

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

53rd Rencontres de Moriond – EW 2018

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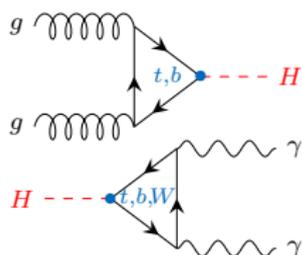
Paper accepted by *Phys. Rev. D*, arXiv: [1712.08891](https://arxiv.org/abs/1712.08891).



# Top quark Yukawa coupling at the LHC

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

→ Two **complementary measurements** of  $\lambda_t$ :



1. **Indirect measurement**: gluon-gluon fusion,  $H \rightarrow \gamma\gamma$  decay:

- Contributions enter from top quark loops by  $\lambda_t^2$ .
- Run 1 ATLAS+CMS combination measured

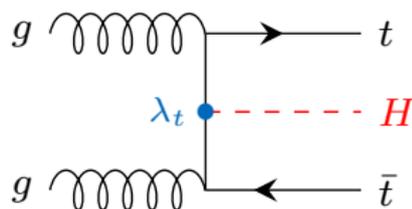
$$\kappa_t = \lambda_t / \lambda_t^{\text{SM}} = 0.87 \pm 0.15 \quad (\text{JHEP } 1608 \text{ (2016) } 045).$$

2.  **$t\bar{t}H$  production** best way for **direct** measurement:

- Tree-level process, cross-section proportional to  $\lambda_t^2$ .
- Run 1 ATLAS+CMS result on signal strength:

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

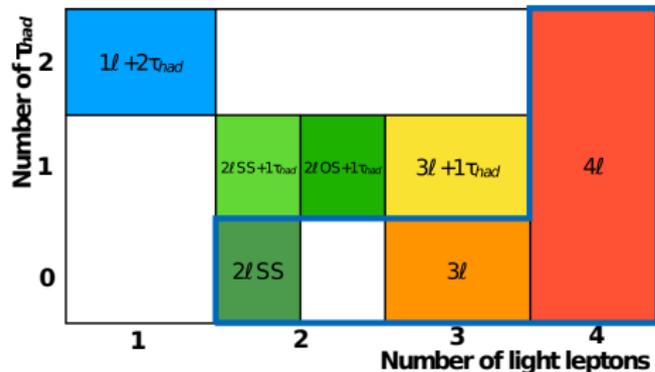
Obs. (exp.) significance of  $4.4\sigma$  ( $2.0\sigma$ ) (JHEP 1608 (2016) 045).



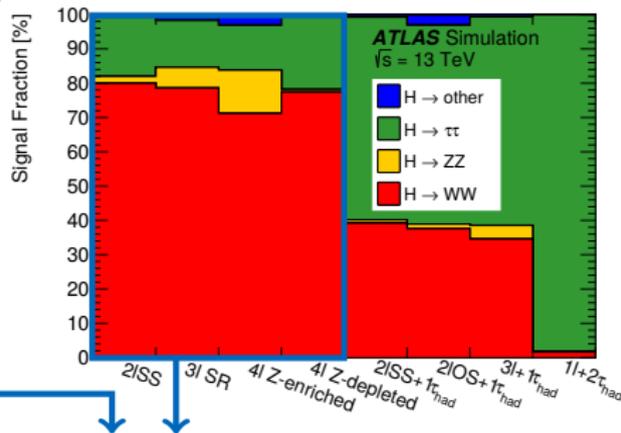
- **Any deviation from the SM could indicate new physics.**

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

- Use  $36.1 \text{ fb}^{-1}$  of  $p$ - $p$  collision data from the ATLAS experiment in 2015–2016.
- Main background  $t\bar{t}$  with  $\sigma_{t\bar{t}} = 1600 \times \sigma_{t\bar{t}H} \rightarrow$  suppressed by the requirement of at least two same-sign leptons (SS).
- 7 orthogonal channels with light leptons ( $\ell = e, \mu$ ) and hadronic taus ( $\tau_{\text{had}}$ ):



- Higgs boson decay modes:



- Jet requirement:  $N_{\text{jet}} \geq 2, N_{b\text{-tag}} \geq 1$ ,
  - $2\ell \text{ SS}, 2\ell \text{ SS} + 1\tau_{\text{had}}$ :  $N_{\text{jet}} \geq 4$ ,
  - $2\ell \text{ OS} + 1\tau_{\text{had}}, 1\ell + 2\tau_{\text{had}}$ :  $N_{\text{jet}} \geq 3$ .

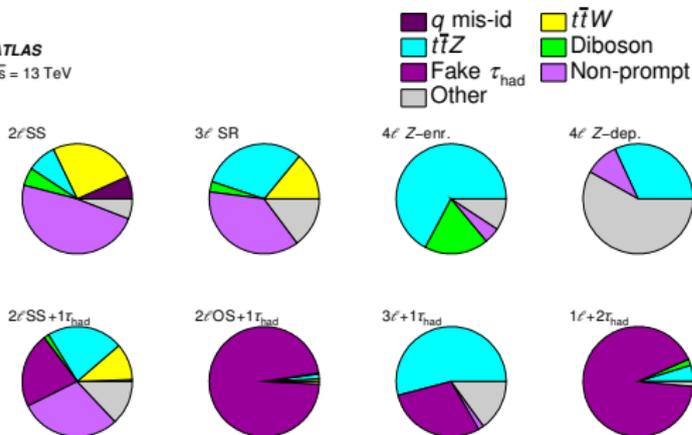
- Light-lepton channels target mainly  $H \rightarrow WW^*$  decays.
- Channels with  $\tau_{\text{had}}$  more sensitive to  $H \rightarrow \tau\tau$  decays.

- Eight signal regions with different event topologies.

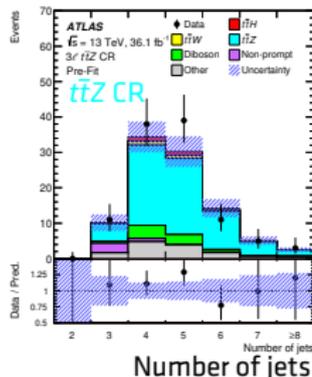
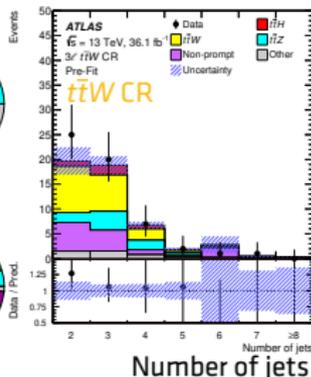
# Backgrounds

## • Different background composition in SRs: 1. Prompt lepton backgrounds:

ATLAS  
 $\sqrt{s} = 13 \text{ TeV}$



- estimated from Monte Carlo (MC),
- validated in  $3\ell$  CRs:

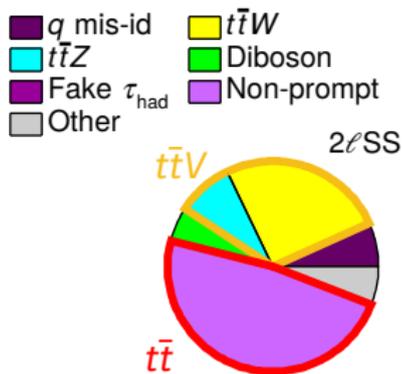


## 2. Reducible backgrounds:

- Non-prompt light leptons: from  $b$ -hadron decays ( $t\bar{t}$ ) and photon conversions,
  - Electron charge mis-identification ( $q$  mis-id): from  $2\ell$ OS  $t\bar{t}$  events,
  - Fake  $\tau_{\text{had}}$ : from light flavour jets and mis-identified electrons.
- Reduced with boosted decision trees (BDTs) using lepton isolation and track variables.
- Estimated with different data-driven techniques.
- Have robust estimate of background yields and shape prediction.

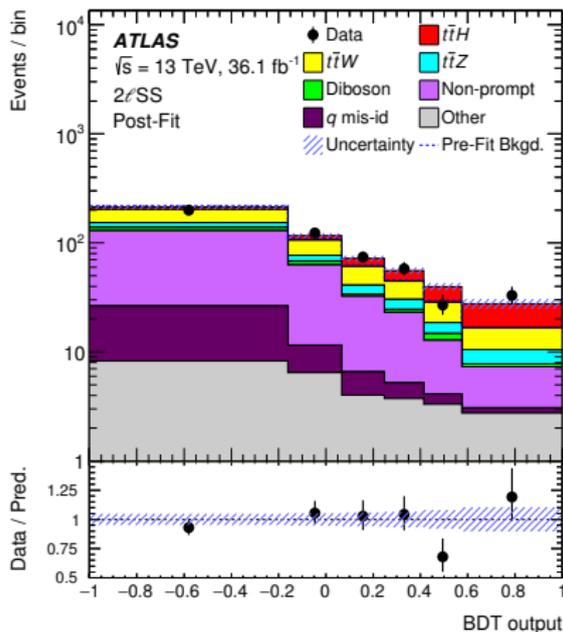
# Example: Event BDTs in $2\ell$ SS channel

- In  $2\ell$ SS 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:

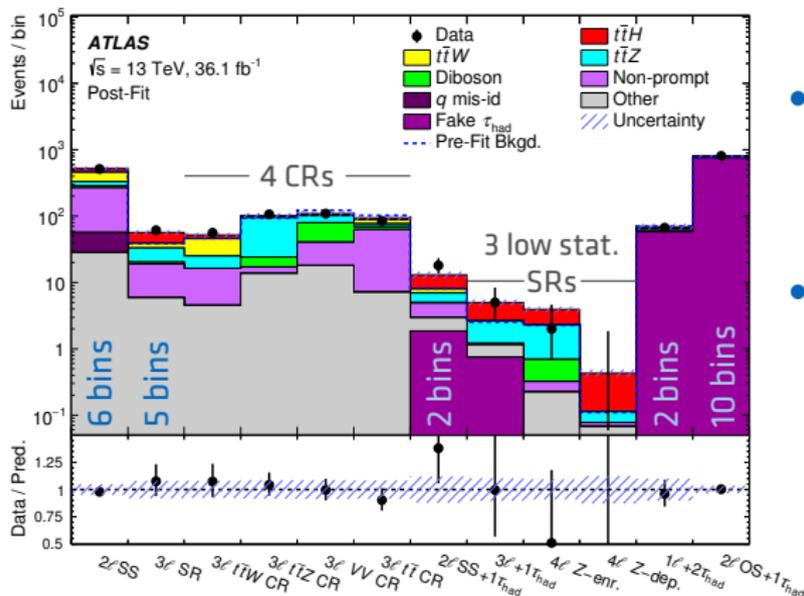
- lepton properties,
  - jet and  $b$ -tagged jet multiplicities,
  - angular distances
  - and missing transverse momentum.
- In 6 of 7 channels event BDTs are used for best signal-background separation.



→ Data agrees well with prediction.

# Fit set-up

- Parameter of interest is the  $t\bar{t}H$  signal strength  $\mu_{t\bar{t}H} = \sigma_{t\bar{t}H} / \sigma_{t\bar{t}H}^{\text{SM}}$ .
- Binned maximum-likelihood fit is performed in 8 SRs + 4 CRs simultaneously:



- Fit BDT shape in 5 SRs and single event counts in 3 $\ell$  CRs and SRs with low statistics.
  - in total 32 bins.
- Systematics model with 315 nuisance parameters:
  - NPs dropped if size < 1% to decrease time of the fit,
  - NP shapes smoothed to reduce local fluctuations,

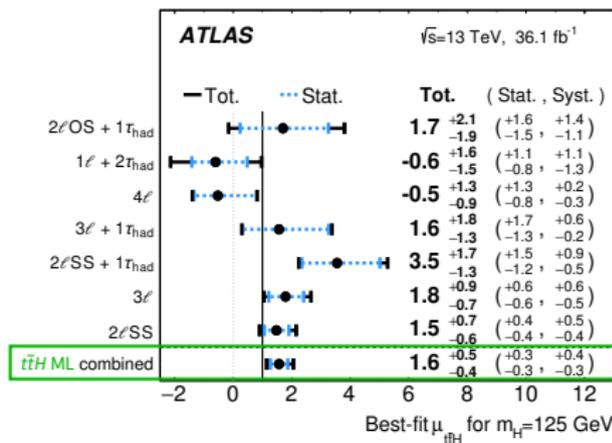
- All systematics have been studied in single channels and in combination.

# Results

- Major 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 $\tau_{\text{had}}$ 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 $\tau_{\text{had}}$ 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

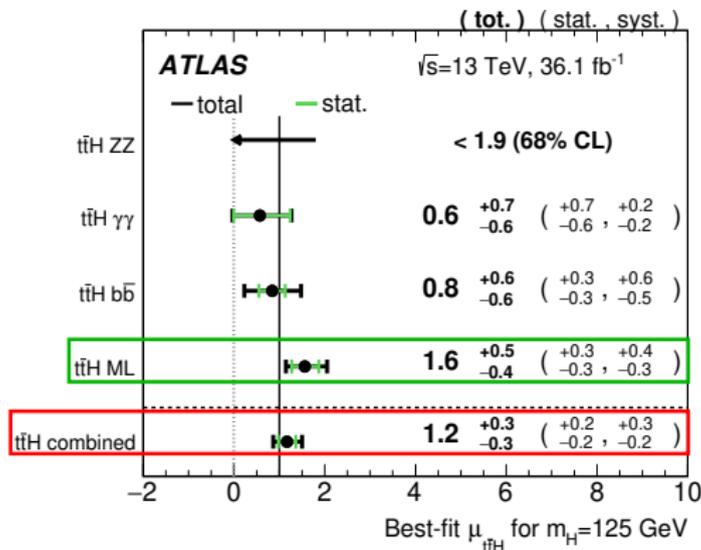
- Observed signal strength  $\mu_{t\bar{t}H}$ :



- 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:  $4.1\sigma$  ( $2.8\sigma$ ).
- Cross-section  $\sigma_{t\bar{t}H} = 790^{+230}_{-210}$  fb (expected:  $507^{+35}_{-50}$  fb).

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

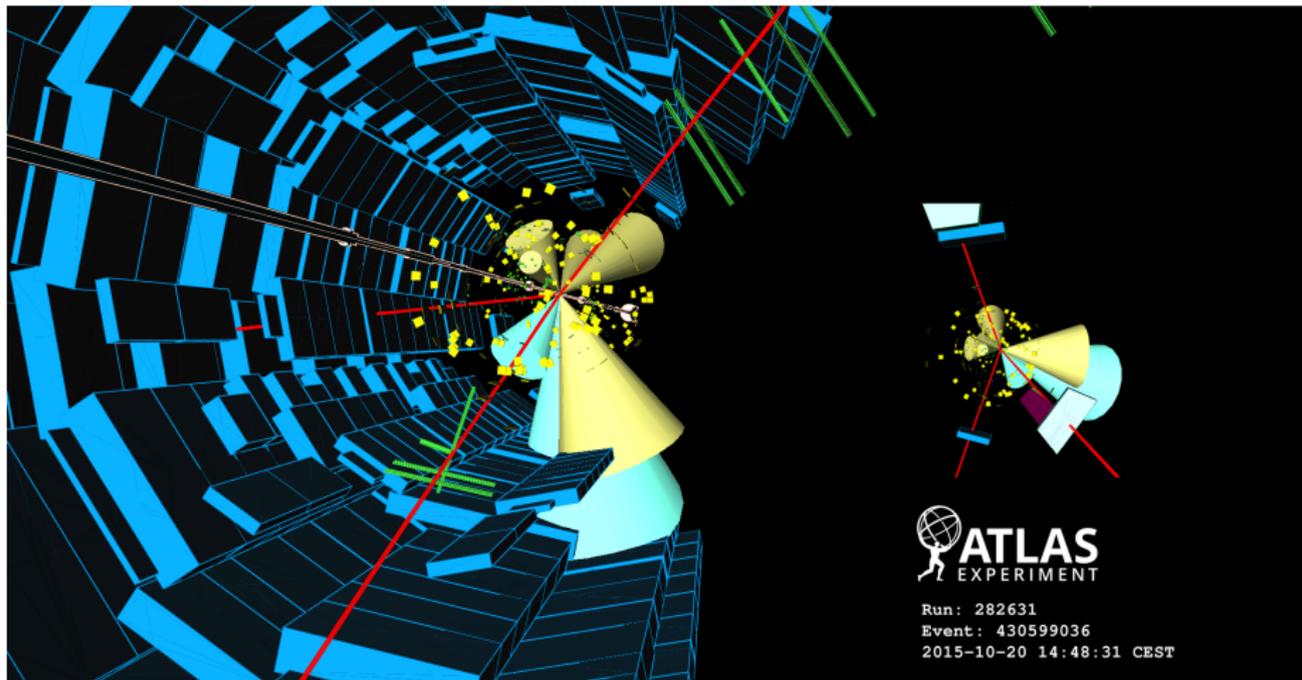
- Search for  $t\bar{t}H \rightarrow$  multilepton has major impact on combination results:



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

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

- Paper accepted by *Phys. Rev. D*, arXiv: [1712.08891](https://arxiv.org/abs/1712.08891).
- More details about combination results in talk by D. Zanzi.



→  $3\mu$  event with 2  $b$ -tagged and 5 non- $b$ -tagged jets ([ATLAS-CONF-2016-058](#))

- 11 Object reconstruction and overlap removal
- 12-13 Event selection in SRs and Non-prompt  $\ell$  and fake  $\tau_{\text{had}}$  CRs
- 14 Non-prompt  $\ell$  BDT
- 15-16 Non-prompt  $\ell$  background estimate in  $2\ell SS$  and  $3\ell$
- 17 Non-prompt  $\ell$  and fake  $\tau_{\text{had}}$  composition
- 18  $q$  mis-id background estimate
- 19-20 List of systematics (NPs)
- 21 SR and CR pre- and post-fit yields
- 22 SR post-fit plots
- 23 Event yields as a function of  $\log(S/B)$
- 24-25 Major uncertainties and NP ranking
- 26 MC samples

# 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,  $L^\dagger$ =loose+isolated,  $L^*=L^\dagger$ +passing X, T=tight,  $T^*$ =very tight)

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

- Multivariate algorithms for reduction of reducible backgrounds:

- Charge mis-assignment veto:  $14\times$  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 ( $\Delta R$ )
electron	electron (low $p_T$ )	0.1
muon	electron	0.1
electron	jet	0.3
jet	muon	$\min(0.4, 0.04 + 10[\text{GeV}]/p_T(\text{muon}))$
electron	tau	0.2
muon	tau	0.2
tau	jet	0.3

# Backup: Event selection in the signal regions

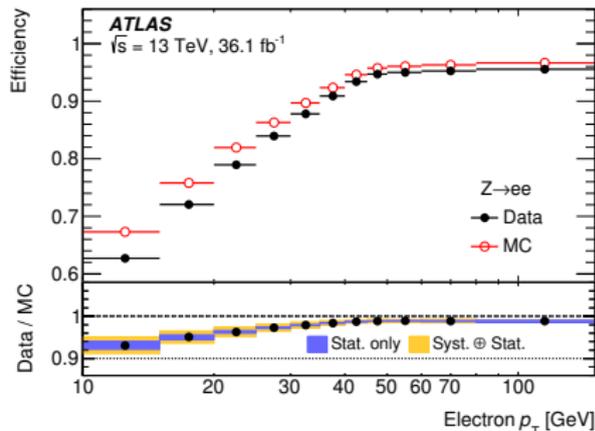
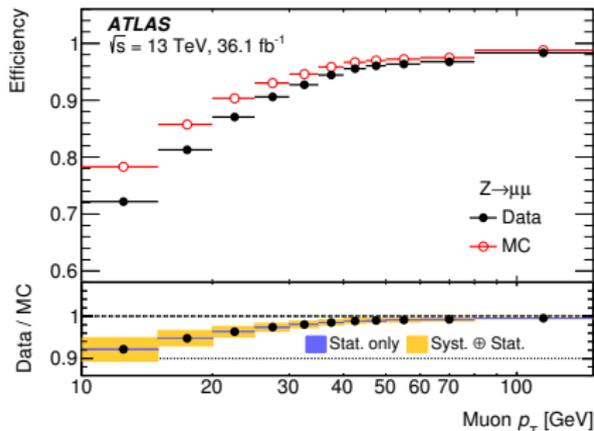
Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
$2\ell\text{SS}$	Two very tight light leptons with $p_T > 20$ GeV Same-charge light leptons Zero medium $\tau_{\text{had}}$ candidates $N_{\text{jets}} \geq 4$ and $N_{b\text{-jets}} < 3$
$3\ell$	Three light leptons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

# Backup: Event selection in non-prompt $\ell$ and fake $\tau_{\text{had}}$ CRs

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

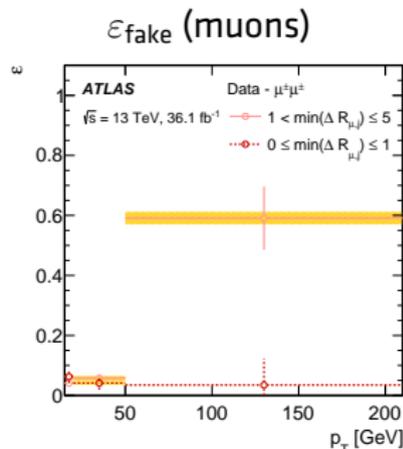
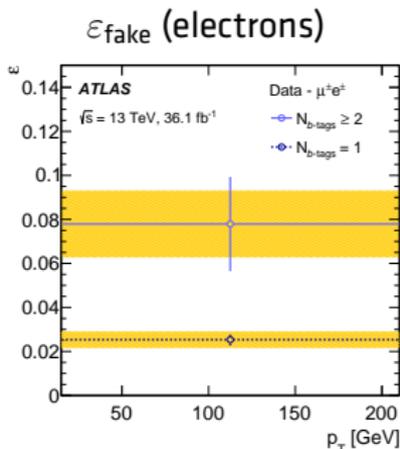
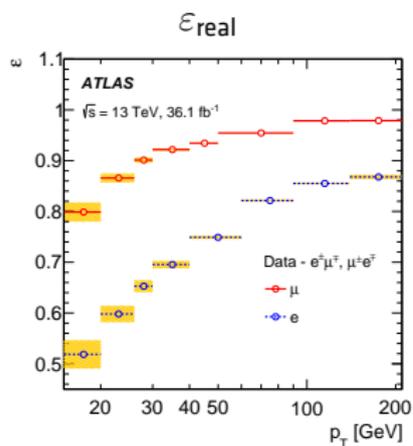
# Backup: Non-prompt light lepton BDT

- 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.  $\rightarrow$  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  $p_T \rightarrow$  ratio plots.



# Backup: Non-prompt light lepton estimate in $2\ell\text{SS}$ & $3\ell$ (1)

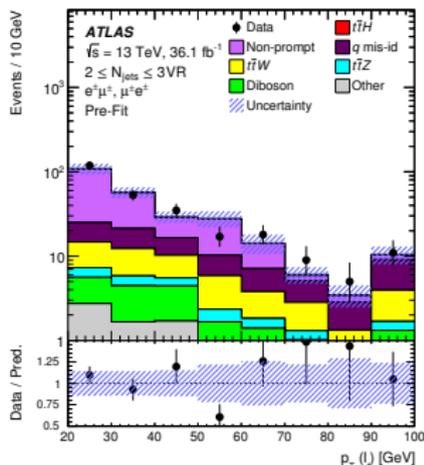
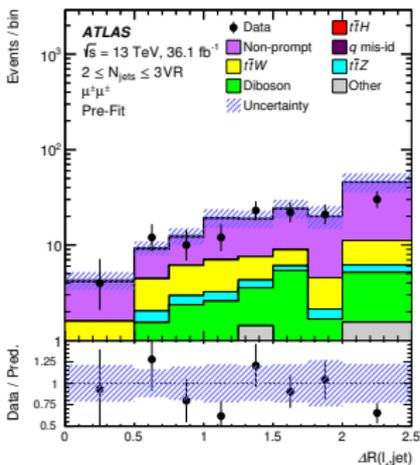
- “Matrix-method” predicts non-prompt lepton events in  $2\ell\text{SS}$  and  $3\ell$  from loose regions (by discarding lepton tight ID and isolation requirements)
  - Loose-to-tight probabilities for prompt and non-prompt leptons as input.
  - Prompt lepton efficiency  $\epsilon_{\text{real}}$  is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



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

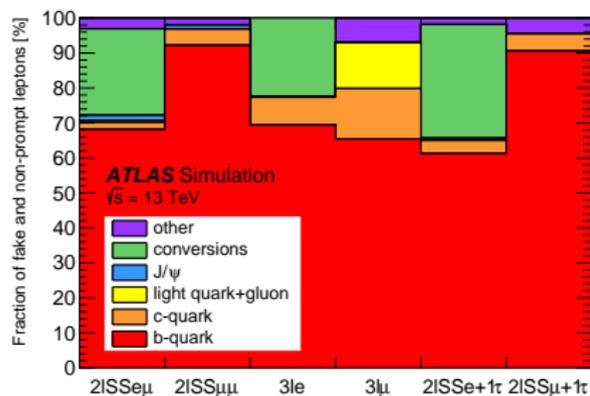
# Backup: Non-prompt light lepton estimate in $2\ell$ SS & $3\ell$ (2)

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

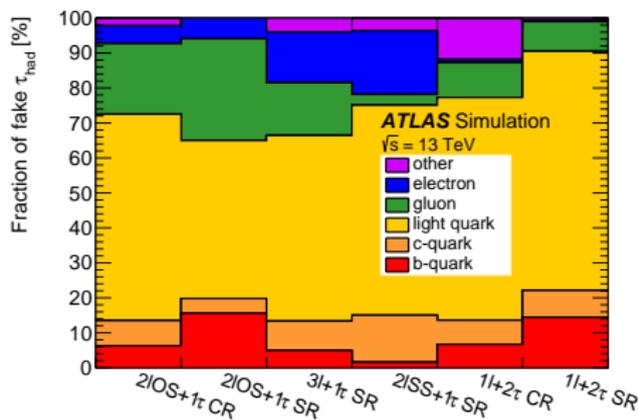


# Backup: Non-prompt $\ell$ and fake $\tau_{\text{had}}$ composition

## Non-prompt light lepton composition

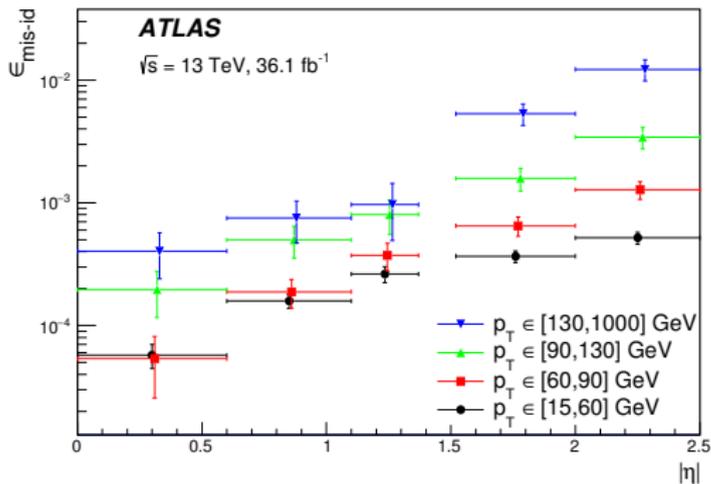


## Fake $\tau_{\text{had}}$ composition



# Backup: Charge mis-assignment background estimate

- Electron charge flips in  $t\bar{t}$  and  $Z$ +jets processes pollute  $2\ell$ SS 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
<b>Physics Objects</b>		
Electron	SN	6
Muon	SN	15
$\tau_{\text{had}}$	SN	10
Jet energy scale and resolution	SN	28
Jet vertex fraction	SN	1
Jet flavor tagging	SN	126
$E_T^{\text{miss}}$	SN	3
Total (Experimental)	–	191
<b>Data-driven non-prompt/fake leptons and charge misassignment</b>		
Control region statistics	SN	38
Light-lepton efficiencies	SN	22
Non-prompt light-lepton estimates: non-closure	N	5
$\gamma$ -conversion fraction	N	5
Fake $\tau_{\text{had}}$ estimates	N/SN	12
Electron charge misassignment	SN	1
Total (Data-driven reducible background)	–	83

## Backup: Systematics – Nuisance parameters (2)

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<b><i>ttH</i> modeling</b>		
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
<b><i>t<math>\bar{t}</math>W</i> modeling</b>		
Cross section	N	2
Renormalization and factorization scales	S	3
Matrix-element MC event generator	SN	1
Shower tune	SN	1
<b><i>t<math>\bar{t}</math>Z</i> modeling</b>		
Cross section	N	2
Renormalization and factorization scales	S	3
Matrix-element MC event generator	SN	1
Shower tune	SN	1
<b>Other background modeling</b>		
Cross section	N	15
Shower tune	SN	1
Total (Signal and background modeling)	–	41
Total (Overall)	–	315

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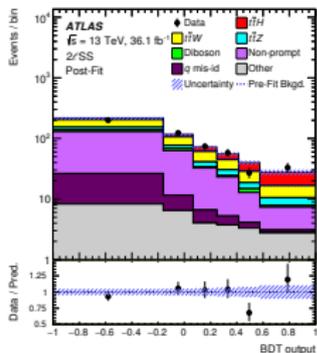
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# Backup: Signal and background yields, pre- and post-fit

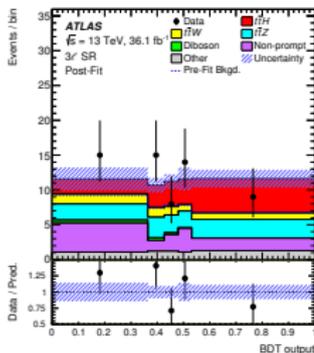
Category	Non-prompt	Fake $\tau_{\text{had}}$	$q$ mis-id	$t\bar{t}W$	$t\bar{t}Z$	Diboson	Other	Total Bkgd.	$t\bar{t}H$	Observed
Pre-fit yields										
2 $\ell$ SS	233 $\pm$ 39	–	33 $\pm$ 11	123 $\pm$ 18	41.4 $\pm$ 5.6	25 $\pm$ 15	28.4 $\pm$ 5.9	484 $\pm$ 38	42.6 $\pm$ 4.2	514
3 $\ell$ SR	14.5 $\pm$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

# Backup: Signal region BDT distributions

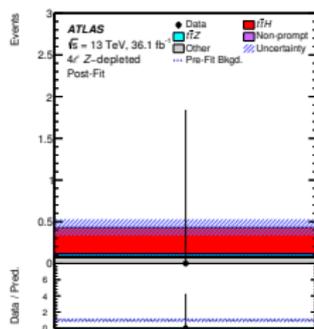
2SS



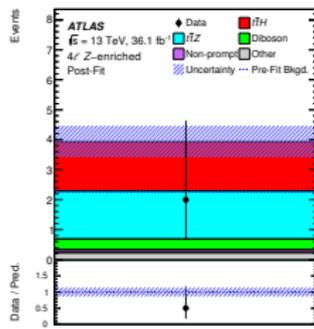
3l



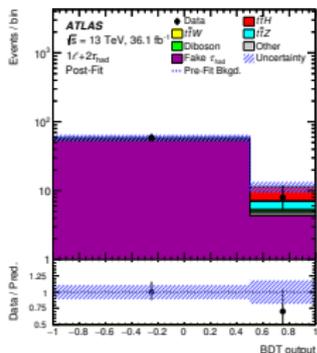
4l Z-depleted



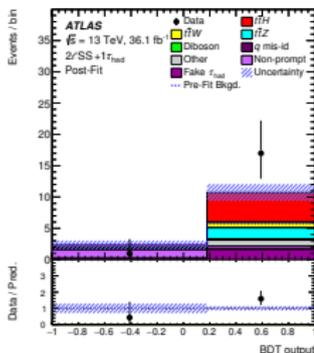
4l Z-enriched



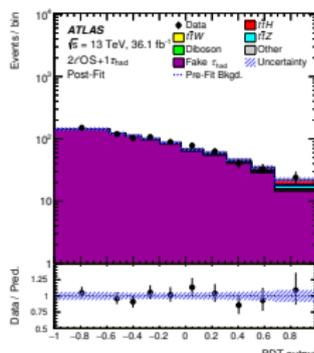
1l+2 $\tau_{had}$



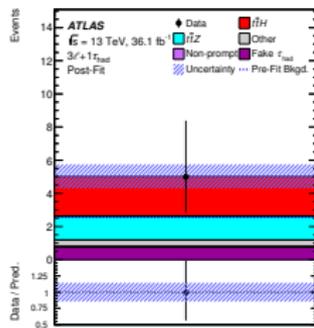
2SS+1 $\tau_{had}$



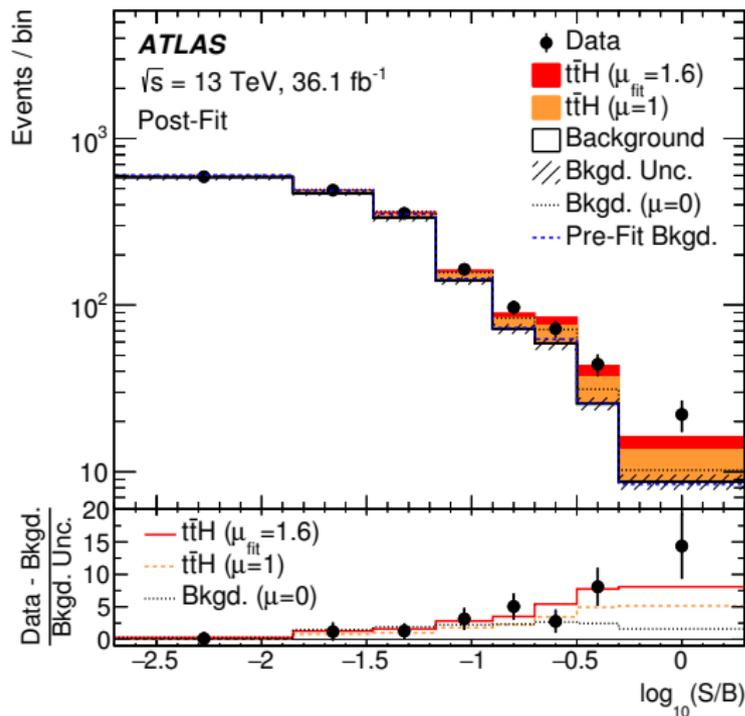
2lOS+1 $\tau_{had}$



3l+1 $\tau_{had}$



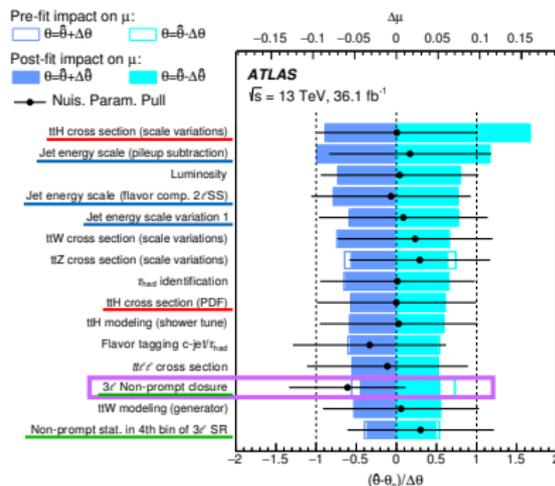
# Backup: Event yields as a function of $\log(S/B)$



- 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	$\Delta\mu$	
<b><math>t\bar{t}H</math> modeling (cross section)</b>	+0.20	-0.09
<b>Jet energy scale and resolution</b>	+0.18	-0.15
<b>Non-prompt light-lepton estimates</b>	+0.15	-0.13
Jet flavor tagging and $\tau_{\text{had}}$ 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 $\tau_{\text{had}}$ 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  $\rightarrow$  theory,
  - Jet energy scale and resolution,
  - Non-prompt light lepton estimates  $\rightarrow$  large contribution of CR statistics.
- No nuisance parameters pulls and constraints apart from  $3\ell$  Non-prompt estimate closure uncertainty  $\rightarrow$  deficit in  $3\ell t\bar{t}$  CR.
- All uncertainties well controlled.

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

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

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 $\tau_{\text{had}}$ 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: Monte Carlo samples

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
$t\bar{t}t, t\bar{t}t$	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
$s-, t\text{-channel},$ $Wt$ 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