ttH Analysis in 3 Leptons Final State at ATLAS

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On behalf of the ATLAS collaboration

Workshop on the Standard Model and Beyond

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Higgs and Top

"Higgs Boson"

"Top Quark"

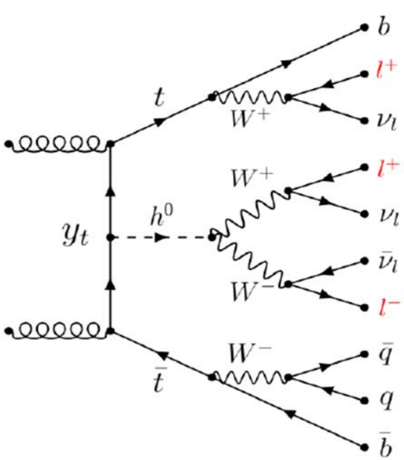
Yukawa Coupling

$$y_t = \sqrt{2} m_t / v \simeq 1$$

Special role for the top quark in electroweak symmetry breaking?

Close to unity - Why?

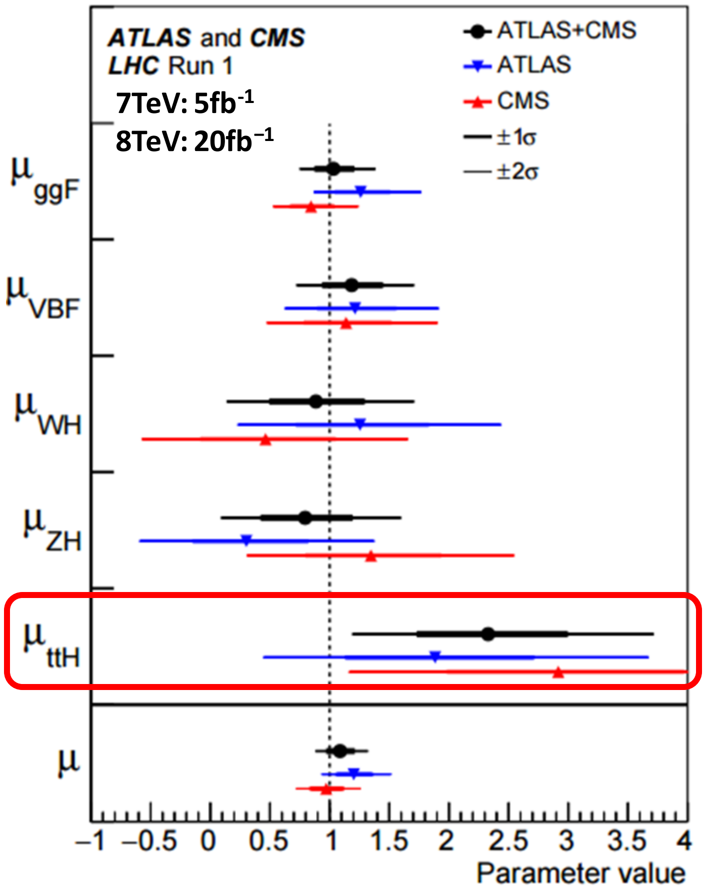
Why is the top so heavy?



$t\bar{t}H$ production can test Higgs properties and give direct access to top-Higgs coupling

Review of ttH Measurements in Run1

Run1



Production process	ATLAS + CMS	ATLAS	CMS
$\mu_{t\bar{t}H}$	$2.3^{+0.7}_{-0.6}$	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$

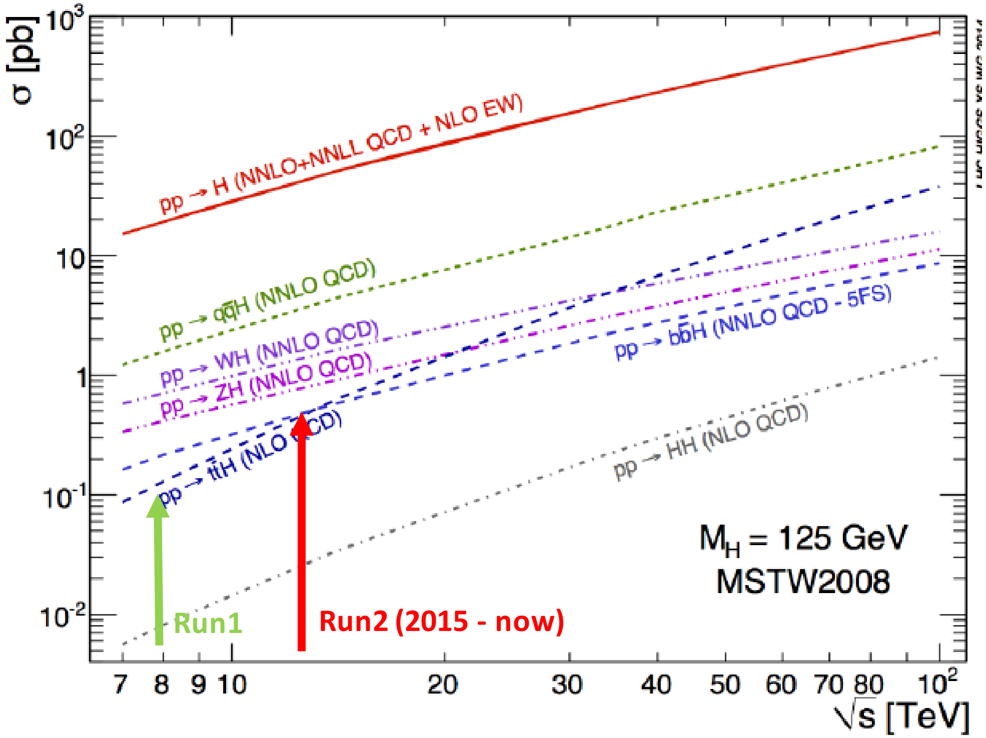
ATLAS: the combined observed significance is 2.33σ, 1.53σ is expected with 20.3 fb^{-1}(8TeV)
(CERN-EP-2016-058, JHEP 1605 (2016) 160)

CMS: the combined observed significance of 2σ with 5.1 fb^{-1}(7TeV) and 19.7 fb^{-1}(8TeV)
(CMS-HIG-13-029, JHEP 1409 (2014) 087)

The **combined** observed significance is 4.4σ, 2.0σ is expected
(CERN-EP-2016-100, JHEP 1608 (2016) 045)

Overview of ttH Measurements in Run2

Run2



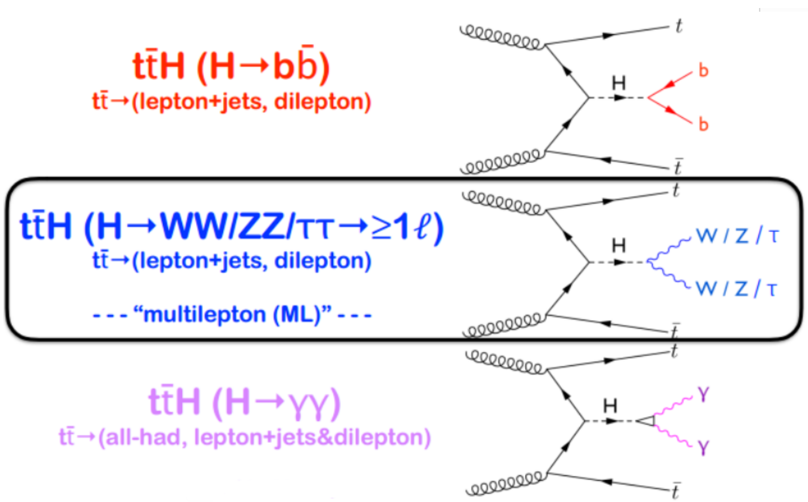
Cross Section (pb) of ttH	
8 TeV	0.13
13 TeV	0.5085

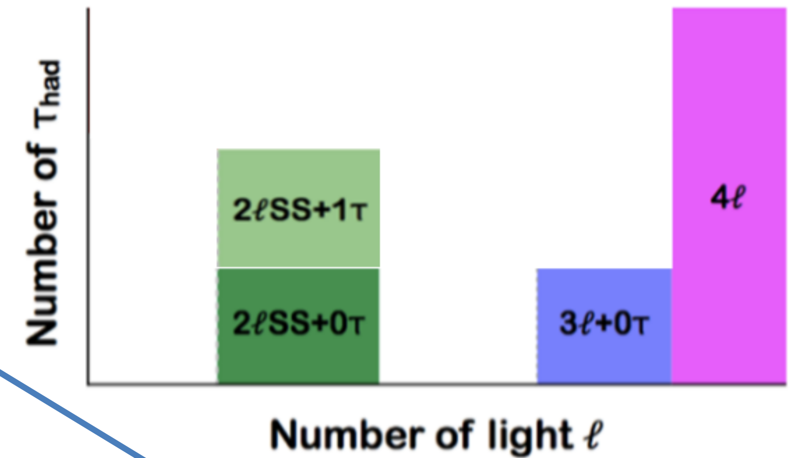
A factor of 4 in 13 TeV

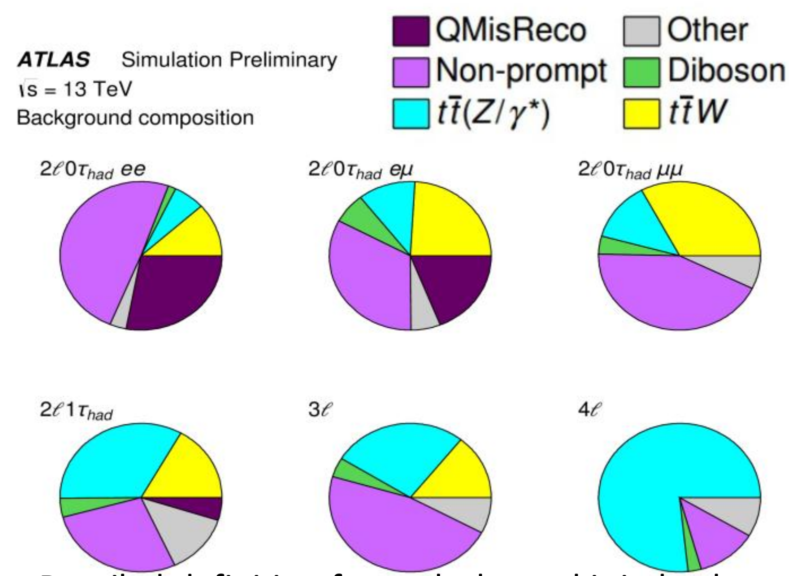
The higher energy and Lumi give us good chance to search for the ttH production in Run2

The background is also increased and need to be estimated carefully

ttH Analyses at ATLAS







Multilepton channel has clean final state
&&
Irreducible background (ttW and ttZ) can be checked in corresponding control regions

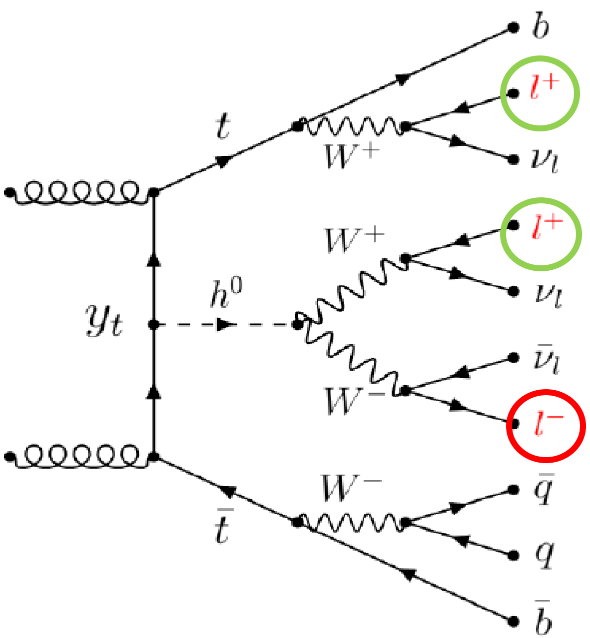
Detailed definition for each channel is in backup
(ATLAS-CONF-2016-068)

3l Analysis Overview

Category	Higgs boson decay mode WW^*	$\tau\tau$	ZZ^*	Other	$A \times \epsilon$ $(\times 10^{-4})$
$2\ell 0\tau_{\text{had}}$	77%	17%	3%	3%	14
$2\ell 1\tau_{\text{had}}$	46%	51%	2%	1%	2.2
3ℓ	74%	20%	4%	2%	9.2
4ℓ	72%	18%	9%	2%	0.88

3l lepton channel mainly targets H->WW*

3l H-> WW* final state



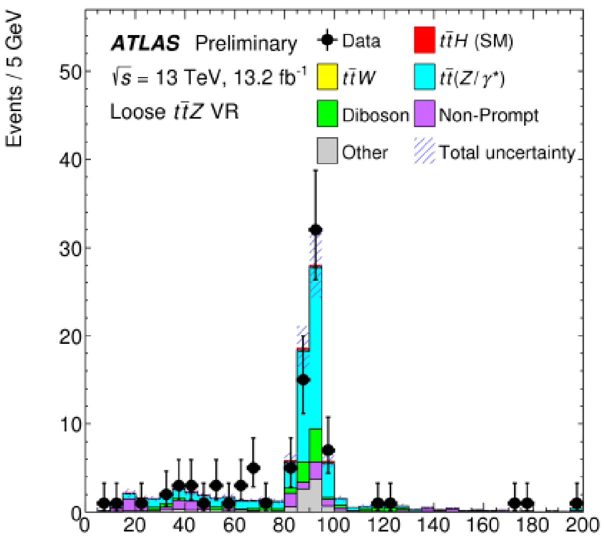
	Leptons	Jets	B-Tags	Trigger match
Definition of Signal Region in 3l	==3 $\Sigma Q_{lep}=\pm1$ l1 & l2: Tight, $p_T > 20$ GeV (*) l0: Loose, $p_T > 10$ GeV (*) $\lvert M_{ll,OS-SF}$ - 91.2 GeV $\rvert > 10$ GeV $M_{ll,OS-SF} > 12$ GeV $\lvert M_{lll}$ - 91.2 GeV $\rvert > 10$ GeV	$N_{jet} \geq 4$ & $N_b \geq 1$ or $N_{jet} == 3$ & $N_b \geq 2$		at least one trigger matched lepton with $p_T > 25$ GeV (21 GeV for muon in 2015)

- Fakes (reducible, mainly the fakes from ttbar+jets) are dominant background
- ttW, ttZ (irreducible) background are estimated with MC

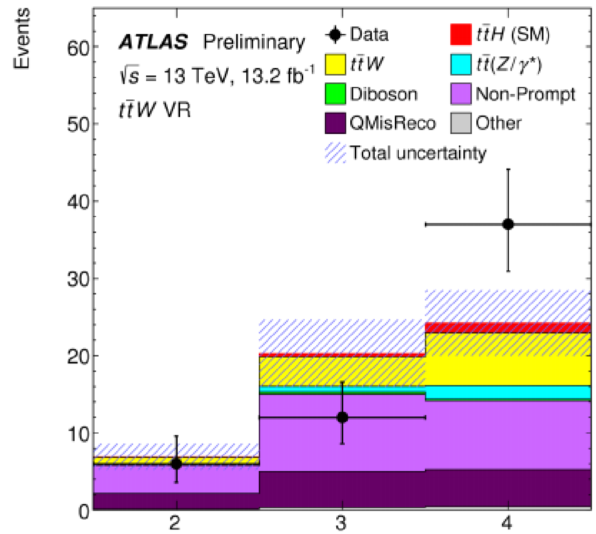
*l0 (with opposite sign charge) *l1 and l2(with same sign charge)

Background Estimation

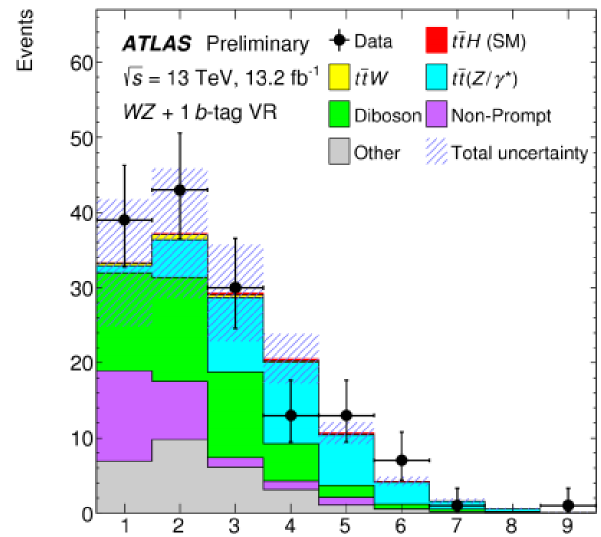
Irreducible Background



ttZ purity 58%



ttW purity 22%

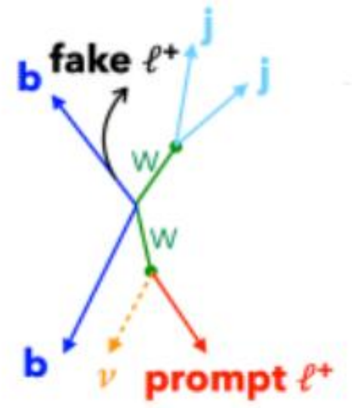


WZ purity 33%

Irreducible background:

- ttV (ttW and ttZ) is estimated with MC
  - ✓ Both modelling have been checked in the control region
  - ✓ The purity in the corresponding control regions is good
- Diboson is estimated with MC as well and modelling is good

Fake Estimation in 3l



Fake leptons in 3l
Major source:
leptons within jets, from heavy hadrons

Partially removed by:
Isolation or overlap removal requirements

Fake factor is employed to estimate the fake leptons in 3l
Assumption on lep0 :
Most lep0 (with opposite charge) are prompt and checked by MC
Advantages:
Only need to apply the non-prompt estimate to lepton 1 and 2
The fake factor is defined as the ratio between the number of same-sign events with tight leptons only and events with one anti-tight lepton.

$$\theta_\ell = \frac{N_{\ell\ell}}{N_{\ell\not\ell}}$$

$$\theta_e = \frac{N_{ee}}{N_{e\not e}}(\leq 4\text{jets}) = \frac{N_{ee}^{Data} - N_{ee}^{\text{Prompt SS}}}{N_{e\not e}^{Data} - N_{e\not e}^{\text{Prompt SS}}}$$

$$\theta_\mu = \frac{N_{\mu\mu}}{N_{\mu\not\mu}}(\leq 4\text{jets}) = \frac{N_{\mu\mu}^{Data} - N_{\mu\mu}^{\text{Prompt SS}}}{N_{\mu\not\mu}^{Data} - N_{\mu\not\mu}^{\text{Promt SS}}}$$

$$N_{\text{estimated fakes},SR} = \left[N_{data,CR} - N_{\text{prompts}MC}\right] \cdot \theta$$

Fake Estimation in 3l

Closure test is performed in a low jet region of 3l
Predictions of fakes in 3l channel (2-3 jets, 1b) compared to observed numbers
Generally, the non-closure is about 20% and are compatible within the uncertainty

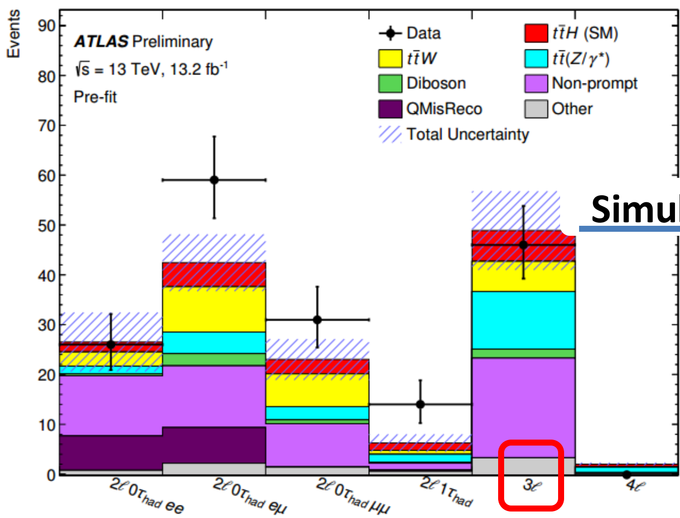
Yields (pre-fit) in signal region for all channels

	$2\ell 0\tau_{\rm had}$ ee	$2\ell 0\tau_{\rm had}$ $e\mu$	$2\ell 0\tau_{\rm had}$ $\mu\mu$	$2\ell 1\tau_{\rm had}$	3ℓ	4ℓ
$t\bar{t}W$	2.9 ± 0.7	9.1 ± 2.5	6.6 ± 1.6	0.8 ± 0.4	6.1 ± 1.3	—
$t\bar{t}(Z/\gamma^*)$	1.55 ± 0.29	4.3 ± 0.9	2.6 ± 0.6	1.6 ± 0.4	11.5 ± 2.0	1.12 ± 0.20
Diboson	0.38 ± 0.25	2.5 ± 1.4	0.8 ± 0.5	0.20 ± 0.15	1.8 ± 1.0	0.04 ± 0.04
Non-prompt leptons	12 ± 6	12 ± 5	8.7 ± 3.4	1.3 ± 1.2	20 ± 6	0.18 ± 0.10
Charge misreconstruction	6.9 ± 1.3	7.1 ± 1.7	—	0.24 ± 0.03	—	—
Other	0.81 ± 0.22	2.2 ± 0.6	1.4 ± 0.4	0.63 ± 0.15	3.3 ± 0.8	0.12 ± 0.05
Total background	25 ± 6	38 ± 6	20 ± 4	4.8 ± 1.4	43 ± 7	1.46 ± 0.25
$t\bar{t}H$ (SM)	2.0 ± 0.5	4.8 ± 1.0	2.9 ± 0.6	1.43 ± 0.31	6.2 ± 1.1	0.59 ± 0.10
Data	26	59	31	14	46	0

Results

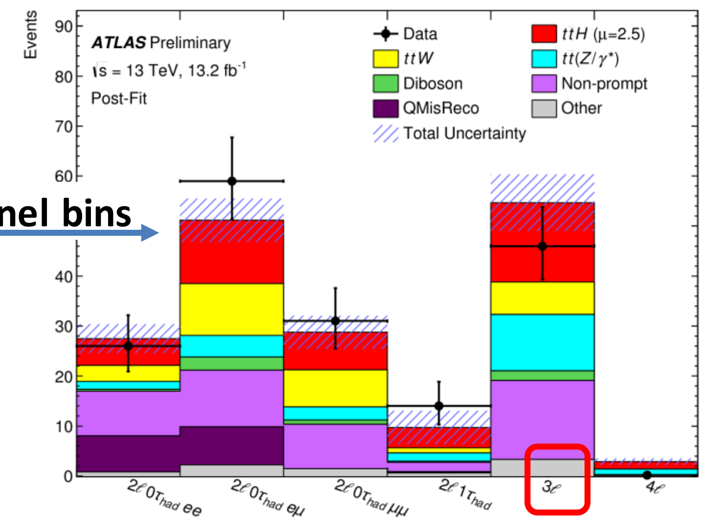
Multilepton Channel

Pre-fit

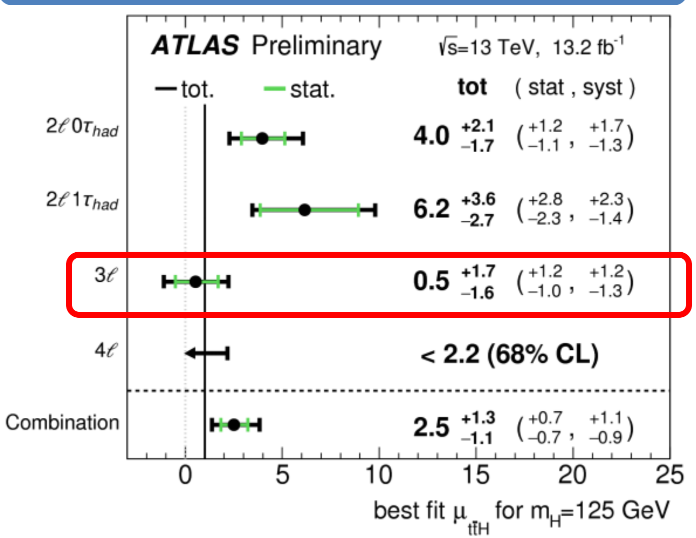


Simultaneous fit in 6 channel bins

Post-fit



Measured signal strength

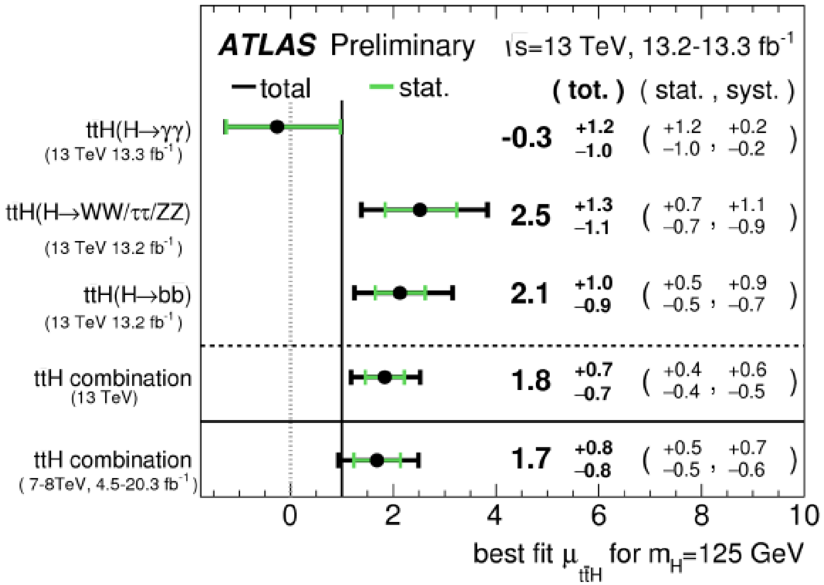


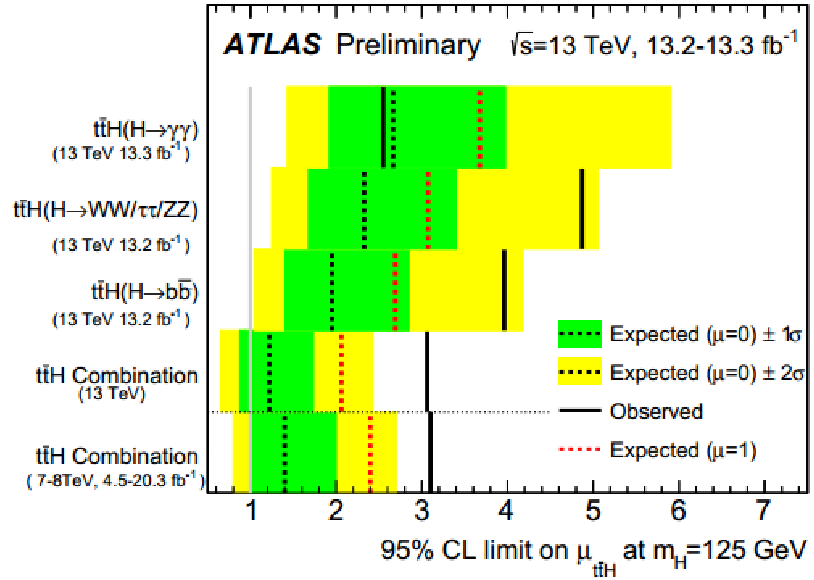
The best-fit result of the μ is 2.5 ± 0.7 (stat.) $^{+1.1}_{-0.9}$ (syst.), is consistent with the Standard Model expectation with $13.2 fb^{-1}$ (ATLAS-CONF-2016-058)

Systematic uncertainty is dominated by uncertainties from non-prompt backgrounds estimates in the 2l, 3l

Latest Combined Results

ttH signal strength and upper limits





Measured significance of ttH production

Channel	Significance	
	Observed [σ]	Expected [σ]
$t\bar{t}H,\ H \to \gamma\gamma$	−0.2	0.9
$t\bar{t}H,\ H \to (WW, \tau\tau, ZZ)$	2.2	1.0
$t\bar{t}H,\ H \to b\bar{b}$	2.4	1.2
$t\bar{t}H$ combination	2.8	1.8

Combined ATLAS ttH results with 13.2 fb $^{-1}$

The best fit value of the signal strength is 1.8 $\pm$ 0.7, which corresponds to 2.8 (1.8) σ observed (expected) significance

(ATLAS-CONF-2016-068)

Conclusions

- **Promising Run1 combined results in the search of ttH production**

- ✓ **Analysis strategy works well with Run2 dataset (13.2 fb^{-1}, 13 TeV)**
  - ✓ ttV modelling is checked by MC
  - ✓ Fake leptons are estimated with data-driven method (fake factor)

- ✓ **Results show improvements and are compatible with Run1 results**
  - ✓ Run2(13.2fb^{-1}): the combined observed significance is 2.8σ, 1.8σ is expected


Thank you for your
attention!

Backup

MC list and Overlap Removal

Process	ME Generator	Parton Shower	PDF	Tune
$t\bar{t}H$	MG5_aMC [12]	Pythia 8 [13]	NNPDF 3.0 NLO [14]/ NNPDF 2.3 LO [16]	A14 [15]
$tHqb$	MG5_aMC	Pythia 8	CT10 [17]/NNPDF 2.3 LO	A14
tHW	MG5_aMC	Herwig++ [18]	CT10/CTEQ6L1 [19, 20]	UE-EE-5 [21]
$t\bar{t}W$	MG5_aMC	Pythia 8	NNPDF 3.0 NLO/2.3 LO	A14
$t\bar{t}(Z/\gamma^*)$	MG5_aMC	Pythia 8	NNPDF 3.0 NLO/2.3 LO	A14
$t(Z/\gamma^*)$	MG5_aMC	Pythia 6 [22]	CTEQ6L1	Perugia2012 [23]
$tW(Z/\gamma^*)$	MG5_aMC	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}t\bar{t}$	MG5_aMC	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}W^+W^-$	MG5_aMC	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}$	Powheg-BOX [24]	Pythia 6	CT10/CTEQ6L1	Perugia2012
s-, t-channel, Wt single top	Powheg-BOX [25, 26]	Pythia 6	CT10/CTEQ6L1	Perugia2012
VV, $qqVV$, VVV	Sherpa 2.1.1 [27]	Sherpa	CT10	Sherpa default
$Z \to \ell^+\ell^-$	Sherpa 2.2	Sherpa	NNPDF 3.0 NLO	Sherpa default

Keep	**Remove**	**Cone size (Δ R) or track**
electron	tau	0.2
muon	tau	0.2
electron	CaloTagged muon	shared track
muon	electon	shared track
electron	jet	0.2
jet	electron	0.4
muon	jet	(0.2 or ghost-matched to muon) and (numJetTrk $\leq$2)
jet	muon	0.4
tau	jet	0.2

Channel	Leptons	Hadronic Taus	Jets	B-Tags	Lepton flavour	Trigger match
2ℓss	==2 $\Sigma Q_{lep}=\pm 2$ $p_T^{lead} > 25$ GeV $p_T^{lead} > 25$ GeV $\|\eta^{elec}\| < 1.37$	== 0	$\geq$5	$\geq$1	ee $e\mu$ $\mu\mu$	at least one trigger matched lepton with $p_T > 25$ GeV (21 GeV for muon in 2015)
3ℓ	==3 $\Sigma Q_{lep}=\pm 1$ $\ell 1$ & $\ell 2$: Tight, $p_T > 20$ GeV (*) $\ell 0$: Loose, $p_T > 10$ GeV (*) $\|M_{ll,OS-SF}$ - 91.2 GeV $\| > 10$ GeV $M_{ll,OS-SF} > 12$ GeV $\|M_{lll}$ - 91.2 GeV $\| > 10$ GeV	–	$N_{jet} \geq 4$ & $N_b \geq 1$ or $N_{jet} == 3$ & $N_b \geq 2$		–	at least one trigger matched lepton with $p_T > 25$ GeV (21 GeV for muon in 2015)
4ℓ	==4 $p_T > 10$ GeV Loose def + Gradient Iso $\Sigma Q_{lep}=0$ $\|M_{ll,OS-SF}$ - 91.2 GeV $\| > 10$ GeV $M_{ll,OS-SF} > 12$ GeV M_{4l} within [100, 350] GeV M_{4l} veto $\pm$ 5 GeV around M_H = 125.0 GeV	–	$\geq$ 2	$\geq$ 1	–	at least one trigger matched lepton with $p_T > 25$ GeV (21 GeV for muon in 2015)
2ℓSS+1τ_{had}	==2 $\Sigma Q_{lep}=\pm 2$ $p_{T,lep}^{lead} > 25$ GeV $p_{T,lep}^{sub} > 15$ GeV $\|M_{ee}$ - 91.2 GeV $\| > 10$ GeV	== 1 $Q_\tau = -Q_{lep}$	$\geq$4	$\geq$1	–	at least one trigger matched lepton with $p_T > 25$ GeV (21 GeV for muon in 2015)

Channel	Region	$t\bar{t}H$ (S)	Bkgd (B)	$tHjb + WtH$	S/B
$H \to (WW, \tau\tau, ZZ)$	2ℓSS ee	1.99 ± 0.51	22.2 ± 3.4	0.10 ± 0.03	0.09
	2ℓSS $e\mu$	4.82 ± 0.95	38.5 ± 5.1	0.26 ± 0.07	0.13
	2ℓSS $\mu\mu$	2.85 ± 0.58	21.2 ± 3.8	0.15 ± 0.04	0.13
	2ℓSS $+\tau_{had}$	1.43 ± 0.31	5.7 ± 1.7	0.11 ± 0.03	0.25
	3ℓ	6.2 ± 1.1	38.9 ± 5.3	0.30 ± 0.08	0.16
	4ℓ	0.59 ± 0.10	1.42 ± 0.24	0.014 ± 0.006	0.42

Definition of Lepton and VR

	Loose		Tight	
	e	μ	e	μ
Track isolation	99% eff.	99% eff.	$< 0.06 \times p_T$ (*)	$< 0.06 \times p_T$ (*)
Calorimeter isolation	99% eff.	99% eff.	$< 0.06 \times p_T$ (*)	99% eff. (*)
Identification working point	Loose	Loose	Tight	Loose
Transverse impact parameter $\|d_0\|/\sigma_{d_0}$	< 5	< 3	< 5	< 3
z impact parameter $\|\Delta z_0 \sin\theta_\ell\|$	< 0.5 mm	< 0.5 mm	< 0.5 mm	< 0.5 mm

VR	Tight $t\bar{t}Z$	3ℓ lepton selection At least one $\ell^+\ell^-$ pair with $\|m(\ell^+\ell^-) - 91.2\text{ GeV}\| < 10$ GeV $N_{\text{jets}} \geq 4$ and $N_{b\text{-jets}} \geq 2$
VR	Loose $t\bar{t}Z$	3ℓ lepton selection At least one $\ell^+\ell^-$ pair with $\|m(\ell^+\ell^-) - 91.2\text{ GeV}\| < 10$ GeV $N_{\text{jets}} \geq 4$ and $N_{b\text{-jets}} \geq 1$, or $N_{\text{jets}} = 3$ and $N_{b\text{-jets}} \geq 2$
VR	$WZ + 1$ b-tag	3ℓ lepton selection At least one $\ell^+\ell^-$ pair with $\|m(\ell^+\ell^-) - 91.2\text{ GeV}\| < 10$ GeV $N_{\text{jets}} \geq 1$ and $N_{b\text{-jets}} = 1$
VR	$t\bar{t}W$	$2\ell 0\tau_{\text{had}}$ lepton selection $2 \leq N_{\text{jets}} \leq 4$ and $N_{b\text{-jets}} \geq 2$ $H_{\text{T,jets}} > 220$ GeV for ee and $e\mu$ events $E_{\text{T}}^{\text{miss}} > 50$ GeV and ($m(ee) < 75$ or $m(ee) > 105$ GeV) for ee events

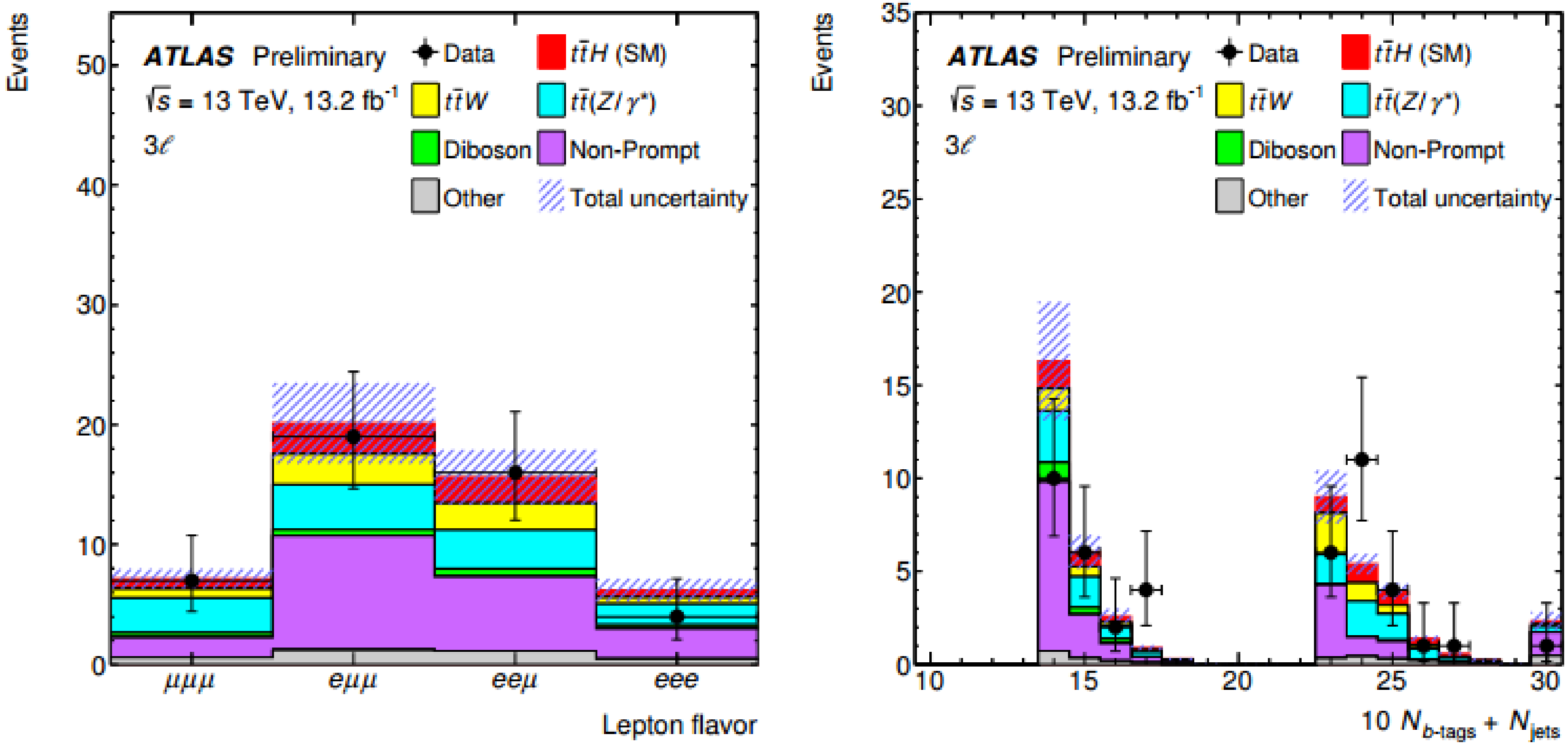
Uncertainties' source on 3l fakes estimation

Uncertainties [%]		Channels			
		$2\ell \geq 5$ jets			3ℓ
		$e^{\pm}e^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}$	
Statistical	$\Delta\theta_e^{\text{stat}}$	24.159	–	18.231	12.902
	$\Delta\theta_\mu^{\text{stat}}$	–	18.622	4.5696	8.6768
	$\Delta N_{\ell\ell}(\geq 5\text{ jets})(\text{stat})$	19.872	27.533	21.03	16.999
Systematics	$\Delta\theta_e^{\text{syst}}$ (closure)	24.792	–	18.708	13.24
	$\Delta\theta_\mu^{\text{syst}}$ (closure)	–	9.7602	2.395	4.5476
	$\Delta\theta^{\text{syst}}$ (other fakes)	19	19	15.077	13.466
	MC Q Mis Id ($\ell\ell$)	15.161	–	9.935	8.0968
Total		**46.734**	**39.511**	**38.435**	**31.203**
Correlated Systematics	Q Mis Id ($\ell\ell$)	18.989	–	14.329	10.141

Summary of the effects of the systematic uncertainties on μ

Uncertainty Source	$\Delta\mu$	
Non-prompt leptons and charge misreconstruction	+0.56	−0.64
Jet-vertex association, pileup modeling	+0.48	−0.36
$t\bar{t}W$ modeling	+0.29	−0.31
$t\bar{t}H$ modeling	+0.31	−0.15
Jet energy scale and resolution	+0.22	−0.18
$t\bar{t}Z$ modeling	+0.19	−0.19
Luminosity	+0.19	−0.15
Diboson modeling	+0.15	−0.14
Jet flavor tagging	+0.15	−0.12
Light lepton (e, μ) and τ_{had} ID, isolation, trigger	+0.12	−0.10
Other background modeling	+0.11	−0.11
Total systematic uncertainty	+1.1	−0.9

Plots in Signal Region

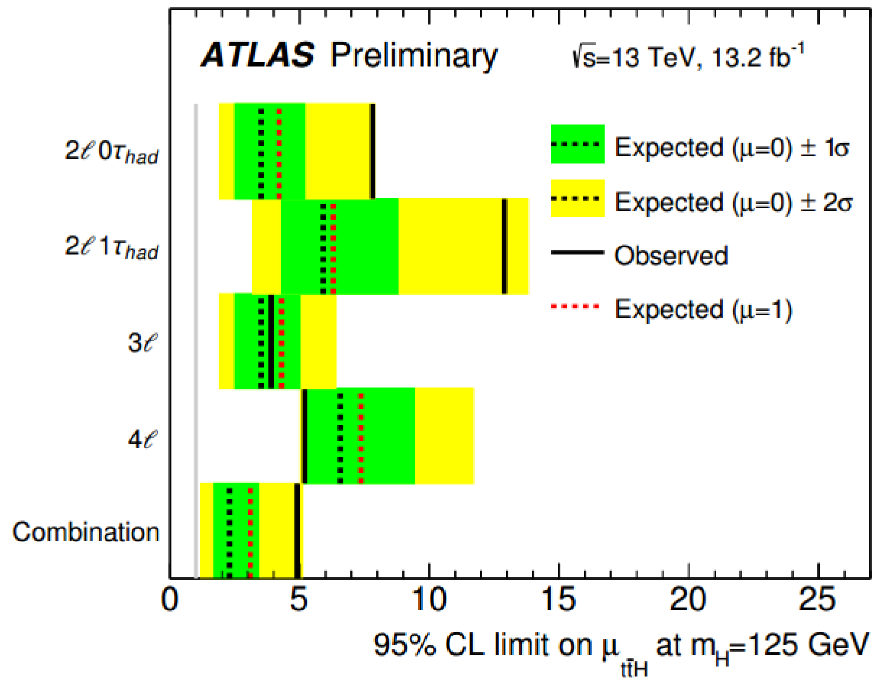


(a) (b)

Characteristics of events in the 3ℓ signal region: (a) lepton flavor composition; (b) 10× the number of b-tagged jets plus the total number of jets. The signal is set to the SM expectation ($\mu_{t\bar{t}H} = 1$) and the background expectation is pre-fit (using initial values of the background systematic uncertainty nuisance parameters). The hatched region shows the total uncertainty on the background plus SM signal prediction in each bin.

Expected Yields Table and Upper Limits

	$2\ell 0\tau_{had}$ ee	$2\ell 0\tau_{had}$ $e\mu$	$2\ell 0\tau_{had}$ $\mu\mu$	$2\ell 1\tau_{had}$	3ℓ	4ℓ
$t\bar{t}W$	2.9 ± 0.7	9.1 ± 2.5	6.6 ± 1.6	0.8 ± 0.4	6.1 ± 1.3	—
$t\bar{t}(Z/\gamma^*)$	1.55 ± 0.29	4.3 ± 0.9	2.6 ± 0.6	1.6 ± 0.4	11.5 ± 2.0	1.12 ± 0.20
Diboson	0.38 ± 0.25	2.5 ± 1.4	0.8 ± 0.5	0.20 ± 0.15	1.8 ± 1.0	0.04 ± 0.04
Non-prompt leptons	12 ± 6	12 ± 5	8.7 ± 3.4	1.3 ± 1.2	20 ± 6	0.18 ± 0.10
Charge misreconstruction	6.9 ± 1.3	7.1 ± 1.7	—	0.24 ± 0.03	—	—
Other	0.81 ± 0.22	2.2 ± 0.6	1.4 ± 0.4	0.63 ± 0.15	3.3 ± 0.8	0.12 ± 0.05
Total background	25 ± 6	38 ± 6	20 ± 4	4.8 ± 1.4	43 ± 7	1.46 ± 0.25
$t\bar{t}H$ (SM)	2.0 ± 0.5	4.8 ± 1.0	2.9 ± 0.6	1.43 ± 0.31	6.2 ± 1.1	0.59 ± 0.10
Data	26	59	31	14	46	0



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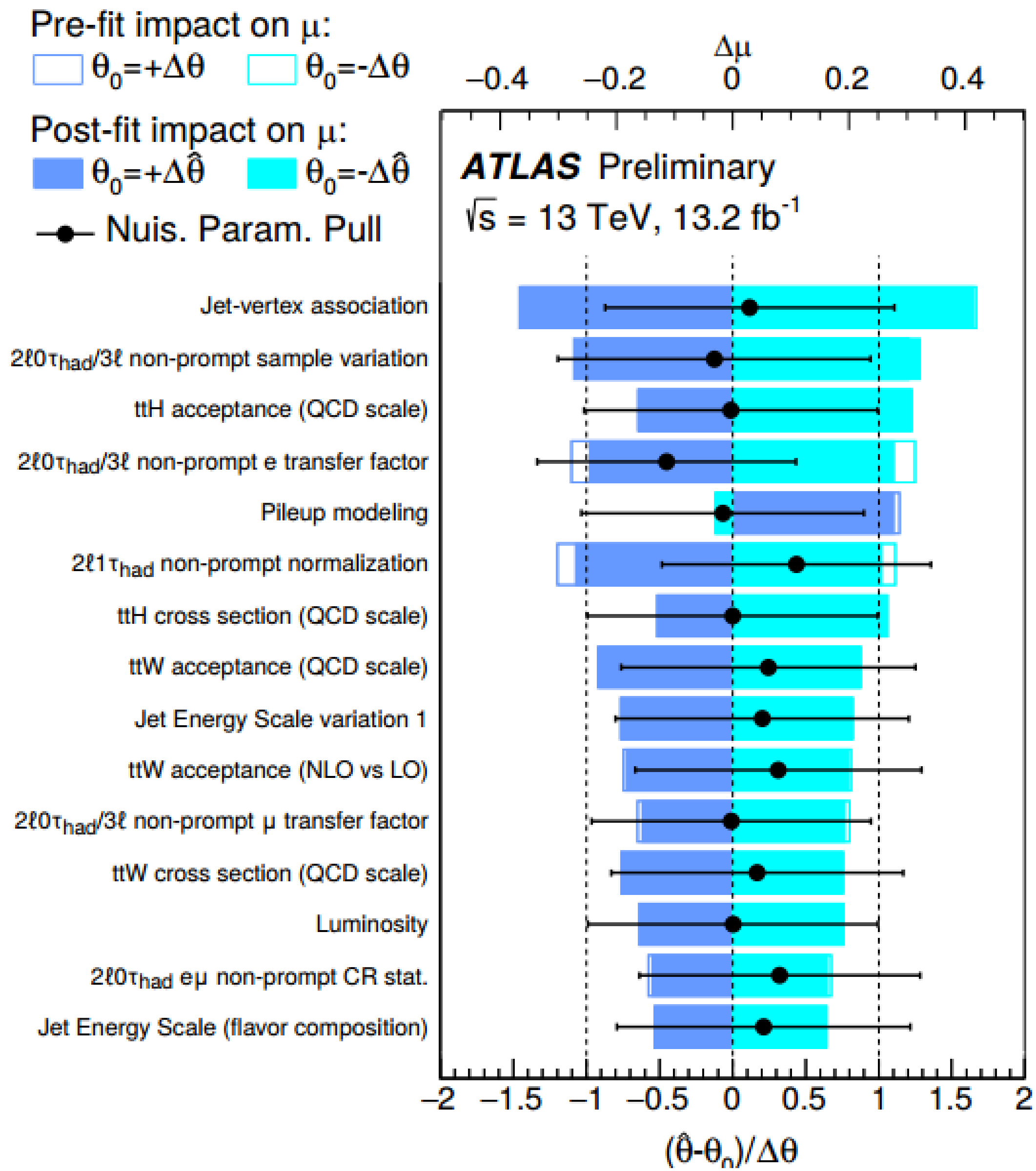

Pre-fit impact on μ:
θ0=+Δθ
θ0=-Δθ
Post-fit impact on μ:
θ0=+Δθ̂
θ0=-Δθ̂
Nuis. Param. Pull
Δμ
−0.4 −0.2 0 0.2 0.4
ATLAS Preliminary
√s = 13 TeV, 13.2 fb-1
Jet-vertex association
2ℓ0τhad/3ℓ non-prompt sample variation
ttH acceptance (QCD scale)
2ℓ0τhad/3ℓ non-prompt e transfer factor
Pileup modeling
2ℓ1τhad non-prompt normalization
ttH cross section (QCD scale)
ttW acceptance (QCD scale)
Jet Energy Scale variation 1
ttW acceptance (NLO vs LO)
2ℓ0τhad/3ℓ non-prompt μ transfer factor
ttW cross section (QCD scale)
Luminosity
2ℓ0τhad eμ non-prompt CR stat.
Jet Energy Scale (flavor composition)
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2
(θ̂-θ0)/Δθ

Upper limits on the *ttH* signal strength for the individual analyses