Evidence for the $t\bar{t}H$ production at $\sqrt{s} = 13$ TeV with the ATLAS detector

Top LHC France 2018

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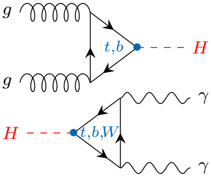
Top quark Yukawa coupling at the LHC

- The Higgs boson with SM properties has been discovered during Run 1 of LHC.
- Interaction with SM particles: top quark Yukawa coupling $\lambda_t = \sqrt{2}m_t/v \approx 1$.

→ Two complementary measurements of λ_t:



1. Indirect measurement: gluon-gluon fusion, $H \to \gamma\gamma$ decay:
   - Contributions enter from top quark loops by λ_t^2.
   - Run 1 ATLAS+CMS combination measured

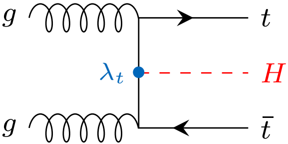
$$\kappa_t = \lambda_t/\lambda_t^{\text{SM}} = 0.87 \pm 0.15 \;(\text{JHEP } \mathbf{1608}\ (2016)\ 045).$$

   - Heavy particles from new physics could contribute to loops.

2. $t\bar{t}H$ production best way for direct measurement:
   - Tree-level process, cross-section proportional to λ_t^2.
   - Run 1 ATLAS+CMS result on signal strength:

$$\mu_{t\bar{t}H} = \sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}^{\text{SM}} = 2.3^{+0.7}_{-0.6},$$

Obs. (exp.) significance of 4.4σ (2.0σ) (JHEP **1608** (2016) 045).

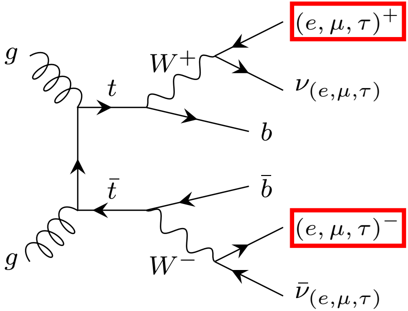


- Any deviation from the SM could indicate new physics.

$t\bar{t}H$ analysis in multileptonic final states

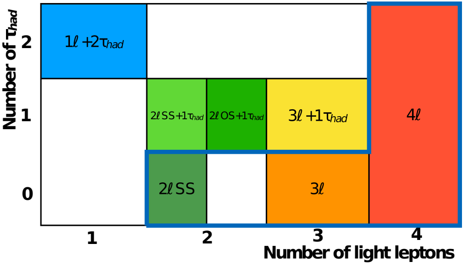
- Use 36.1 fb^{-1} of 13 TeV *p*-*p* collision data from the ATLAS experiment in 2015/16.

- Main background $t\bar{t}$ with $\sigma_{t\bar{t}} = 1600 \times \sigma_{t\bar{t}H}$:



→ Suppressed by requirement of at least two same-sign leptons (SS) or additional leptons.

- 7 orthogonal channels with light leptons ($\ell = e, \mu$) and hadronic taus (τ_{had}):

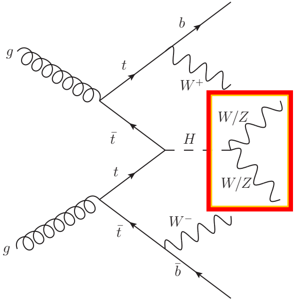


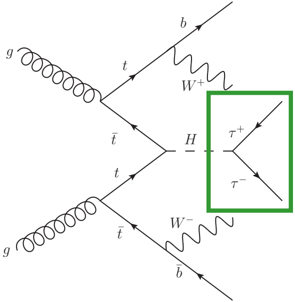
- Jet requirement: $N_{\text{jet}} \geq 2$, $N_{b\text{-tag}} \geq 1$,
  - 2ℓSS, 2ℓSS+$1\tau_{\text{had}}$: $N_{\text{jet}} \geq 4$,
  - 2ℓOS+$1\tau_{\text{had}}$, 1ℓ+$2\tau_{\text{had}}$: $N_{\text{jet}} \geq 3$.

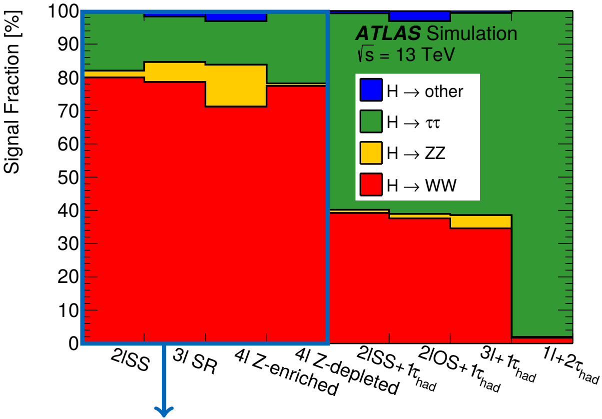
→ Reject backgrounds with low N_{jet}.

- Rich channel variety with *e*, μ, τ_{had}, (*b*-tagged) jets and $E_{\text{T}}^{\text{miss}}$ (from ν).

Higgs boson decays in $t\bar{t}H$ signal



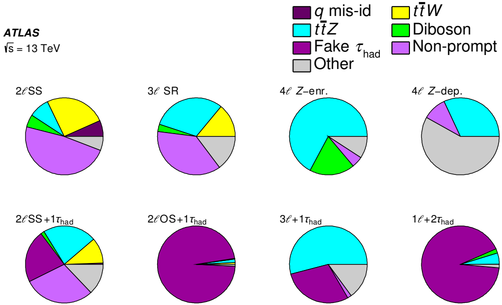




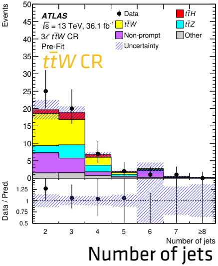
- Light-lepton channels target mainly $H \rightarrow WW^*$.
- Channels with τ_{had} more sensitive to $H \rightarrow \tau\tau$.
- Have eight signal regions (SRs) with different signal event topologies.

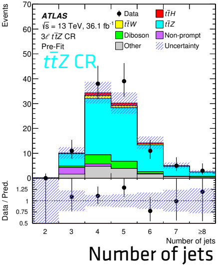
Backgrounds

- Different background composition in SRs:



1. Prompt lepton backgrounds:
   - estimated from Monte Carlo (MC),
   - validated in 3ℓ CRs:





2. Reducible backgrounds:
   - Non-prompt light leptons: from b-hadron decays ($t\bar{t}$) and photon conversions,
   - Electron charge mis-identification (q mis-id): from 2ℓOS $t\bar{t}$ events,
   - Fake τ_{had}: from light flavour jets and mis-identified electrons.

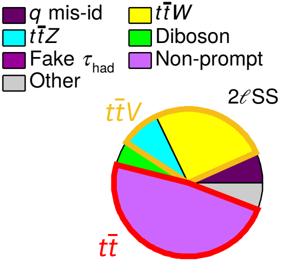
   → Reduced by boosted decision trees (BDTs) using isolation, track & b-tagging variables.

   → Estimated with different data-driven techniques.

- Robust estimate of background yields and shapes is critical for the analysis.

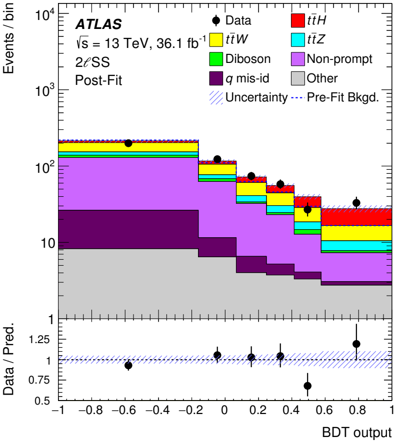
Example: Event BDTs in 2ℓSS channel

- In 2ℓSS channel the dominant backgrounds are $t\bar{t}V$ and $t\bar{t}$ (non-prompt ℓ):



→ Use two independent event BDTs $t\bar{t}H$ vs. $t\bar{t}V$ and vs. $t\bar{t}$ with input variables:

- lepton properties,
- jet and b-tagged jet multiplicities,
- angular distances
- and missing transverse momentum.

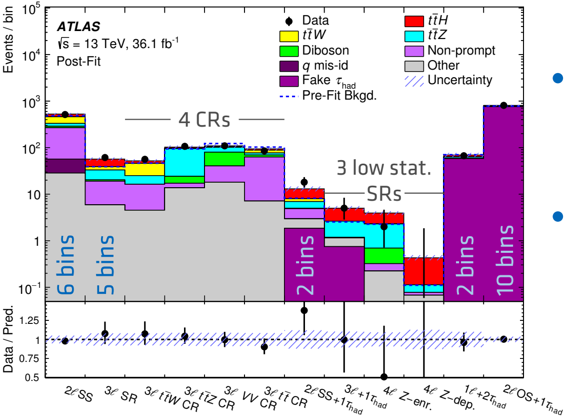


→ Data agrees well with prediction.

- In 6 of 7 channels event BDTs are used for best signal-background separation.

Fit set-up

- Parameter of interest (POI) is the $t\bar{t}H$ signal strength $\mu_{t\bar{t}H} = \sigma_{t\bar{t}H}/\sigma^{\mathrm{SM}}_{t\bar{t}H}$.
- Nuisance parameters (NPs) for systematic and statistical uncertainties θ_i.
- Binned maximum-likelihood fit is performed in 8 SRs + 4 CRs simultaneously:



- Fit BDT shape in 5 SRs and single event counts in 3ℓ CRs and SRs with low statistics.

  → in total 32 bins.

- Test statistic

  $$q_\mu = -2\ln\frac{\mathfrak{L}(\mu,\hat{\hat{\boldsymbol{\theta}}}_\mu)}{\mathfrak{L}(\hat{\mu},\hat{\boldsymbol{\theta}})},$$

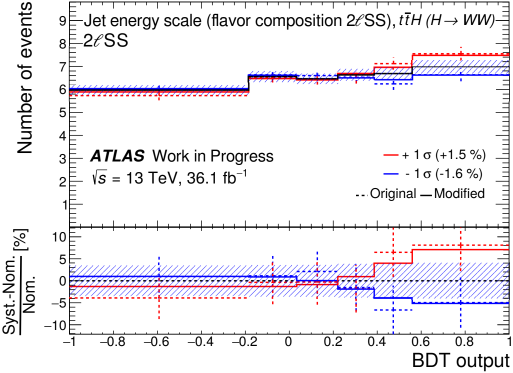
  $\hat{\mu}, \hat{\boldsymbol{\theta}}$: maximise likelihood $\mathfrak{L}$,

  $\hat{\hat{\boldsymbol{\theta}}}_\mu$: maximises $\mathfrak{L}$ for given μ.

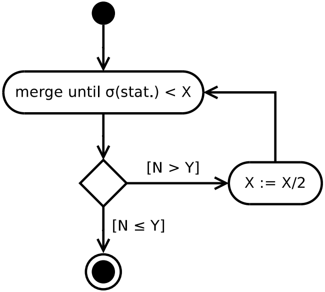
- All systematics have been studied in single channels and in combination.

Smoothing of NP shapes

- NP with norm (here $^{+1.5}_{-1.6}$%) and shape (here up to $^{+7.0}_{-5.1}$%):



Smoothing procedure:


merge until σ(stat.) < X

[N > Y]

X := X/2

[N ≤ Y]

- To reduce statistical fluctuations in estimate templates NP shapes smoothing:
  1. Merge bins with statistical uncertainty σ(stat.) $>$ X $=$ 8%.
  2. Iteratively reduce number of derivative changes N until N $\leq$ Y $=$ 4.
- All NP shapes are smoothed in $t\bar{t}H \to$ multilepton analysis.

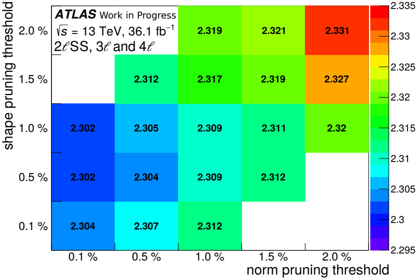
Dropping of NP shapes and normalisation

- Systematics model with 315 NPs very computationally intensive.

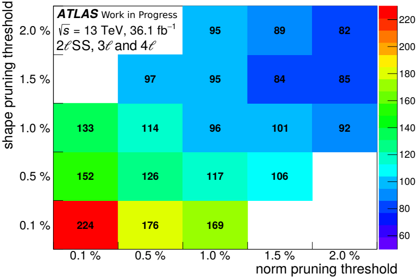
→ Drop NPs with little impact on sensitivity.

- Fit to Asimov data (simulated data with $\mu_{t\bar{t}H} = 1$) in no-τ_{had} channels:

Signal significance [σ]



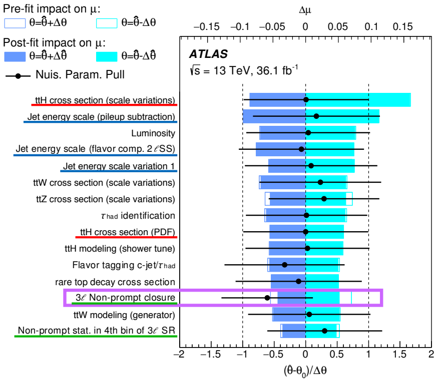
Fitting Time [s]



- Optimal at both shape and norm dropping threshold of 1%:
  - Fitting time < 100 seconds,
  - Stable signal significance at lower thresholds,
  - Kept 230 NPs (+32 NPs for MC statistics).
- All NP norms and shapes dropped if their size $<$ 1%.

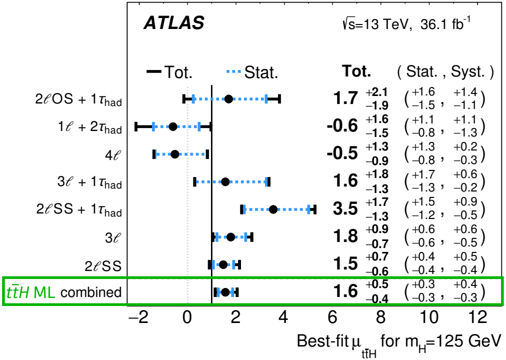
Major uncertainties and NP ranking

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



- Systematic uncertainties with largest impact on errors on $\mu_{t\bar{t}H}$ are
  - $t\bar{t}H$ cross section uncertainty → theory,
  - Jet energy scale (JES) and resolution,
  - Non-prompt light lepton estimates → large contribution of CR statistics.
- No nuisance parameters pulls and constraints apart from
  - Small pull (0.5σ) in 3ℓ Non-prompt estimate closure uncertainty → deficit in 3ℓ $t\bar{t}$ CR.
- Bahaviour of all uncertainties in the fit is well understood.

Results

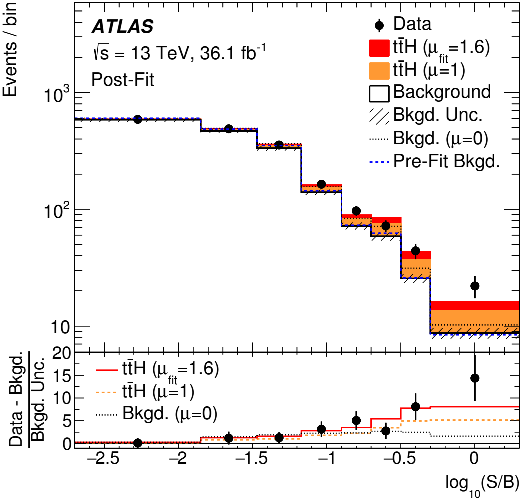


significance obs. (exp.)
0.9σ (0.5σ)
– (0.6σ)
– (0.8σ)
1.3σ (0.9σ)
3.4σ (1.1σ)
2.4σ (1.5σ)
2.7σ (1.9σ)
4.1σ (2.8σ)

- All results are compatible with each other and with SM expectation of $\mu_{t\bar{t}H} = 1$.
- Best-fit signal strength $\mu_{t\bar{t}H} = 1.6^{+0.5}_{-0.4}$, obs. (exp.) significance: 4.1σ (2.8σ).
- Cross-section $\sigma_{t\bar{t}H} = 790^{+230}_{-210}$ fb (expected: 507^{+35}_{-50} fb).

Event yields as a function of $\log(S/B)$

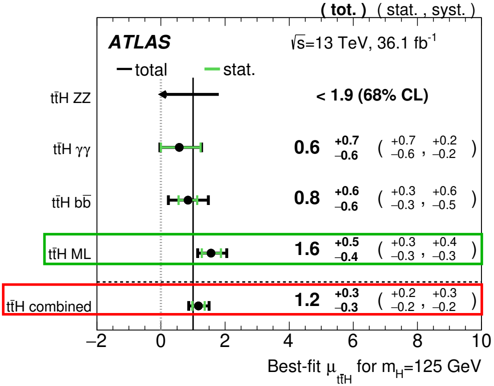
- All SR bins combined into bins of $\log_{10}(S/B)$:



- Background B at fitted yield.
- Signal S expected signal at $\mu_{t\bar{t}H} = 1$ and 1.6.
- No significant change from pre- to post-fit background → few NP pulls.
- Data prefers $\mu_{t\bar{t}H} = 1.6$.
- Background-only fit ($\mu_{t\bar{t}H} = 0$) does not reflect data well.

Combination with other searches for $t\bar{t}H$ in ATLAS

- Search for $t\bar{t}H \rightarrow$ multilepton has major impact on combination results:

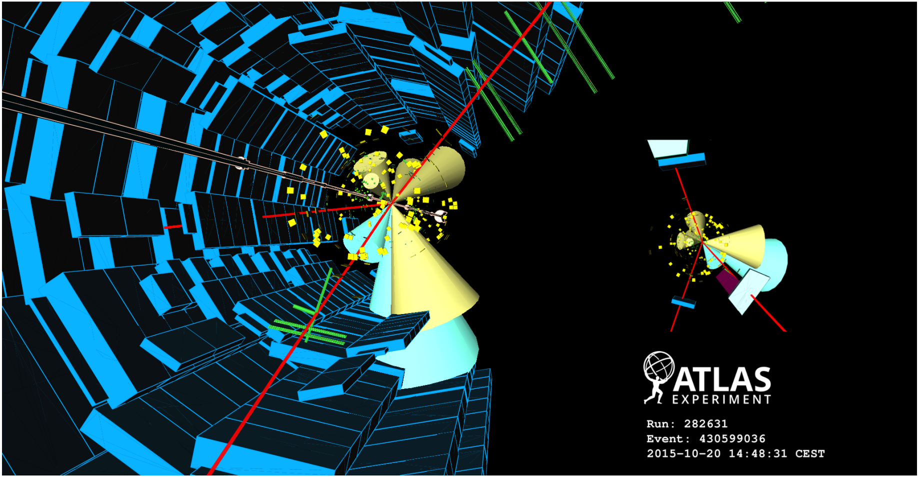


- Combined best-fit value: $\mu_{t\bar{t}H} = 1.2 \pm 0.3$, significance: 4.2σ (expected: 3.8σ).

$\rightarrow$ Evidence for $t\bar{t}H$ production with 13 TeV data!

- Paper published: Phys. Rev. D **97** (2018) 072003, arXiv: `1712.08891`.

3ℓ signal event candidate as seen by the ATLAS



→ 3μ event with 2 *b*-tagged and 5 non-*b*-tagged jets (ATLAS-CONF-2016-058)

What's next?

Re-interpretation of $t\bar{t}H \rightarrow$ multilepton results with 36.1 fb^{-1}

- Search for FCNC $t \rightarrow Hq$ signal published (arXiv: 1805.03483, talk by Daniel F.) with best observed (expected) 95% CL limits to date (SM expectation $\sim 10^{-15}$):

$$\mathfrak{B}(t \rightarrow Hu) < 0.19\ (0.15)\%,\ \mathfrak{B}(t \rightarrow Hc) < 0.16\ (0.15)\%.$$

$t\bar{t}H \rightarrow$ multilepton analysis prospects

- Currently studying 80 fb^{-1} of 2015–2017 data.
- At the end of Run 2, expect $\sim 4\sigma$ significance (currently 2.8σ) for 150 fb^{-1}.
  - Own extrapolation with same systematic uncertainties as current analysis.
  - Expect errors on $\mu_{t\bar{t}H}$ to be dominated by systematics → improvement possible.
  - Large contribution of non-prompt CR statistics should reduce with more data.
  - Increased pile-up may worsen sensitivity (high ranked JES pile-up subtraction)

$t\bar{t}H$ combination prospects

- Expect discovery of $t\bar{t}H$ production at $\sqrt{s} = 13$ TeV with Run 2 data.

→ Expect $\sim$ 10% precision on direct measurement of top Yukawa coupling.

  - CMS published observation in Run 1+2, (25+36) fb^{-1} combination (arXiv: 1804.02610).

→ Stay tuned!

Backup

Backup: Object reconstruction and overlap removal

- Triggers: Lowest unprescaled single- and dilepton trigger chains

- Standard objects:
  - Jets from anti-k_t algorithm with $R = 0.4$, b-tagging with MV2c10 algorithm at 70 % efficiency.
  - Loose and tight leptons (see table).
  - Hadronic decaying taus with medium tau ID.

(L=loose, L†=loose+isolated, L*=L†+passing X, T=tight, T*=very tight)

	e					μ		
	L	L†	L*	T	T*	L	L†	L*/T/T*
Isolation	No	Yes				No	Yes	
Non-prompt lepton BDT	No		Yes			No		Yes
Identification	Loose			Tight		Loose		
Charge mis-assignment BDT	No				Yes	No		
Tranverse impact parameter significance $\|d_0\|/\sigma_{d_0}$	$< 5\sigma$					$< 3\sigma$		
Longitudinal impact parameter $\|z_0 \sin\theta\|$	< 0.5 mm							

- Multivariate algorithms for reduction of reducible backgrounds:
  - Charge mis-assignment veto: 14× background rejection for 95 % signal efficiency,
  - Non-prompt lepton MVA: identify non-prompt light leptons using lifetime information associated with a track jet from track impact parameters.

- Overlap removal:

Keep	Remove	Cone size (Δ R)
electron	electron (low p_T)	0.1
muon	electron	0.1
electron	jet	0.3
jet	muon	min(0.4, $0.04 + 10[\text{GeV}]/p_T$(muon))
electron	tau	0.2
muon	tau	0.2
tau	jet	0.3

Backup: Event selection in the signal regions

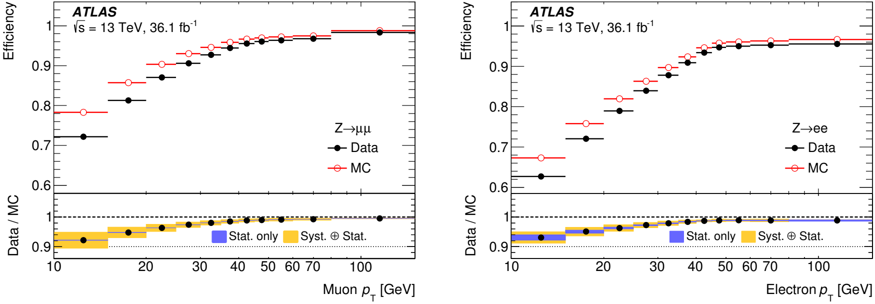
Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
2ℓSS	Two very tight light leptons with $p_{\text{T}} > 20$ GeV Same-charge light leptons Zero medium τ_{had} candidates $N_{\text{jets}} \geq 4$ and $N_{b\text{-jets}} < 3$
3ℓ	Three light leptons with $p_{\text{T}} > 10$ 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)
$1\ell + 2\tau_{\text{had}}$	One tight light lepton with $p_{\text{T}} > 27$ GeV Two medium τ_{had} candidates of opposite charge, at least one being tight $N_{\text{jets}} \geq 3$
$2\ell\text{SS} + 1\tau_{\text{had}}$	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
$2\ell\text{OS} + 1\tau_{\text{had}}$	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 $N_{\text{jets}} \geq 3$
$3\ell + 1\tau_{\text{had}}$	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

Backup: Event selection in non-prompt ℓ and fake τ_{had} CRs

Channel	Region	Selection criteria
2ℓSS		$2 \leq N_{\text{jets}} \leq 3$ 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
2ℓSS+$1\tau_{\text{had}}$		$2 \leq N_{\text{jets}} \leq 3$ 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
1ℓ+$2\tau_{\text{had}}$		$N_{\text{jets}} \geq 3$ 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
2ℓOS+$1\tau_{\text{had}}$		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 $N_{b\text{-jets}} = 0$

Backup: Non-prompt light lepton BDT

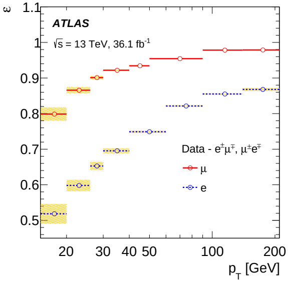
- To further reject non-prompt leptons from *b*-hadron decays, a cut on lepton BDT discriminant is required, achieving rejection factor of 20 with high prompt lepton efficiencies. → bottom plots.
- Sensitive variables: angular distance between leptons and jet, b-tagging algorithm output, lepton isolation, number of tracks in jet and ratio between lepton p_T and jet p_T.
- The efficiency for prompt leptons are measured in data using *Z*-decays events. The corrections to MC (scale factors) are at most 10 % at low p_T → ratio plots.



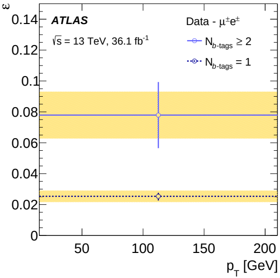
Backup: Non-prompt light lepton estimate in 2ℓSS & 3ℓ (1)

- "Matrix-method" predicts non-prompt 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 is 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 $\Delta R(\mu, \text{jet})$ is measured in low-N_jet non-prompt lepton control region (2ℓSS, [2,3] jets, $N_{b\text{-tag}} \geq 1$)

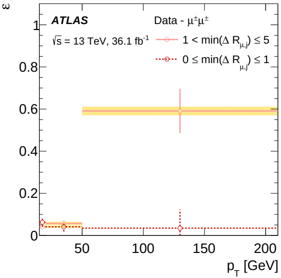
ε_real



ε_fake (electrons)



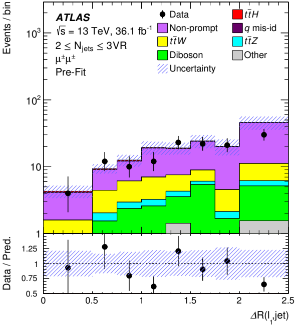
ε_fake (muons)

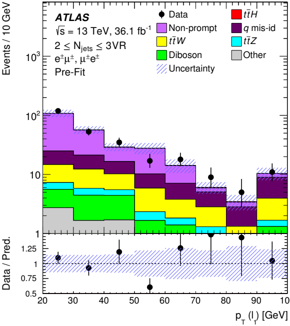


$$\varepsilon_\text{fake} = \frac{N^\text{tight}_\text{data} - N^\text{tight}_{q\ \text{mis-id (data)}} - N^\text{tight}_\text{prompt (MC)}}{N^\text{loose}_\text{data} - N^\text{loose}_{q\ \text{mis-id (MC)}} - N^\text{loose}_\text{prompt (MC)}},\ q\ \text{mis-id subtraction for}\ e^\pm.$$

Backup: Non-prompt light lepton estimate in 2ℓSS & 3ℓ (2)

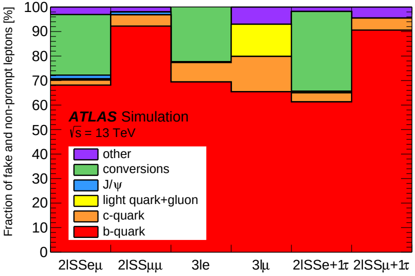
- Closure test for matrix method whole procedure is performed on $t\bar{t}$ simulated samples.
  → Non-closure is taken as one source of systematics:
  11 ± 8 % (2ℓSS) and 9 ± 18 % (3ℓ).
- The non-prompt lepton estimates has been validated in various control regions (close to SR but orthogonal to SR in N_{jet} requirement).



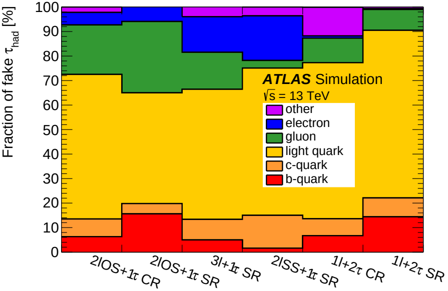


Backup: Non-prompt ℓ and fake τ_{had} composition

Non-prompt light lepton composition

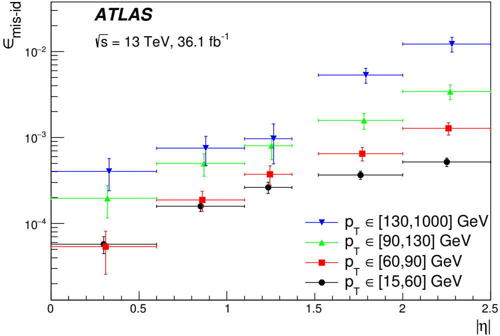


Fake τ_{had} composition



Backup: Charge mis-assignment background estimate

- Electron charge flips in $t\bar{t}$ and Z+jets processes pollute 2ℓSS events.
- Electron charge flip rates vs p_T and $|\eta|$ are measured from OS/SS electron pairs from Z decays $\rightarrow$ electron charge flip background is extracted from OS data after applying rates.



- The total systematic uncertainty of this background estimates is about 30 %, with the dominant contribution at low p_T from method non-closure and at high p_T from limited statistics of $Z \rightarrow ee$ events.

Backup: Systematics – Nuisance parameters (1)

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
$E_{\text{T}}^{\text{miss}}$	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

Backup: Systematics – Nuisance parameters (2)

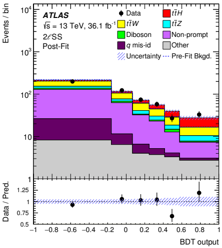
$t\bar{t}H$ **modeling**		
Cross section	N	2
Renormalization and factorization scales	S	3
Parton shower and hadronization model	SN	1
Higgs boson branching fraction	N	4
Shower tune	SN	1
$t\bar{t}W$ **modeling**		
Cross section	N	2
Renormalization and factorization scales	S	3
Matrix-element MC event generator	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

Backup: Signal and background yields, pre- and post-fit

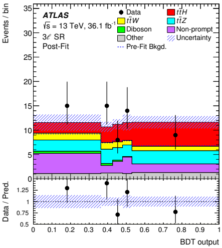
Category	Non-prompt	Fake τ_{had}	q mis-id	$t\bar{t}W$	$t\bar{t}Z$	Diboson	Other	Total Bkgd.	$t\bar{t}H$	Observed
					Pre-fit yields					
2ℓSS	233 ± 39	–	33 ± 11	123 ± 18	41.4 ± 5.6	25 ± 15	28.4 ± 5.9	484 ± 38	42.6 ± 4.2	514
3ℓ SR	14.5 ± 4.3	–	–	5.5 ± 1.2	12.0 ± 1.8	1.2 ± 1.2	5.8 ± 1.4	39.1 ± 5.2	11.2 ± 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+$2\tau_{\text{had}}$	–	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+$1\tau_{\text{had}}$	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+$1\tau_{\text{had}}$	–	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+$1\tau_{\text{had}}$	–	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+$2\tau_{\text{had}}$	–	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+$1\tau_{\text{had}}$	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+$1\tau_{\text{had}}$	–	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+$1\tau_{\text{had}}$	–	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

Backup: Signal region BDT distributions

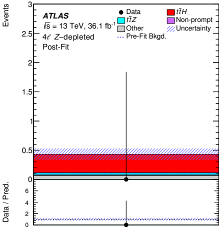
2ℓSS



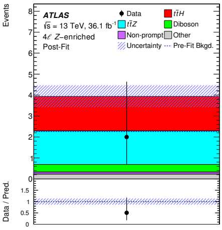
3ℓ



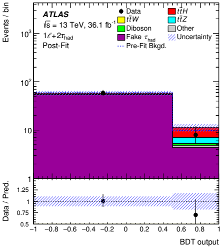
4ℓ Z-depleted



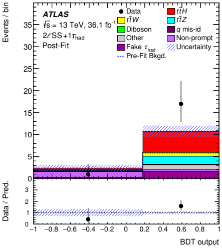
4ℓ Z-enriched



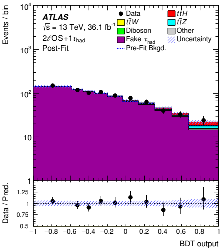
$1\ell+2\tau_{\mathrm{had}}$



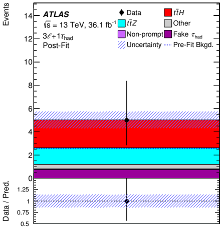
2ℓSS$+1\tau_{\mathrm{had}}$



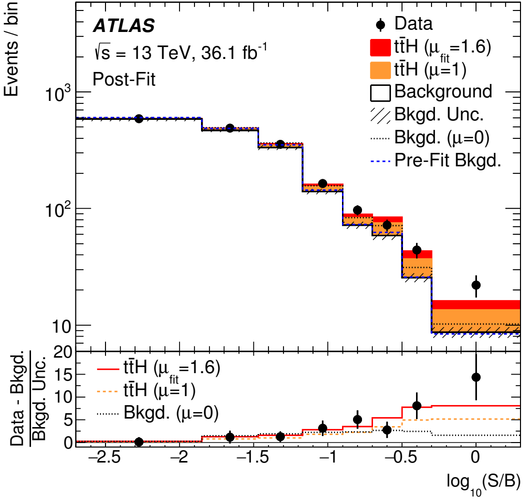
2ℓOS$+1\tau_{\mathrm{had}}$



$3\ell+1\tau_{\mathrm{had}}$



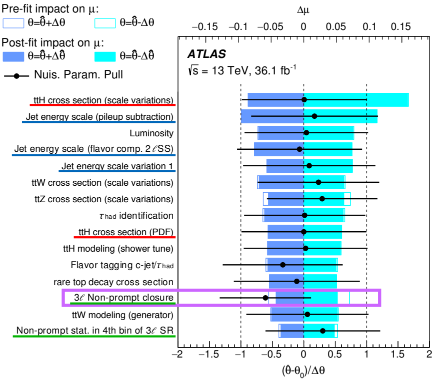
Backup: Event yields as a function of $\log(S/B)$



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

Backup: Major uncertainties and NP ranking

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



- Systematic uncertainties with largest impact on errors on $\mu_{t\bar{t}H}$ are
  - $t\bar{t}H$ cross section uncertainty → theory,
  - Jet energy scale and resolution,
  - Non-prompt light lepton estimates → large contribution of CR statistics.
- No nuisance parameters pulls and constraints apart from 3ℓ Non-prompt estimate closure uncertainty → deficit in 3ℓ $t\bar{t}$ CR.
- All uncertainties well controlled.

Backup: $t\bar{t}H$ combination with other channels

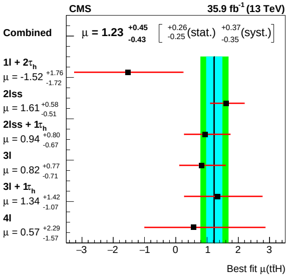
Channel	Best-fit μ		Significance	
	Observed	Expected	Observed	Expected
Multilepton	$1.6\ ^{+0.5}_{-0.4}$	$1.0\ ^{+0.4}_{-0.4}$	4.1σ	2.8σ
$H \rightarrow b\bar{b}$	$0.8\ ^{+0.6}_{-0.6}$	$1.0\ ^{+0.6}_{-0.6}$	1.4σ	1.6σ
$H \rightarrow \gamma\gamma$	$0.6\ ^{+0.7}_{-0.6}$	$1.0\ ^{+0.8}_{-0.6}$	0.9σ	1.7σ
$H \rightarrow 4\ell$	< 1.9	$1.0\ ^{+3.2}_{-1.0}$	—	0.6σ
Combined	$1.2\ ^{+0.3}_{-0.3}$	$1.0\ ^{+0.3}_{-0.3}$	4.2σ	3.8σ

Uncertainty Source	$\Delta\mu$	
$t\bar{t}$ modeling in $H \rightarrow b\bar{b}$ analysis	$+0.15$	-0.14
$t\bar{t}H$ modeling (cross section)	$+0.13$	-0.06
Non-prompt light-lepton and fake τ_{had} estimates	$+0.09$	-0.09
Simulation statistics	$+0.08$	-0.08
Jet energy scale and resolution	$+0.08$	-0.07
$t\bar{t}V$ modeling	$+0.07$	-0.07
$t\bar{t}H$ modeling (acceptance)	$+0.07$	-0.04
Other non-Higgs boson backgrounds	$+0.06$	-0.05
Other experimental uncertainties	$+0.05$	-0.05
Luminosity	$+0.05$	-0.04
Jet flavor tagging	$+0.03$	-0.02
Modeling of other Higgs boson production modes	$+0.01$	-0.01
Total systematic uncertainty	$+0.27$	-0.23
Statistical uncertainty	$+0.19$	-0.19
Total uncertainty	$+0.34$	-0.30

Backup: $t\bar{t}H \rightarrow$ multilepton analysis in CMS, 2015/16 data

- $t\bar{t}H \rightarrow$ multilepton analysis from CMS with 2015/16 data submitted to JHEP, arXiv: 1803.05485.

$\rightarrow$ Six channels, observed (expected) significance of 3.2σ (2.8σ).



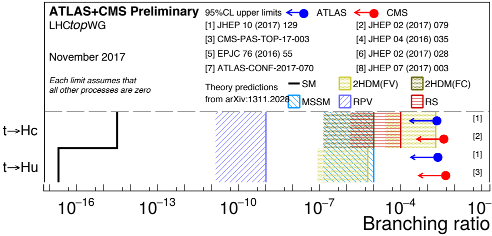
Source	Uncertainty [%]	$\Delta\mu/\mu$ [%]
e, μ selection efficiency	2–4	11
τ_h selection efficiency	5	4.5
b tagging efficiency	2–15 [**?**]	6
Reducible background estimate	10–40	11
Jet energy calibration	2–15 [**?**]	5
τ_h energy calibration	3	1
Theoretical sources	$\approx$10	12
Integrated luminosity	2.5	5

Backup: Monte Carlo samples, $t\bar{t}H \rightarrow$ multilepton (ATLAS)

Process	Event generator	ME order	Parton Shower	PDF	Tune
$t\bar{t}H$	MG5_aMC (MG5_aMC)	NLO (NLO)	Pythia 8 (Herwig++)	NNPDF 3.0 NLO [71] (CT10 [72])	A14 (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 (Sherpa 2.1.1)	NLO (LO multileg)	Pythia 8 (Sherpa)	NNPDF 3.0 NLO (NNPDF 3.0 NLO)	A14 (Sherpa default)
$t\bar{t}(Z/\gamma^* \rightarrow ll)$	MG5_aMC (Sherpa 2.1.1)	NLO (LO multileg)	Pythia 8 (Sherpa)	NNPDF 3.0 NLO (NNPDF 3.0 NLO)	A14 (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
$VV(\rightarrow llXX)$, $qqVV$, VVV	Sherpa 2.1.1	MEPS NLO	Sherpa	CT10	Sherpa default
$Z \rightarrow l^+l^-$	Sherpa 2.2.1	MEPS NLO	Sherpa	NNPDF 3.0 NLO	Sherpa default

Backup: FCNC $t \to Hq \to$ multilepton ($q = u, c$)

- Flavour-changing neutral currents (FCNC) are forbidden at tree level, strongly suppressed in SM: $\mathcal{B}(t \to Hc) \sim 10^{-15}$ (full plot).



- Large enhancements possible in some BSM scenarios up to $\mathcal{B}(t \to Hc) = 0.1\,\%$.
- Search for FCNC in $t\bar{t}$ decays, cross section $\sigma = 2 \cdot \sigma_{t\bar{t}} \cdot \mathcal{B} \cdot (1 - \mathcal{B})$.
- 95 % CL. obs.(exp.) upper limits on $\mathcal{B}$ (ATLAS, Run 1):

$$\mathcal{B}(t \to Hu) < 0.45(0.29)\,\% \textbf{ and } \mathcal{B}(t \to Hc) < 0.46(0.25)\,\%.$$

- Many Higgs decays possible and studied in ATLAS, Run 2:
  - $H \to \gamma\gamma$: $\mathcal{B}(t \to Hc) < 0.22(0.16)\,\%$ (paper: JHEP **10** (2017) 129),
  - $H \to WW^*, ZZ^*, \tau_{\text{lep}}\tau_{\text{lep}}$ (this paper),
- Decay chain for $H \to WW^*$:

$$t\bar{t} \to WbHq \to 3W + b + q$$

$$\to 4\,\text{jets (inc. } 1b) + 2\ell\text{SS} + E_{\text{T}}^{\text{miss}} \textbf{ or } 2\,\text{jets (inc. } 1b) + 3\ell + E_{\text{T}}^{\text{miss}}$$

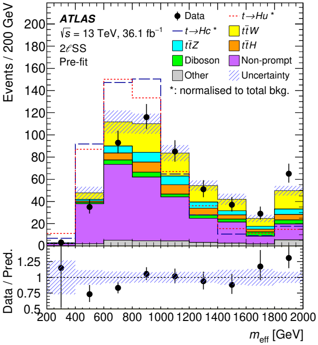
Backup: FCNC – Analysis strategy

- This analysis considers two final states: 2ℓSS and 3ℓ, $N_{b\text{-tag}} \geq 1$.
- Non-prompt lepton background is estimated in 2ℓSS CR with $N_{\text{jet}} = 2, 3$

$\rightarrow$ Use $N_{\text{jet}} \geq 4$ in 2ℓSS and $N_{\text{jet}} \geq 2$ in 3ℓ.

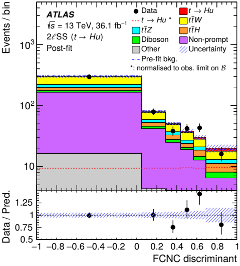
- Have similar pre-MVA regions as in $t\bar{t}H \rightarrow$ multilepton analysis (1712.08891)
  $\rightarrow$ Take advantage of the developments with 36.1 fb^{-1}:
  - Non-prompt lepton BDT to reject non-prompt lepton background,
  - Matrix method non-prompt lepton estimate,
  - Fit set-up, etc.

- Use two event BDTs in 2ℓSS and 3ℓ channel of FCNC signal against:
  - $t\bar{t}V$ and non-prompt lepton background,
  - Optimized 1D discriminant combining the two BDTs.
- Non-negligible signal contamination in non-prompt lepton efficiency control region treated fully correlated with measured $\mathcal{B}$.

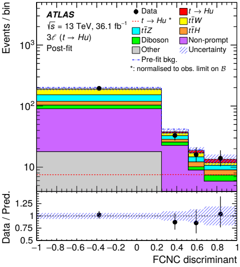


Backup: FCNC – Results

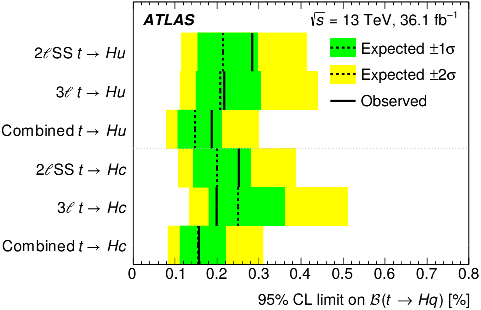
2ℓSS $(t \to Hu)$



3ℓ $(t \to Hu)$



- Measure $\mathcal{B}(t \to Hu)$ and $\mathcal{B}(t \to Hc)$ separately.
- The best-fit values of the branching ratio are $\mathcal{B}(t \to Hu) = 0.04^{+0.08}_{-0.07}$ % & $\mathcal{B}(t \to Hc) = -0.01^{+0.08}_{-0.08}$ %, compatible with the no-signal (SM) hypothesis.
- 95 % CL observed (expected) upper limits on $\mathcal{B}$ are 0.19 % (0.15 %) for $t \to Hu$ and 0.16 % (0.15 %) for $t \to Hc$:



- Similar expected limits as in $t \to Hq$, $H \to \gamma\gamma$ analysis.