Observation of $t\bar{t}H$ production with ATLAS

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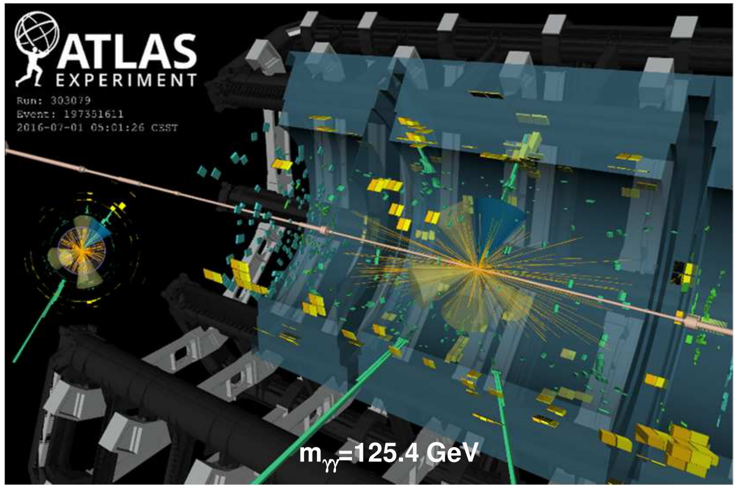
On Behalf of the ATLAS Collaboration

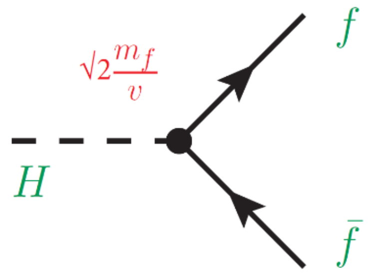


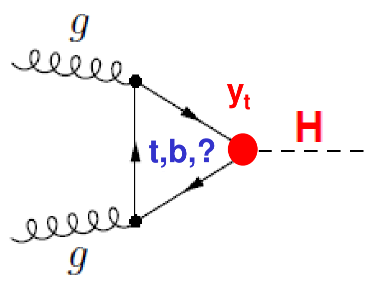
TOP 2018 International Workshop, September 16-21

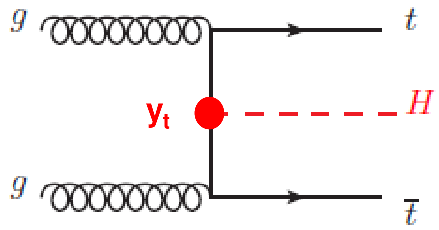
Motivations

- All measurements of Higgs properties consistent with SM so far, but fermion sector less tested
- Higgs coupling to fermions in SM through Yukawa interactions: proportional to fermion mass
- Top Yukawa coupling is predicted to be by far the largest one (top is the heaviest fermion): $y_t = \sqrt{2}\, m_t / v \approx 1$ ➔ intriguing!
- Only coupling which can not be measured directly through Higgs decay for m_H=125 GeV
  - Indirect constraint through loops from gg→H production and H→ $\gamma\gamma$ decay but New Physics could also contribute
    ➔ need direct measurement to disentangle and probe NP
  - Direct measurement through associated $t\bar{t}H$ production (tree level process) → $\sigma(t\bar{t}H) \propto y_t^2$

[also possible through tH production, but SM cross-section ~6 times lower]

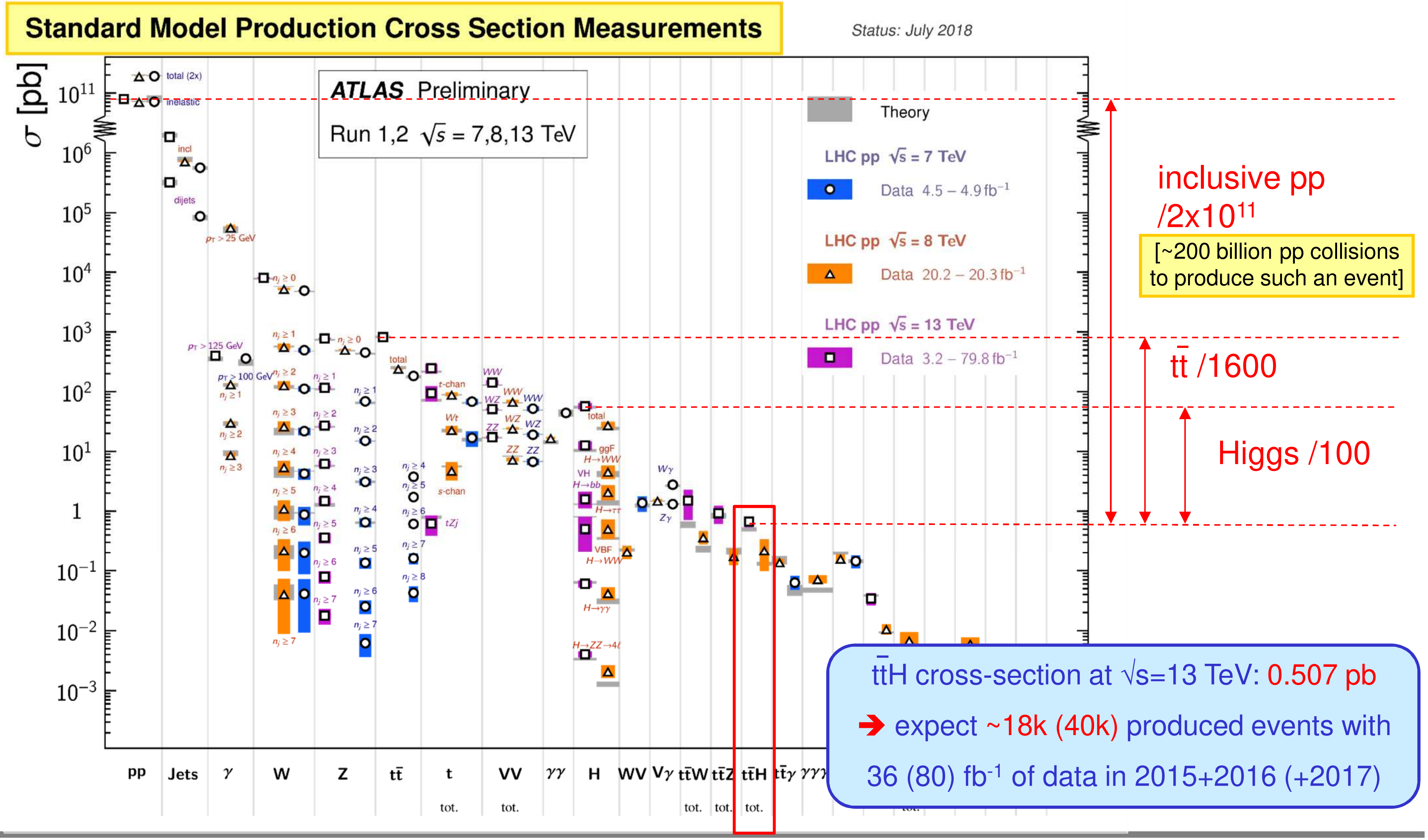






➔ **Allow to simultaneously constrain top Yukawa coupling and possible BSM effects**

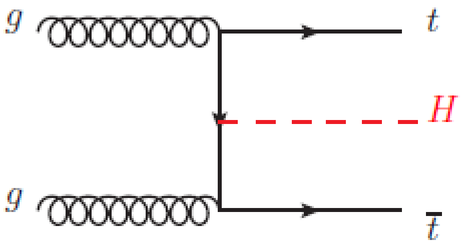
$t\bar{t}H$ production at LHC

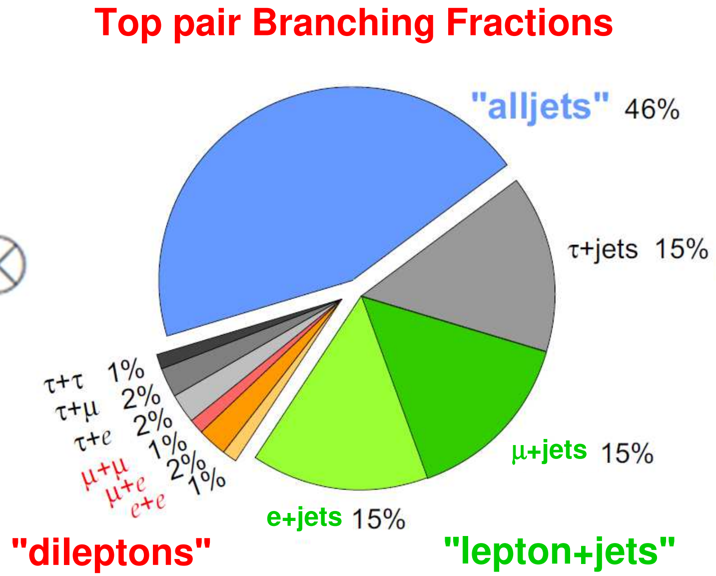


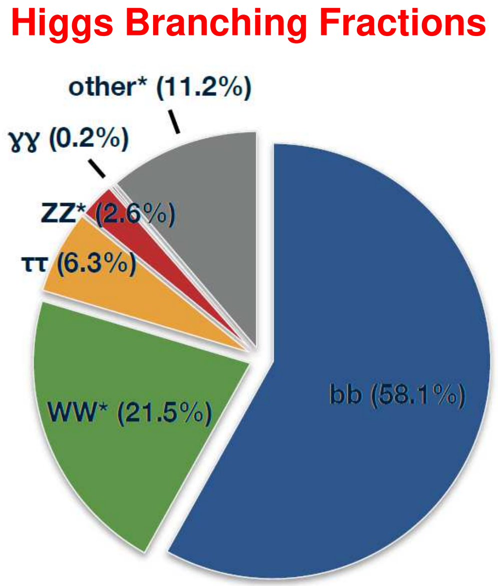
$t\bar{t}H$ cross-section at $\sqrt{s}$=13 TeV: 0.507 pb

➔ expect ~18k (40k) produced events with 36 (80) fb^{-1} of data in 2015+2016 (+2017)

On the hunt for $t\bar{t}$H…





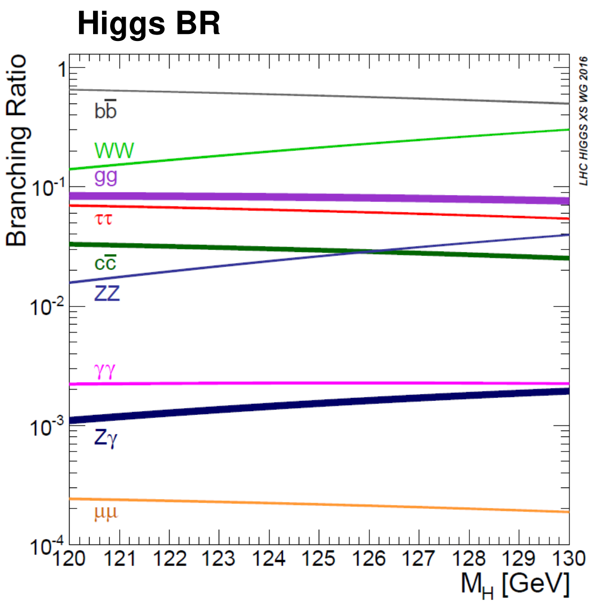


- Combination of $t\bar{t}$+H decays ➔ very rich spectrum of possible signatures
- Broad spectrum of analyses explored to cover these multiple final states ➔ need combination of all these analyses to optimize sensitivity
- Complex final states ➔ need good understanding of all reconstructed objects [e, μ, γ, hadronically decaying τ, jets, b-jets, E_T^{miss}]

$t\bar{t}H$ analysis channels

Large BR

Low purity



Small BR

High purity

$t\bar{t}H$, $H\rightarrow b\bar{b}$

36.1 fb^{-1}, $\sqrt{s}$=13 TeV

BR~58%, S/B~1-5%

Phys. Rev. D 97 (2018) 072016

$t\bar{t}H$, multi-leptons ($H\rightarrow WW^*,\tau\tau,ZZ^*$)

36.1 fb^{-1}, $\sqrt{s}$=13 TeV

BR~30%, S/B~2-60%

Phys. Rev. D 97 (2018) 072003

$t\bar{t}H$, $H\rightarrow\gamma\gamma$

79.8 fb^{-1}, $\sqrt{s}$=13 TeV

BR~0.23%, S/B~5-200%

Phys. Lett. B 784 (2018) 173

$t\bar{t}H$, $H\rightarrow ZZ^*\rightarrow 4l$

79.8 fb^{-1}, $\sqrt{s}$=13 TeV

BR~0.01%, S/B~50-500%

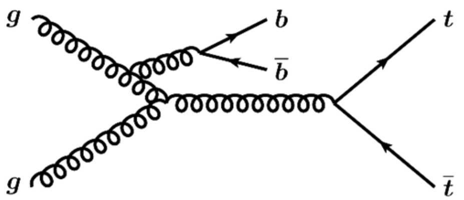
Phys. Lett. B 784 (2018) 173

Combination

Phys. Lett. B 784 (2018) 173

$t\bar{t}H$, $H\rightarrow b\bar{b}$

- Most abundant, but huge combinatorics and large irreducible background with big theoretical uncertainty (from $t\bar{t}$+jets, especially $t\bar{t}$+Heavy Flavour)
- Main challenge: modelling of $t\bar{t}$+HF (≥1b,≥1c) and associated uncertainties ➔ use state-of-the-art MC generators and constrain from data (➔ see backup slides 42-44 for more details)



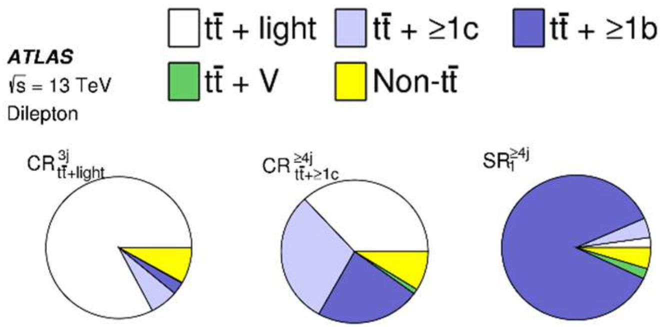
Dominant background: $t\bar{t}+b\bar{b}$

- Nominal $t\bar{t}$ sample: inclusive NLO generator (2→2 process, additional radiations from PS), normalised to NNLO+NNLL
- Main systematics: alternative samples (generator, PS model, …)
- Normalisation of $t\bar{t}$+≥1b and $t\bar{t}$+≥1c derived from data

➢ Selection of semi- and di-leptonic $t\bar{t}$ decays
  [Fully hadronic channel used in Run-1 still at work]

➢ Further categorisation based on jet multiplicity and b-tag score of jets (4 working points, ε_b=85%→60%)

➢ 9 SR + 10 CR with very different signal purity (best is ~5%) and bkgnd fractions ($t\bar{t}$+light, $t\bar{t}$+≥1c, $t\bar{t}$+≥1b), with a "boosted" category targeting high p_T top/Higgs



Exemple of a few dilepton categories

$t\bar{t}H$, $H \rightarrow b\bar{b}$

- Cascade of MVA classifiers in Signal Regions to enhance signal sensitivity

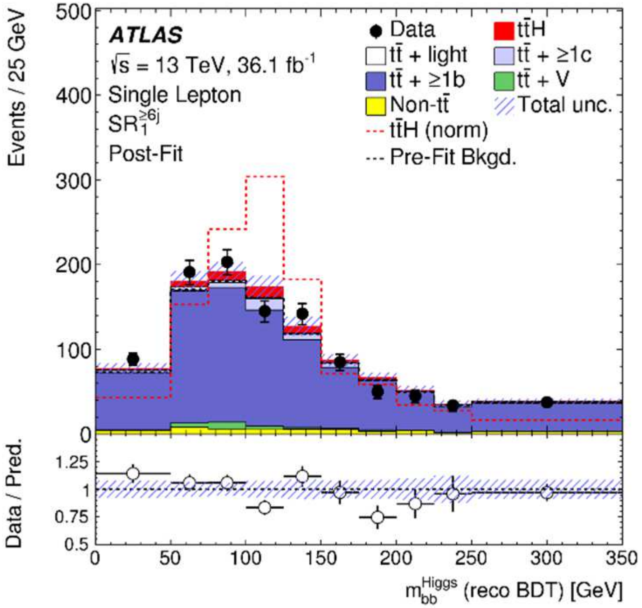
Reconstruction

- Solve combinatorics to identify best jet-parton assignment and reconstruct final state
- $t\bar{t}H$ system reconstruction BDT + Likelihood discriminant + Matrix Element Method

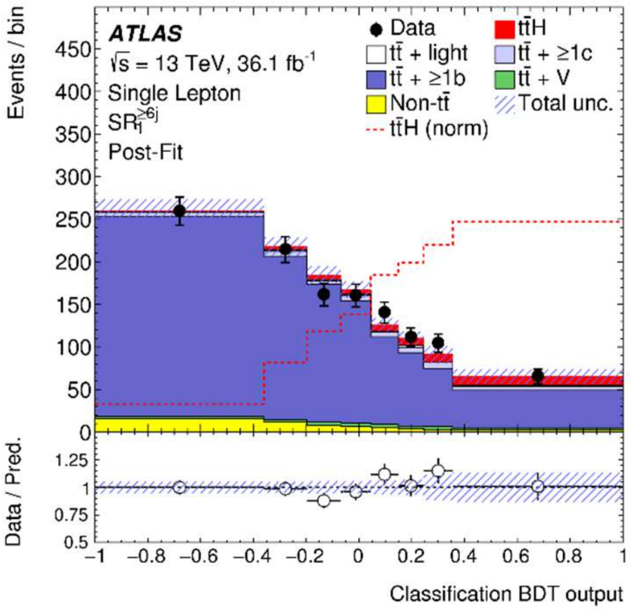
Classification

- BDT for $t\bar{t}H$ vs background in each SR
- Inputs: reconstruction discriminants & related H/top properties, event kinematic variables, b-tag information

Example: reconstructed Higgs mass



Example in purest single-lepton SR



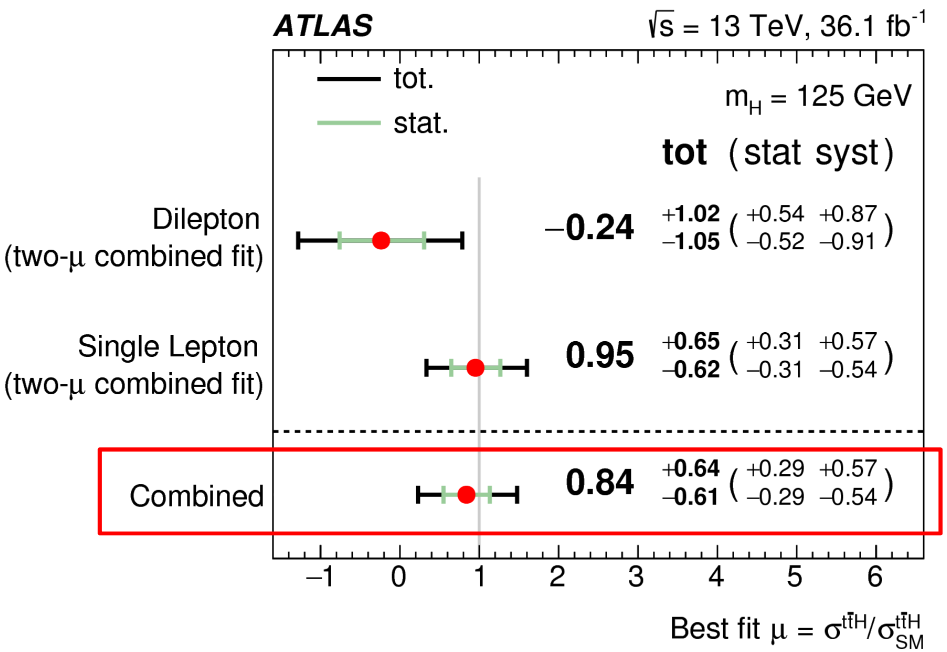
$t\bar{t}H$, $H \rightarrow b\bar{b}$

- Combined likelihood fit across all SR & CR

[classification BDT output in SR, event yields in most CR]

- Normalisation of $t\bar{t}$+≥1b & $t\bar{t}$+≥1c free-floating
- Leading systematics: modelling of $t\bar{t}$+≥1b

  [PowhegPy8 vs Sherpa 5FS], limited MC stat.



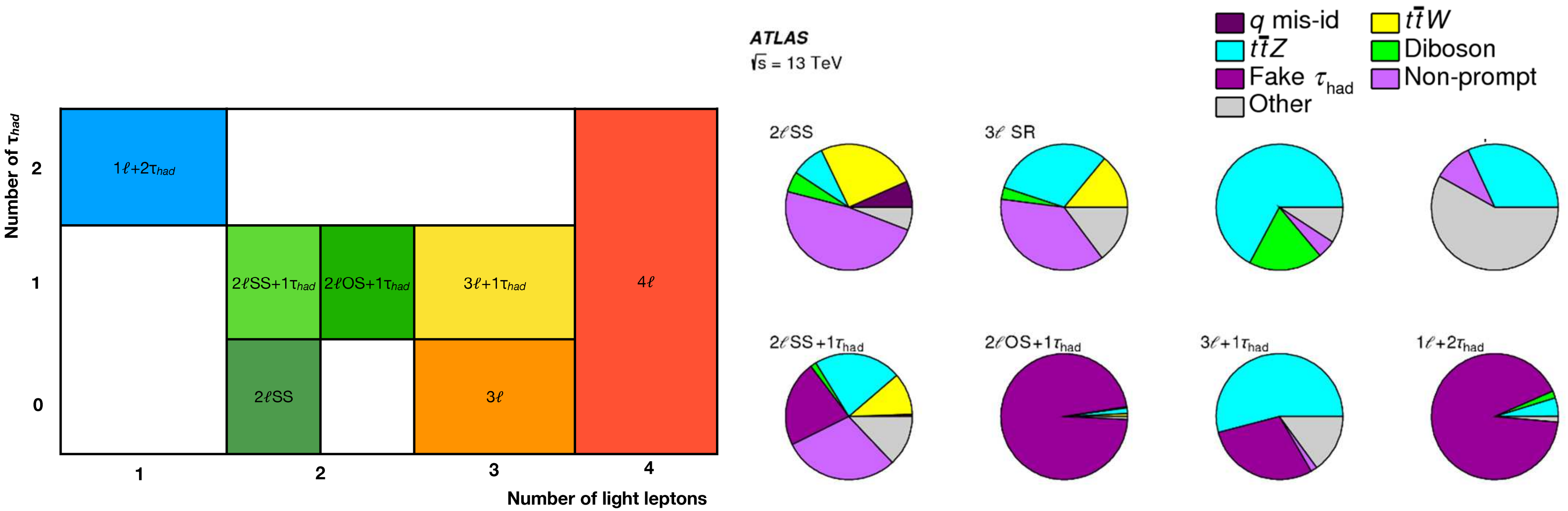
Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modeling	$+0.46$	-0.46
Background-model stat. unc.	$+0.29$	-0.31
b-tagging efficiency and mis-tag rates	$+0.16$	-0.16
Jet energy scale and resolution	$+0.14$	-0.14
⋮		
Total systematic uncertainty	$+0.57$	-0.54
$t\bar{t}+\geq 1b$ normalization	$+0.09$	-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

- ➔ Signal significance 1.4σ (1.6σ expected)
- ➔ Good agreement with SM predictions
- ➔ Precision ±75% (35% stat, 65% syst)
- ➔ Systematically limited by modelling of $t\bar{t}$+≥1b background

$t\bar{t}H$, Multileptons

- Targets H→WW*(→lνlν, lνqq), H→ττ and H→ZZ*(→llνν, llqq) decays [dedicated analysis for H→ZZ*→4l, see later]
- Main background $t\bar{t}$ suppressed by requirement of two same-sign or at least 3 leptons
- 7 orthogonal channels categorised by multiplicity of e/μ and hadronic τ candidates

  Requirements on (b-)jet multiplicities (≥2-4 jets, ≥1 b-jet) to further suppress diboson and $t\bar{t}$ backgrounds
- Wide range of yields and S/B purity, with different background composition in the various SR



$t\bar{t}H$, Multileptons

Irreducible background

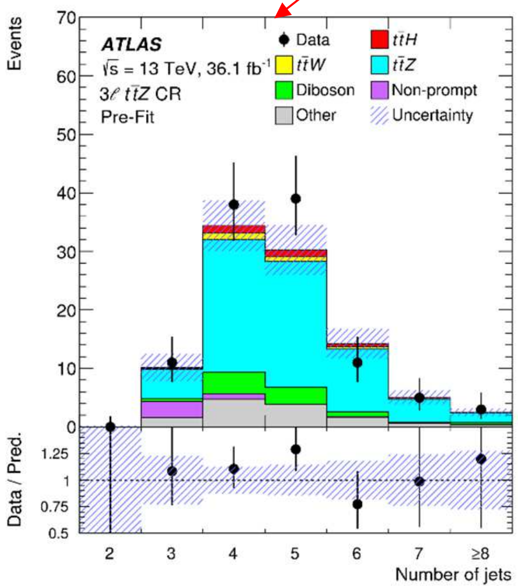
- Dominated by $t\bar{t}$+W, $t\bar{t}$+Z and VV
- Estimated from NLO MC predictions
- Validated in various dedicated regions

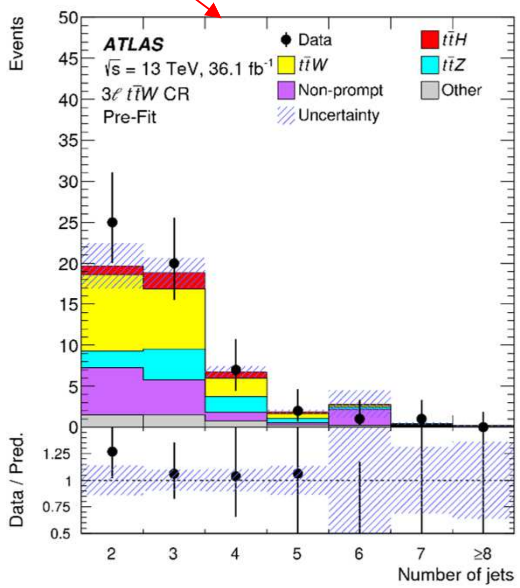
Reducible background

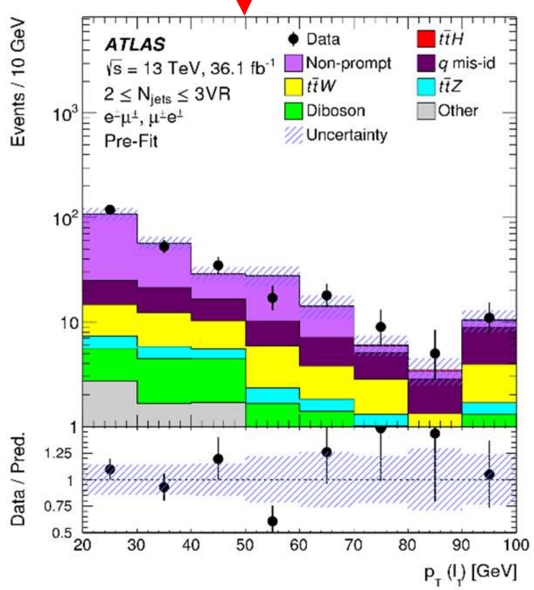
- Mainly from $t\bar{t}$ events, with non-prompt light leptons from b-hadron decay, fake τ_{had} from light flavour jet or charge misidentified electron
- Reduction by lepton isolation / q-misid BDTs
- Data-driven estimates, validated in various regions, such as low N_{jets}

$t\bar{t}$+Z CR

$t\bar{t}$+W CR

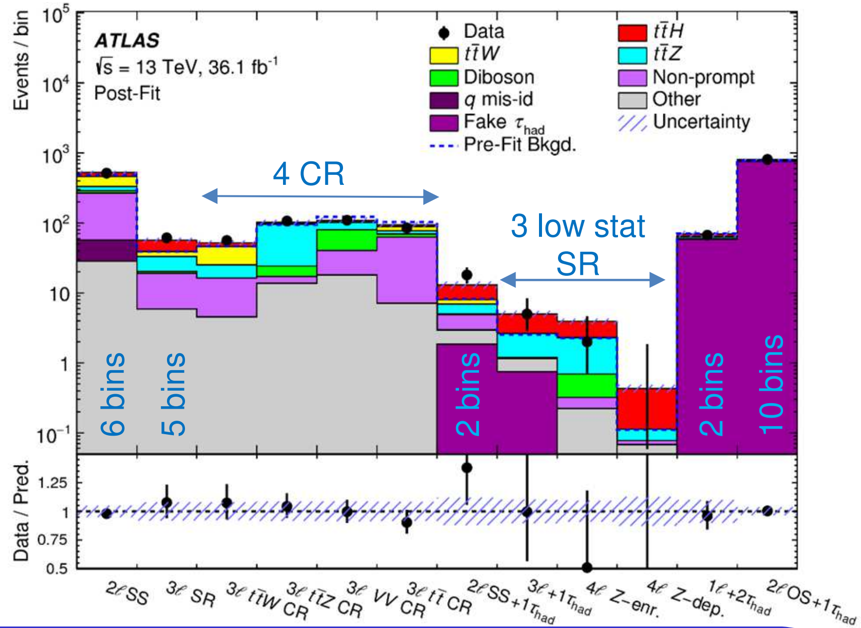


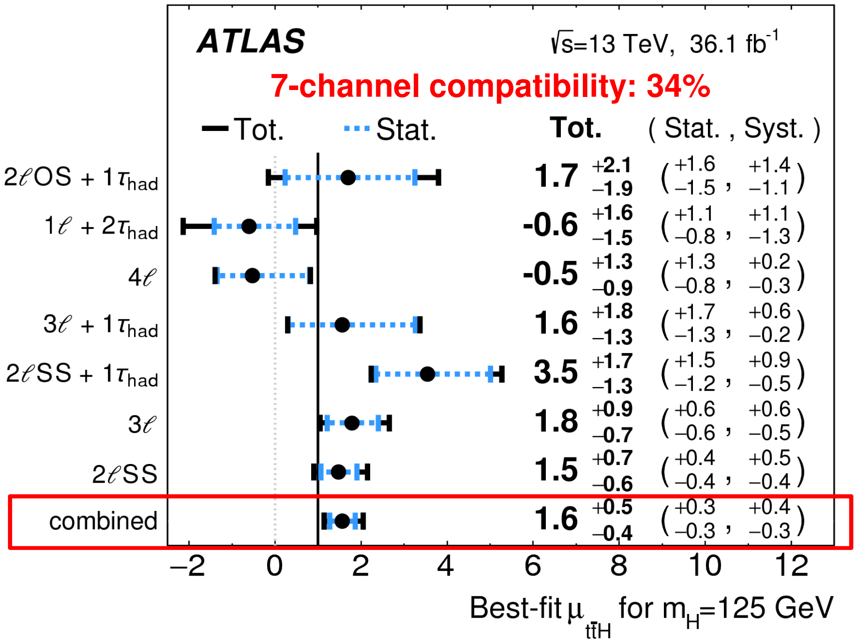




$t\bar{t}H$, Multileptons

- Dedicated MVA approaches in 6 of 7 channels for further signal-background separation
- Combined likelihood fit across all categories including main bknd CR [BDT shape used in 5 SR]
- Leading systematics: $t\bar{t}H$ and $t\bar{t}V$ modelling, non-prompt lepton estimates (large contribution from limited CR stat) and jet energy scale/resolution



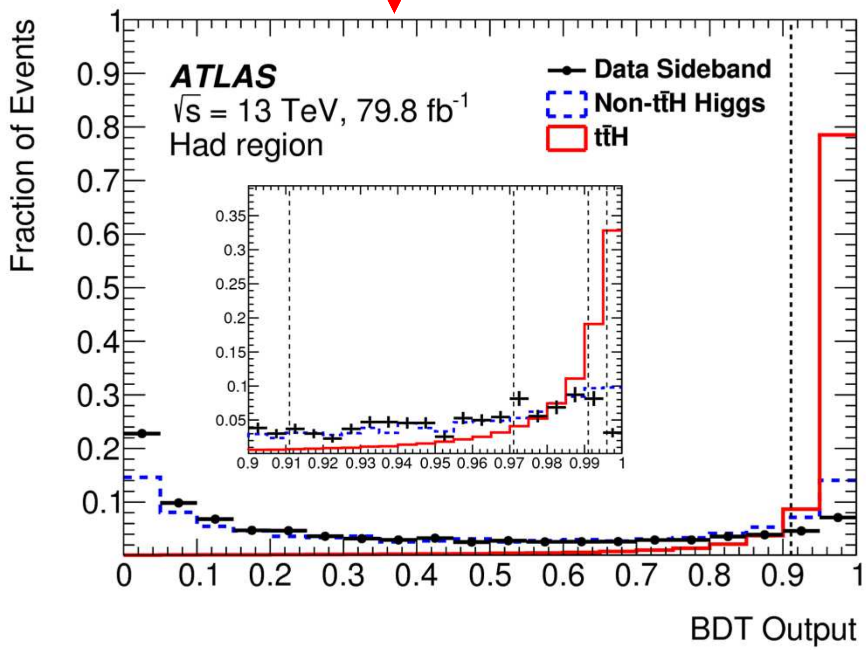


- Signal significance **4.1σ** (2.8σ expected)
- Good agreement with SM predictions
- Precision ±30% (20% stat, 20% syst)
- Several categories still statistically limited
- Alternative fit with free floating $t\bar{t}V$ normalisation
  - Same best fit with 15% degraded sensitivity
  - $\mu_{ttW} = 0.92 \pm 0.32$, $\mu_{ttZ} = 1.17^{+0.25}_{-0.22}$

$t\bar{t}H$, H→γγ

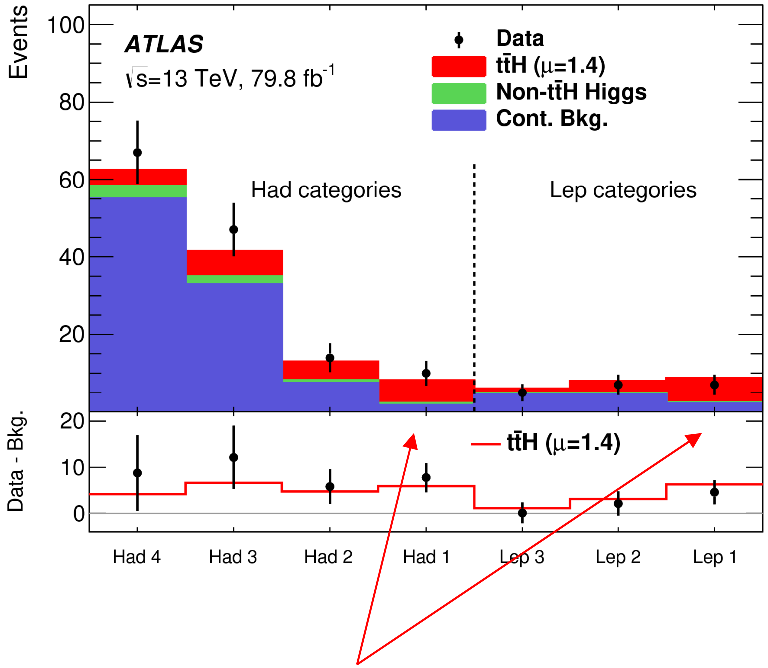
- Small rate: expect ~92 $t\bar{t}H$, H→γγ produced events with 79.8 fb^{-1} of data in 2015+2016+2017
- But narrow peak in $m_{\gamma\gamma}$ over smooth continuum bkgnd, extrapolated from side-bands in data
- Standard H→γγ selection: 2 high-E_T isolated photons $p_T/m_{\gamma\gamma}$>0.35 (0.25), 105<$m_{\gamma\gamma}$<160 GeV
- Categorisation based on $t\bar{t}$ decay ➔ *Lep* (≥1l,≥1j,≥1b) and *Had* (0l,≥3j,≥1b) categories
- Further separation power based on BDT discriminant → 4 hadronic and 3 leptonic categories

> - Main backgrounds: γγ continuum and non-$t\bar{t}H$ Higgs productions
> - Training: deep neural networks using $t\bar{t}H$ MC vs background events from data control regions
> - Input variables: photon kinematics ($p_T/m_{\gamma\gamma}$, η, ϕ), jet/lepton 4-vectors, E_T^{miss}, b-tag (*Had*)

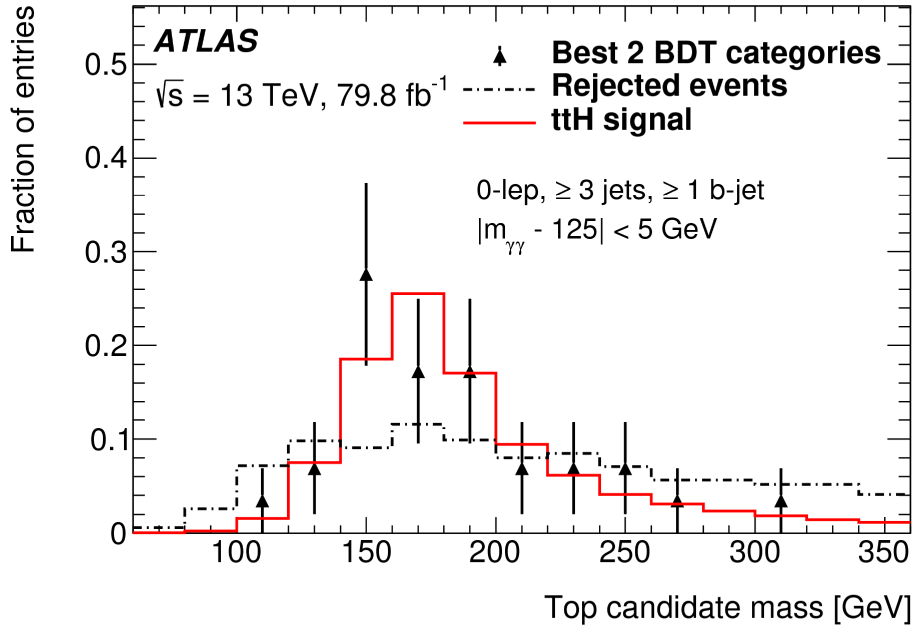


$t\bar{t}H$, H→γγ

Event count in mass window containing 90% of $t\bar{t}H$ signal



Check: reconstructed top candidate mass (*Had*) for events with $120<m_{\gamma\gamma}<130$ GeV

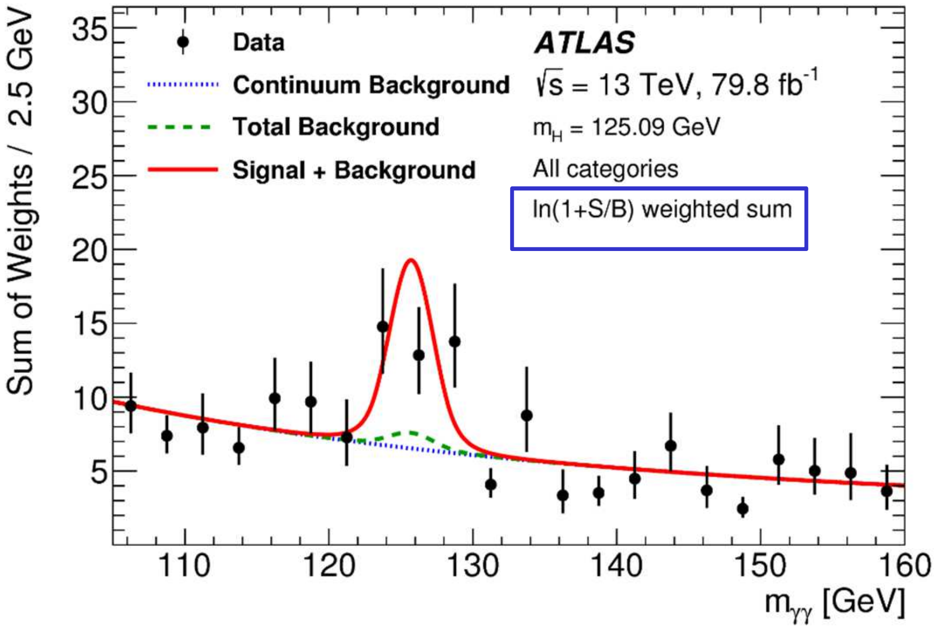


- S/B~1.9 in best BDT bins
- Background dominated by γγ continuum (including $t\bar{t}$+γγ)

- Mass reconstructed from jet triplet selected with dedicated BDT
- Data peaks around m_t for best BDT categories
- Not used in analysis, for illustration purpose

$t\bar{t}H$, $H \rightarrow \gamma\gamma$

- Combined unbinned fit to $m_{\gamma\gamma}$ distributions in the 7 categories
- Higgs modelling: double-sided Crystal Ball from MC. Non-$t\bar{t}H$ Higgs processes fixed to SM.
- Continuum background modelling: functional form from simulation (*Lep*) and dedicated data CR (*Had*), with parameters free in the fit
- Dominant systematics: $t\bar{t}H$ parton shower model (8%), photon energy resolution (6%)



- ➔ Number of fitted $t\bar{t}H$ events: 36^{+12}_{-11}

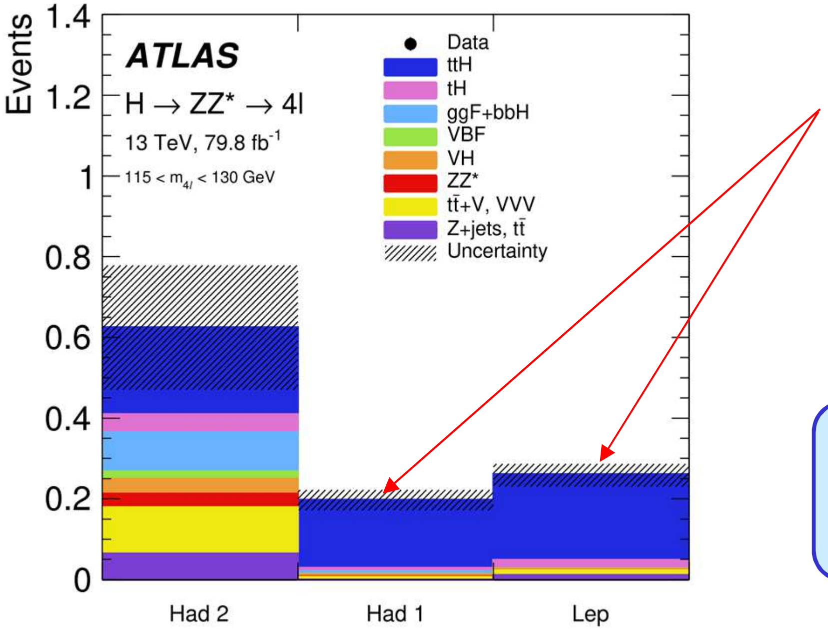
  $\mu = 1.39^{+0.42}_{-0.38}\,\text{(stat)}\,^{+0.23}_{-0.17}\,\text{(syst)}$

- ➔ Signal significance **4.1σ** (3.7σ expected)
- ➔ Good agreement with SM predictions
- ➔ Precision ±30% (30% stat, 15% syst)
- ➔ Currently statistically limited

$t\bar{t}H$, H→ZZ*→4l (l=e,μ)

- Very small rate: expect ~5 $t\bar{t}H$, H→ZZ*→4l produced events with 79.8 fb^{-1} of data
- But very clean final state and narrow peak in m_{4l} distribution
- Standard H→ZZ*→4l selection: ≥4 isolated leptons (p_T>25/15/10/5-7 GeV), 115<m_{4l}<130 GeV
- Categorisation based on $t\bar{t}$ decay ➔ *Lep* (≥1l,≥2j,≥1b) and *Had* (0l,≥4j,≥1b) categories
- Further separation power based on BDT discriminant in *Had* → 2 categories

[inputs: production and decay kinematic variables]



➔ S/B>5 in *Lep* and *Had* best BDT bin

➔ Background dominated by $t\bar{t}V$ and non-$t\bar{t}H$ Higgs productions (fixed to SM)

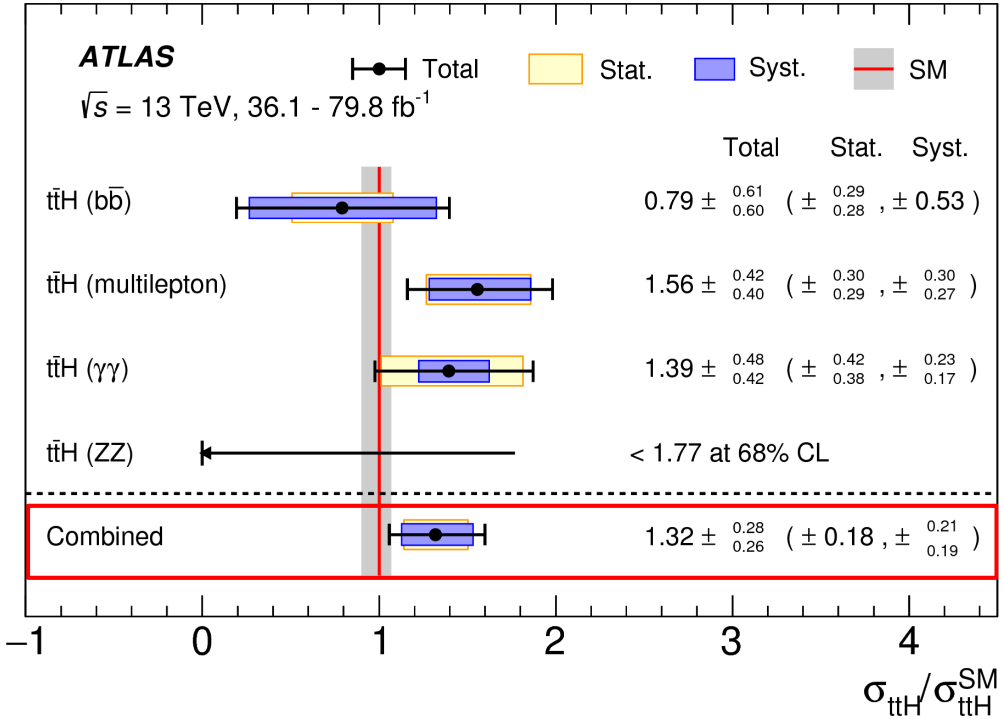
➔ Expected significance 1.2σ (0.6 $t\bar{t}H$ events)

➔ Observe 0 event → μ<1.77 at 68% CL

➔ Largely statistically limited

Combined results

- Combination based on simultaneous fit to signal and control regions of individual analyses
- Correlation scheme of all systematics studied in detail
- Contributions from non-$t\bar{t}H$ Higgs production fixed to SM predictions



Significance

Obs. (Exp.)

1.4σ (1.6σ)

4.1σ (2.8σ)

4.1σ (3.7σ)

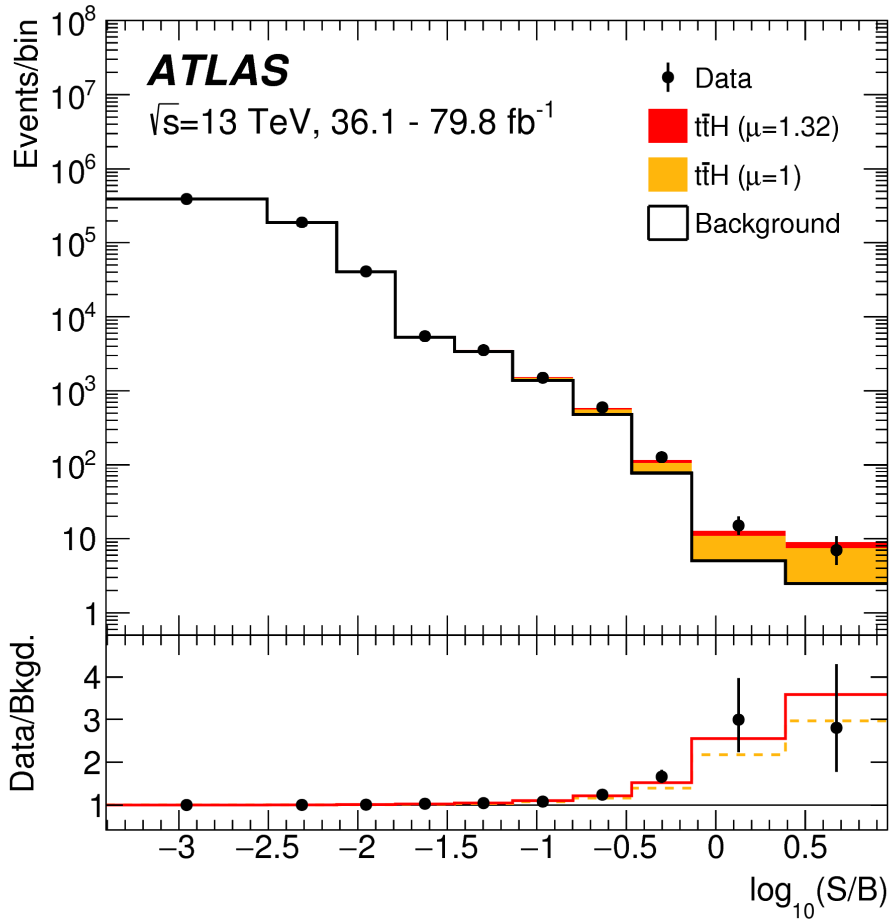
0σ (1.2σ)

5.8σ (4.9σ)	6.3σ (5.1σ)
13 TeV only	7, 8 and 13 TeV

➔ Observation of $t\bar{t}H$ process: major milestone in LHC Run-2 already reached

Combined results

Visualisation of $t\bar{t}H$ signal-like excess ($\sqrt{s}$=13 TeV)



[event yields in all analysis categories binned according to S/B]

➔ **Observation of $t\bar{t}H$ process: major milestone in LHC Run-2 already reached**

$t\bar{t}H$ cross-section at 13 TeV

- Total $t\bar{t}H$ cross-section extracted assuming SM Higgs branching fractions

13 TeV

Analysis	$t\bar{t}H$ cross section [fb]	
$H \to \gamma\gamma$	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	[statistically limited]
$H \to$ multilepton	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)	[statistics ~ systematics]
$H \to b\bar{b}$	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)	[limited by systematics]
$H \to ZZ^* \to 4\ell$	<900 (68% CL)	[statistically limited]
Combined (13 TeV)	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	

(13%) (16%) →

- $t\bar{t}$+heavy flavour modelling (9.9%)
- $t\bar{t}H$ modelling (6.0%)
- Non-prompt leptons (5.2%)

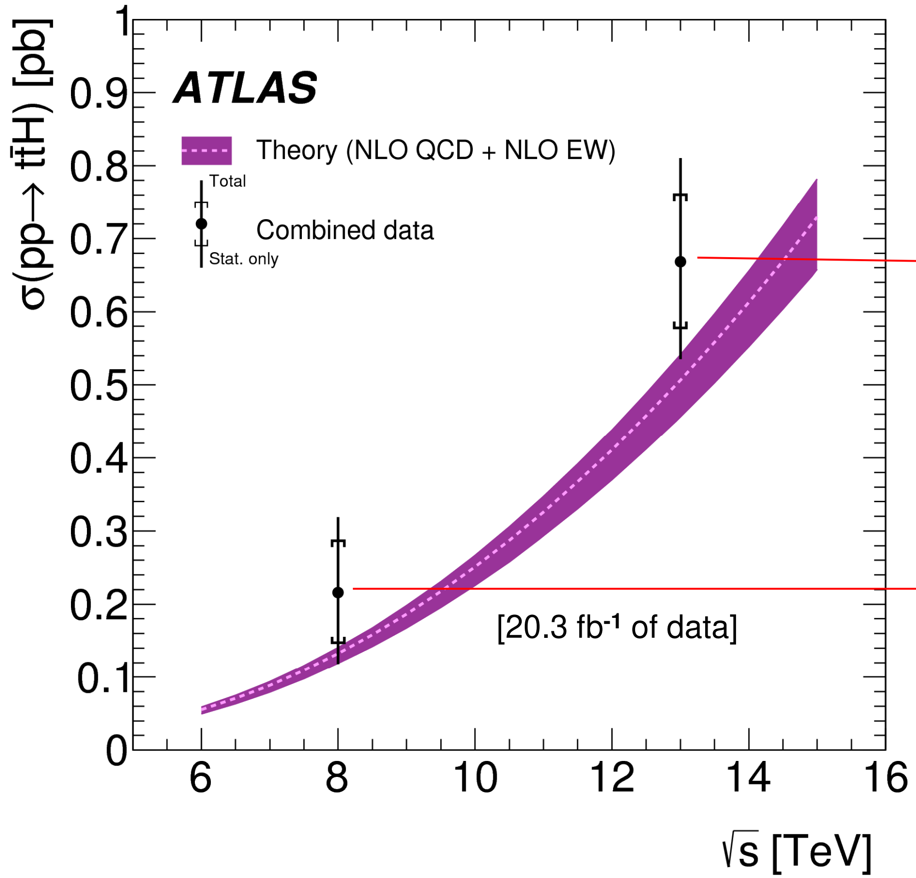
➔ Total cross-section at $\sqrt{s}$=13 TeV measured with 20% precision

➔ Precision slightly dominated by systematics

➔ Agreement with SM expectation (NLO) $507\ ^{+35}_{-50}$ fb

$t\bar{t}H$ cross-section vs $\sqrt{s}$

➢ Total $t\bar{t}H$ cross-section extracted assuming SM Higgs branching fractions



670 ± 90 (stat) $^{+110}_{-100}$ (syst) fb

(13%) (16%)

SM: 507 $^{+35}_{-50}$ fb

220 ± 100 (stat) ± 70 (syst) fb

(45%) (32%)

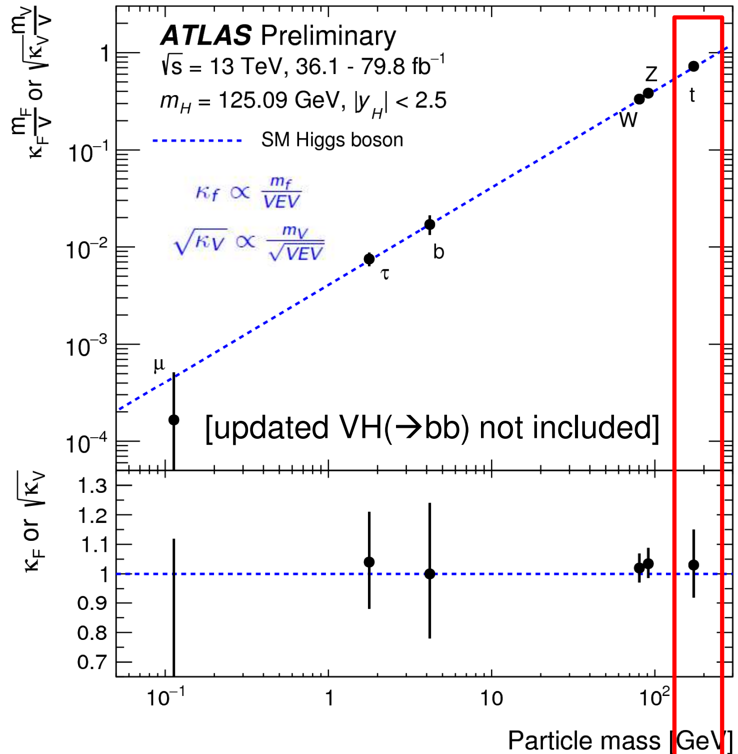
SM: 133 $^{+6}_{-13}$ fb

Top Yukawa coupling

➢ Combination of all ATLAS Higgs analyses for top Yukawa coupling measurement

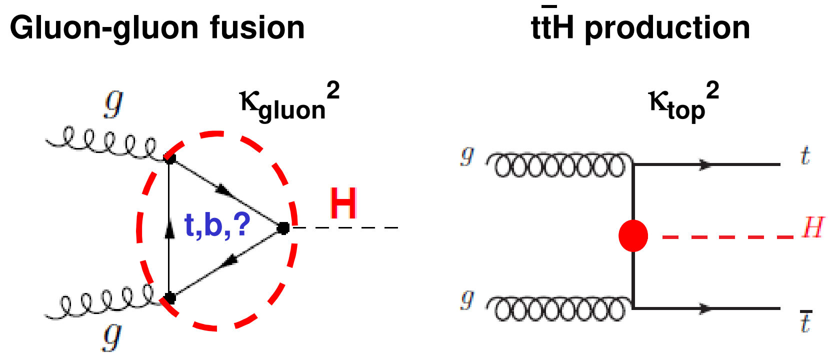
Assuming SM particles only

[gg→H and H→γγ loops resolved with SM particles]



$\kappa_{top} = y_t/y_t^{SM} = 1.03^{+0.12}_{-0.11}$

New particles allowed in loops



- ➢ Effective coupling $\kappa_{top} / \kappa_{gluon} = 1.09 \pm 0.14$
- ➢ Consistent with SM Higgs boson coupling
- ➢ Constrains BSM contribution in the loop

ATLAS-CONF-2018-031

Conclusions

❑ **Observation of $t\bar{t}H$ process: major milestone in LHC Run-2 already reached**

- 6.3σ (5.1σ) observed (expected) significance combining 7, 8 and 13 TeV data (up to 80 fb^{-1})
- Cross-section at $\sqrt{s}$=13 TeV measured with 20% precision (slightly dominated by systematics)
- Constitutes a direct observation of top Yukawa coupling
- Measurements in good agreement with SM predictions
- Put constrains on BSM contributions
- Precise measurements of $t\bar{t}$+HF, $t\bar{t}$+V important to further increase ttH($b\bar{b}$/ML) sensitivity
  - ➢ See talks by A. Khanov and C. Nellist

❑ **2018: observation of Higgs coupling to all charged 3rd generation fermions**

- Together with H→ττ and H→$b\bar{b}$ observations ➢ See talk by W. Yao

➔ Firmly establish the existence of Yukawa interactions

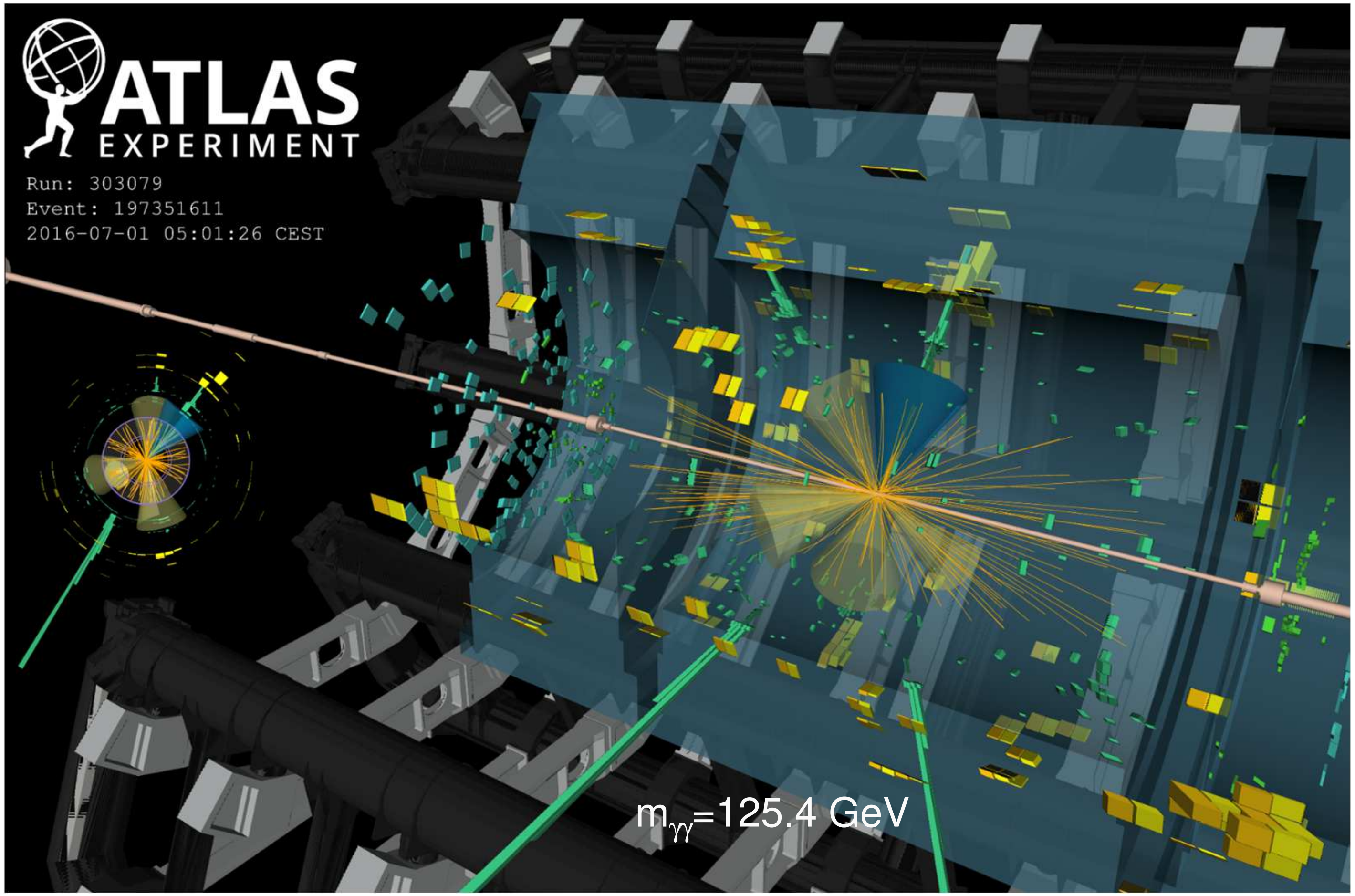
For more details…

- Closely related ATLAS talks/posters at TOP2018
  - $t\bar{t}$ + $b\bar{b}$ at ATLAS and CMS: Alexander Khanov
  - $t\bar{t}$ + Z,W at ATLAS: Clara Nellist
  - Higgs (general) at ATLAS: Weiming Yao
  - Search for $t\bar{t}H(\rightarrow b\bar{b})$ with the ATLAS detector: Ian Connelly (Poster)
  - Top associated Higgs production in the diphoton decay channel with 79.8 fb^{-1} of data in the ATLAS detector: Rachel Hyneman (Poster)
  - Measurement of the $t\bar{t}Z$ and $t\bar{t}W$ production cross section in multilepton final states with the ATLAS detector: Sebastian Heer (Poster)

- Bibliography

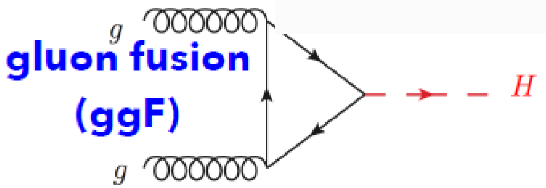
  - $t\bar{t}H$ ATLAS observation paper: Phys. Lett. B784, 2018, 173 (arXiv:1806.00425)
  - ATLAS $t\bar{t}H$(multileptons): Phys. Rev. D97, 2018, 072003 (arXiv:1712.08891)
  - ATLAS $t\bar{t}H(b\bar{b})$: Phys. Rev. D97, 2018, 072016 (arXiv:1712.08895)
  - ATLAS Higgs combination: ATLAS-CONF-2018-031

SPARES

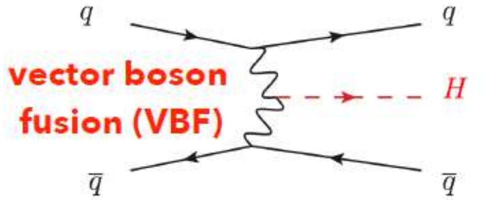

ATLAS
EXPERIMENT
Run: 303079
Event: 197351611
2016-07-01 05:01:26 CEST
$m_{\gamma\gamma}$=125.4 GeV

Higgs production at LHC

87%



7%



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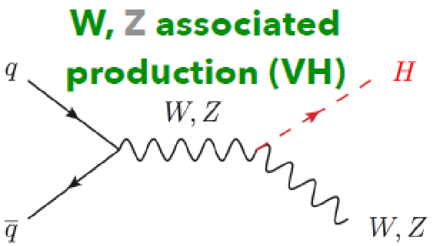
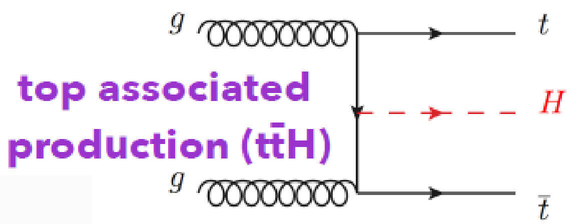
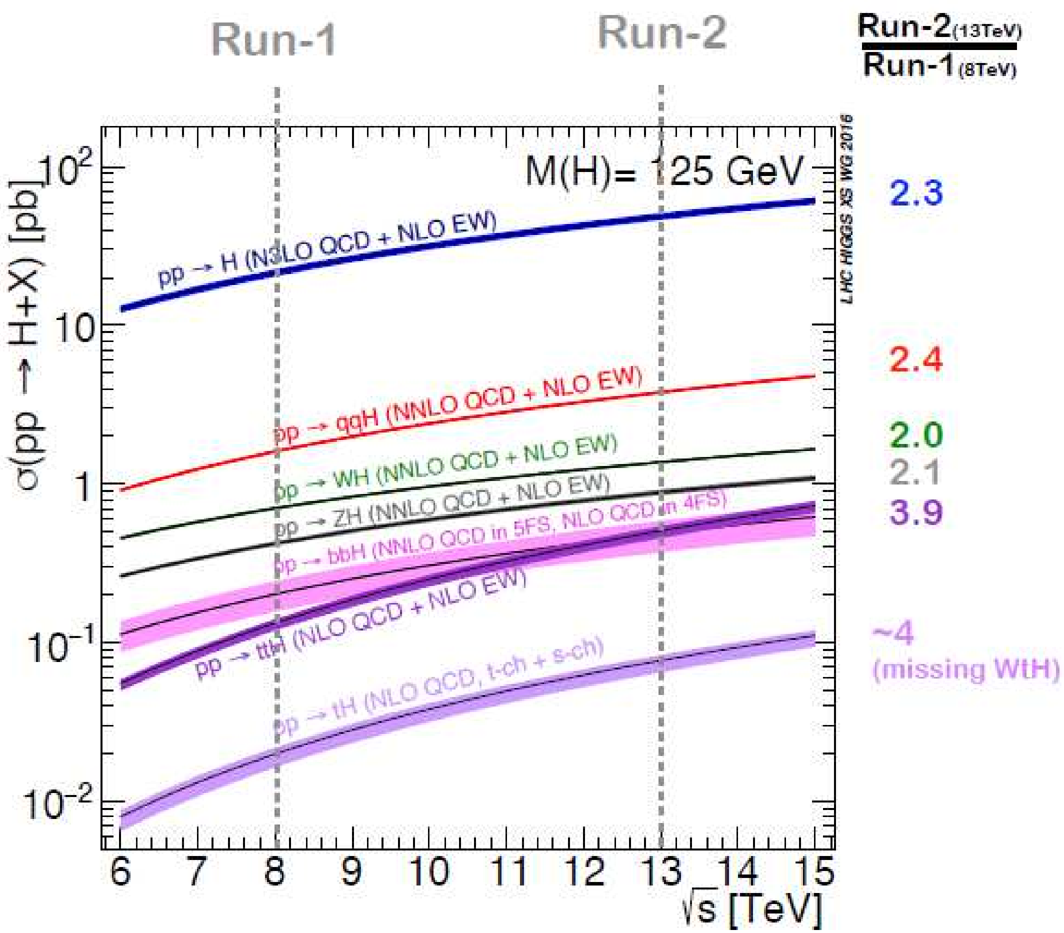


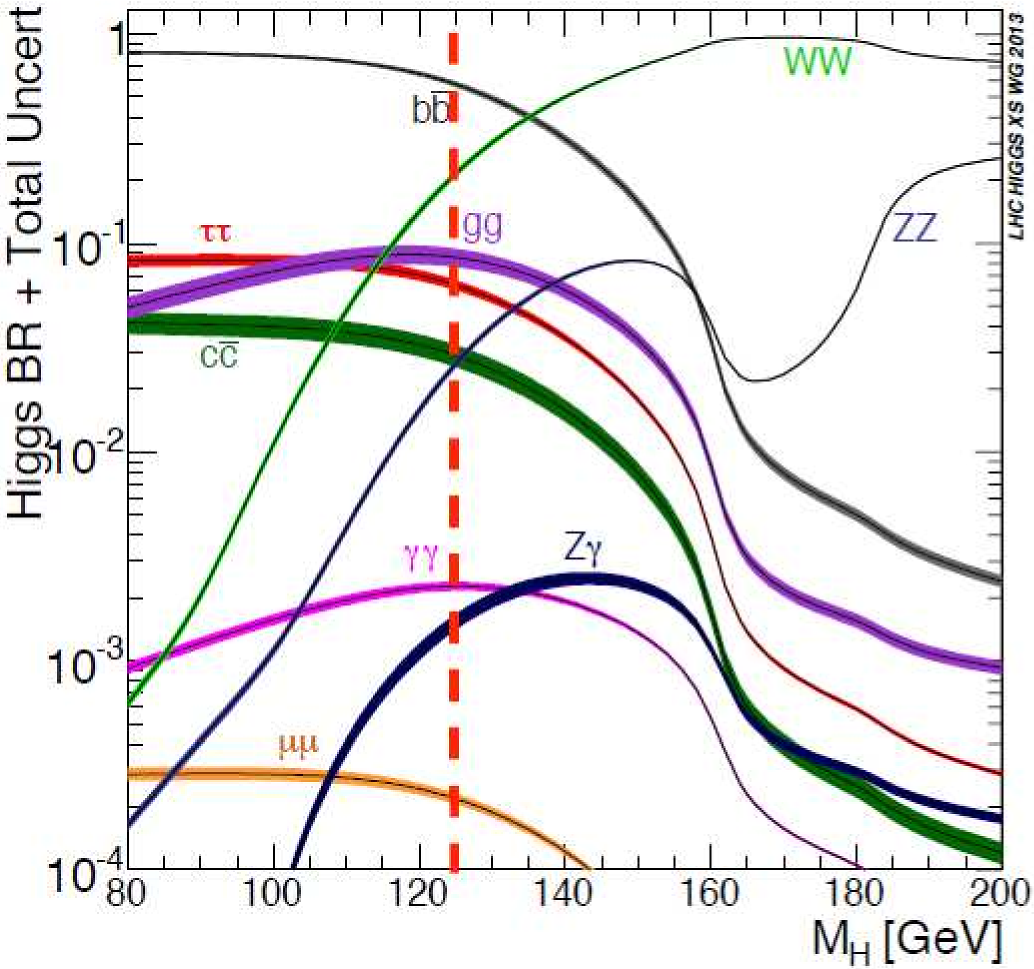
1%

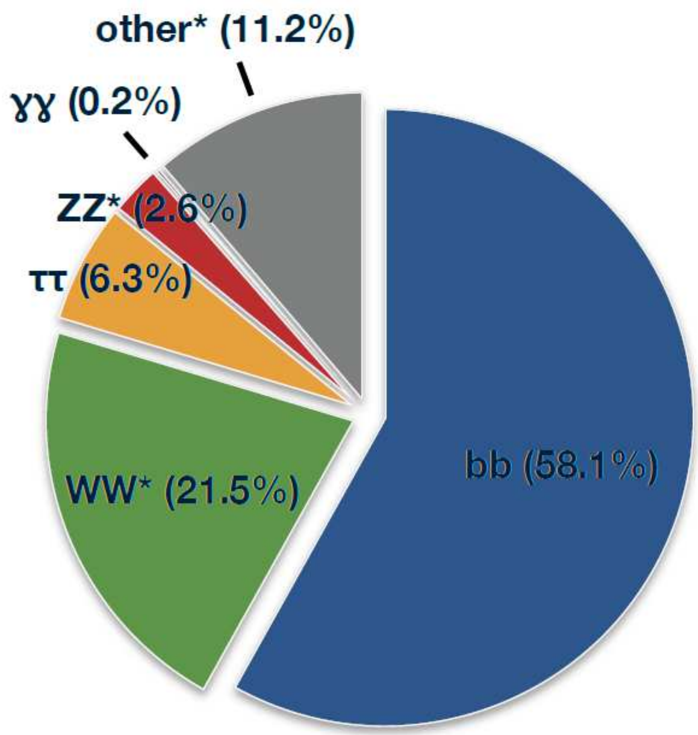


Total cross-section @ 13 TeV ~56 pb



Higgs decay





From YR4, m_H=125.1 GeV

$t\bar{t}H$, $H\rightarrow b\bar{b}$: b-tagging

- Large improvement in b-tag performance in Run-2 due to the additional Insertable B-Layer (radius: 3.3 cm)
- Multivariate discriminator trained to separate b-jets from c-jets and light-jets
- Input: variables describing track impact parameters, displaced secondary vertices and the decay chain of B-hadrons

Working point	loose	medium	tight	very tight
ε(b)	85%	77%	70%	60%
1/ε(c)	3	6	12	34
1/ε(light)	33	134	381	1538

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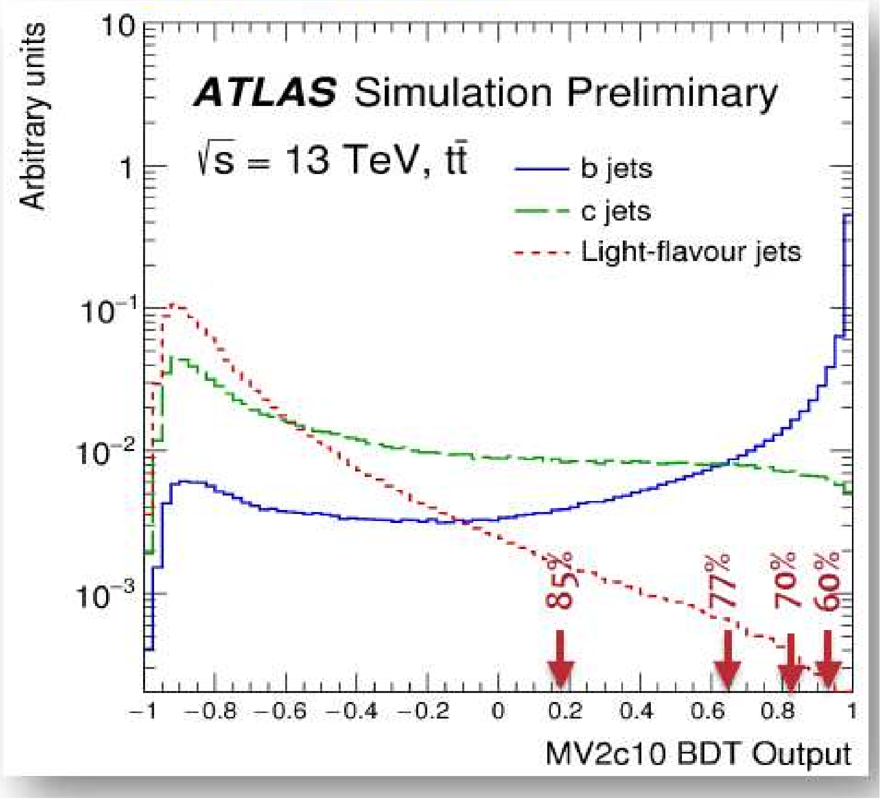


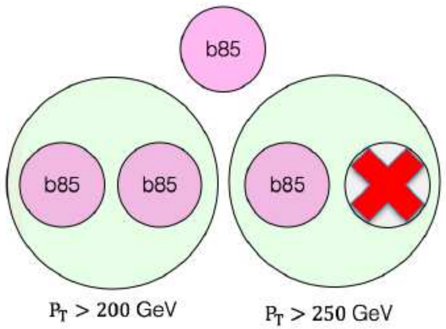
- b-jets calibrated with $t\bar{t}$ events (2-10% uncertainty, dominated by $t\bar{t}$ modelling)
- c-jets calibrated with $t\bar{t}$ events ($W\rightarrow cs$) and W+c events (5-20% uncertainty)
- light-jets calibrated with dijets events (10-50% uncertainty)

$t\bar{t}H$, $H\rightarrow b\bar{b}$: selection

- Single lepton triggers
- Dilepton: 2 OS leptons with p_T>27,15/10 GeV (m_{ll}~m_Z veto, τ_{had} veto), ≥ 3 jets and ≥ 2 medium b-tagged jets
- Single lepton: 1 lepton with p_T > 27 GeV (veto events with ≥2τ_{had})
  - Resolved: ≥ 5 jets and [≥ 2 very-tight b-tagged jets or ≥ 3 medium b-tagged jets]
  - Boosted: boosted Higgs (p_T > 200 GeV) and top (p_T > 250 GeV) candidates with large-radius (R=1.0) jet (taking selected smaller radius R=0.4 jets as input)

    Higgs candidate: 2 loose b-tagged jet. Top candidate: 1 loose b-tagged jet and 1 jet.

	Top	Higgs
p_T [GeV]	> 250	> 200
Constituent jets	2	2
Tagged @ 85%	==1	2



➔ 2.5/8.7/0.1% of simulated $t\bar{t}H(H\rightarrow b\bar{b})$ events pass dilepton/resolved/boosted selections

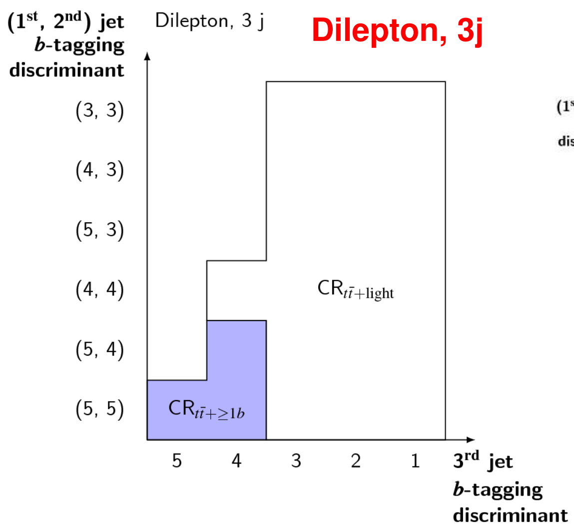
$t\bar{t}H$, $H\to b\bar{b}$: categories

Jets ordered according to their value of the b-tagging discriminant in descending order.

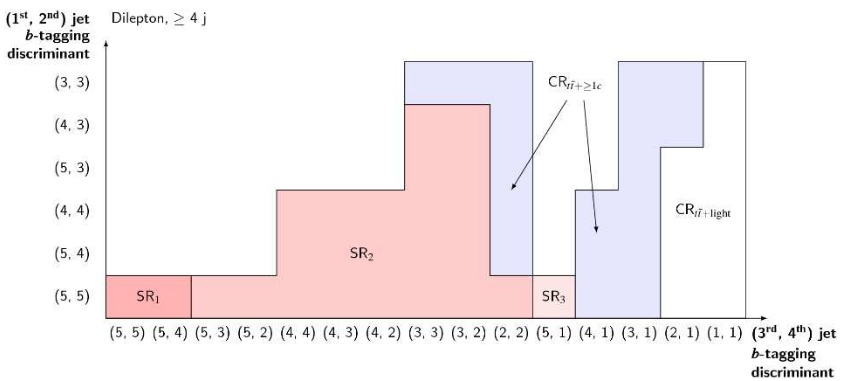
1 = no b-tagging criteria fulfilled
2 = loose = 85%
3 = medium = 77%
4 = tight = 70%
5 = very tight = 60%

SRs | $t\bar{t}$ + light | $t\bar{t}$ + ≥1c | $t\bar{t}$ + ≥1b

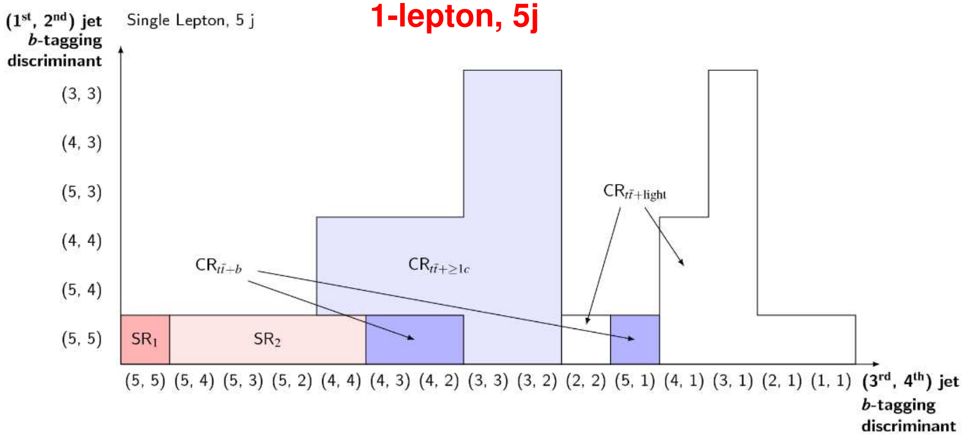
Dilepton, 3j



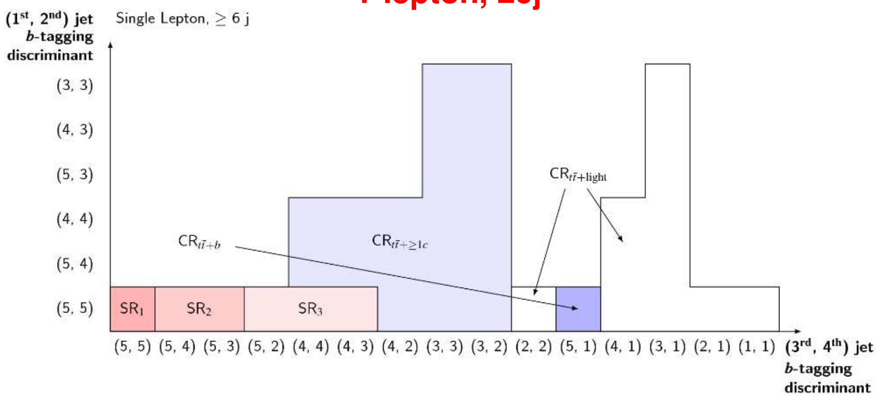
Dilepton, ≥4j



1-lepton, 5j

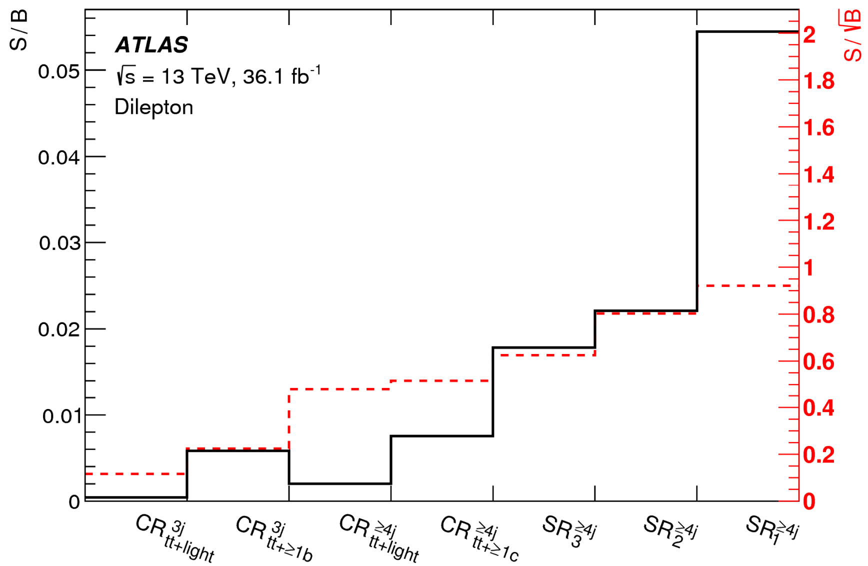


1-lepton, ≥6j

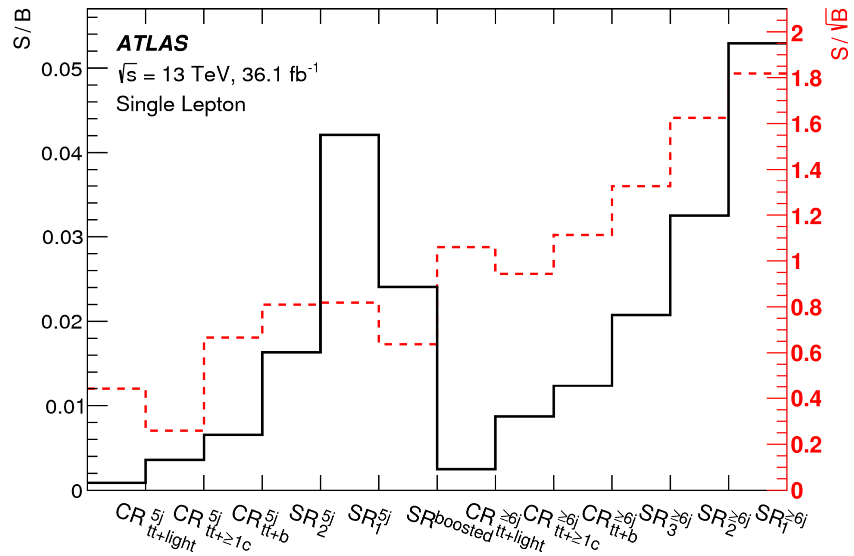


$t\bar{t}H$, $H\rightarrow b\bar{b}$: categories

Dilepton



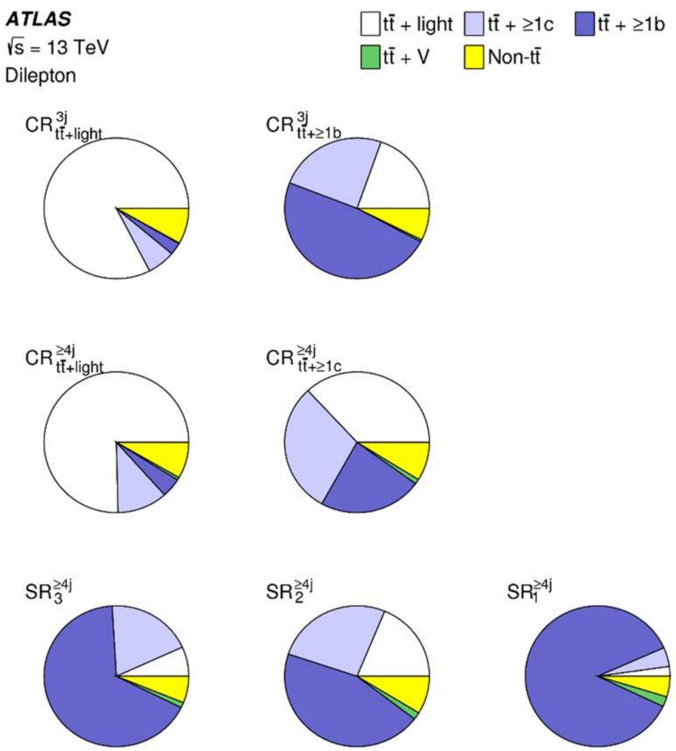
1-lepton



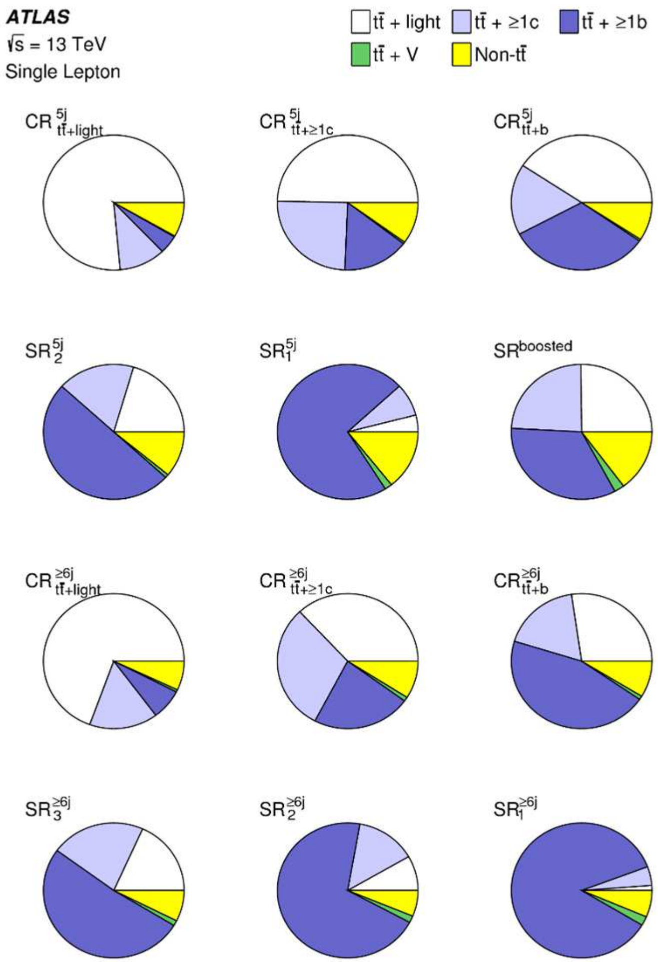
➔ 89/96/86% of $t\bar{t}H$ events in dilepton/resolved/boosted SR are from $H\rightarrow b\bar{b}$

$t\bar{t}H$, $H \rightarrow b\bar{b}$: categories

Dilepton

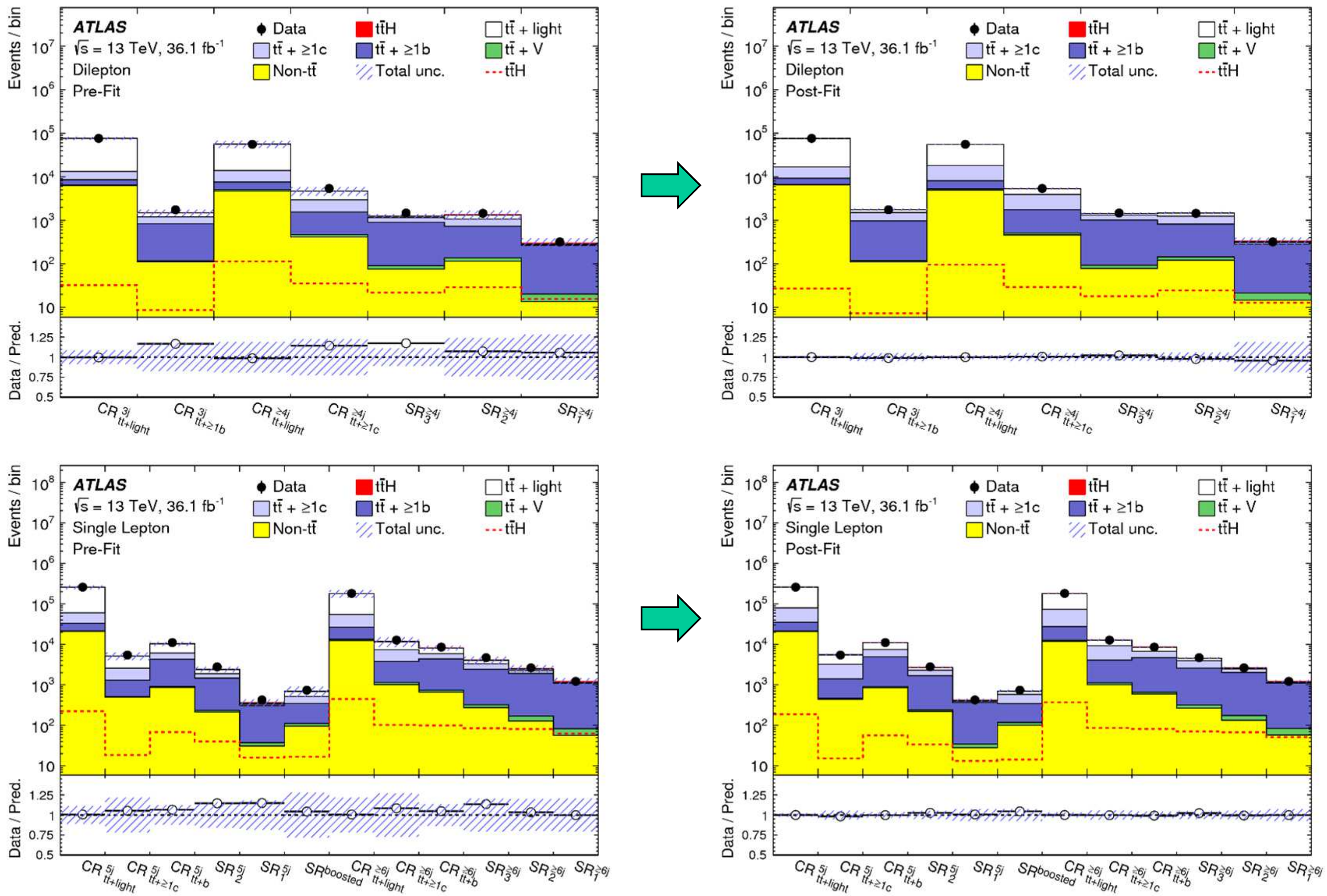


1-lepton



$t\bar{t}H$, $H\rightarrow b\bar{b}$: event yields

Pre- and Post-fit event yields



$t\bar{t}H$, $H \rightarrow b\bar{b}$: event yields

Pre- and Post-fit event yields

Sample	$CR^{3j}_{t\bar{t}+light}$ Pre-fit	$CR^{3j}_{t\bar{t}+light}$ Post-fit	$CR^{3j}_{t\bar{t}+\geq 1b}$ Pre-fit	$CR^{3j}_{t\bar{t}+\geq 1b}$ Post-fit	$CR^{\geq 4j}_{t\bar{t}+light}$ Pre-fit	$CR^{\geq 4j}_{t\bar{t}+light}$ Post-fit	$CR^{\geq 4j}_{t\bar{t}+\geq 1c}$ Pre-fit	$CR^{\geq 4j}_{t\bar{t}+\geq 1c}$ Post-fit
$t\bar{t}H$	32.2 ± 3.8	27 ± 20	8.7 ± 1.1	7.3 ± 5.4	114 ± 11	95 ± 70	35.3 ± 3.6	29 ± 22
$t\bar{t}$ + light	63 100 ± 5500	59 100 ± 1400	290 ± 110	255 ± 44	42 500 ± 9700	37 100 ± 1300	1730 ± 730	1410 ± 180
$t\bar{t}$ + ≥1c	4800 ± 2100	7700 ± 1100	360 ± 160	536 ± 89	6300 ± 2800	10 300 ± 1400	1410 ± 590	2160 ± 290
$t\bar{t}$ + ≥1b	2130 ± 230	2620 ± 240	710 ± 140	848 ± 75	2510 ± 280	2850 ± 290	1080 ± 120	1240 ± 110
$t\bar{t}$ + V	113 ± 31	112 ± 29	7 ± 27	7 ± 30	350 ± 180	330 ± 170	52 ± 41	50 ± 39
Non-$t\bar{t}$	6300 ± 1500	6500 ± 1200	110 ± 29	112 ± 23	4700 ± 1100	4930 ± 910	420 ± 120	460 ± 100
Total	76 400 ± 6500	76 010 ± 390	1500 ± 260	1765 ± 60	56 000 ± 11 000	55 650 ± 420	4700 ± 1100	5350 ± 120
Data	76 025		1744		55 627		5389	

Sample	$SR^{\geq 4j}_{3}$ Pre-fit	$SR^{\geq 4j}_{3}$ Post-fit	$SR^{\geq 4j}_{2}$ Pre-fit	$SR^{\geq 4j}_{2}$ Post-fit	$SR^{\geq 4j}_{1}$ Pre-fit	$SR^{\geq 4j}_{1}$ Post-fit
$t\bar{t}H$	21.9 ± 2.5	18 ± 13	29.1 ± 4.2	25 ± 18	15.6 ± 2.5	12.9 ± 9.5
$t\bar{t}$ + light	83 ± 41	95 ± 30	250 ± 110	215 ± 43	6.4 ± 9.9	11.1 ± 9.3
$t\bar{t}$ + ≥1c	235 ± 61	313 ± 53	340 ± 210	427 ± 89	12.6 ± 9.4	25.8 ± 7.8
$t\bar{t}$ + ≥1b	819 ± 85	917 ± 71	590 ± 96	669 ± 59	247 ± 61	263 ± 20
$t\bar{t}$ + V	15 ± 35	15 ± 34	22 ± 38	22 ± 39	7 ± 56	7 ± 57
Non-$t\bar{t}$	75 ± 17	78 ± 16	115 ± 36	121 ± 29	13.6 ± 3.8	14.6 ± 3.8
Total	1250 ± 140	1436 ± 55	1350 ± 320	1479 ± 66	302 ± 85	334 ± 59
Data	1467		1444		319	

Sample	$CR^{5j}_{t\bar{t}+light}$ Pre-fit	$CR^{5j}_{t\bar{t}+light}$ Post-fit	$CR^{5j}_{t\bar{t}+\geq 1c}$ Pre-fit	$CR^{5j}_{t\bar{t}+\geq 1c}$ Post-fit	$CR^{5j}_{t\bar{t}+b}$ Pre-fit	$CR^{5j}_{t\bar{t}+b}$ Post-fit
$t\bar{t}H$	224 ± 22	190 ± 140	18.7 ± 2.5	15 ± 12	68.0 ± 7.6	57 ± 42
$t\bar{t}$ + light	197 000 ± 26 000	179 900 ± 4900	2580 ± 720	2300 ± 210	4250 ± 920	3560 ± 240
$t\bar{t}$ + ≥1c	27 500 ± 4300	44 100 ± 5500	1280 ± 500	1840 ± 250	1770 ± 270	2590 ± 390
$t\bar{t}$ + ≥1b	11 300 ± 1100	13 500 ± 1300	790 ± 130	944 ± 94	3400 ± 440	4030 ± 320
$t\bar{t}$ + V	589 ± 55	584 ± 54	23.2 ± 4.1	21.3 ± 2.9	48.1 ± 5.9	46.6 ± 5.4
Non-$t\bar{t}$	21 300 ± 4100	20 900 ± 3200	520 ± 180	440 ± 100	960 ± 190	860 ± 160
Total	258 000 ± 29 000	259 320 ± 910	5200 ± 1100	5560 ± 160	10 400 ± 1300	11 140 ± 290
Data	259 320		5465		11 095	

Sample	SR^{5j}_{2} Pre-fit	SR^{5j}_{2} Post-fit	SR^{5j}_{1} Pre-fit	SR^{5j}_{1} Post-fit	$SR^{boosted}$ Pre-fit	$SR^{boosted}$ Post-fit
$t\bar{t}H$	40.1 ± 5.1	34 ± 25	15.9 ± 2.1	13.3 ± 9.8	16.9 ± 1.9	14 ± 10
$t\bar{t}$ + light	500 ± 210	393 ± 67	15 ± 33	12.5 ± 9.3	180 ± 120	112 ± 32
$t\bar{t}$ + ≥1c	436 ± 92	610 ± 100	30 ± 17	28 ± 14	168 ± 70	235 ± 39
$t\bar{t}$ + ≥1b	1230 ± 200	1450 ± 110	273 ± 53	335 ± 25	236 ± 89	229 ± 33
$t\bar{t}$ + V	19.9 ± 2.9	19.7 ± 2.4	6.4 ± 1.3	6.4 ± 1.2	16.1 ± 2.9	16.6 ± 2.4
Non-$t\bar{t}$	269 ± 64	220 ± 52	54 ± 11	28.1 ± 8.4	104 ± 30	101 ± 26
Total	2440 ± 390	2724 ± 70	371 ± 68	423 ± 23	710 ± 200	708 ± 40
Data	2798		426		740	

Sample	$CR^{\geq 6j}_{t\bar{t}+light}$ Pre-fit	$CR^{\geq 6j}_{t\bar{t}+light}$ Post-fit	$CR^{\geq 6j}_{t\bar{t}+\geq 1c}$ Pre-fit	$CR^{\geq 6j}_{t\bar{t}+\geq 1c}$ Post-fit	$CR^{\geq 6j}_{t\bar{t}+b}$ Pre-fit	$CR^{\geq 6j}_{t\bar{t}+b}$ Post-fit
$t\bar{t}H$	450 ± 48	370 ± 280	102 ± 13	87 ± 64	100 ± 12	83 ± 61
$t\bar{t}$ + light	125 000 ± 34 000	108 200 ± 4300	4300 ± 2000	3350 ± 430	2220 ± 520	1820 ± 17
$t\bar{t}$ + ≥1c	28 400 ± 7200	45 700 ± 5100	3600 ± 1300	5300 ± 680	1460 ± 330	2080 ± 30
$t\bar{t}$ + ≥1b	13 100 ± 1800	14 600 ± 1400	2660 ± 540	2950 ± 280	3670 ± 500	4080 ± 32
$t\bar{t}$ + V	1010 ± 120	996 ± 91	118 ± 21	118 ± 14	70.5 ± 8.5	67.9 ± 7.
Non-$t\bar{t}$	12 600 ± 3000	11 800 ± 2000	1060 ± 340	1000 ± 210	710 ± 160	600 ± 11
Total	181 000 ± 39 000	181 690 ± 860	11 800 ± 3200	12 810 ± 260	8200 ± 1100	8730 ± 230
Data	181 706		12 778		8576	

Sample	$SR^{\geq 6j}_{3}$ Pre-fit	$SR^{\geq 6j}_{3}$ Post-fit	$SR^{\geq 6j}_{2}$ Pre-fit	$SR^{\geq 6j}_{2}$ Post-fit	$SR^{\geq 6j}_{1}$ Pre-fit	$SR^{\geq 6j}_{1}$ Post-fit
$t\bar{t}H$	85 ± 10	71 ± 52	81 ± 10	68 ± 50	62 ± 11	51 ± 38
$t\bar{t}$ + light	750 ± 370	586 ± 98	210 ± 210	96 ± 33	14 ± 10	12.1 ± 5.8
$t\bar{t}$ + ≥1c	880 ± 350	1330 ± 190	350 ± 100	473 ± 99	53 ± 33	44 ± 20
$t\bar{t}$ + ≥1b	2100 ± 420	2290 ± 170	1750 ± 370	1850 ± 130	1010 ± 240	1032 ± 59
$t\bar{t}$ + V	51.2 ± 7.4	50.8 ± 5.9	40.8 ± 5.7	40.3 ± 4.8	25.8 ± 3.7	25.3 ± 3.2
Non-$t\bar{t}$	303 ± 82	267 ± 63	155 ± 52	134 ± 46	75 ± 20	58 ± 17
Total	4140 ± 850	4590 ± 110	2550 ± 510	2657 ± 82	1220 ± 250	1223 ± 42
Data	4698		2641		1222	

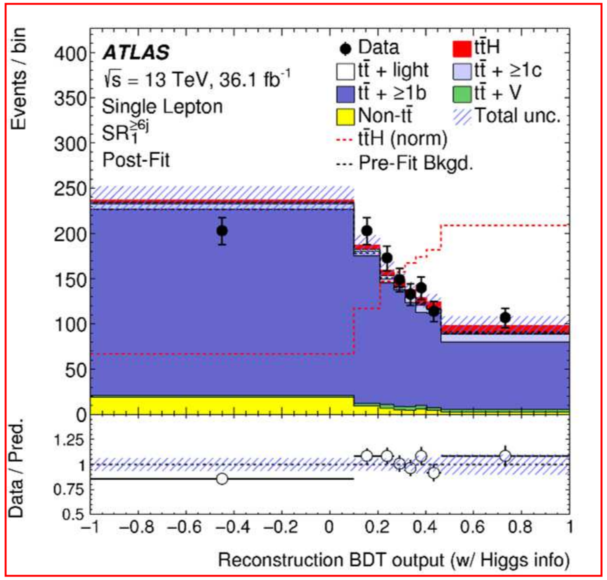
$t\bar{t}H$, $H \rightarrow b\bar{b}$: event reconstruction

- Reconstruction BDT: identify jet assignment from Higgs and top decays to reconstruct the $t\bar{t}H(b\bar{b})$ system. Use invariant masses and angular separations of jets/leptons.

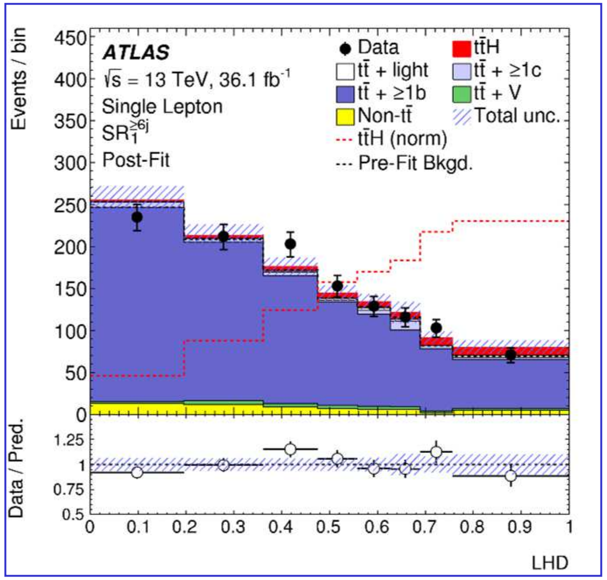
  Higgs boson correctly reconstructed in purest channels in 49% (32%) with (without) Higgs kinematics included in the BDT

- Likelihood discriminant: probability for $t\bar{t}H$ and $t\bar{t}+\geq 1b$ hypotheses using product of 1D-pdf's of reconstructed variables (invariant mass, angular distributions, …); combines all permutations.

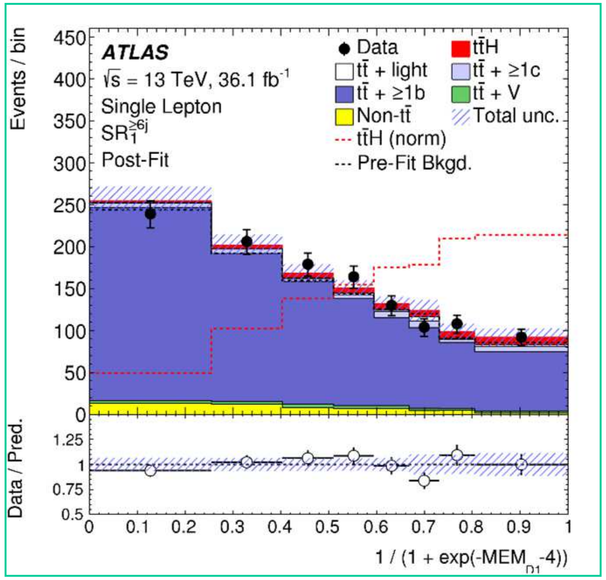
- Matrix Element Method: Signal and $t\bar{t}+b\bar{b}$ probabilities using LO ME at parton level (MadGraph5_aMC@NLO). Transfer functions map detector level quantities to parton level.



Used in all resolved SR



Used in all 1-lepton resolved SR



Used only in purest 1-lepton SR

$t\bar{t}H$, $H \rightarrow b\bar{b}$: event reconstruction

Reconstruction BDT in dilepton channel

Variables	BDT with Higgs info. $SR_{1,2}^{\geq 4j}$	BDT with Higgs info. $SR_{3}^{\geq 4j}$	BDT w/o Higgs info. $SR_{1,2}^{\geq 4j}$	BDT w/o Higgs info. $SR_{3}^{\geq 4j}$
Topological information from $t\bar{t}$				
Mass of top	✓	✓	✓	✓
Mass of anti-top	✓	✓	✓	✓
Mass difference between top and anti-top	✓	✓	✓	✓
$\Delta R(\ell, b)$ from top	✓	✓	✓	✓
$\Delta R(\ell, b)$ from anti-top	✓	✓	✓	✓
—$\Delta R(\ell, b)$ from top - $\Delta R(\ell, b)$ from anti-top—	-	-	✓	✓
$\Delta\phi(b$ from top, b from anti-top$)$	-	✓	✓	✓
$\Delta R(b$ from top, b from anti-top$)$	✓	-	-	-
p_T b from top	-	-	✓	✓
p_T b from anti-top	-	-	✓	✓
Min. $\Delta\eta(\ell, b$ from top or anti-top$)$	-	-	✓	✓
Topological information from the Higgs-boson candidate				
Min. $\Delta R(b$ from Higgs, $\ell)$	-	✓	-	-
Max. $\Delta R($Higgs, b from top or anti-top$)$	✓	-	-	-
Mass of Higgs	✓	✓	-	-
$\Delta\phi($Higgs,$t\bar{t})$	-	✓	-	-
$\Delta R($Higgs,$t\bar{t})$	✓	-	-	-
p_T b from Higgs with lowest b-tagging discriminant	-	✓	-	-
$\Delta R(b_1$ from Higgs, b_2 from Higgs$)$	✓	✓	-	-

$t\bar{t}H$, $H\rightarrow b\bar{b}$: event reconstruction

Reconstruction BDT in 1-lepton channel

Variable	$SR^{\geq 6j}_{1,2,3}$	$SR^{5j}_{1,2}$
Topological information from $t\bar{t}$		
Mass of top_{lep}	✓	✓
Mass of top_{had}	✓	–
Mass of q_1 from W_{had} and b from top_{had}	–	✓
Mass of W_{had}	✓	–
Mass of W_{had} and b from top_{lep}	✓	–
Mass of q_1 from W_{had} and b from top_{lep}	–	✓
Mass of W_{lep} and b from top_{had}	✓	✓
$\Delta R(W_{had}, b \text{ from } top_{had})$	✓	–
$\Delta R(q_1 \text{ from } W_{had}, b \text{ from } top_{had})$	–	✓
$\Delta R(W_{had}, b \text{ from } top_{lep})$	✓	–
$\Delta R(q_1 \text{ from } W_{had}, b \text{ from } top_{lep})$	–	✓
$\Delta R(\ell, b \text{ from } top_{lep})$	✓	✓
$\Delta R(\ell, b \text{ from } top_{had})$	✓	✓
$\Delta R(b \text{ from } top_{lep}, b \text{ from } top_{had})$	✓	✓
$\Delta R(q_1 \text{ from } W_{had}, q_2 \text{ from } W_{had})$	✓	–
$\Delta R(b \text{ from } t_{had}, q_1 \text{ from } W_{had})$	✓	–
$\Delta R(b \text{ from } t_{had}, q_2 \text{ from } W_{had})$	✓	–
Min. $\Delta R(b \text{ from } top_{had}, q_i \text{ from } W_{had})$	✓	–
$\Delta R(\text{lep}, b \text{ from } top_{lep})$ - min. $\Delta R(b \text{ from } top_{had}, q_i \text{ from } W_{had})$	✓	✓
Topological information from the Higgs-boson candidate		
Mass of Higgs	✓	✓
Mass of Higgs and q_1 from W_{had}	✓	✓
$\Delta R(b_1 \text{ from Higgs}, b_2 \text{ from Higgs})$	✓	✓
$\Delta R(b_1 \text{ from Higgs, lepton})$	✓	✓
$\Delta R(b_1 \text{ from Higgs}, b \text{ from } top_{lep})$	–	✓
$\Delta R(b_1 \text{ from Higgs}, b \text{ from } top_{had})$	–	✓

$t\bar{t}H$, $H \rightarrow b\bar{b}$: event reconstruction

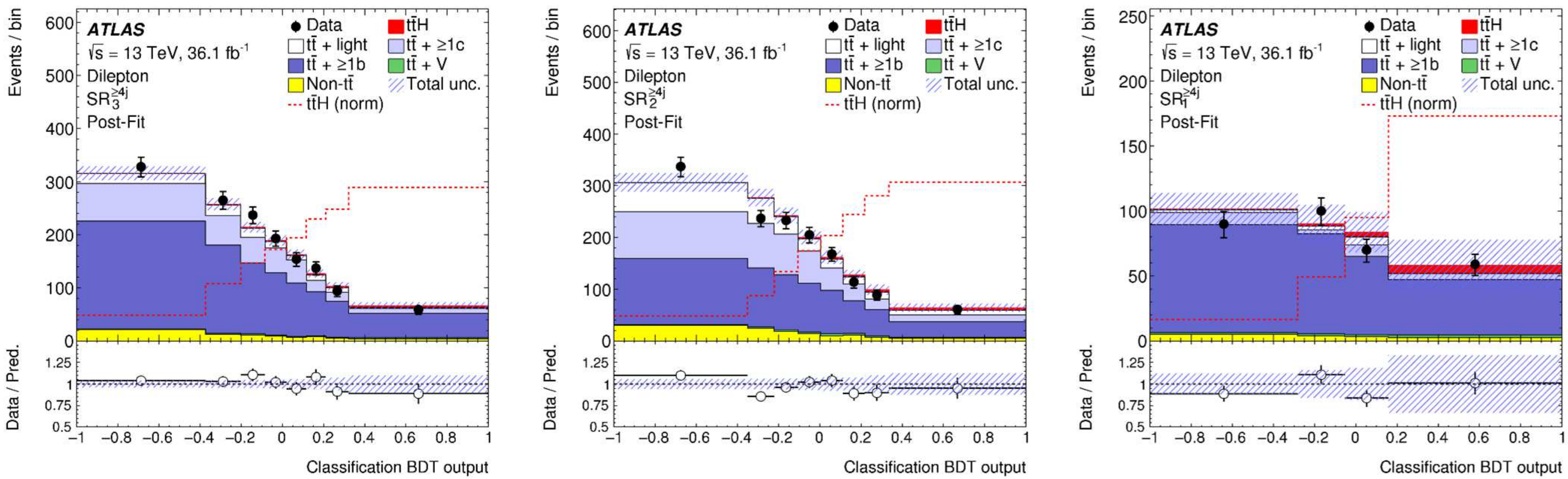
pdfs used in calculation of signal and background probabilities for likelihood discriminant variables

$\mathrm{SR}^{\geq 6\mathrm{j}}_{1,2,3}$	$\mathrm{SR}^{5\mathrm{j}}_{1,2}$
$M_H(b_1, b_2)$	$M_H(b_1, b_2)$
$M_{t_l}(l, \nu, b_l)$	$M_{t_l}(l, \nu, b_l)$
$M_{W_h}(q_1, q_2)$	–
$[M_{t_h} - M_{W_h}](b_h, q_1, q_2)$	$M_{t_h}(b_h, q_1)$
$[M_{t_h t_l} - M_{t_h} - M_{t_l}](l, \nu, b_l, b_h, q_1, q_2)$	$[M_{t_h t_l} - M_{t_h} - M_{t_l}](l, \nu, b_l, b_h, q_1)$
$[M_{t_h t_l b_1 b_2} - M_{t_l t_h} - M_H](l, \nu, b_l, b_h, q_1, q_2, b_1, b_2)$	$[M_{t_h t_l b_1 b_2} - M_{t_l t_h} - M_H](l, \nu, b_l, b_h, q_1, b_1, b_2)$
$\cos\theta^*_{b_{1/2},H}(b_1, b_2)$	$\cos\theta^*_{b,H}(b_1, b_2)$
$\cos\theta^*_{b_1 b_2, t_h t_l b_1 b_2}(l, \nu, b_l, b_h, q_1, q_2, b_1, b_2)$	$\cos\theta^*_{b_1 b_2, t_h t_l b_1 b_2}(l, \nu, b_l, b_h, q_1, b_1, b_2)$

$t\bar{t}H$, $H\rightarrow b\bar{b}$: classification BDT

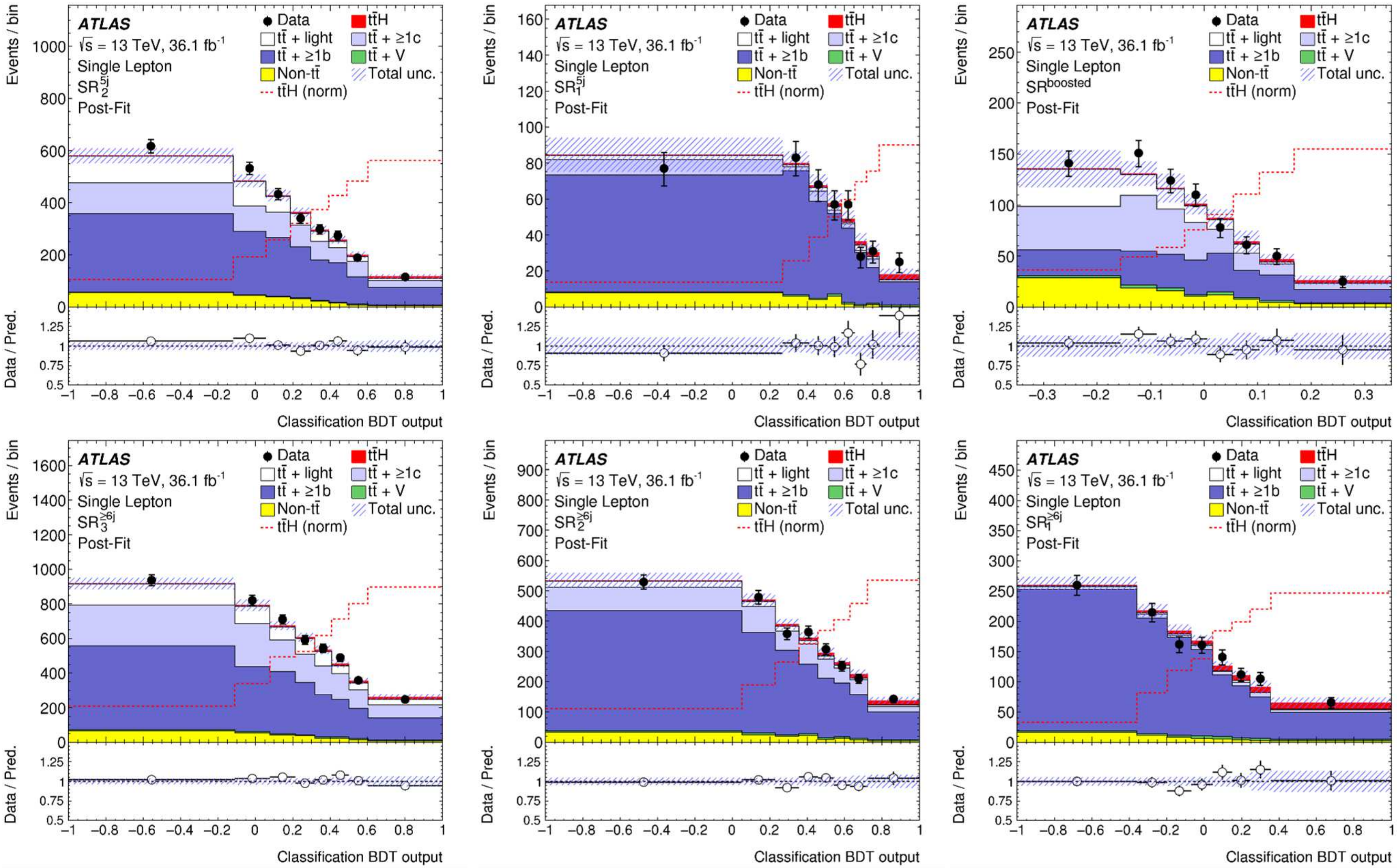
- Trained to separate signal from $t\bar{t}$ background
- Inputs: reconstruction discriminants (+related variables), event kinematic variables, b-tag information (+ large R-jets and their constituents in boosted category)
- 20/23/8 variables in dilepton/single lepton/boosted categories

Dilepton signal regions



$t\bar{t}H$, $H \rightarrow b\bar{b}$: classification BDT

1-lepton signal regions



$t\bar{t}H$, $H\rightarrow b\bar{b}$: classification BDT

Classification BDT in dilepton channel

Variable	Definition	$SR_1^{\geq 4j}$	$SR_2^{\geq 4j}$	$SR_3^{\geq 4j}$
General kinematic variables				
m_{bb}^{min}	Minimum invariant mass of a b-tagged jet pair	✓	✓	-
m_{bb}^{max}	Maximum invariant mass of a b-tagged jet pair	-	-	✓
$m_{bb}^{\text{min }\Delta R}$	Invariant mass of the b-tagged jet pair with minimum ΔR	✓	-	✓
$m_{\text{jj}}^{\text{max }p_{\text{T}}}$	Invariant mass of the jet pair with maximum p_{T}	✓	-	-
$m_{bb}^{\text{max }p_{\text{T}}}$	Invariant mass of the b-tagged jet pair with maximum p_{T}	✓	-	✓
$\Delta\eta_{bb}^{\text{avg}}$	Average $\Delta\eta$ for all b-tagged jet pairs	✓	✓	✓
$\Delta\eta_{\ell,\text{j}}^{\text{max}}$	Maximum $\Delta\eta$ between a jet and a lepton	-	✓	✓
$\Delta R_{bb}^{\text{max }p_{\text{T}}}$	ΔR between the b-tagged jet pair with maximum p_{T}	-	✓	✓
$N_{bb}^{\text{Higgs }30}$	Number of b-tagged jet pairs with invariant mass within 30 GeV of the Higgs-boson mass	✓	✓	-
$n_{\text{jets}}^{p_{\text{T}}>40}$	Number of jets with $p_{\text{T}} > 40$ GeV	-	✓	✓
$\text{Aplanarity}_{b\text{-jet}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [100] built with all b-tagged jets	-	✓	-
$H_{\text{T}}^{\text{all}}$	Scalar sum of p_{T} of all jets and leptons	-	-	✓
Variables from reconstruction BDT				
BDT output	Output of the reconstruction BDT	✓**	✓**	✓
m_{bb}^{Higgs}	Higgs candidate mass	✓	-	✓
$\Delta R_{H,t\bar{t}}$	ΔR between Higgs candidate and $t\bar{t}$ candidate system	✓*	-	-
$\Delta R_{H,\ell}^{\text{min}}$	Minimum ΔR between Higgs candidate and lepton	✓	✓	✓
$\Delta R_{H,b}^{\text{min}}$	Minimum ΔR between Higgs candidate and b-jet from top	✓	✓	-
$\Delta R_{H,b}^{\text{max}}$	Maximum ΔR between Higgs candidate and b-jet from top	-	✓	-
$\Delta R_{bb}^{\text{Higgs}}$	ΔR between the two jets matched to the Higgs candidate	-	✓	-
Variables from b-tagging				
$w_{b\text{-tag}}^{\text{Higgs}}$	Sum of b-tagging discriminants of jets from best Higgs candidate from the reconstruction BDT	-	✓	-

$t\bar{t}H$, $H \to b\bar{b}$: classification BDT

Classification BDT in single lepton channel

Variable	Definition	$SR^{\geq 6j}_{1,2,3}$	$SR^{5j}_{1,2}$
General kinematic variables			
ΔR^{avg}_{bb}	Average ΔR for all b-tagged jet pairs	✓	✓
$\Delta R^{max\ p_T}_{bb}$	ΔR between the two b-tagged jets with the largest vector sum p_T	✓	–
$\Delta\eta^{max}_{jj}$	Maximum $\Delta\eta$ between any two jets	✓	✓
$m^{min\ \Delta R}_{bb}$	Mass of the combination of two b-tagged jets with the smallest ΔR	✓	–
$m^{min\ \Delta R}_{jj}$	Mass of the combination of any two jets with the smallest ΔR	–	✓
$N^{Higgs\ 30}_{bb}$	Number of b-tagged jet pairs with invariant mass within 30 GeV of the Higgs-boson mass	✓	✓
H^{had}_T	Scalar sum of jet p_T	–	✓
$\Delta R^{min}_{\ell,bb}$	ΔR between the lepton and the combination of the two b-tagged jets with the smallest ΔR	–	✓
Aplanarity	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [100] built with all jets	✓	✓
H_1	Second Fox–Wolfram moment computed using all jets and the lepton	✓	✓
Variables from reconstruction BDT			
BDT output	Output of the reconstruction BDT	✓*	✓*
m^{Higgs}_{bb}	Higgs candidate mass	✓	✓
$m_{H,b_{lep\ top}}$	Mass of Higgs candidate and b-jet from leptonic top candidate	✓	–
ΔR^{Higgs}_{bb}	ΔR between b-jets from the Higgs candidate	✓	✓
$\Delta R_{H,t\bar{t}}$	ΔR between Higgs candidate and $t\bar{t}$ candidate system	✓*	✓*
$\Delta R_{H,lep\ top}$	ΔR between Higgs candidate and leptonic top candidate	✓	–
$\Delta R_{H,b_{had\ top}}$	ΔR between Higgs candidate and b-jet from hadronic top candidate	–	✓*
Variables from likelihood and matrix element method calculations			
LHD	Likelihood discriminant	✓	✓
MEM_{D1}	Matrix element discriminant (in $SR^{\geq 6j}_1$ only)	✓	–
Variables from b-tagging (not in $SR^{\geq 6j}_1$)			
$w^{Higgs}_{b\text{-tag}}$	Sum of b-tagging discriminants of jets from best Higgs candidate from the reconstruction BDT	✓	✓
B^3_{jet}	3^{rd} largest jet b-tagging discriminant	✓	✓
B^4_{jet}	4^{th} largest jet b-tagging discriminant	✓	✓
B^5_{jet}	5^{th} largest jet b-tagging discriminant	✓	✓

$t\bar{t}H$, $H\rightarrow b\bar{b}$: classification BDT

Classification BDT in boosted channel

Variable	Definition
Variables from jet reclustering	
$\Delta R_{H,t}$	ΔR between the Higgs-boson and top-quark candidates
$\Delta R_{t,b^{\mathrm{add}}}$	ΔR between the top-quark candidate and additional b-jet
$\Delta R_{H,b^{\mathrm{add}}}$	ΔR between the Higgs-boson candidate and additional b-jet
$\Delta R_{H,\ell}$	ΔR between the Higgs-boson candidate and lepton
$m_{\mathrm{Higgs\ candidate}}$	Higgs-boson candidate mass
$\sqrt{d_{12}}$	Top-quark candidate first splitting scale [101]
Variables from b-tagging	
$w_{b\text{-tag}}$	Sum of b-tagging discriminants of all b-jets
$w^{\mathrm{add}}_{b\text{-tag}}/w_{b\text{-tag}}$	Ratio of sum of b-tagging discriminants of additional b-jets to all b-jets

$t\bar{t}H$, $H \rightarrow b\bar{b}$: modelling

Settings used for simulation of $t\bar{t}$ samples

ME gen. / PS/UE gen.	POWHEG / PYTHIA 8	POWHEG / PYTHIA 8	POWHEG / PYTHIA 8	POWHEG / HERWIG 7	SHERPA 2.2.1	SHERPA 2.1
Ren. scale	$m_{\mathrm{T},t}$	$\frac{1}{2} \cdot m_{\mathrm{T},t}$	$2 \cdot m_{\mathrm{T},t}$	$m_{\mathrm{T},t}$	$\sqrt{\frac{m^2_{\mathrm{T},t}+m^2_{\mathrm{T},\bar{t}}}{2}}$	μ_{CMMPS}
Fact. scale	$m_{\mathrm{T},t}$	$\frac{1}{2} \cdot m_{\mathrm{T},t}$	$2 \cdot m_{\mathrm{T},t}$	$m_{\mathrm{T},t}$	$\sqrt{\frac{m^2_{\mathrm{T},t}+m^2_{\mathrm{T},\bar{t}}}{2}}$	$H_{\mathrm{T}}/2$
h_{damp}	$1.5 \cdot m_t$	$3 \cdot m_t$	$1.5 \cdot m_t$	$1.5 \cdot m_t$	–	–
ME PDF	NNPDF3.0NLO	NNPDF3.0NLO	NNPDF3.0NLO	NNPDF3.0NLO	NNPDF3.0NNLO	CT10 4F
PS/UE PDF	NNPDF2.3LO	NNPDF2.3LO	NNPDF2.3LO	MMHT2014LO		
Tune	A14	A14 Var3c up	A14 Var3c down	H7-UE-MMHT	Author's tune	Author's tune

Nominal MC generators

	ME	PS	tune
$t\bar{t}H$	aMC@NLO	Pythia8	A14
$t\bar{t}$	Powheg	Pythia8	A14
$t\bar{t}V$	aMC@NLO	Pythia8	A14
sgtop tW	Powheg	Pythia6	Perugia
sgtop t-chan.	Powheg(4fs)	Pythia6	Perugia
sgtop s-chan.	Powheg	Pythia6	Perugia
V+jets	Sherpa	Sherpa	author
diboson	Sherpa	Sherpa	author

$t\bar{t}H$, H→$b\bar{b}$: modelling

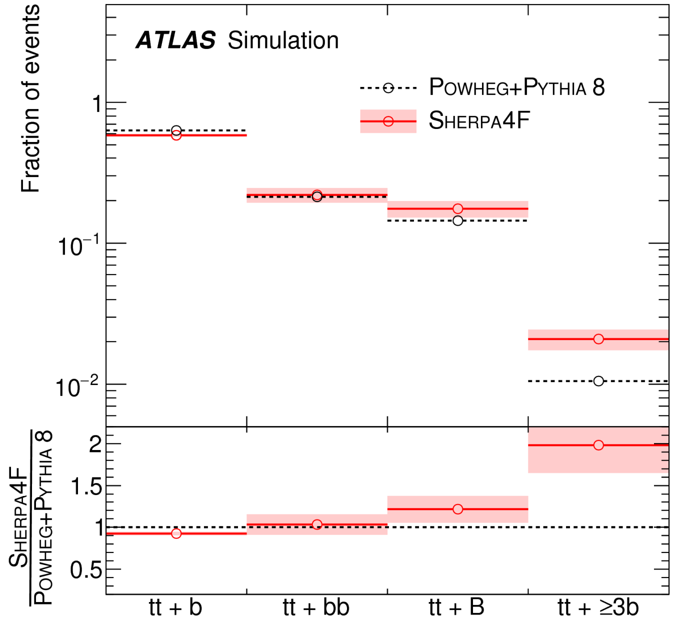
$t\bar{t}$+jets modelling

- Powheg+Pythia8 normalised to NNLO+NNLL prediction
- Event classification at truth level based on flavor of additional jets at particle level matched to hadrons (ΔR<0.4): $t\bar{t}$+≥1b, $t\bar{t}$+≥1c, $t\bar{t}$+light
- Further split $t\bar{t}$+≥1b by number of additional b-hadrons in jets → $t\bar{t}$+b, $t\bar{t}$+B (only one b-jet matched to 2 b-hadrons), $t\bar{t}$+$b\bar{b}$ and $t\bar{t}$+≥3b → corrected to Sherpa+OpenLoops: NLO $t\bar{t}$+$b\bar{b}$, 4-FS (massive b-quarks, g→$b\bar{b}$ from ME)
- Normalisation of $t\bar{t}$+≥1b and $t\bar{t}$+≥1c left free-floating in the fit

$$NF(t\bar{t}+\geq 1b) = 1.24 \pm 0.10$$

$$NF(t\bar{t}+\geq 1c) = 1.63 \pm 0.23$$

process	#jets	w/ #hadrons
$t\bar{t}+\geq 1b$	≥ 1	$\geq 1b$
$t\bar{t}+b$	$=1$	$=1b$
$t\bar{t}+bb$	$=2$	$=1b$
$t\bar{t}+B$	$=1$	$\geq 2b$
$t\bar{t}+\geq 3b$	other $t\bar{t}+\geq 1b$ events	
$t\bar{t}+b(MPI/FSR)$	all b-jets from MPI/FSR	
$t\bar{t}+\geq 1c$	≥ 1	$\geq 1c$
$t\bar{t}$+light	other $t\bar{t}$+jets events	



$t\bar{t}H$, $H \to b\bar{b}$: modelling

Systematic source	Description	$t\bar{t}$ categories
$t\bar{t}$ cross-section	Up or down by 6%	All, correlated
$k(t\bar{t} + \geq 1c)$	Free-floating $t\bar{t} + \geq 1c$ normalization	$t\bar{t} + \geq 1c$
$k(t\bar{t} + \geq 1b)$	Free-floating $t\bar{t} + \geq 1b$ normalization	$t\bar{t} + \geq 1b$
SHERPA5F vs. nominal	Related to the choice of NLO event generator	All, uncorrelated
PS & hadronization	POWHEG+HERWIG 7 vs. POWHEG+PYTHIA 8	All, uncorrelated
ISR / FSR	Variations of μ_R, μ_F, h_{damp} and A14 Var3c parameters	All, uncorrelated
$t\bar{t} + \geq 1c$ ME vs. inclusive	MG5_aMC@NLO+HERWIG++: ME prediction (3F) vs. incl. (5F)	$t\bar{t} + \geq 1c$
$t\bar{t} + \geq 1b$ SHERPA4F vs. nominal	Comparison of $t\bar{t} + b\bar{b}$ NLO (4F) vs. POWHEG+PYTHIA 8 (5F)	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ renorm. scale	Up or down by a factor of two	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ resumm. scale	Vary μ_Q from $H_T/2$ to μ_{CMMPS}	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ global scales	Set μ_Q, μ_R, and μ_F to μ_{CMMPS}	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ shower recoil scheme	Alternative model scheme	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ PDF (MSTW)	MSTW vs. CT10	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ PDF (NNPDF)	NNPDF vs. CT10	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ UE	Alternative set of tuned parameters for the underlying event	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ MPI	Up or down by 50%	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 3b$ normalization	Up or down by 50%	$t\bar{t} + \geq 1b$

Norm only

Shape only

$t\bar{t}$+≥1b fractions

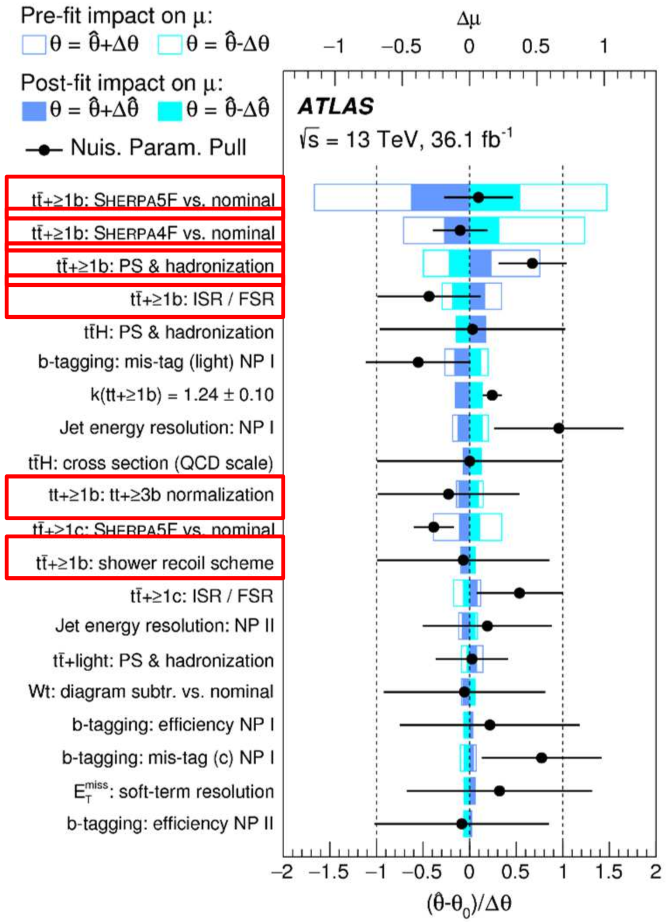
- Uncertainties on $t\bar{t}$ cross-section correlated across all $t\bar{t}$+jets components
- Shape uncertainties on $t\bar{t}$+jets, uncorrelated across $t\bar{t}$+≥1b, $t\bar{t}$+≥1c, and $t\bar{t}$ +light → comparisons to alternative setups - NLO matching, PS model, additional radiations
- Shape uncertainty on $t\bar{t}$+≥1c - comparison of aMC@NLO+Herwig $t\bar{t}$+$c\bar{c}$ 3fs to $t\bar{t}$+≥1c 5fs
- Shape uncertainty on $t\bar{t}$+≥1b : comparison of Powheg+P8 to Sherpa(4fs)
- Uncertainties on $t\bar{t}$+b, $t\bar{t}$+$b\bar{b}$, $t\bar{t}$+B, $t\bar{t}$+≥3b fractions, from Sherpa(4fs) $t\bar{t}$+$b\bar{b}$ prediction (QCD scales, PDF, UE) + additional 50% uncertainties on $t\bar{t}$+≥3b and $t\bar{t}$+b(MPI) rates

→ **13/4/3 independent sources of modelling uncertainties for $t\bar{t}$+≥1b, $t\bar{t}$+ ≥ 1c and $t\bar{t}$+light**

$t\bar{t}H$, H→$b\bar{b}$: results

Impact of systematic uncertainties

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



- Constraints for nuisance parameters associated to larger variation than observed in data
- Some NPs shifted from their nominal value – low impact on signal strength

$t\bar{t}$H, Multileptons: MC samples

Event generation configuration for signal and backgrounds

Process	Event generator	ME order	Parton Shower	PDF	Tune
$t\bar{t}H$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO [71]	A14
	(MG5_aMC)	(NLO)	(Herwig++)	(CT10 [72])	(UE-EE-5)
$tHqb$	MG5_aMC	LO	Pythia 8	CT10	A14
tHW	MG5_aMC	NLO	Herwig++	CT10	UE-EE-5
$t\bar{t}W$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO	A14
	(Sherpa 2.1.1)	(LO multileg)	(Sherpa)	(NNPDF 3.0 NLO)	(Sherpa default)
$t\bar{t}(Z/\gamma^* \to ll)$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO	A14
	(Sherpa 2.1.1)	(LO multileg)	(Sherpa)	(NNPDF 3.0 NLO)	(Sherpa default)
tZ	MG5_aMC	LO	Pythia 6	CTEQ6L1	Perugia2012
tWZ	MG5_aMC	NLO	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}t$, $t\bar{t}t\bar{t}$	MG5_aMC	LO	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}W^+W^-$	MG5_aMC	LO	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}$	Powheg-BOX v2 [73]	NLO	Pythia 8	NNPDF 3.0 NLO	A14
$t\bar{t}\gamma$	MG5_aMC	LO	Pythia 8	NNPDF 2.3 LO	A14
s-, t-channel, Wt single top	Powheg-BOX v1 [74,75,76]	NLO	Pythia 6	CT10	Perugia2012
$VV(\to llXX)$, $qqVV$, VVV	Sherpa 2.1.1	MEPS NLO	Sherpa	CT10	Sherpa default
$Z \to l^+l^-$	Sherpa 2.2.1	MEPS NLO	Sherpa	NNPDF 3.0 NLO	Sherpa default

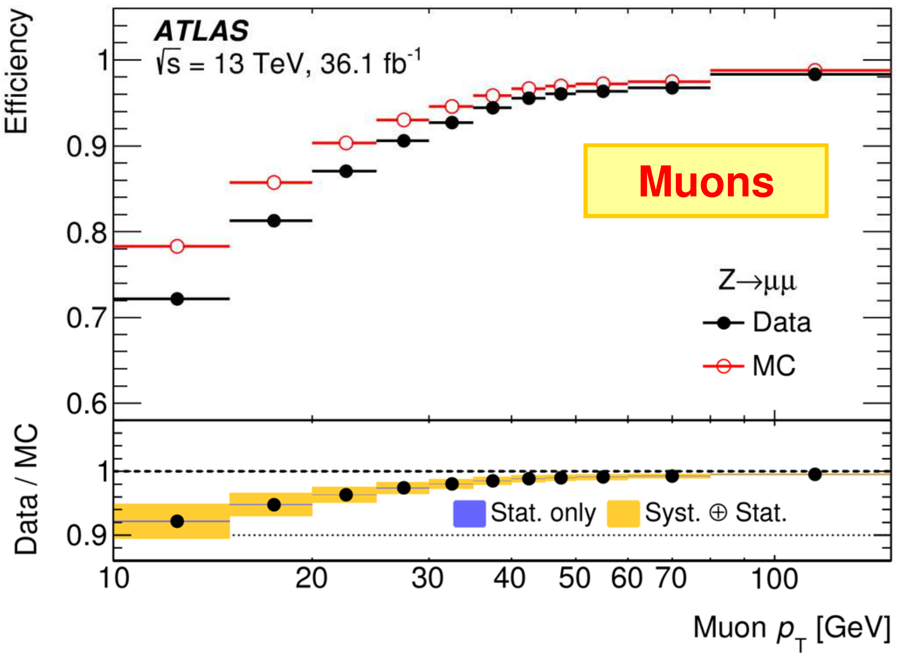
$t\bar{t}$H, Multileptons: MC samples

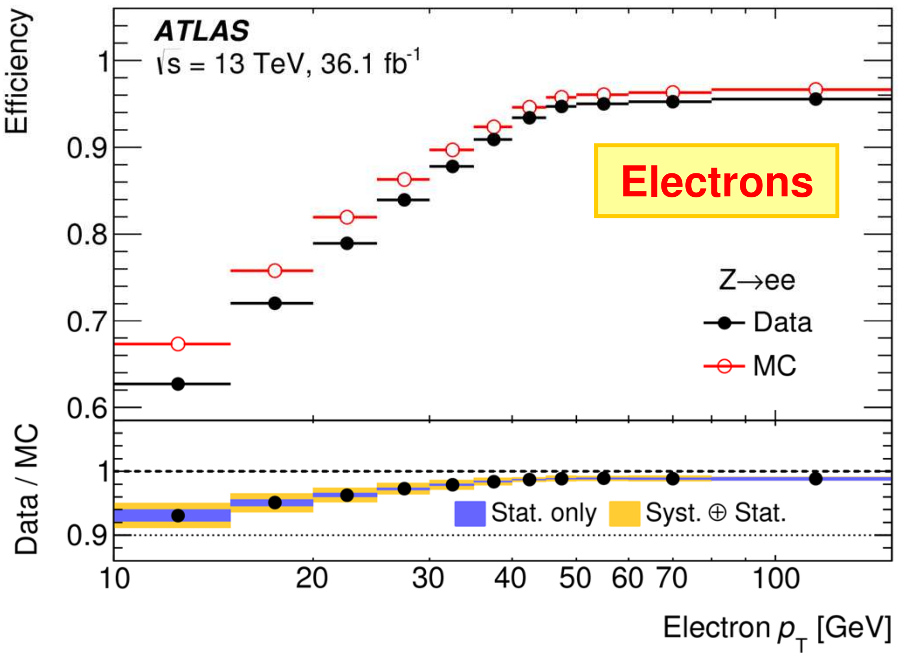
Cross-sections used for MC samples in the analysis

Process	Cross section [pb]	QCD scale [%]	PDF+α_S [%]	Order
$t\bar{t}H$	0.51	$^{+5.8}_{-9.2}$	± 3.6	NLO QCD+EWK
$tHqb$	0.074	$^{+6.5}_{-15}$	± 3.7	NLO QCD
tHW	0.015	$^{+4.9}_{-6.7}$	± 6.3	NLO QCD
$t\bar{t}W$	0.60	$^{+13}_{-12}$	± 3.4	NLO QCD+EWK
$t\bar{t}(Z/\gamma^* \to ll)$	0.12	$^{+9.6}_{-11}$	± 4.0	NLO QCD+EWK
$t\bar{t}t\bar{t}$	0.0092	$^{+31}_{-26}$	$^{+5.5}_{-5.9}$	NLO QCD
$t\bar{t}W^+W^-$	0.0099	$^{+11}_{-12}$	± 2.1	NLO QCD
$t\bar{t}$	832	$^{+2.4}_{-3.5}$	± 4.2	NNLO QCD + NNLL
$t\bar{t}\gamma$	5.7	± 50		NLO QCD
tZ	0.61	± 50		LO QCD
tWZ	0.16	± 50		NLO QCD
Single t (s-channel)	10	± 4		NLO QCD
Single t (t-channel)	217	± 4		NLO QCD
Single t (Wt)	72	± 5		NLO QCD + NNLL
$VV(\to llXX)$	37	± 50		NLO QCD
$Z \to l^+l^-$	2070	± 5		NNLO QCD

$t\bar{t}H$, Multileptons: non-prompt BDT

- To further reject non-prompt leptons from b-hadron decays, a cut on lepton BDT discriminant is required, achieving rejection factor of ~20 with high prompt lepton efficiencies
- Input variables: isolation variables, jet reconstruction and b-tagging algorithms using tracks around the leptons
- The efficiency for prompt leptons are measured in data using Z→ll events
  → corrections to MC (scale factors) are at most 10 % at low p_T





$t\bar{t}H$, Multileptons: selection (SR)

Signal region selections

Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
2ℓSS	Two very tight light leptons with $p_{\text{T}} > 20$ GeV Same-charge light leptons Zero medium τ_{had} candidates $N_{\text{jets}} \geq 4$ and $N_{b\text{-jets}} < 3$
3ℓ	Three light leptons with $p_{\text{T}} > 10$ GeV; sum of light-lepton charges ± 1 Two same-charge leptons must be very tight and have $p_{\text{T}} > 15$ GeV The opposite-charge lepton must be loose, isolated and pass the non-prompt BDT Zero medium τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2 \text{ GeV}\rvert > 10$ GeV for all SFOC pairs $\lvert m(3\ell) - 91.2 \text{ GeV}\rvert > 10$ GeV
4ℓ	Four light leptons; sum of light-lepton charges 0 Third and fourth leading leptons must be tight $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2 \text{ GeV}\rvert > 10$ GeV for all SFOC pairs $\lvert m(4\ell) - 125 \text{ GeV}\rvert > 5$ GeV Split 2 categories: Z-depleted (0 SFOC pairs) and Z-enriched (2 or 4 SFOC pairs)
1ℓ+$2\tau_{\text{had}}$	One tight light lepton with $p_{\text{T}} > 27$ GeV Two medium τ_{had} candidates of opposite charge, at least one being tight $N_{\text{jets}} \geq 3$
2ℓSS+$1\tau_{\text{had}}$	Two very tight light leptons with $p_{\text{T}} > 15$ GeV Same-charge light leptons One medium τ_{had} candidate, with charge opposite to that of the light leptons $N_{\text{jets}} \geq 4$ $\lvert m(ee) - 91.2 \text{ GeV}\rvert > 10$ GeV for ee events
2ℓOS+$1\tau_{\text{had}}$	Two loose and isolated light leptons with $p_{\text{T}} > 25$, 15 GeV One medium τ_{had} candidate Opposite-charge light leptons One medium τ_{had} candidate $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2 \text{ GeV}\rvert > 10$ GeV for the SFOC pair $N_{\text{jets}} \geq 3$
3ℓ+$1\tau_{\text{had}}$	3ℓ selection, except: One medium τ_{had} candidate, with charge opposite to the total charge of the light leptons The two same-charge light leptons must be tight and have $p_{\text{T}} > 10$ GeV The opposite-charge light lepton must be loose and isolated

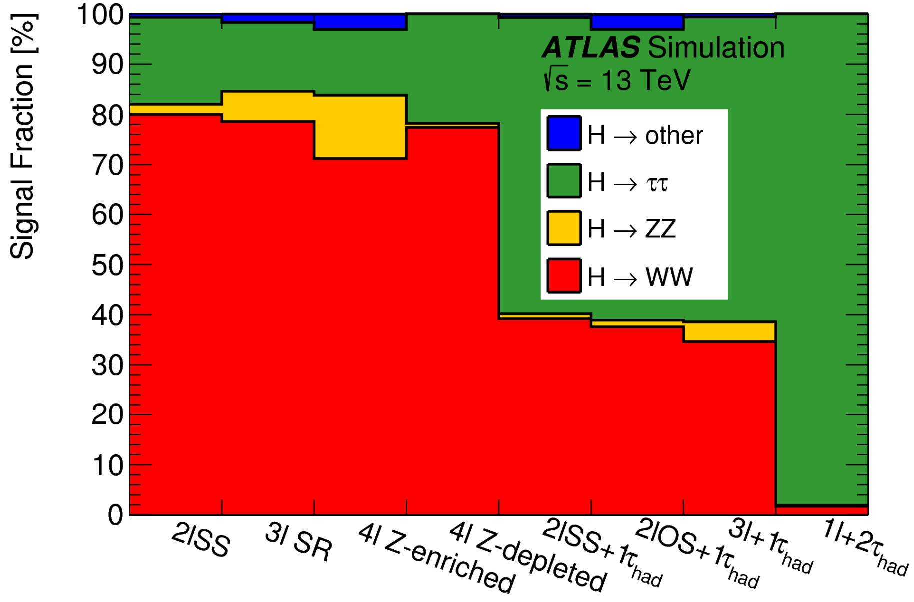
$t\bar{t}H$, Multileptons: selection (CR)

Control region selections

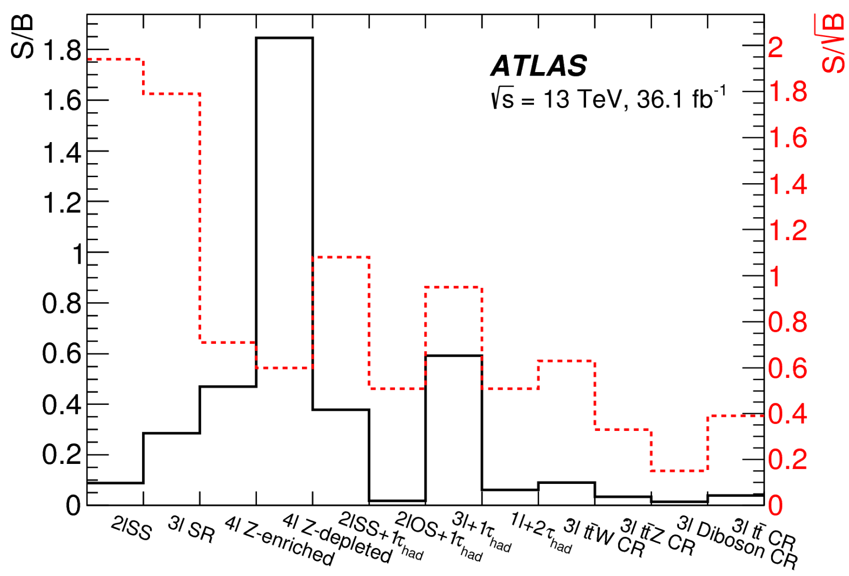
Channel	Region	Selection criteria
$2\ell SS$		$2 \leq N_{\text{jets}} \leq 3$ and $N_{b\text{-jets}} \geq 1$
(3ℓ)		One very tight, one loose light lepton with $p_{\text{T}} > 20$ (15) GeV
		Zero τ_{had} candidates
	ϵ_{real}	Opposite charge; opposite flavor
	ϵ_{fake}	Same charge; opposite flavor or $\mu\mu$
4ℓ		$1 \leq N_{\text{jets}} \leq 2$
		Three loose light leptons; sum of light lepton charges ± 1
		Subleading same-charge lepton must be tight
		Veto on 3ℓ selection
	Either	One SFOC pair with $\lvert m(\ell^+\ell^-) - 91.2\ \text{GeV}\rvert < 10$ GeV
		$E_{\text{T}}^{\text{miss}} < 50$ GeV, $m_{\text{T}} < 50$ GeV
	or	No SFOC pair
		Subleading jet $p_{\text{T}} > 30$ GeV
$2\ell SS{+}1\tau_{\text{had}}$		$2 \leq N_{\text{jets}} \leq 3$ and $N_{b\text{-jets}} \geq 1$
		One very tight, one loose light lepton with $p_{\text{T}} > 15$ GeV
		A SFSC pair
		$\lvert m(ee) - 91.2\ \text{GeV}\rvert > 10$ GeV
		Zero or one medium τ_{had} candidate, opposite in charge to the light leptons
$1\ell{+}2\tau_{\text{had}}$		$N_{\text{jets}} \geq 3$ and $N_{b\text{-jets}} \geq 1$
		One tight light lepton, with $p_{\text{T}} > 27$ GeV
		Two τ_{had} candidates of same charge
		At least one τ_{had} candidate has to satisfy tight identification criteria
$2\ell OS{+}1\tau_{\text{had}}$		Two loose and isolated light leptons, with $p_{\text{T}} > 25$, 15 GeV
		One loose τ_{had} candidate
		$\lvert m(\ell^+\ell^-) - 91.2\ \text{GeV}\rvert > 10$ GeV and $m(\ell^+\ell^-) > 12$ GeV
		$N_{\text{jets}} \geq 3$ and $N_{b\text{-jets}} = 0$

$t\bar{t}H$, Multileptons: categories

Expected signal fraction in each SR



S/B and S/√B in each SR/CR (pre-fit)



$t\bar{t}H$, Multileptons: summaries

Signal region selections summary

	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{\text{had}}$	2ℓSS$+1\tau_{\text{had}}$	2ℓOS$+1\tau_{\text{had}}$	$3\ell+1\tau_{\text{had}}$
Light lepton	2T*	1L*, 2T*	2L, 2T	1T	2T*	2L†	1L†, 2T
τ_{had}	0M	0M	–	1T, 1M	1M	1M	1M
N_{jets}, $N_{b\text{-jets}}$	$\geq 4, = 1, 2$	$\geq 2, \geq 1$	$\geq 2, \geq 1$	$\geq 3, \geq 1$	$\geq 4, \geq 1$	$\geq 3, \geq 1$	$\geq 2, \geq 1$

Fake and non-prompt background estimation: strategy summary

	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{\text{had}}$	2ℓSS$+1\tau_{\text{had}}$	2ℓOS$+1\tau_{\text{had}}$	$3\ell+1\tau_{\text{had}}$
Non-prompt lepton strategy	DD (MM)	DD (MM)	semi-DD (SF)	MC	DD (FF)	MC	MC
Fake τ_{had} strategy	–	–	–	DD (SS data)	semi-DD (SF)	DD (FF)	semi-DD (SF)
Control Region Selection							
Light lepton	1T*, 1L		3L	1T	1T*, 1L	2L†	–
τ_{had}	0M			1T, 1M	≤ 1M	1L	–
N_{jets}	$2 \leq N_{\text{jets}} \leq 3$		$1 \leq N_{\text{jets}} \leq 2$	≥ 3	$2 \leq N_{\text{jets}} \leq 3$	≥ 3	–
$N_{b\text{-jets}}$	≥ 1					$= 0$	–

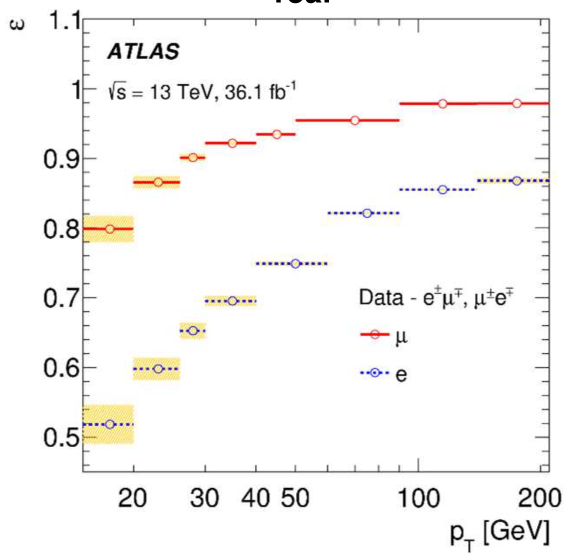
Analysis strategy summary

	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{\text{had}}$	2ℓSS$+1\tau_{\text{had}}$	2ℓOS$+1\tau_{\text{had}}$	$3\ell+1\tau_{\text{had}}$
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	-	-	-	-	-

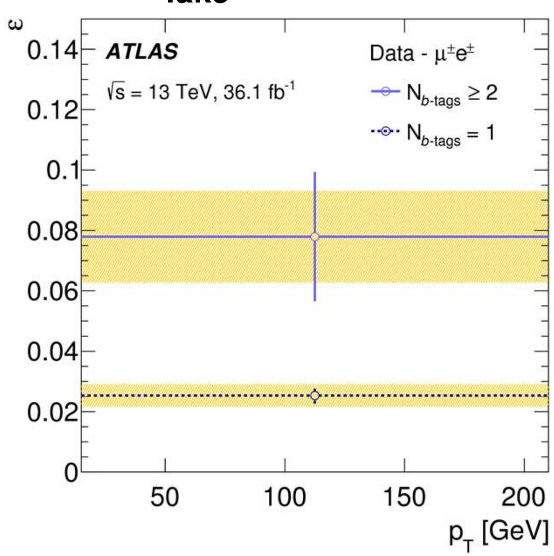
$t\bar{t}H$, Multileptons: background

- "Matrix-method" predicts non-prompt light lepton events in 2ℓSS and 3ℓ from loose regions (by discarding lepton tight ID and isolation requirements)
- Loose-to-tight probabilities for prompt and non-prompt leptons as input
- Prompt lepton efficiency ε_{real} measured in prompt lepton control region from leptonic $t\bar{t}$ decays (2ℓOFOS, [2,3] jets, $N_{b\text{-}tag} \geq 1$)
- Non-prompt lepton efficiency ε_{fake} vs p_T, $N_{b\text{-}tag}$ or min$\Delta R(\mu,\text{jet})$ measured in low-Njet non-prompt lepton control region (2ℓSS, [2,3] jets, $N_{b\text{-}tag} \geq 1$)

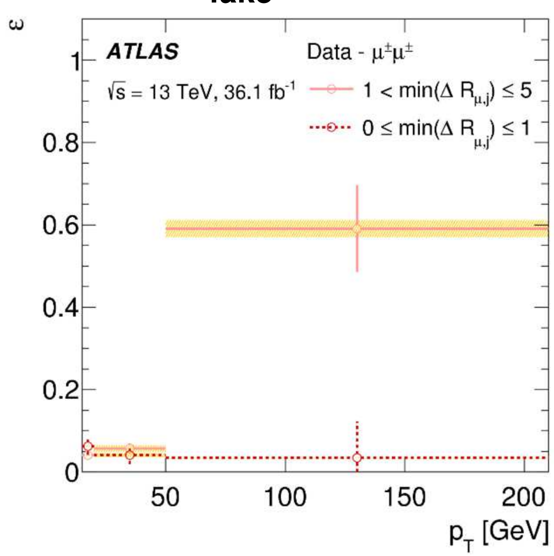
ε_{real}



ε_{fake} (electrons)

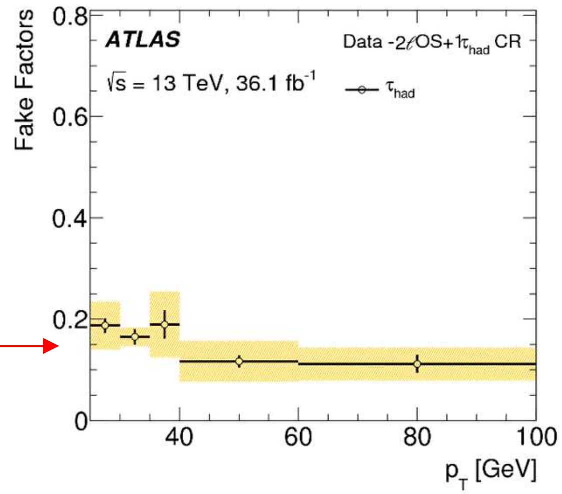


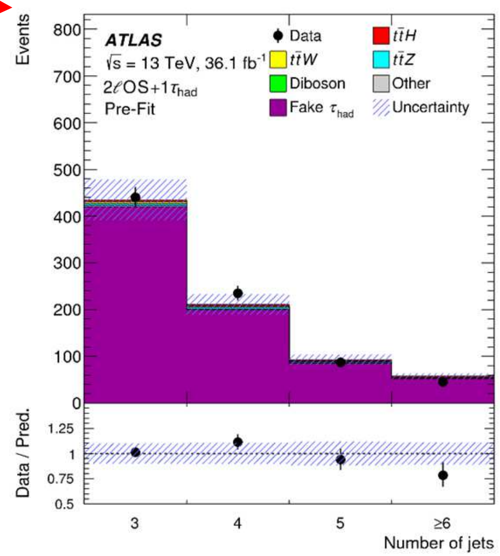
ε_{fake} (muons)



$t\bar{t}H$, Multileptons: background

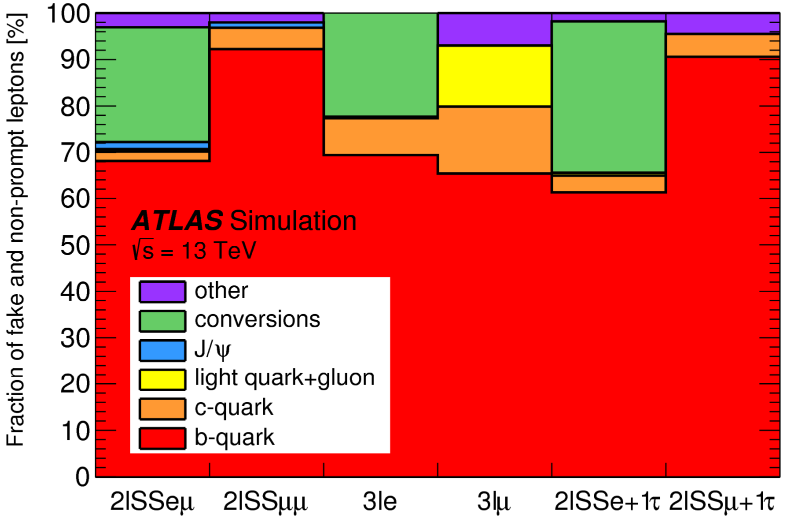
- Fake τ_{had} background from $t\bar{t}$ or $t\bar{t}V$ relevant for all SRs including τ_{had}
- $1\ell+2\tau_{had}$: using CR with two same-sign τ_{had}, extrapolated to SR using MC
- $2\ell OS+1\tau_{had}$: fake factors measured in a CR (≥3 jets, b-tag veto), inverting part of the τ_{had} identification requirements
- Good agreement with data for $2\ell OS+1\tau_{had}$
- Very similar fake τ_{had} origin in the $2\ell OS/2\ell SS/3\ell+1\tau_{had}$ SRs
- Use data-driven estimates from $2\ell OS+1\tau_{had}$ as a correction factor for the fake τ_{had} +prompt ℓ MC in $2\ell SS/3\ell+1\tau_{had}$
- Negligible fake/non-prompt light leptons, except for $2\ell SS+1\tau_{had}$ → estimated from data using fake factor method



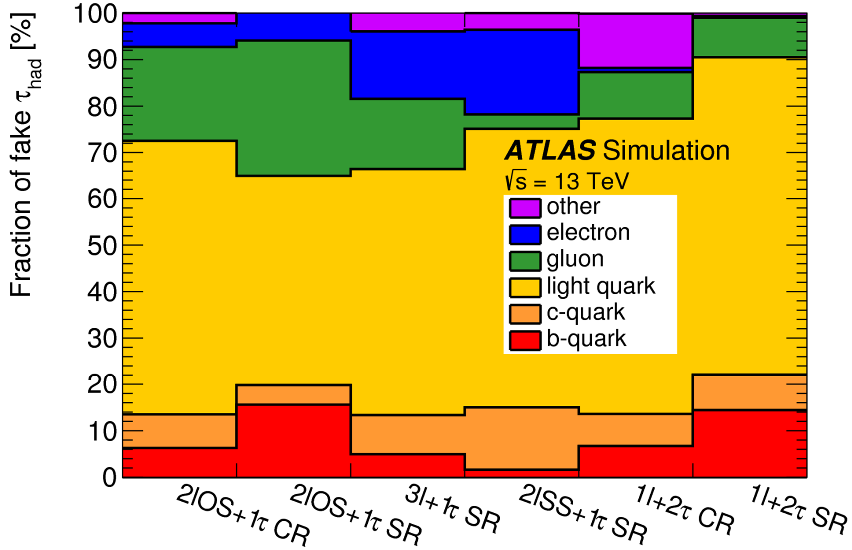


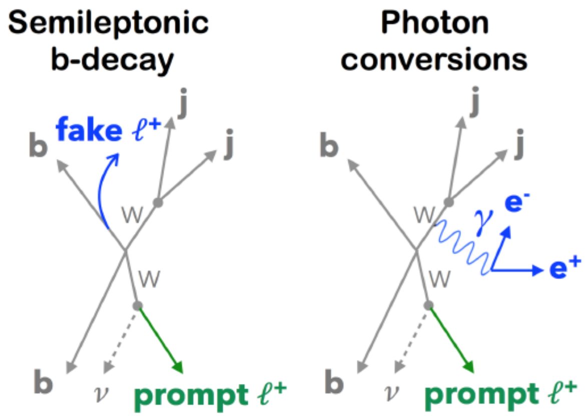
$t\bar{t}H$, Multileptons: background

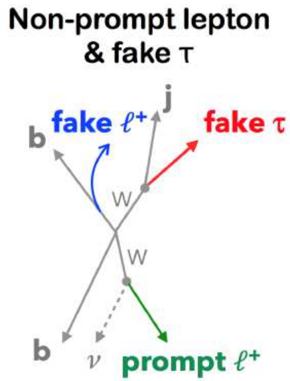
Non-prompt light lepton composition in CR



Fake τ_{had} composition



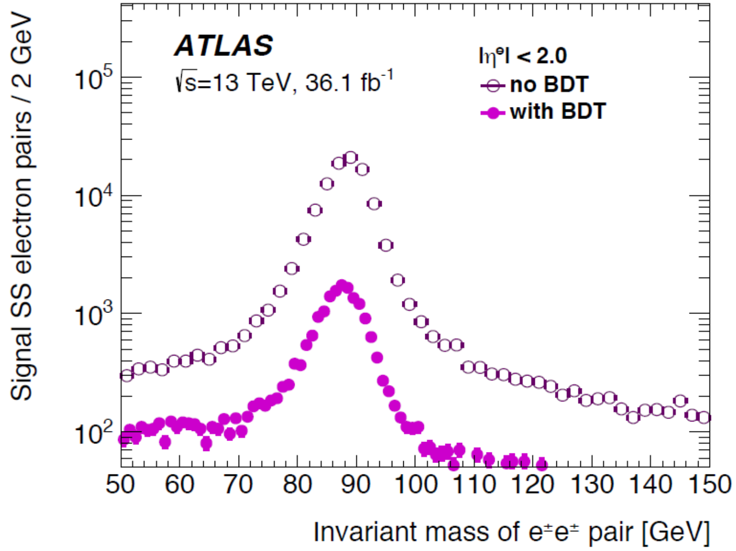




tt̄H, Multileptons: charge misid

BDT to reduce electron charge mis-identification

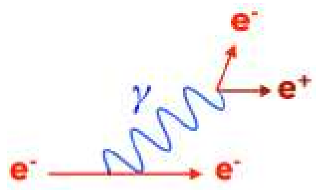
- Use electron calorimeter and track variables
- 95% efficiency for right charge electrons
- Rejection ~17 of wrong charge electrons



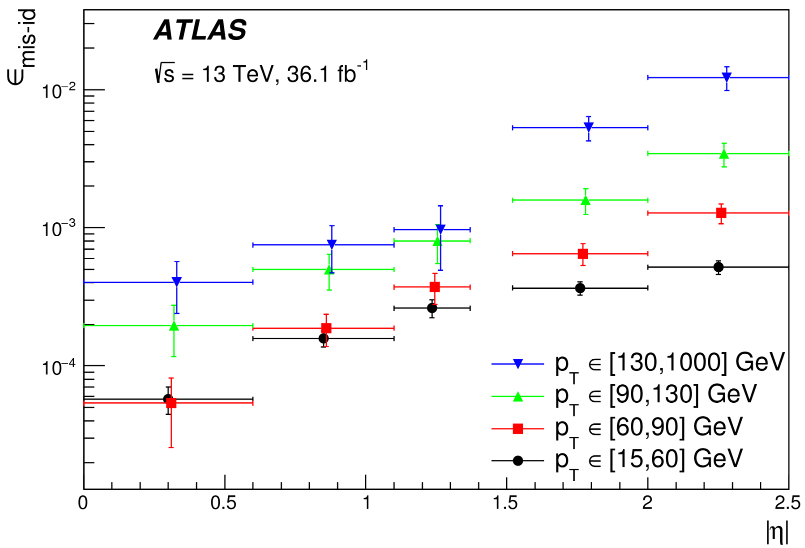
Variable	Description
p_T	Transverse momentum
η	Pseudo-rapidity
charge$\times d_0$	Electric charge times the transverse impact parameter
E/p	Ratio of the cluster energy to the track momentum
R_ϕ	Ratio of the energy in 3×3 cells over the energy in 3×7 cells centred at the electron cluster position
$\Delta\phi_1$	$\Delta\phi$ between the cluster position in the strip layer and the extrapolated track
$\Delta\phi_{rescaled}$	$\Delta\phi$ between the cluster position in the middle layer and the extrapolated track, where the track momentum is rescaled to the cluster energy before extrapolating the track to the middle layer
$\frac{q/p}{\sigma_{q/p}}$	Significance of the curvature of the track defined as the ratio of the reconstructed charge to the track momentum

$t\bar{t}H$, Multileptons: charge misid

- Electron charge flips in $t\bar{t}$ and Z+jets processes pollute 2ℓSS events
  - Hard Bremsstrahlung → photon conversion, where wrong charge electron inherits largest p_T fraction
  - mis-reconstruction of the electron charge due to small track curvature in the inner detector (dominant at high p_T)



- Electron charge flip rates vs p_T and $|\eta|$ measured from OS/SS electron pairs from Z decays → electron charge flip background extracted from OS data after applying rates



- Total systematic uncertainty ~30 %
- Dominant contribution at low p_T from method non-closure and at high p_T from limited statistics of Z→ee events

$t\bar{t}H$, Multileptons: event yields

Pre- and post-fit event yields

Category	Non-prompt	Fake τ_{had}	q mis-id	$t\bar{t}W$	$t\bar{t}Z$	Diboson	Other	Total Bkgd.	$t\bar{t}H$	Observed
Pre-fit yields										
2ℓSS	233 ± 39	–	33 ± 11	123 ± 18	41.4 ± 5.6	25 ± 15	28.4 ± 5.9	484 ± 38	42.6 ± 4.2	514
3ℓ SR	14.5 ± 4.3	–	–	5.5 ± 1.2	12.0 ± 1.8	1.2 ± 1.2	5.8 ± 1.4	39.1 ± 5.2	11.2 ± 1.6	61
3ℓ $t\bar{t}W$ CR	13.3 ± 4.3	–	–	19.9 ± 3.1	8.7 ± 1.1	< 0.2	4.53 ± 0.92	46.5 ± 5.4	4.18 ± 0.46	56
3ℓ $t\bar{t}Z$ CR	3.9 ± 2.5	–	–	2.71 ± 0.56	66 ± 11	8.4 ± 5.3	12.9 ± 4.2	93 ± 13	3.17 ± 0.41	107
3ℓ VV CR	27.7 ± 8.7	–	–	4.9 ± 1.0	21.3 ± 3.4	51 ± 30	17.9 ± 6.1	123 ± 32	1.67 ± 0.25	109
3ℓ $t\bar{t}$ CR	70 ± 17	–	–	10.5 ± 1.5	7.9 ± 1.1	7.2 ± 4.8	7.3 ± 1.9	103 ± 17	4.00 ± 0.49	85
4ℓ Z-enr.	0.11 ± 0.07	–	–	< 0.01	1.52 ± 0.23	0.43 ± 0.23	0.21 ± 0.09	2.26 ± 0.34	1.06 ± 0.14	2
4ℓ Z-dep.	0.01 ± 0.01	–	–	< 0.01	0.04 ± 0.02	< 0.01	0.06 ± 0.03	0.11 ± 0.03	0.20 ± 0.03	0
1ℓ+$2\tau_{had}$	–	65 ± 21	–	0.09 ± 0.09	3.3 ± 1.0	1.3 ± 1.0	0.98 ± 0.35	71 ± 21	4.3 ± 1.0	67
2ℓSS+$1\tau_{had}$	2.4 ± 1.4	1.80 ± 0.30	0.05 ± 0.02	0.88 ± 0.24	1.83 ± 0.37	0.12 ± 0.18	1.06 ± 0.24	8.2 ± 1.6	3.09 ± 0.46	18
2ℓOS+$1\tau_{had}$	–	756 ± 80	–	6.5 ± 1.3	11.4 ± 1.9	2.0 ± 1.3	5.8 ± 1.5	782 ± 81	14.2 ± 2.0	807
3ℓ+$1\tau_{had}$	–	0.75 ± 0.15	–	0.04 ± 0.04	1.38 ± 0.24	0.002 ± 0.002	0.38 ± 0.10	2.55 ± 0.32	1.51 ± 0.23	5
Post-fit yields										
2ℓSS	211 ± 26	–	28.3 ± 9.4	127 ± 18	42.9 ± 5.4	20.0 ± 6.3	28.5 ± 5.7	459 ± 24	67 ± 18	514
3ℓ SR	13.2 ± 3.1	–	–	5.8 ± 1.2	12.9 ± 1.6	1.2 ± 1.1	5.9 ± 1.3	39.0 ± 4.0	17.7 ± 4.9	61
3ℓ $t\bar{t}W$ CR	11.7 ± 3.0	–	–	20.4 ± 3.0	8.9 ± 1.0	< 0.2	4.54 ± 0.88	45.6 ± 4.0	6.6 ± 1.9	56
3ℓ $t\bar{t}Z$ CR	3.5 ± 2.1	–	–	2.82 ± 0.56	70.4 ± 8.6	7.1 ± 3.0	13.6 ± 4.2	97.4 ± 8.6	5.1 ± 1.4	107
3ℓ VV CR	22.4 ± 5.7	–	–	5.05 ± 0.94	22.0 ± 3.0	39 ± 11	18.1 ± 5.9	106.8 ± 9.4	2.61 ± 0.82	109
3ℓ $t\bar{t}$ CR	56.0 ± 8.1	–	–	10.7 ± 1.4	8.1 ± 1.0	5.9 ± 2.7	7.1 ± 1.8	87.8 ± 7.9	6.3 ± 1.8	85
4ℓ Z-enr.	0.10 ± 0.07	–	–	< 0.01	1.60 ± 0.22	0.37 ± 0.15	0.22 ± 0.10	2.29 ± 0.28	1.65 ± 0.47	2
4ℓ Z-dep.	0.01 ± 0.01	–	–	< 0.01	0.04 ± 0.02	< 0.01	0.07 ± 0.03	0.11 ± 0.03	0.32 ± 0.09	0
1ℓ+$2\tau_{had}$	–	58.0 ± 6.8	–	0.11 ± 0.11	3.31 ± 0.90	0.98 ± 0.75	0.98 ± 0.33	63.4 ± 6.7	6.5 ± 2.0	67
2ℓSS+$1\tau_{had}$	1.86 ± 0.91	1.86 ± 0.27	0.05 ± 0.02	0.97 ± 0.26	1.96 ± 0.37	0.15 ± 0.20	1.09 ± 0.24	7.9 ± 1.2	5.1 ± 1.3	18
2ℓOS+$1\tau_{had}$	–	756 ± 28	–	6.6 ± 1.3	11.5 ± 1.7	1.64 ± 0.92	6.1 ± 1.5	782 ± 27	21.7 ± 5.9	807
3ℓ+$1\tau_{had}$	–	0.75 ± 0.14	–	0.04 ± 0.04	1.42 ± 0.22	0.002 ± 0.002	0.40 ± 0.10	2.61 ± 0.30	2.41 ± 0.68	5

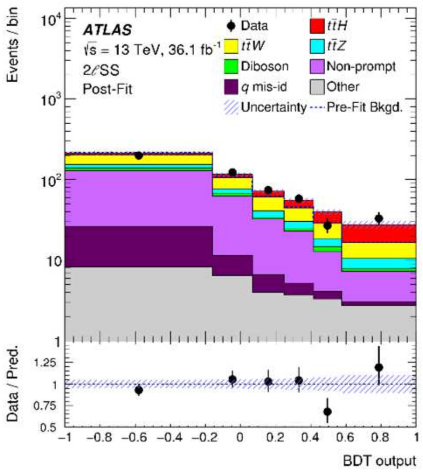
$t\bar{t}H$, Multileptons: event MVA

BDT input variables

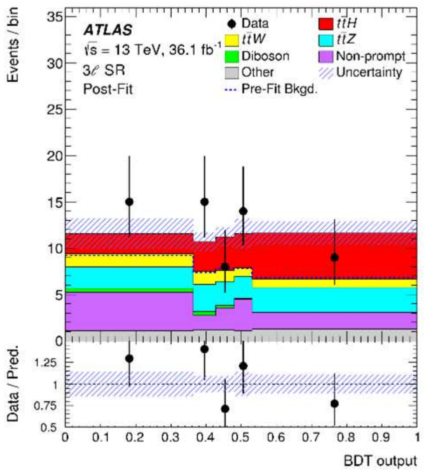
	Variable	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{had}$	2ℓSS$+1\tau_{had}$	2ℓOS$+1\tau_{had}$
Lepton properties	Leading lepton p_T		×				
	Second leading lepton p_T	×	×			×	
	Third lepton p_T		×				
	Dilepton invariant mass (all combinations)	×	×∗				×
	Three-lepton invariant mass		×				
	Four-lepton invariant mass			×			
	Best Z-candidate dilepton invariant mass			×			
	Other Z-candidate dilepton invariant mass			×			
	Scalar sum of all leptons p_T			×			×
	Second leading lepton track isolation					×	
	Maximum $\|\eta\|$ (lepton 0, lepton 1)	×				×∗	
	Lepton flavor	×∗	×∗				
	Lepton charge		×				
Jet properties	Number of jets	×∗	×∗		×	×	×
	Number of b-tagged jets	×∗	×∗		×	×	×
	Leading jet p_T						×
	Second leading jet p_T		×			×∗	
	Leading b-tagged jet p_T		×				
	Scalar sum of all jets p_T		×		×	×	×
	Scalar sum of all b-tagged jets p_T						×
	Has leading jet highest b-tagging weight?		×				
	b-tagging weight of leading jet		×				
	b-tagging weight of second leading jet		×			×	
	b-tagging weight of third leading jet					×	
	Pseudorapidity of fourth leading jet					×	
τ_{had}	Leading τ_{had} p_T				×		×
	Second leading τ_{had} p_T				×		
	Di-τ_{had} invariant mass				×		
	Invariant mass τ_{had}–furthest lepton					×	
Angular distances	ΔR(lepton 0, lepton 1)		×				
	ΔR(lepton 0, lepton 2)		×				
	ΔR(lepton 0, closest jet)	×	×				
	ΔR(lepton 0, leading jet)		×			×	
	ΔR(lepton 0, closest b-jet)		×				
	ΔR(lepton 1, closest jet)	×	×				
	ΔR(lepton 2, closest jet)		×				
	Smallest ΔR(lepton, jet)		×				×
	Smallest ΔR(lepton, b-tagged jet)						×
	Smallest ΔR(non-tagged jet, b-tagged jet)						×
	ΔR(lepton 0, τ_{had})						×
	ΔR(lepton 1, τ_{had})						×
	Minimum ΔR between all jets				×		
	ΔR between two leading jets					×	
$\vec{p}_T^{\,miss}$	Missing transverse momentum E_T^{miss}	×		×			
	Azimuthal separation $\Delta\phi$(leading jet, $\vec{p}_T^{\,miss}$)		×				
	Transverse mass leptons (H/Z decay) - $\vec{p}_T^{\,miss}$			×			
	Pseudo-Matrix-Element			×			

$t\bar{t}H$, Multileptons: event MVA

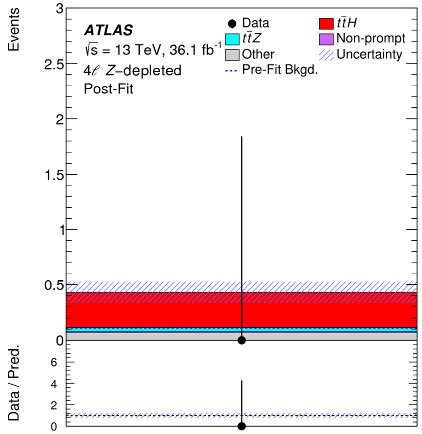
2ℓss



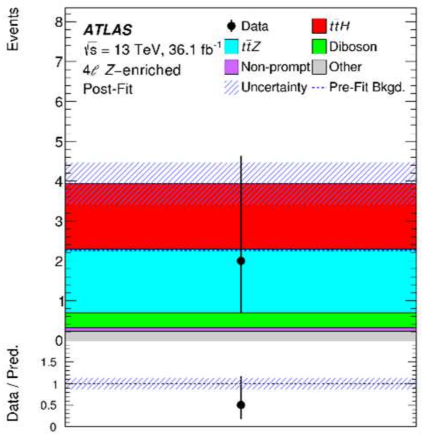
3ℓ



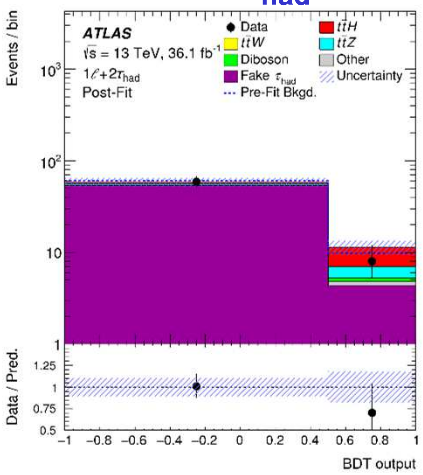
4ℓ Z-depleted



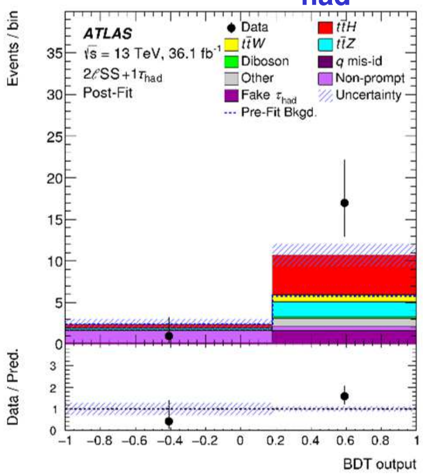
4ℓ Z-enriched



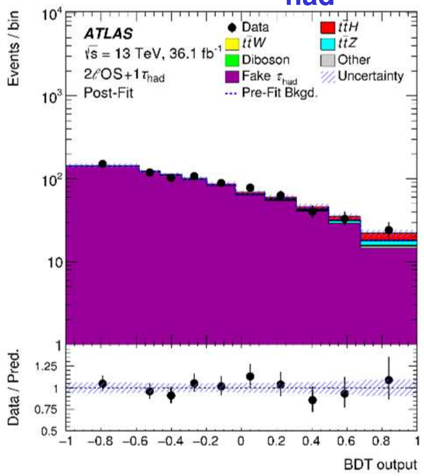
1ℓ+2τ_{had}



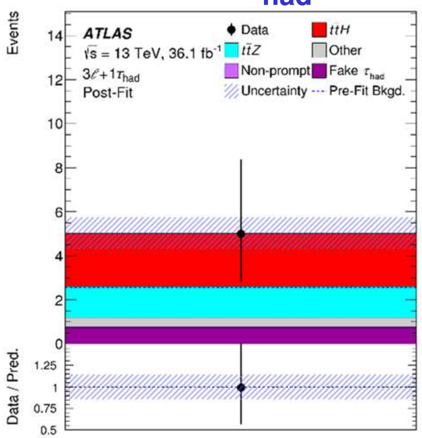
2ℓSS+1τ_{had}



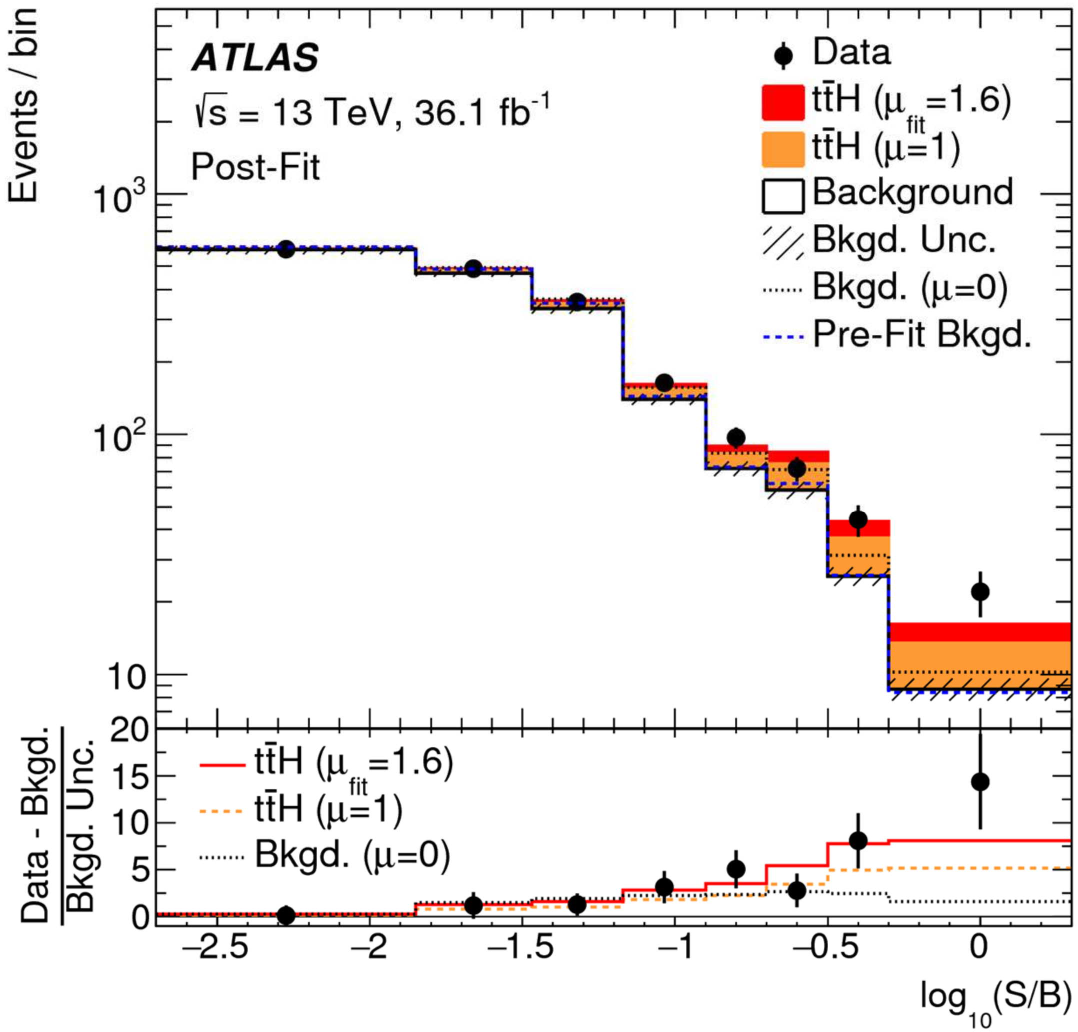
2ℓOS+1τ_{had}



3ℓ+1τ_{had}



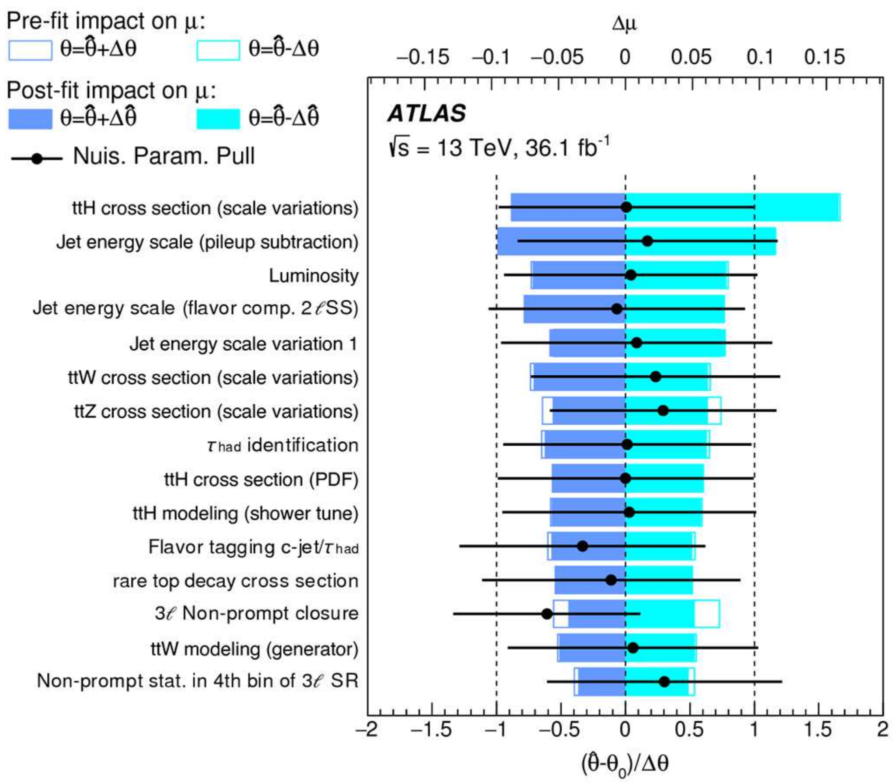
$t\bar{t}H$, Multileptons: results



All SR bins combined into bins of log(S/B) with expected signal S and fitted background B

$t\bar{t}H$, Multileptons: results

Impact of systematic uncertainties



Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modeling (cross section)	+0.20	−0.09
Jet energy scale and resolution	+0.18	−0.15
Non-prompt light-lepton estimates	+0.15	−0.13
Jet flavor tagging and τ_{had} identification	+0.11	−0.09
$t\bar{t}W$ modeling	+0.10	−0.09
$t\bar{t}Z$ modeling	+0.08	−0.07
Other background modeling	+0.08	−0.07
Luminosity	+0.08	−0.06
$t\bar{t}H$ modeling (acceptance)	+0.08	−0.04
Fake τ_{had} estimates	+0.07	−0.07
Other experimental uncertainties	+0.05	−0.04
Simulation sample size	+0.04	−0.04
Charge misassignment	+0.01	−0.01
Total systematic uncertainty	+0.39	−0.30

$t\bar{t}H$, Multileptons: results

Observed and expected significance and $\mu_{t\bar{t}H}$ for $t\bar{t}H$ multileptons channels

Channel	Best-fit μ		Significance	
	Observed	Expected	Observed	Expected
$2\ell OS+1\tau_{had}$	$1.7\ ^{+1.6}_{-1.5}$ (stat.) $^{+1.4}_{-1.1}$ (syst.)	$1.0\ ^{+1.5}_{-1.4}$ (stat.) $^{+1.2}_{-1.1}$ (syst.)	0.9σ	0.5σ
$1\ell+2\tau_{had}$	$-0.6\ ^{+1.1}_{-0.8}$ (stat.) $^{+1.1}_{-1.3}$ (syst.)	$1.0\ ^{+1.1}_{-0.9}$ (stat.) $^{+1.2}_{-1.1}$ (syst.)	–	0.6σ
4ℓ	$-0.5\ ^{+1.3}_{-0.8}$ (stat.) $^{+0.2}_{-0.3}$ (syst.)	$1.0\ ^{+1.7}_{-1.2}$ (stat.) $^{+0.4}_{-0.2}$ (syst.)	–	0.8σ
$3\ell+1\tau_{had}$	$1.6\ ^{+1.7}_{-1.3}$ (stat.) $^{+0.6}_{-0.2}$ (syst.)	$1.0\ ^{+1.5}_{-1.1}$ (stat.) $^{+0.4}_{-0.2}$ (syst.)	1.3σ	0.9σ
$2\ell SS+1\tau_{had}$	$3.5\ ^{+1.5}_{-1.2}$ (stat.) $^{+0.9}_{-0.5}$ (syst.)	$1.0\ ^{+1.1}_{-0.8}$ (stat.) $^{+0.5}_{-0.3}$ (syst.)	3.4σ	1.1σ
3ℓ	$1.8\ ^{+0.6}_{-0.6}$ (stat.) $^{+0.6}_{-0.5}$ (syst.)	$1.0\ ^{+0.6}_{-0.5}$ (stat.) $^{+0.5}_{-0.4}$ (syst.)	2.4σ	1.5σ
$2\ell SS$	$1.5\ ^{+0.4}_{-0.4}$ (stat.) $^{+0.5}_{-0.4}$ (syst.)	$1.0\ ^{+0.4}_{-0.4}$ (stat.) $^{+0.4}_{-0.4}$ (syst.)	2.7σ	1.9σ
Combined	$1.6\ ^{+0.3}_{-0.3}$ (stat.) $^{+0.4}_{-0.3}$ (syst.)	$1.0\ ^{+0.3}_{-0.3}$ (stat.) $^{+0.3}_{-0.3}$ (syst.)	4.1σ	2.8σ

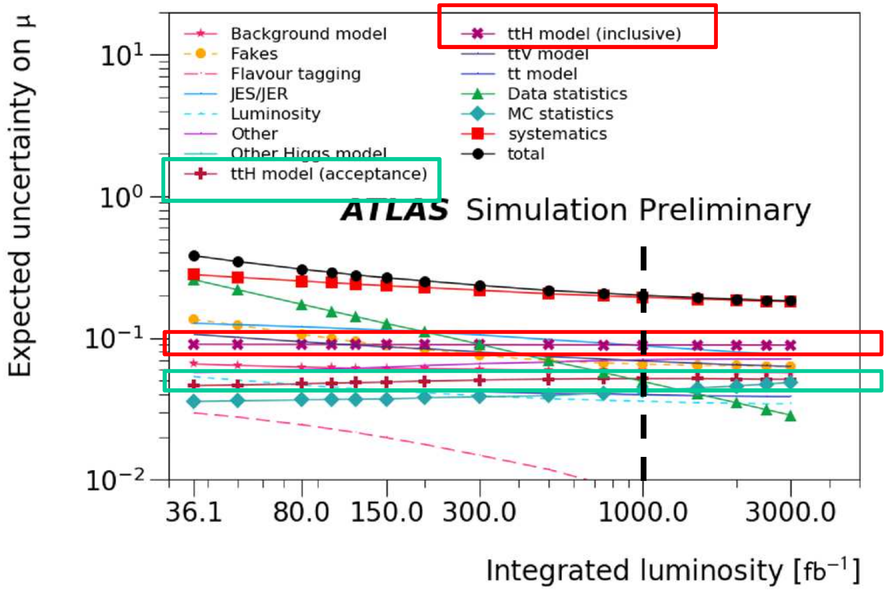
$t\bar{t}$H, Multileptons: HL-LHC

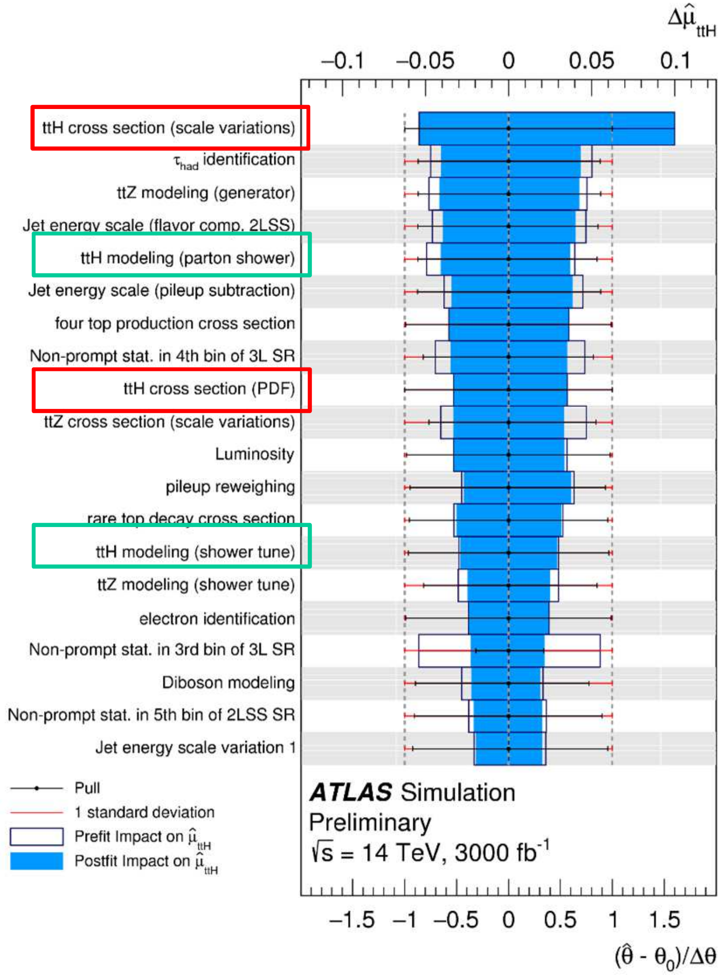
ATLAS-PHYS-PUB-2018-010

$t\bar{t}$H→Multileptons extrapolation at HL-LHC

Results extrapolated from Run-2 36 fb^{-1} analysis

- Largest signal theory uncertainty (QCD scales, PDF) for $\mu=\sigma/\sigma_{SM}$ related to assumed σ_{SM}
- Large contributions also from signal acceptance (PS modelling) which affects measured σ (main component of "$t\bar{t}$H model acceptance")
- Experimental uncertainties expected to be reduced with HL-LHC dataset





$t\bar{t}H(\gamma\gamma/4l)$: MC samples

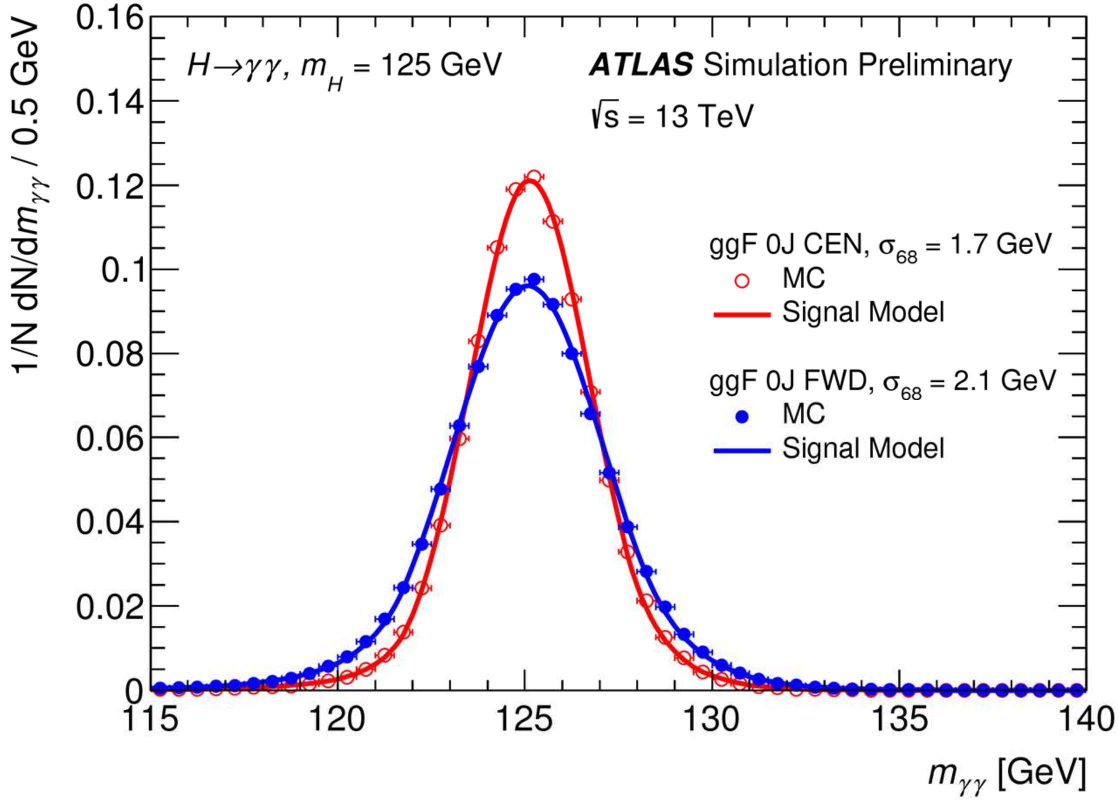
Event generation configuration for Higgs processes

Process	Generator	Showering	PDF set	σ [pb] $\sqrt{s} = 13$ TeV	Order of σ calculation
ggF	Powheg NNLOPS	Pythia 8	PDF4LHC15	48.52	$\mathrm{N^3LO(QCD)+NLO(EW)}$
VBF	Powheg-Box	Pythia 8	PDF4LHC15	3.78	approximate-NNLO(QCD)+NLO(EW)
WH	Powheg-Box	Pythia 8	PDF4LHC15	1.37	NNLO(QCD)+NLO(EW)
$q\bar{q}' \to ZH$	Powheg-Box	Pythia 8	PDF4LHC15	0.76	NNLO(QCD)+NLO(EW)
$gg \to ZH$	Powheg-Box	Pythia 8	PDF4LHC15	0.12	NNLO(QCD)+NLO(EW)
$t\bar{t}H$	Powheg-Box	Pythia 8	PDF4LHC15	0.51	NNLO(QCD)+NLO(EW)
$b\bar{b}H$	Powheg-Box	Pythia 8	PDF4LHC15	0.49	NNLO(QCD)+NLO(EW)
tHq	MG5_aMC@NLO	Pythia 8	CT10	0.07	4FS(LO)
tHW	MG5_aMC@NLO	Herwig++	CT10	0.02	5FS(NLO)

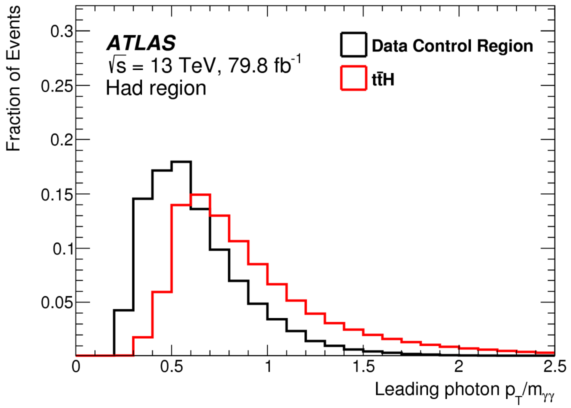
$t\bar{t}H(\gamma\gamma/4l)$: event yields

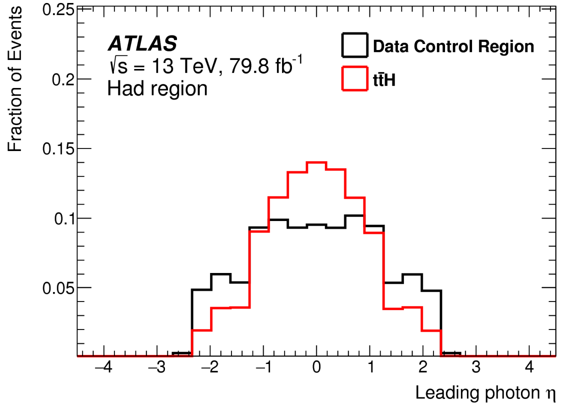
Bin	Expected: $t\bar{t}H$ (signal)		Expected: Non-$t\bar{t}H$ Higgs		Expected: Non-Higgs		Expected: Total		Observed Total	S/B
				$H \to \gamma\gamma$	Numbers of events in smallest diphoton mass window containing 90% of the signal, after fitting to data					
Had 1	4.2	± 1.1	0.49	± 0.33	1.8	± 0.5	6.4	± 1.3	10	1.9
Had 2	3.4	± 0.7	0.7	± 0.6	7.5	± 1.1	11.6	± 1.5	14	
Had 3	4.7	± 0.9	2.0	± 1.7	32.9	± 2.2	39.6	± 3.2	47	
Had 4	3.0	± 0.5	3.2	± 3.1	55.0	± 2.8	61	± 5	67	
Lep 1	4.5	± 1.0	0.24	± 0.09	2.2	± 0.6	6.9	± 1.2	7	1.9
Lep 2	2.2	± 0.4	0.27	± 0.10	4.6	± 0.9	7.1	± 1.0	7	
Lep 3	0.82	± 0.18	0.30	± 0.13	4.6	± 0.9	5.7	± 0.9	5	
				$H \to ZZ^* \to 4\ell$	Numbers of events counted in $115<m_{4l}<130$ GeV mass window					
Had 1	0.169	± 0.031	0.021	± 0.007	0.008	± 0.008	0.198	± 0.033	0	5.8
Had 2	0.216	± 0.032	0.20	± 0.09	0.22	± 0.12	0.63	± 0.16	0	
Lep	0.212	± 0.031	0.0256	± 0.0023	0.015	± 0.013	0.253	± 0.034	0	5.2

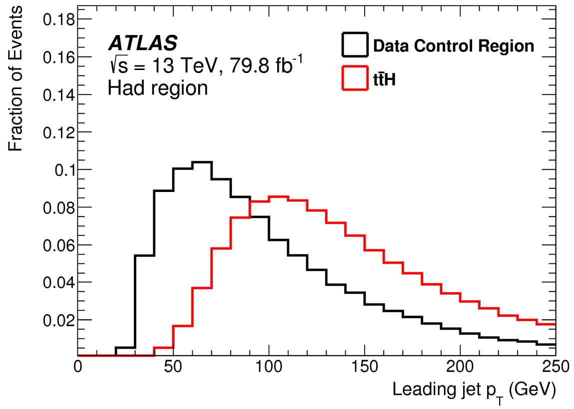
$t\bar{t}H$, $H \rightarrow \gamma\gamma$

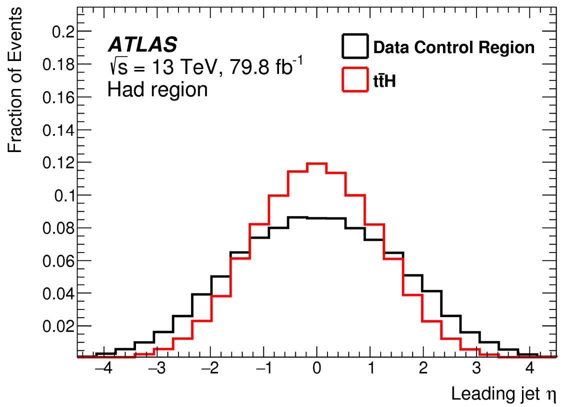


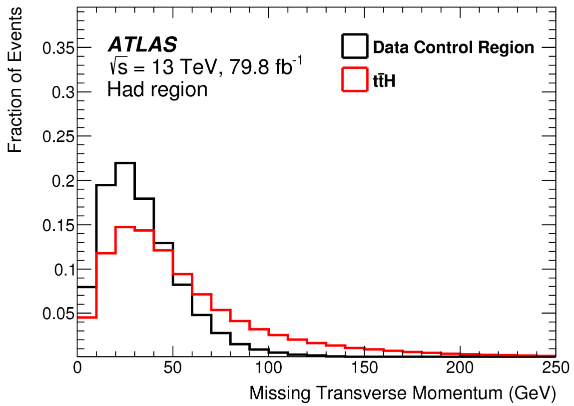
$t\bar{t}H$, $H \rightarrow \gamma\gamma$: event MVA



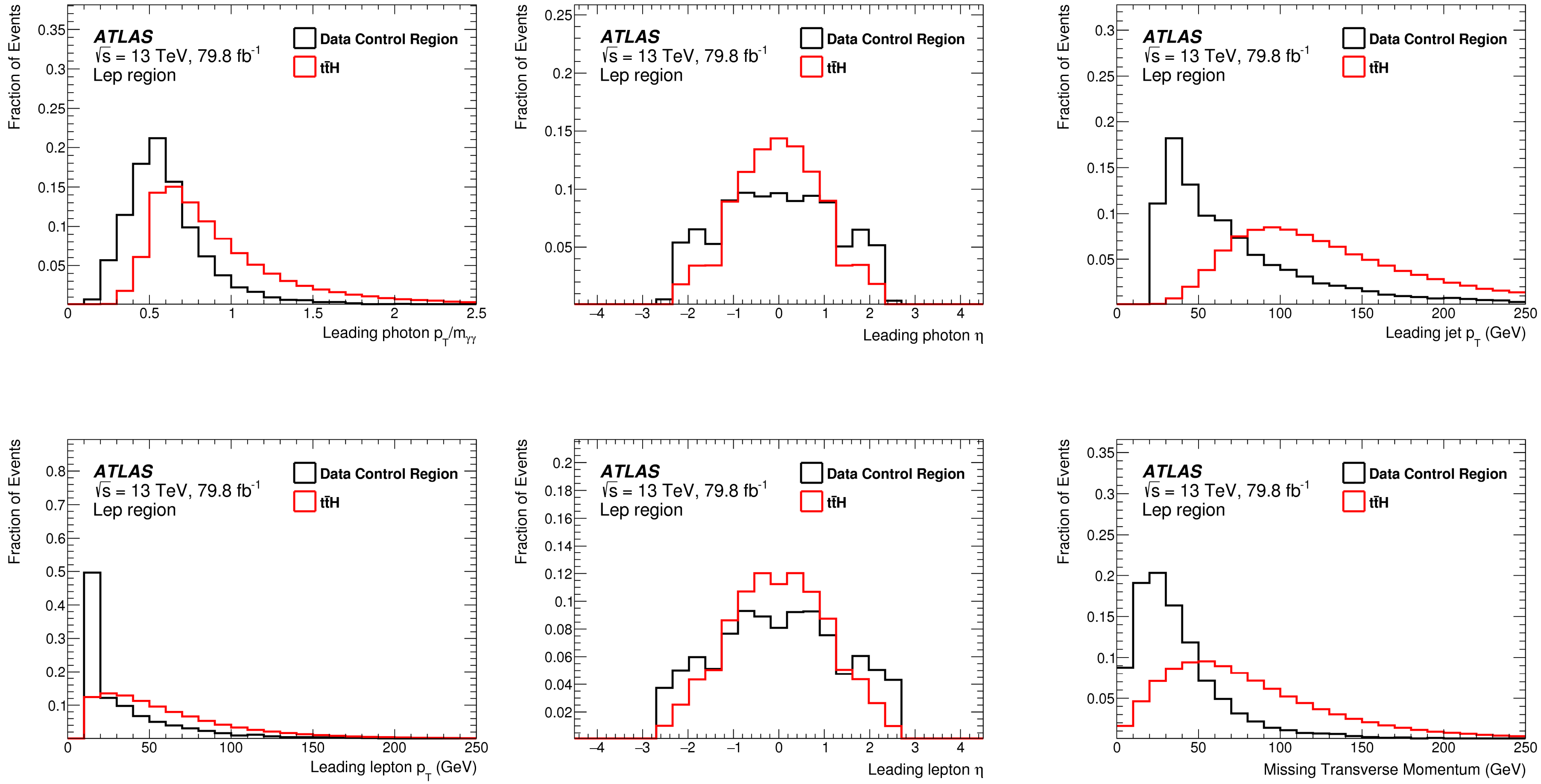




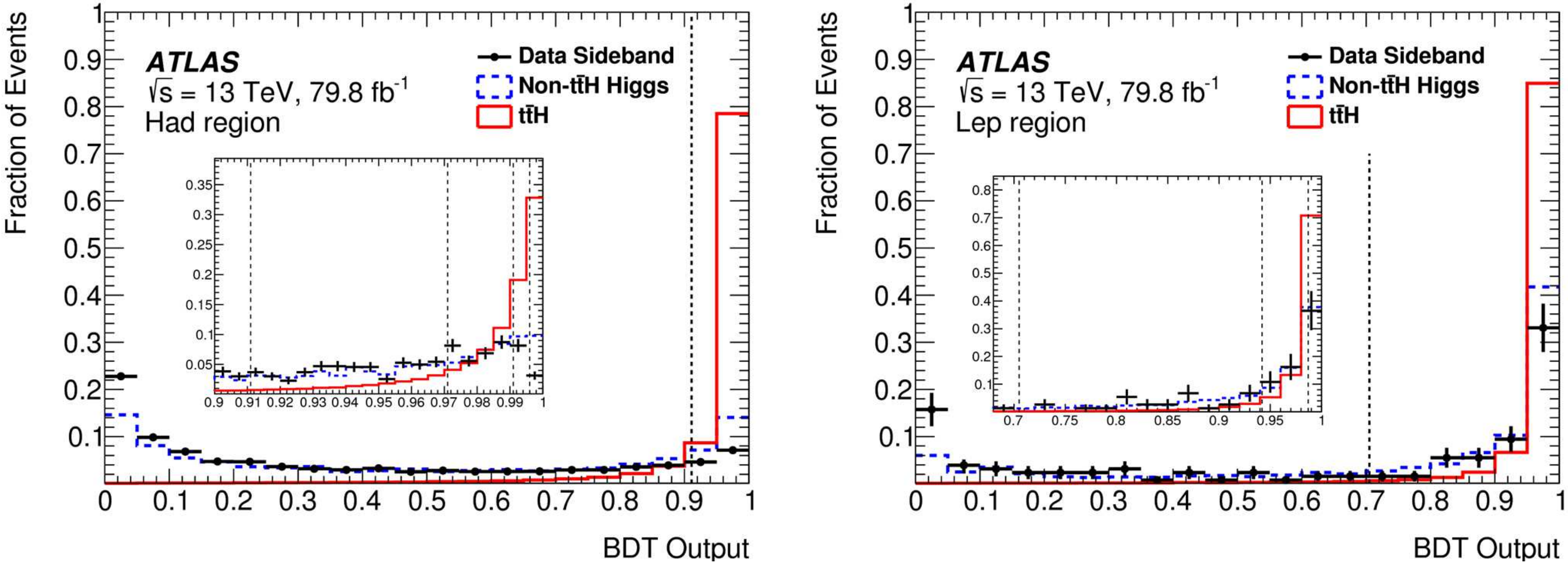




$t\bar{t}H$, $H \rightarrow \gamma\gamma$: event MVA



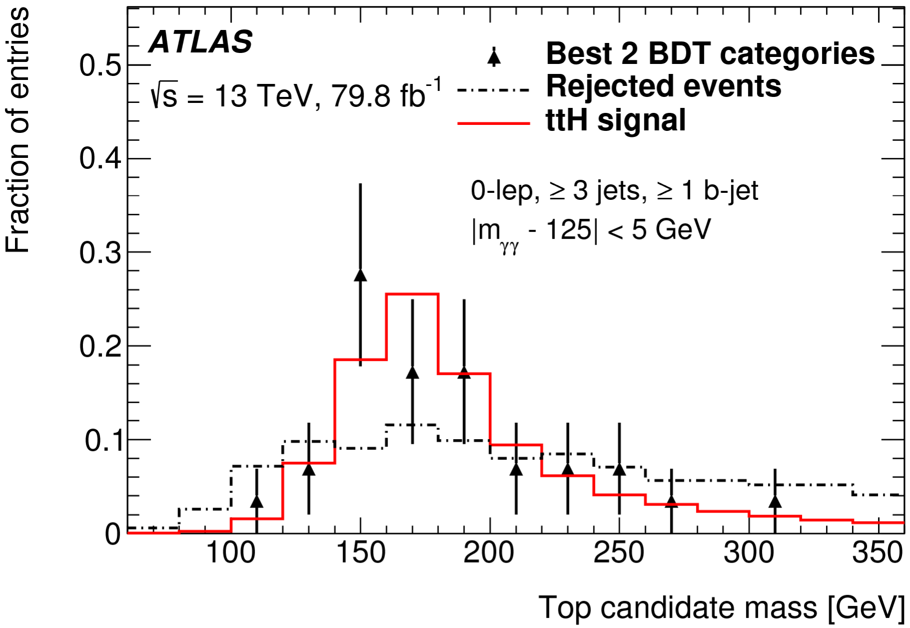
$t\bar{t}H$, $H\rightarrow\gamma\gamma$: event MVA

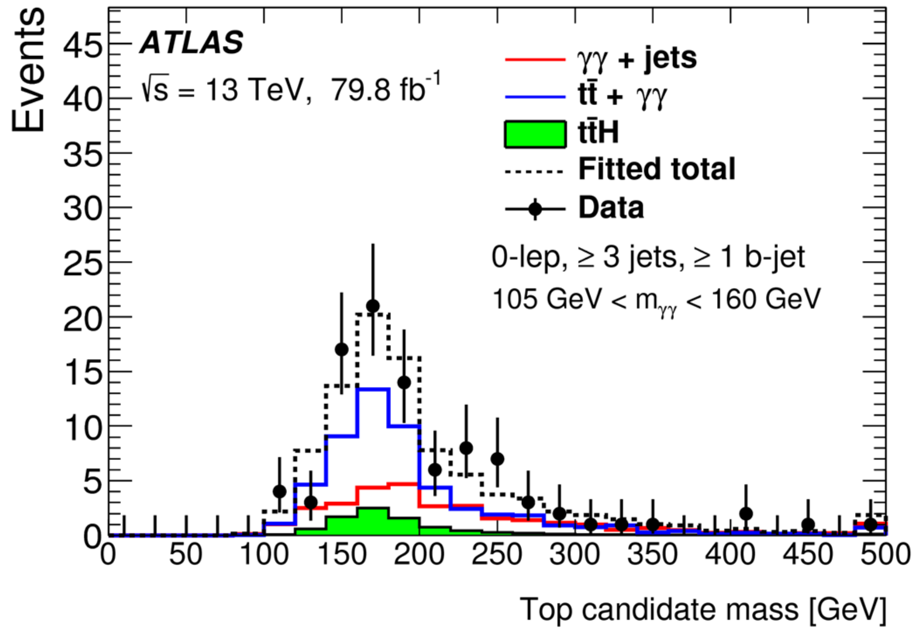


Category label	Selection
ttH lep BDT1	$N_{\rm lep} \geq 1,\ N_{b-{\rm jet}} \geq 1,\ {\rm BDT}_{\rm ttHlep} > 0.987$
ttH lep BDT2	$N_{\rm lep} \geq 1,\ N_{b-{\rm jet}} \geq 1,\ 0.942 < {\rm BDT}_{\rm ttHlep} < 0.987$
ttH lep BDT3	$N_{\rm lep} \geq 1,\ N_{b-{\rm jet}} \geq 1,\ 0.705 < {\rm BDT}_{\rm ttHlep} < 0.942$
ttH had BDT1	$N_{\rm lep} = 0,\ N_{\rm jets} \geq 3,\ N_{b-{\rm jet}} \geq 1,\ {\rm BDT}_{\rm ttHhad} > 0.996$
ttH had BDT2	$N_{\rm lep} = 0,\ N_{\rm jets} \geq 3,\ N_{b-{\rm jet}} \geq 1,\ 0.991 < {\rm BDT}_{\rm ttHhad} < 0.996$
ttH had BDT3	$N_{\rm lep} = 0,\ N_{\rm jets} \geq 3,\ N_{b-{\rm jet}} \geq 1,\ 0.971 < {\rm BDT}_{\rm ttHhad} < 0.991$
ttH had BDT4	$N_{\rm lep} = 0,\ N_{\rm jets} \geq 3,\ N_{b-{\rm jet}} \geq 1,\ 0.911 < {\rm BDT}_{\rm ttHhad} < 0.971$

$t\bar{t}H$, $H\rightarrow\gamma\gamma$: top mass

- ➔ Mass reconstructed from jet triplet selected with dedicated BDT
- ➔ Not used in analysis, for illustration purpose

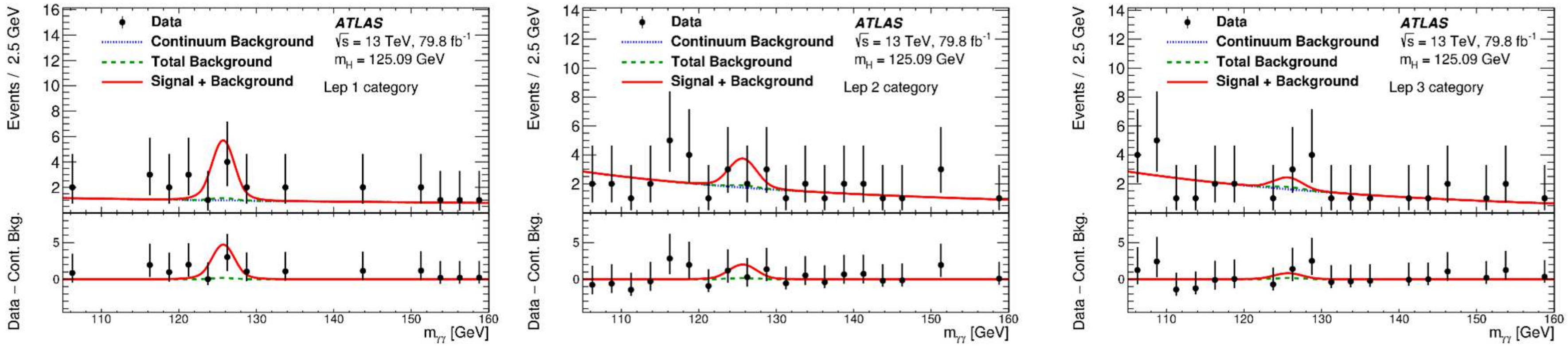




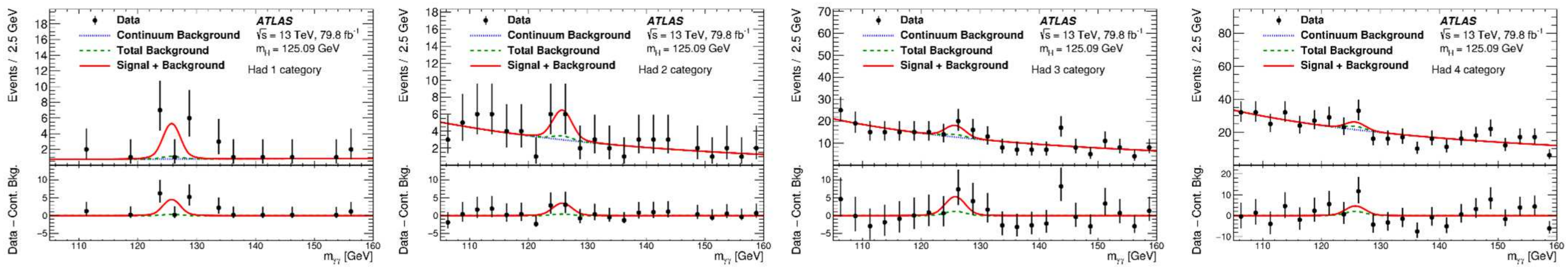
- ➢ Events in the two Had bins with highest S/B, 105 GeV < $m_{\gamma\gamma}$ < 160 GeV
- ➢ MC normalization from fitting top-candidate mass distributions to data (58% $t\bar{t}\gamma\gamma$, 32% $\gamma\gamma$+jets)

$t\bar{t}H$, $H\rightarrow\gamma\gamma$: results

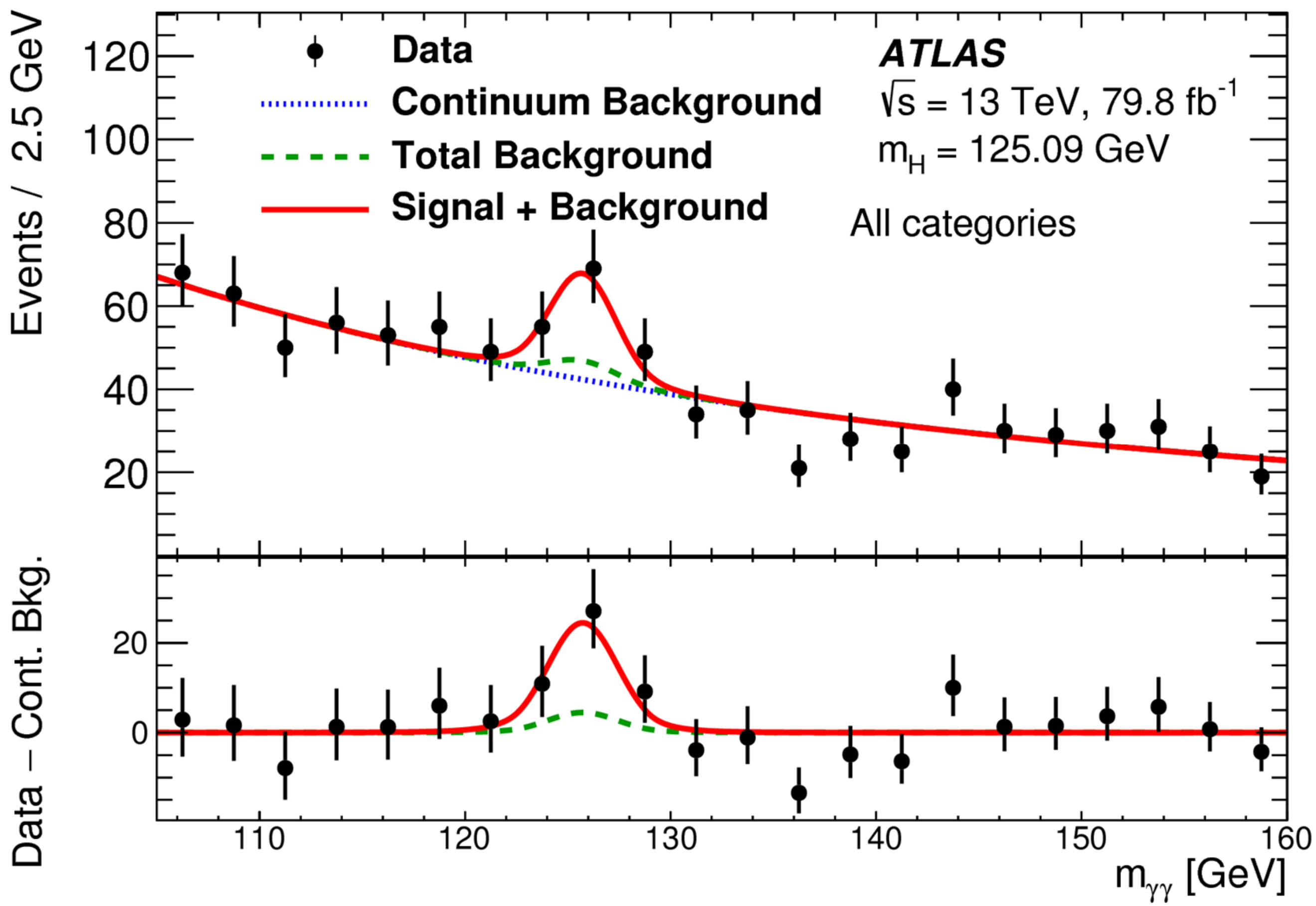
Leptonic categories



Hadronic categories



$t\bar{t}H$, H→γγ: results

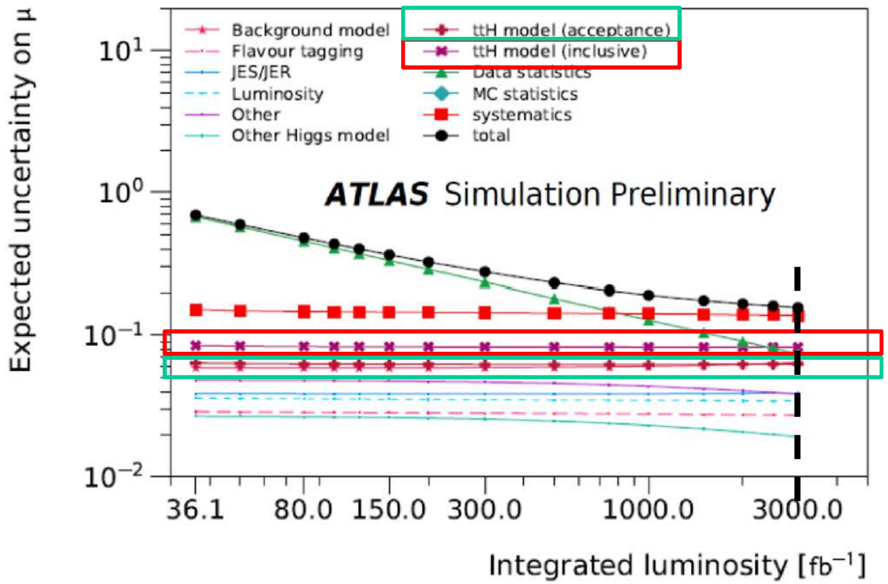


$t\bar{t}H$, H→γγ: HL-LHC

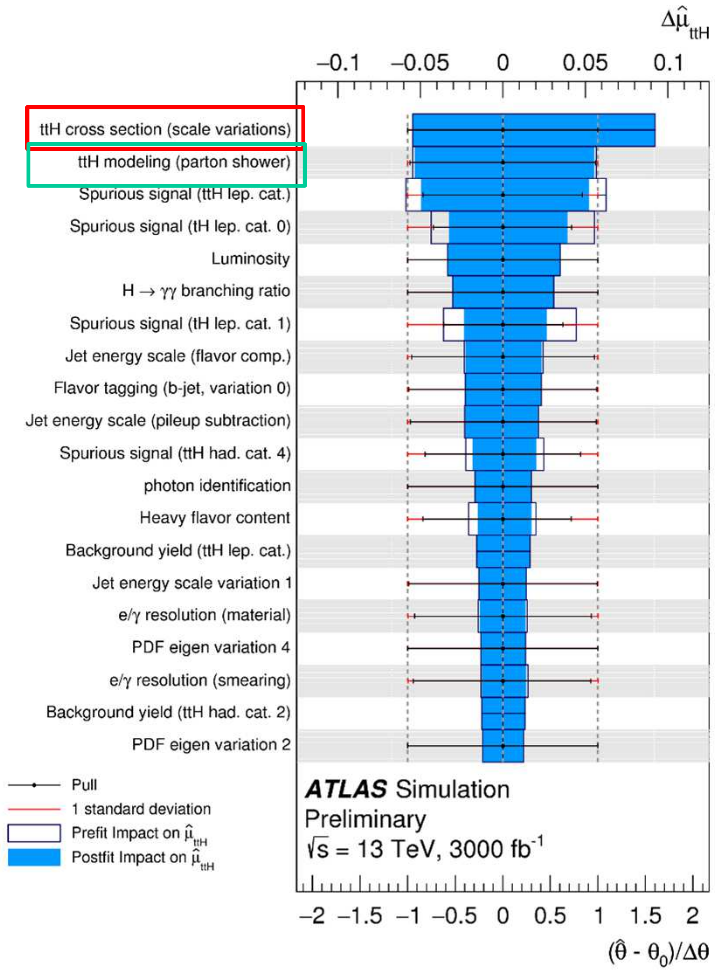
ATLAS-PHYS-PUB-2018-010

$t\bar{t}H$, H→γγ extrapolation at HL-LHC

- Largest signal theory uncertainty (QCD scales, PDF) for $\mu=\sigma/\sigma_{SM}$ related to assumed σ_{SM}
- Large contributions also from signal acceptance (PS modelling) which affects measured σ (main component of "$t\bar{t}H$ model acceptance")
- Experimental uncertainties expected to be reduced with HL-LHC dataset



Results extrapolated from Run-2 36 fb^{-1} analysis

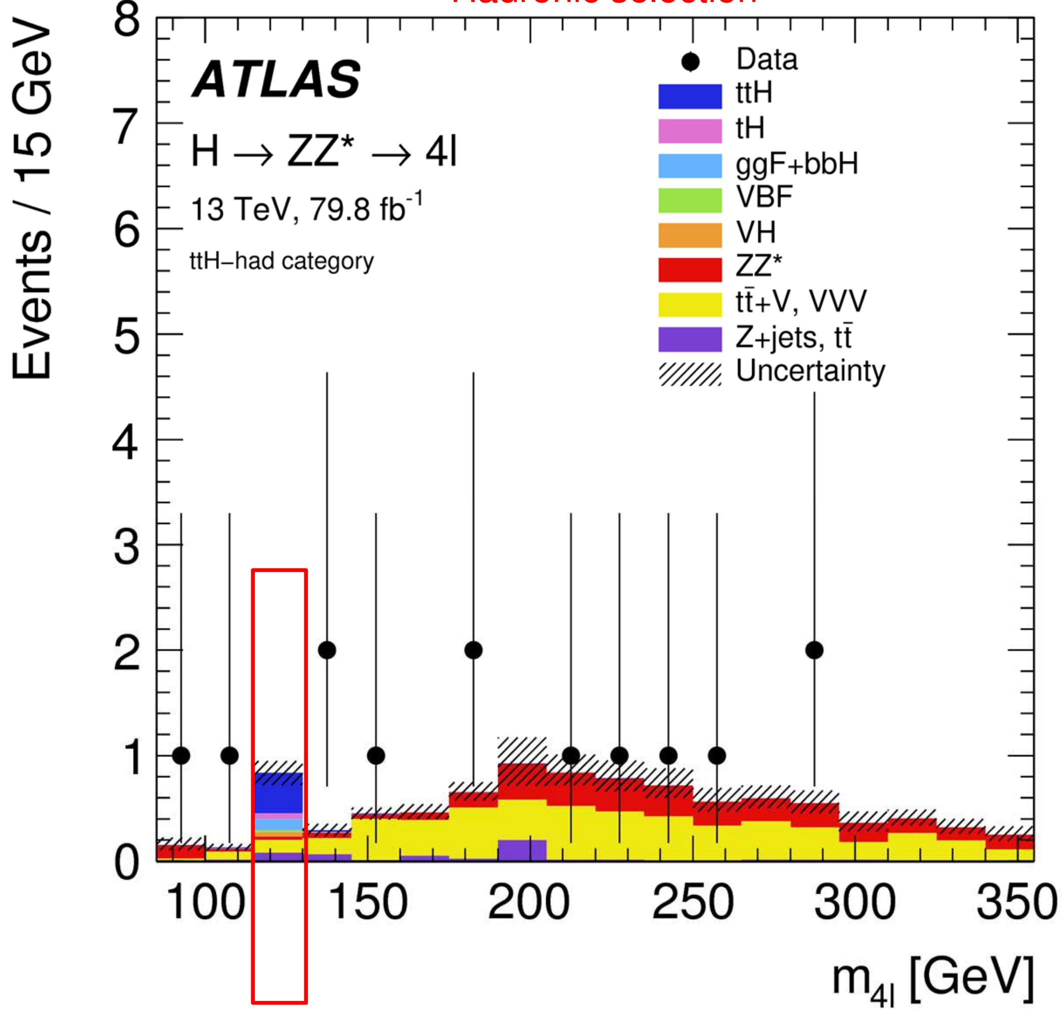


$t\bar{t}H$, $H \rightarrow ZZ^* \rightarrow 4l$ ($l=e,\mu$): event MVA

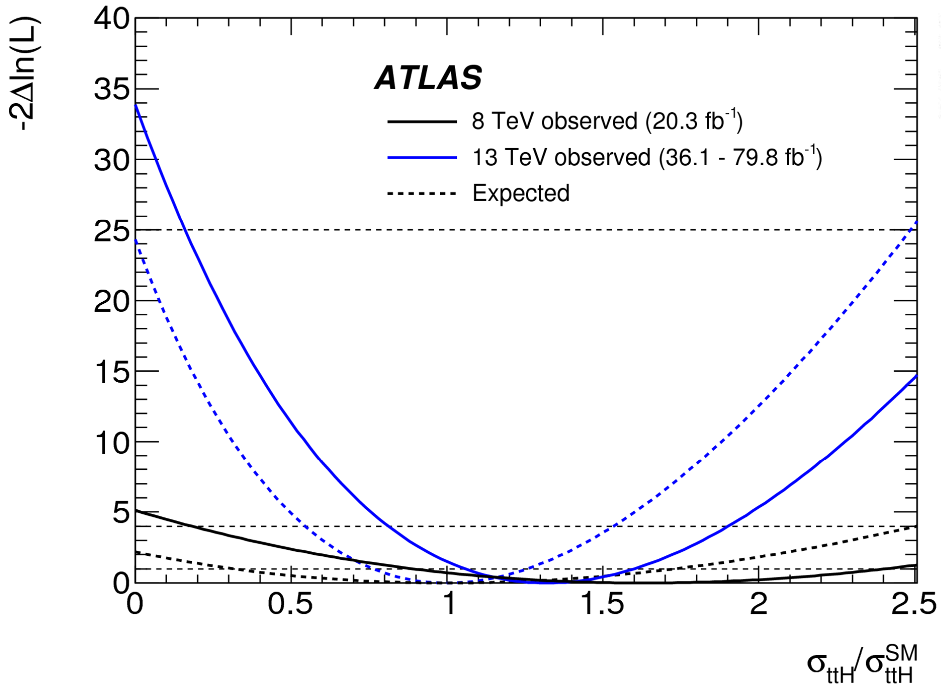
BDT discriminant	Input variables
$\mathrm{BDT}_{ttH\text{-Had}}$	m_{jj}, $\Delta\eta_{jj}$, $\Delta R_{jZ}^{\mathrm{min}}$, $\Delta R(j, 4\ell)$, $\eta_{4\ell}^{*}$, $E_{\mathrm{T}}^{\mathrm{miss}}$, p_{T}^{jj}, N_{jets}, $N_{b-\mathrm{jets}}$, H_{T}, $\mathcal{M}_{sig}$

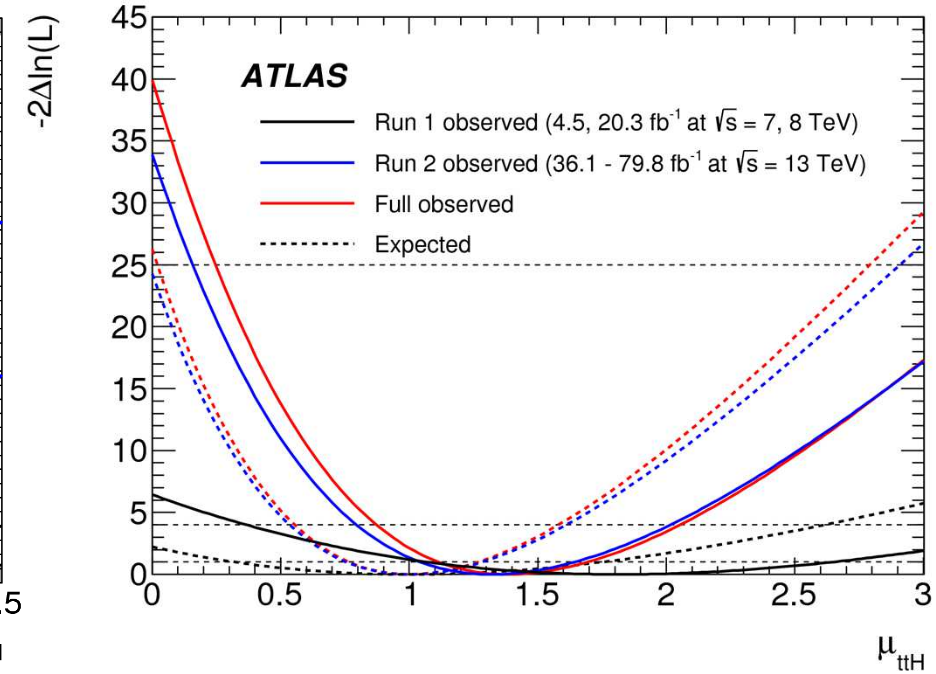
$t\bar{t}H$, $H \rightarrow ZZ^* \rightarrow 4l$ ($l=e,\mu$): results

Hadronic selection



$t\bar{t}H$ combination: results





$t\bar{t}H$ combination: results

13 TeV

Summary of systematic uncertainty sources for the $t\bar{t}H$ combination

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

Top Yukawa coupling

ATLAS-CONF-2018-031

Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (including $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau\tau$	36.1
VH, $H \to b\bar{b}$	36.1
$H \to \mu\mu$	79.8
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1

Parameter	Result
κ_Z	$1.07^{+0.11}_{-0.10}$
κ_W	1.04 ± 0.10
κ_b	$1.00^{+0.24}_{-0.22}$
κ_t	$1.03^{+0.12}_{-0.11}$
κ_τ	$1.04^{+0.17}_{-0.16}$
κ_μ	< 1.63 at 95% CL.

p_{SM}=79%

Parameter	Definition in terms of κ modifiers	Result
κ_{gZ}	$\kappa_g \kappa_Z / \kappa_H$	1.06 ± 0.07
λ_{tg}	κ_t / κ_g	$1.09^{+0.14}_{-0.14}$
λ_{Zg}	κ_Z / κ_g	$1.06^{+0.14}_{-0.13}$
λ_{WZ}	κ_W / κ_Z	$0.99^{+0.09}_{-0.08}$
$\lambda_{\gamma Z}$	κ_γ / κ_Z	$0.95^{+0.08}_{-0.07}$
$\lambda_{\tau Z}$	κ_τ / κ_Z	0.95 ± 0.13
λ_{bZ}	κ_b / κ_Z	$0.91^{+0.17}_{-0.16}$

p_{SM}=86%

κ-framework

ATLAS-CONF-2018-031

Production	Effective modifier	Resolved modifier
σ_{ggF}	κ_g^2	$1.04\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.04\,\kappa_t\kappa_b$
σ_{VBF}	-	$0.73\,\kappa_W^2 + 0.27\,\kappa_Z^2$
$\sigma_{qq/qg \to ZH}$	-	κ_Z^2
$\sigma_{gg \to ZH}$	-	$2.46\,\kappa_Z^2 + 0.46\,\kappa_t^2 - 1.90\,\kappa_Z\kappa_t$
σ_{WH}	-	κ_W^2
$\sigma_{t\bar{t}H}$	-	κ_t^2
σ_{tHW}	-	$2.91\,\kappa_t^2 + 2.31\,\kappa_W^2 - 4.22\,\kappa_t\kappa_W$
σ_{tHq}	-	$2.63\,\kappa_t^2 + 3.58\,\kappa_W^2 - 5.21\,\kappa_t\kappa_W$
$\sigma_{b\bar{b}H}$	-	κ_b^2
Partial decay width	**Effective modifier**	**Resolved modifier**
$\Gamma_{\gamma\gamma}$	κ_γ^2	$1.59\,\kappa_W^2 + 0.07\,\kappa_t^2 - 0.67\,\kappa_W\kappa_t$
Γ_{ZZ}	-	κ_Z^2
Γ_{WW}	-	κ_W^2
$\Gamma_{\tau\tau}$	-	κ_τ^2
Γ_{bb}	-	κ_b^2
$\Gamma_{\mu\mu}$	-	κ_μ^2
Γ_{gg}	κ_g^2	$1.11\,\kappa_t^2 + 0.01\,\kappa_b^2 - 0.12\,\kappa_t\kappa_b$
$\Gamma_{Z\gamma}$	$\kappa_{(Z\gamma)}^2$	$1.12\,\kappa_W^2 - 0.12\,\kappa_W\kappa_t$
Total width	**Efective modifier**	**Resolved modifier**
Γ_H	κ_H^2	$(0.58\,\kappa_b^2 + 0.22\,\kappa_W^2 + 0.08\,\kappa_g^2 + 0.06\,\kappa_\tau^2 + 0.03\,\kappa_Z^2 + 0.03\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2 + 0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2)/(1 - \mathrm{B}_{\mathrm{BSM}})$