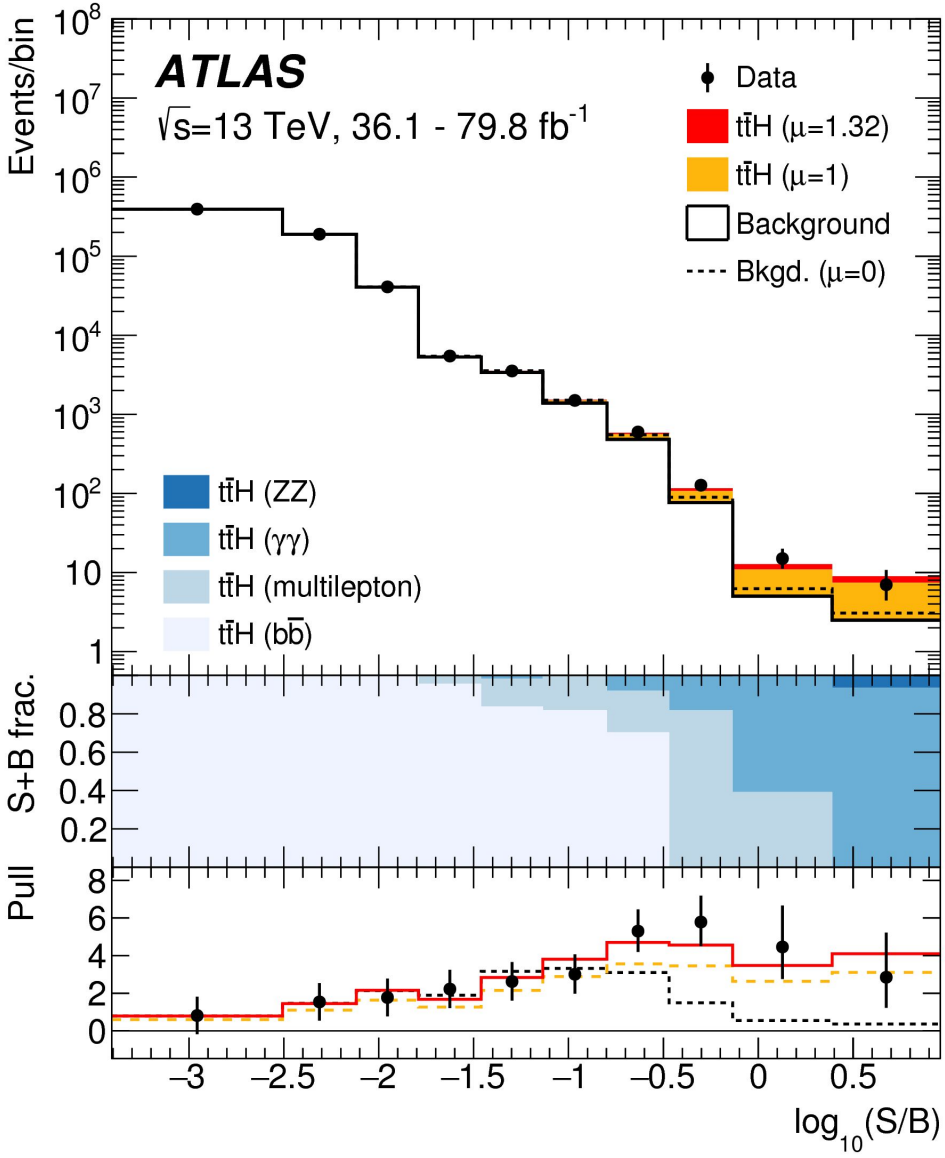


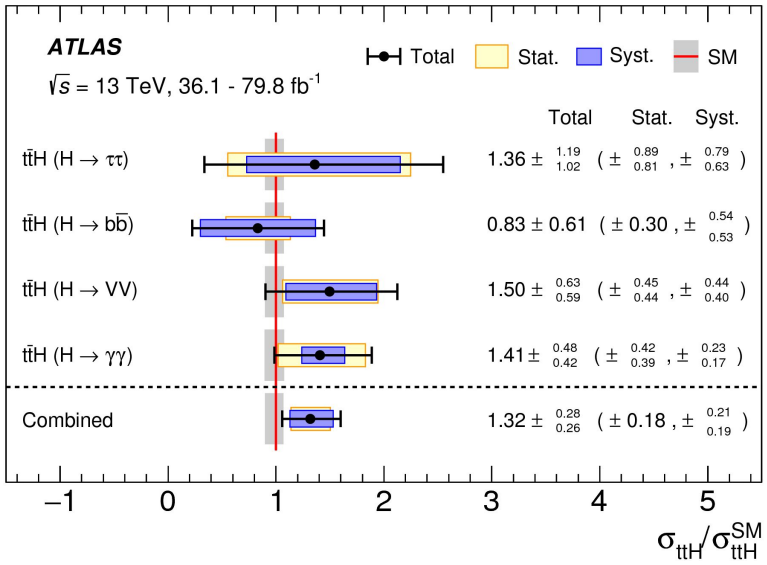






Bin	Expected $t\bar{t}H$ (signal)	Non-$t\bar{t}H$ Higgs	Non-Higgs	Total	Observed Total
		$H \to \gamma\gamma$			
Had 1	4.2(11)	0.49(33)	1.76(55)	6.4(13)	10
Had 2	3.41(74)	0.69(56)	7.5(11)	11.6(15)	14
Had 3	4.70(88)	2.0(17)	32.9(22)	39.6(32)	47
Had 4	3.00(55)	3.2(31)	55.0(28)	61.3(47)	67
Lep 1	4.5(10)	0.25(9)	2.19(59)	6.9(12)	7
Lep 2	2.23(39)	0.27(10)	4.59(91)	7.1(10)	7
Lep 3	0.82(18)	0.30(13)	4.58(91)	5.70(88)	5
		$H \to ZZ^* \to 4\ell$			
Had 1	0.169(31)	0.021(7)	0.008(8)	0.198(33)	0
Had 2	0.216(32)	0.20(9)	0.22(12)	0.63(16)	0
Lep	0.212(31)	0.0256(23)	0.015(13)	0.253(34)	0


ATLAS
√s=13 TeV, 36.1 - 79.8 fb-1
Data
tt̄H (μ=1.32)
tt̄H (μ=1)
Background
Bkgd. (μ=0)
tt̄H (ZZ)
tt̄H (γγ)
tt̄H (multilepton)
tt̄H (bb̄)
Events/bin
S+B frac.
Pull
log10(S/B)


ATLAS
√s = 13 TeV, 36.1 - 79.8 fb-1
Total
Stat.
Syst.
SM
Total Stat. Syst.
tt̄H (H → ττ) 1.36 ± 1.19 1.02 (± 0.89 0.81 , ± 0.79 0.63)
tt̄H (H → bb̄) 0.83 ± 0.61 (± 0.30 , ± 0.54 0.53)
tt̄H (H → VV) 1.50 ± 0.63 0.59 (± 0.45 0.44 , ± 0.44 0.40)
tt̄H (H → γγ) 1.41 ± 0.48 0.42 (± 0.42 0.39 , ± 0.23 0.17)
Combined 1.32 ± 0.28 0.26 (± 0.18 , ± 0.21 0.19)
σttH/σttHSM