Search for the ttH Production in Multilepton Final States with the ATLAS Detector

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Motivation

"Higgs Boson"

"Top Quark"

Yukawa Coupling

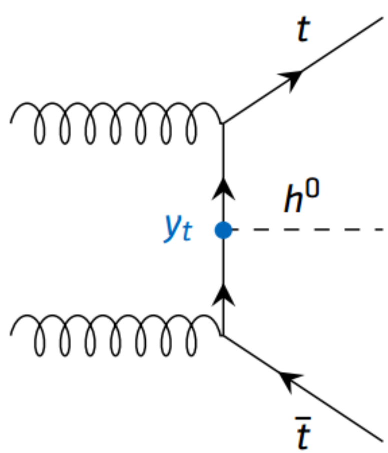
$$y_t = \sqrt{2}m_t/v \simeq 1$$

Special role for the top quark in electroweak symmetry breaking

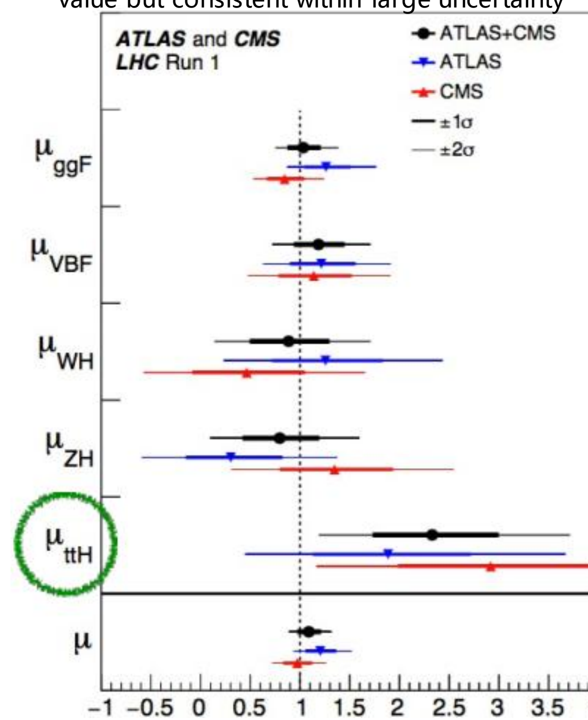
Close to unity

Direct measurement of Top Yukawa coupling via ttH production

Any deviation might be the hint for new physics.



signal strength (μ) and combined significance, cross section above SM
value but consistent within large uncertainty



$t\bar{t}H$ in 13 TeV

Higgs Boson (125GeV) Production at LHC

Cross section (pb) at $\sqrt{s} = 8$ (7) TeV	
ggF	19.52 (15.32)
VBF	1.58 (1.22)
WH	0.70 (0.57)
ZH	0.39 (0.31)
$t\bar{t}H$	0.13 (0.09)
Total	22.32 (17.51)

A factor of 4 in 13 TeV →

Cross Section(pb) at 13TeV	
ggF	43.92
VBF	3.748
WH	1.380
ZH	0.8696
ttH	0.5085

Cross section (fb) @NLO	$t\bar{t}H$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}$ (NNLO)
8 TeV	133	232	206	2,53E+05
13 TeV	507	566	760	8,32E+05
13 TeV / 8TeV	3.8	2.4	3.7	3.3

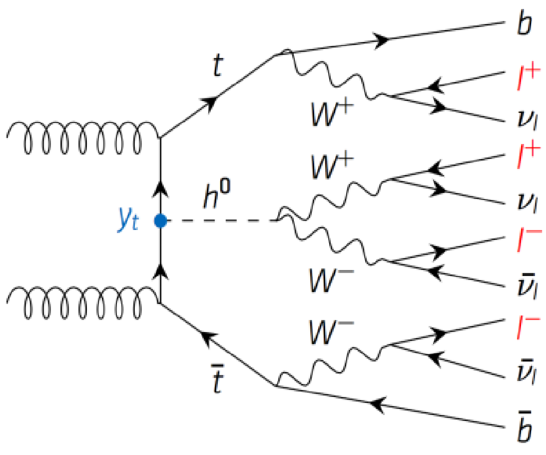
Backgrounds increase at a comparable rate in the signal regions

ATLAS Run 2 ttH results in ICHEP with total luminosity of 13.2 fb-1
ATLAS-COM-CONF-2016-066

$t\bar{t}H$ Signal Channel

Multi-Lepton Final States

- 2 same-sign light leptons, τ veto (2lss)
  (at least 5 jets and at least 1 bjet)
- 2 same-sign light leptons + 1 opposite-sign τ (2lss+1τ)
  (at least 4 jets and at least 1 bjet)
- 3 light leptons with total charge ± 1 (3l)
  (≥ 4jets, ≥ 1bjet, or 3jets, ≥ 2bjets)
- 4 light leptons with total charge 0 (4l)
  (≥ 2jets, ≥ 1bjet)

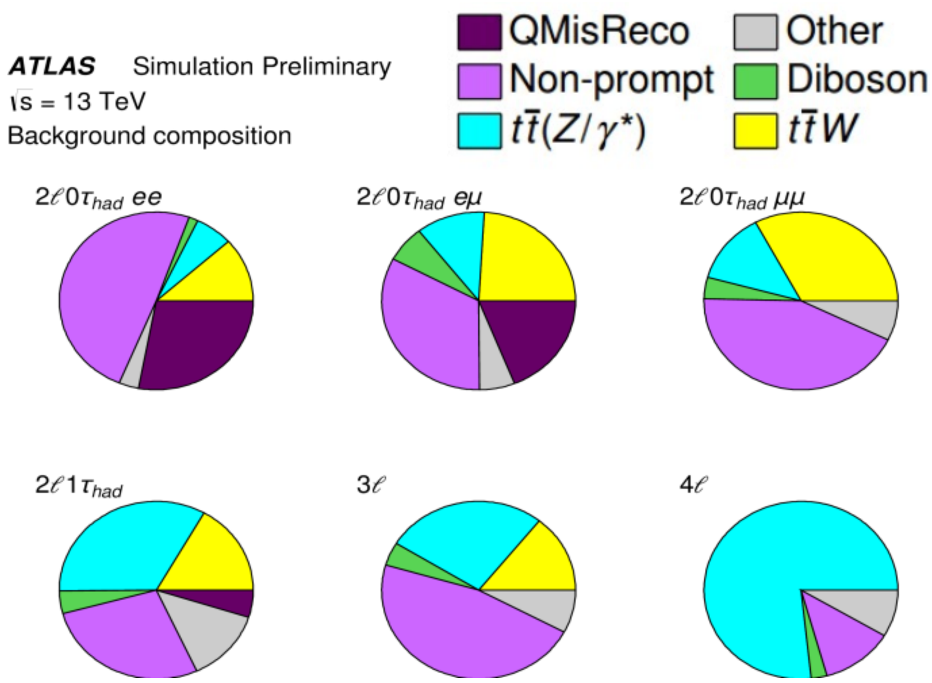


Category	Higgs boson decay mode WW^*	$\tau\tau$	ZZ^*	Other	$A\times\epsilon$ $(\times 10^{-4})$
$2\ell 0\tau_{\mathrm{had}}$	77%	17%	3%	3%	14
$2\ell 1\tau_{\mathrm{had}}$	46%	51%	2%	1%	2.2
3ℓ	74%	20%	4%	2%	9.2
4ℓ	72%	18%	9%	2%	0.88

Background for $t\bar{t}H$

Irreducible backgrounds: same final state as the signal (ttW, ttZ, VV)
Reducible backgrounds: non-prompt or a fake lepton selected as prompt lepton

Background Composition

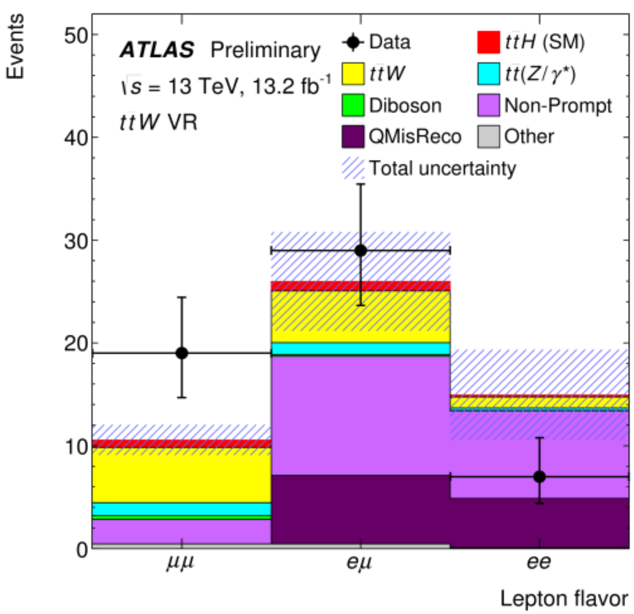


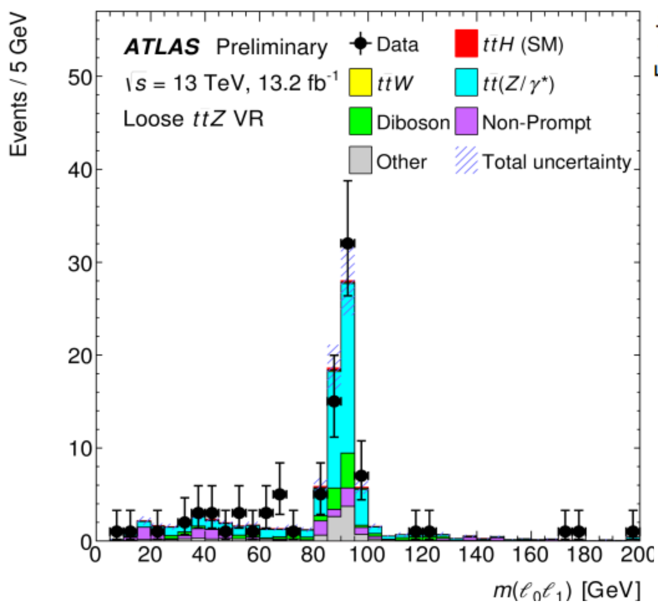
Background Estimation

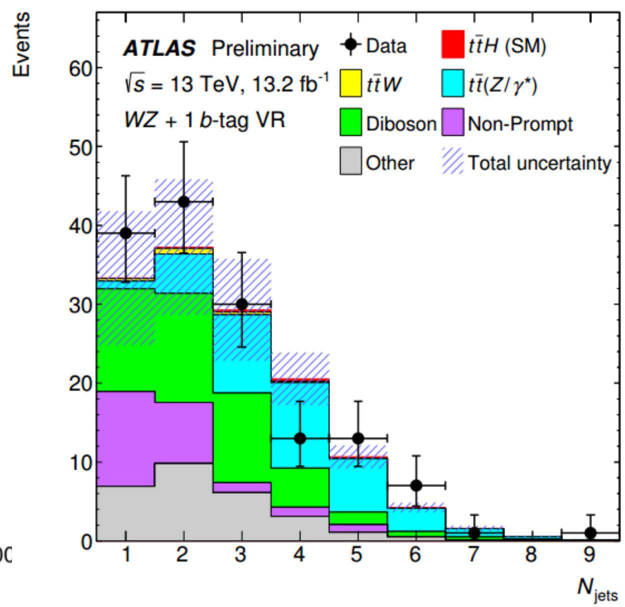
- ☐ ttW, ttZ -> Simulation
- ☐ Diboson (VV) -> Simulation
- ☐ Non-prompt light leptons -> data control region (fake factor in 2lSS, 3l; ABCD in 2lSS1tau)
- ☐ Electron charge misidentification -> data of Z+jets events (likelihood)
- ☐ Hadronic tau misreconstruction -> simulation and normalised to data control region.

Validation Plots

- Control region
  - ttW (left plot): selection close to the 2l0τhad signal region, but with low jet multiplicity.
  - ttZ (middle plot): selection close to the 3l signal region, but within Z mass window.
  - *WZ*+1*b*-tag (right plot): 3l lepton selection At least one lepton pair |mll - 91.2 GeV| < 10 GeV, and jet requirements



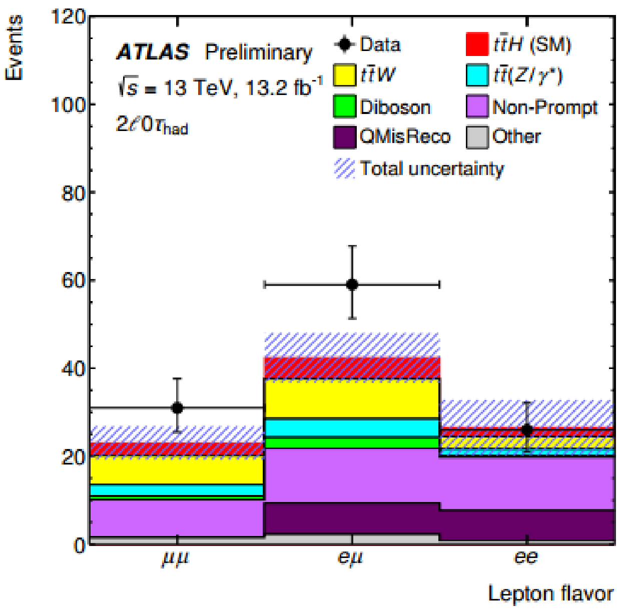


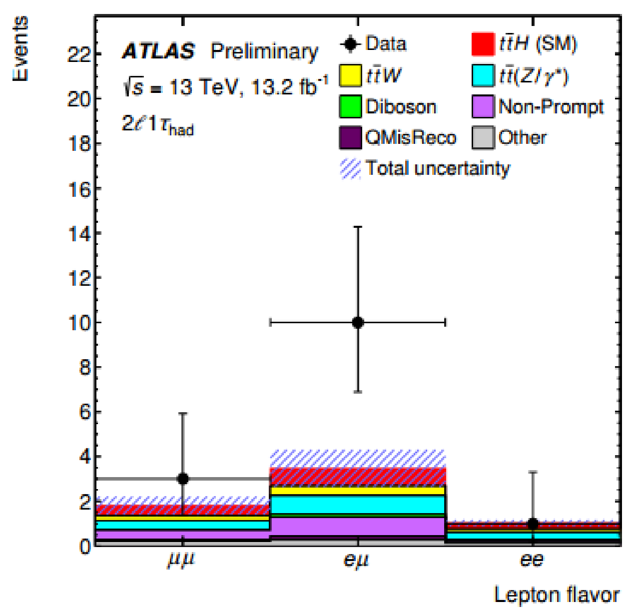


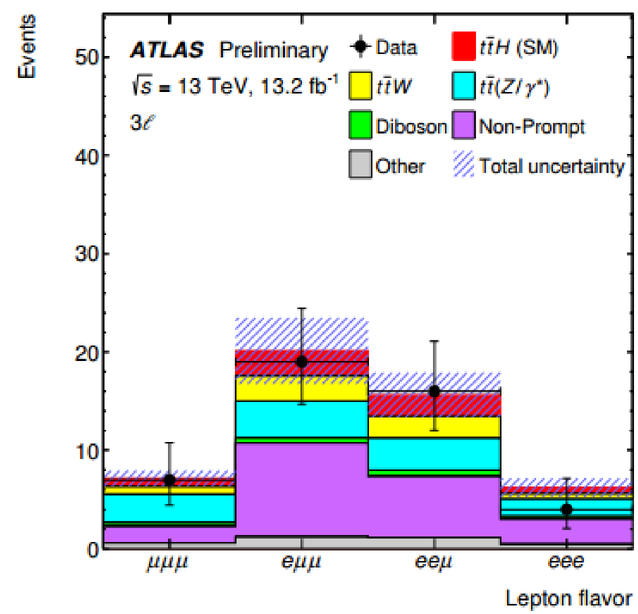
Good modelling in the validation region

Signal Region

- Lepton flavor composition in 2lSS0tau, 2llSS1tau, 3l signal region after fitting
  (detailed definitions in backup)







Generally, good description by the Monte Carlo

Event Yields

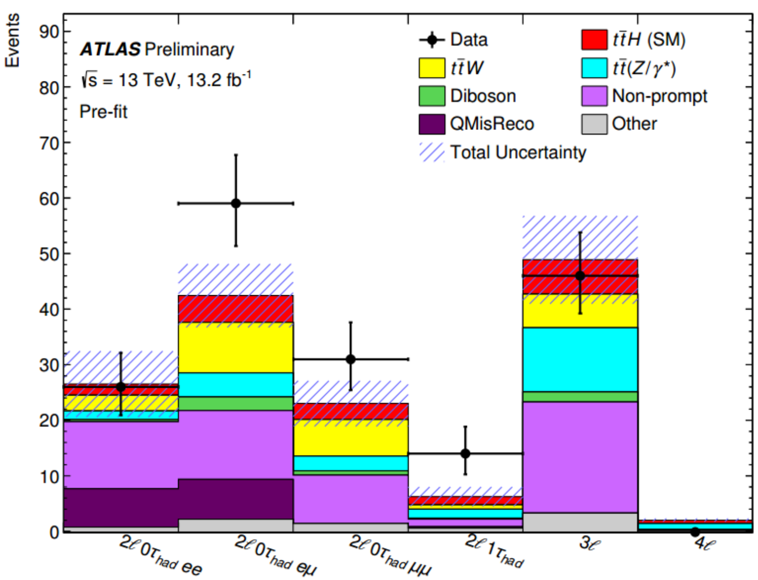
- Cut and count analysis in 6 categories: 2l0τ(*ee,eμ,μμ*), 2l1τhad, 3l and 4l

Expected and observed yields in the six signal regions

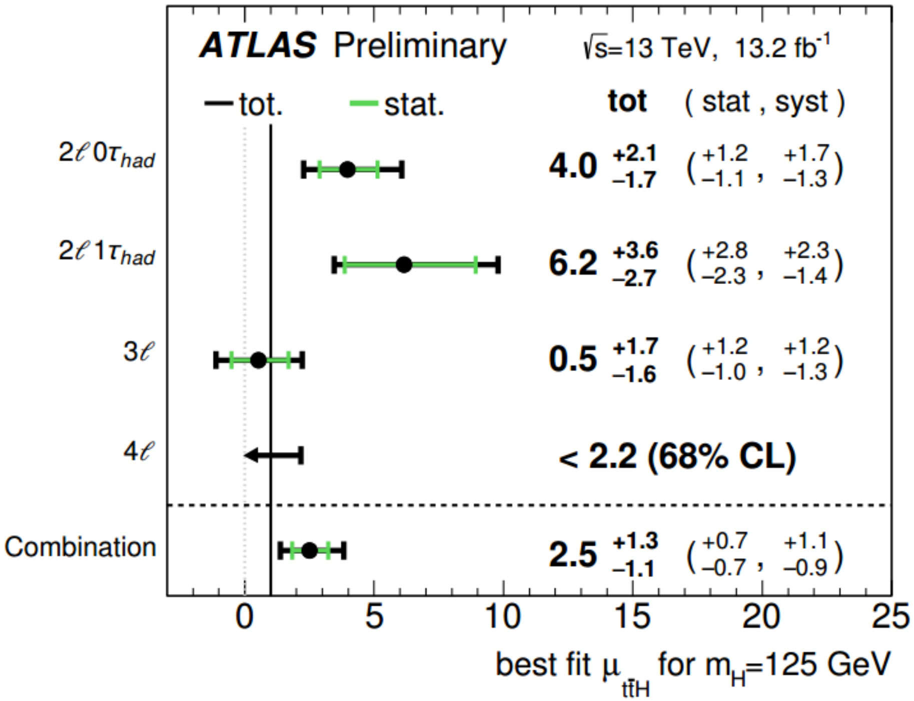
	$2\ell 0\tau_{\rm had}$ ee	$2\ell 0\tau_{\rm had}$ $e\mu$	$2\ell 0\tau_{\rm had}$ $\mu\mu$	$2\ell 1\tau_{\rm had}$	3ℓ	4ℓ
$t\bar{t}W$	2.9 ± 0.7	9.1 ± 2.5	6.6 ± 1.6	0.8 ± 0.4	6.1 ± 1.3	—
$t\bar{t}(Z/\gamma^*)$	1.55 ± 0.29	4.3 ± 0.9	2.6 ± 0.6	1.6 ± 0.4	11.5 ± 2.0	1.12 ± 0.20
Diboson	0.38 ± 0.25	2.5 ± 1.4	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

Pre-fit background and signal predictions and observed data yields for each signal region

Agreement between Data and MC is fine overall



Fit Result and Systematic

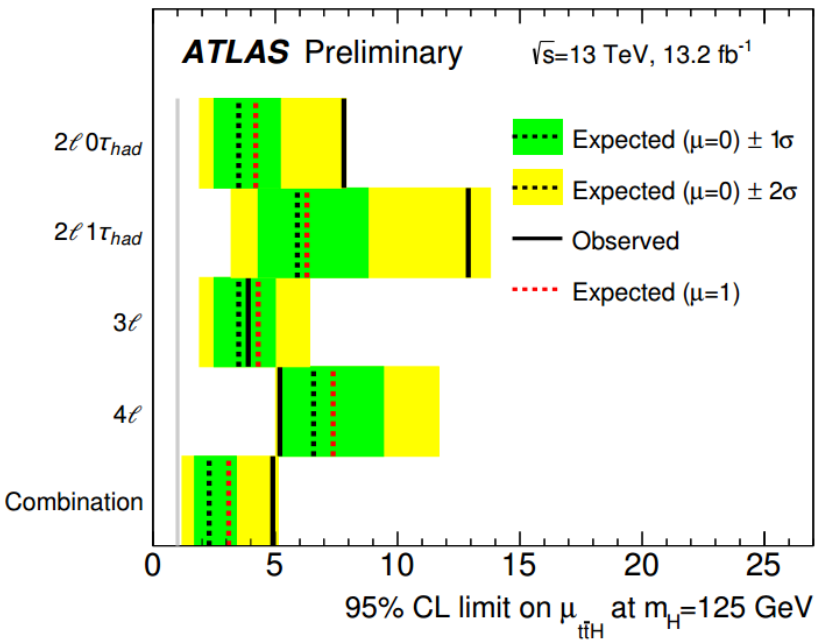


Uncertainty Source	$\Delta\mu$	
Non-prompt leptons and charge misreconstruction	+0.56	−0.64
Jet-vertex association, pileup modeling	+0.48	−0.36
$t\bar{t}W$ modeling	+0.29	−0.31
$t\bar{t}H$ modeling	+0.31	−0.15
Jet energy scale and resolution	+0.22	−0.18
$t\bar{t}Z$ modeling	+0.19	−0.19
Luminosity	+0.19	−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

The best-fit value of μ (combining all channels) is $2.5 \pm 0.7\ (stat)^{+1.1}_{-0.9}(syst)$
Systematic are dominant, main source are come from fake and QmissID

Observed significance: 2.2 sigma (1.3 expected from SM)

Expected and Observed Limits



Category	Best fit $\mu_{t\bar{t}H}$	Observed (expected) 95% CL upper limit	Signal-injected 95% CL upper limit
$2\ell 0\tau_{\mathrm{had}}$	$4.0\,^{+1.2}_{-1.1}\,^{+1.7}_{-1.3}$	$7.8\ (3.5\,^{+1.7}_{-1.0})$	4.2
$2\ell 1\tau_{\mathrm{had}}$	$6.2\,^{+2.8}_{-2.3}\,^{+2.3}_{-1.4}$	$12.9\ (5.9\,^{+2.9}_{-1.6})$	6.3
3ℓ	$0.5\,^{+1.2}_{-1.0}\,^{+1.2}_{-1.3}$	$3.9\ (3.5\,^{+1.5}_{-1.0})$	4.3
4ℓ	< 2.2 (68% CL)	$5.2\ (6.6\,^{+2.9}_{-1.4})$	7.4
Combined	$2.5\,^{+0.7}_{-0.7}\,^{+1.1}_{-0.9}$	$4.9\ (2.3\,^{+1.1}_{-0.6})$	3.1

95% CL upper limit on ttH signal strength: 4.9 (2.3 expected from bkg-only)

Conclusions

A search for ttH production process has been performed ttH (multilepton) using 13.2 fb^{-1} of pp collision data at √s = 13 TeV, recorded by the ATLAS experiment

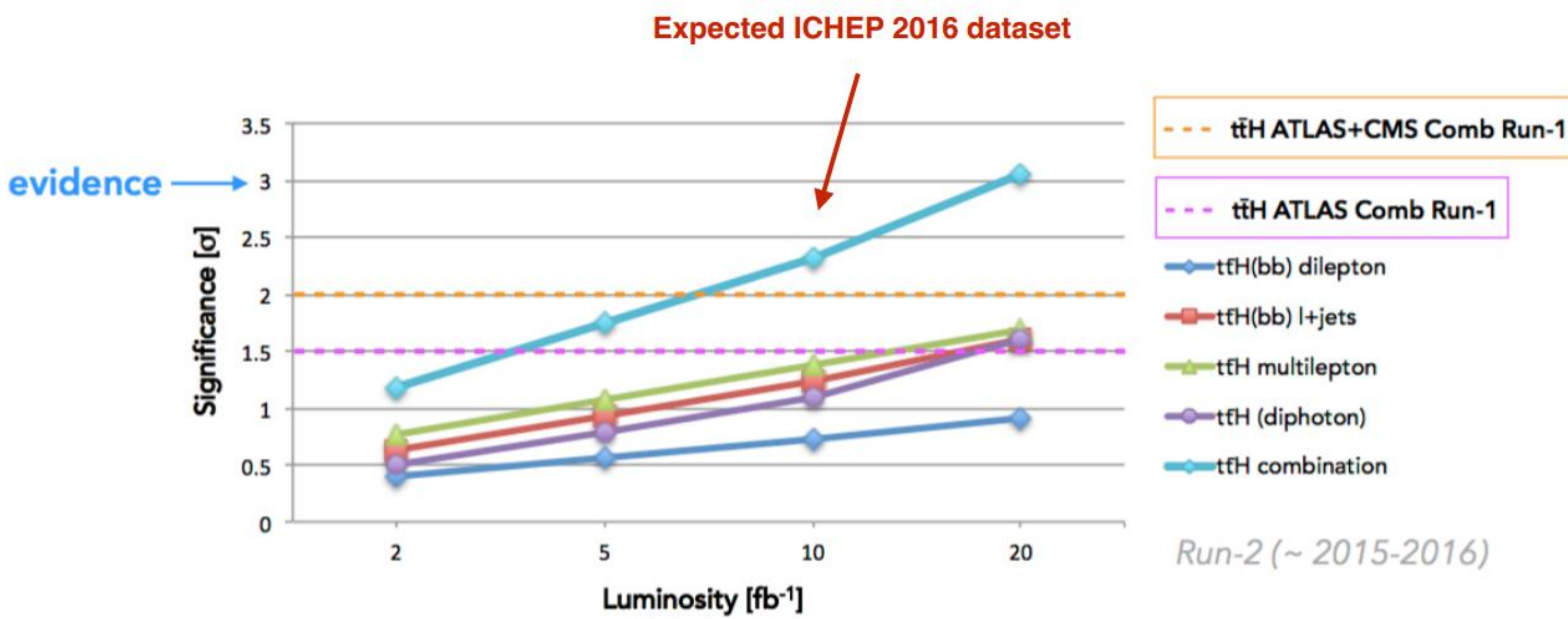
- ✓ The best fit value of the ttH signal strength is 2.5 ± 0.7
- ✓ Observed significance: 2.2 sigma (1.3 expected from SM)
- ✓ 95% CL upper limit on ttH signal strength: 4.9 (2.3 expected from bkg-only)

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

Better precision with new tunes on full 2015 + 2016 dataset

Thank you for your attention!

Backup



Expected ICHEP 2016 dataset
evidence
3.5
3
2.5
2
1.5
1
0.5
0
Significance [σ]
2
5
10
20
Luminosity [fb⁻¹]
tt̄H ATLAS+CMS Comb Run-1
tt̄H ATLAS Comb Run-1
tt̄H(bb) dilepton
tt̄H(bb) l+jets
tt̄H multilepton
tt̄H (diphoton)
tt̄H combination
Run-2 (~ 2015-2016)

Object definition (loose) and overlap removal

- trigger selection (unprescaled single lepton triggers)
  - 2015: HLT_e24_lhmedium_L1EM20VH || HLT_e60_lhmedium || HLT_e120_lhloose || HLT_mu20_iloose_L1MU15 || HLT_mu50
  - 2016: HLT_e24_lhtight_nod0_ivarloose || HLT_e60_lhmedium_nod0 || HLT_e140_lhloose_nod0 || HLT_mu24_ivarmedium || HLT_mu50

- electron:
  - $p_T > 10$ GeV
  - $|\eta| < 2.47$ without crack
  - LooseAndBLayerHit identification WP (95 %)
  - $|z_0 \cdot \sin\theta| < 0.5$ mm
  - $|d_0/\sigma(d_0)| < 5$
  - Loose isolation WP

- muon:
  - $p_T > 10$ GeV
  - $|\eta| < 2.5$
  - Loose ID WP
  - $|z_0 \cdot \sin\theta| < 0.5$ mm
  - $|d_0/\sigma(d_0)| < 3$
  - Loose isolation WP

- hadronic tau:
  - $p_T > 25$ GeV
  - $|\eta| < 2.5$
  - $N_{prong} = 1||3$
  - charge of ±1
  - medium BDT ID WP
  - pass elec-OLR

- jet and b-tagging
  - anti-k_t with $R = 0.4$
  - $p_T > 25$ GeV
  - $|\eta| < 2.5$
  - rejected if |JVT|< 0.59 with $p_T < 60$ GeV & $|\eta| < 2.4$
  - B-tagging: 70 % efficiency WP (MV2C10)

- overlap removal (ASG, MuJetPtRatio & MuJetTrkPtRatio off)

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

Object definition (tight in 2lSS, 2lSS+1τ and 3ℓ) and OLR

- electron:
  - $p_T > 25/20/15$ GeV
  - $|\eta| < 1.37$ for 2ℓ**ss**
  - TightLH identification WP
  - $|z_0 \cdot \sin\theta| < 0.5$ mm
  - $|d_0/\sigma(d_0)| < 5$
  - FixedCutTight isolation

- muon:
  - $p_T > 25/20/15$ GeV
  - $|\eta| < 2.5$
  - Loose ID WP
  - $|z_0 \cdot \sin\theta| < 0.5$ mm
  - $|d_0/\sigma(d_0)| < 3$
  - FixedCutTightTrackOnly isolation WP

- hadronic tau:
  - $p_T > 25$ GeV
  - $|\eta| < 2.5$
  - $N_{\text{prong}} = 1||3$
  - charge of ±1
  - medium BDT ID WP
  - pass elec-OLR

- jet and b-tagging
  - anti-k_t with $R = 0.4$
  - $p_T > 25$ GeV
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- overlap removal (ASG, MuJetPtRatio & MuJetTrkPtRatio off)

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 Definition

Channel	Leptons	Hadronic Taus	Jets	B-Tags	Lepton flavour	Trigger match
2ℓ**ss**	**==2** $\Sigma Q_{lep}=\pm 2$ $p_T^{lead} > 25$ GeV $p_T^{sub} > 25$ GeV $\lvert\eta^{elec}\rvert < 1.37$	== 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 (*) $\lvert M_{ll,OS-SF}$ - 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)
4ℓ	**==4** p_T>10 GeV Loose def + Gradient Iso $\Sigma Q_{lep}=0$ $\lvert M_{ll,OS-SF}$ - 91.2 GeV $\rvert > 10$ 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	–	≥ 2	≥ 1	–	at least one trigger matched lepton with $p_T > 25$ GeV (21 GeV for muon in 2015)
2ℓ**ss**+1τ_{had}	**==2** $\Sigma Q_{lep}=\pm 2$ $p_{T,lep}^{lead} > 25$ GeV $p_{T,lep}^{sub} > 15$ GeV $\lvert M_{ee}$ - 91.2 GeV $\rvert > 10$ GeV	== 1 Q_τ = -Q_{lep}	$\geq$4	$\geq$1	–	at least one trigger matched lepton with $p_T > 25$ GeV (21 GeV for muon in 2015)

* in 3ℓ channel: $\ell 0$ is lepton with opposite charge to $\ell 1$ and $\ell 2$. $\ell 1$ is closest in distance to $\ell 0$.

Contribution of each Higgs decay in the most sensitive signal regions

Channel	Region	WW	$\tau\tau$	ZZ	$b\bar{b}$	$\gamma\gamma$
$H \rightarrow \gamma\gamma$	all-hadronic	–	–	–	–	100%
	leptonic	–	–	–	–	100%
$H \rightarrow (WW, \tau\tau, ZZ)$	2ℓSS ee	76%	17%	2%	4%	–
	2ℓSS $e\mu$	77%	17%	3%	3%	–
	2ℓSS $\mu\mu$	79%	17%	3%	1%	–
	2ℓSS $+\tau_{\mathrm{had}}$	46%	51%	2%	1%	–
	3ℓ	74%	20%	4%	1%	–
	4ℓ	72%	18%	9%	–	–
$H \rightarrow b\bar{b}$	ℓ+jets ($\geq$ 6j,3bj)	5%	1%	1%	90%	–
	ℓ+jets (5j,$\geq$ 4bj)	–	–	–	99%	–
	ℓ+jets ($\geq$ 6j,$\geq$ 4bj)	1%	–	1%	97%	–
	dilepton ($\geq$ 4j,3bj)	6%	1%	1%	90%	–
	dilepton ($\geq$ 4j,$\geq$ 4bj)	–	–	–	98%	–

Fakes in 3l

- estimation using fake factors (assume stability with jet multiplicity)

$$\theta_\ell = \frac{N_{\ell\ell}}{N_{\ell\not\ell}}(\leq 4\text{jets}) = \frac{N_{\ell\ell}^{\text{Data}} - N_{\ell\ell}^{\text{Prompt ss}} - N_{\ell\ell}^{\text{QMisId}}}{N_{\ell\not\ell}^{\text{Data}} - N_{\ell\not\ell}^{\text{Prompt ss}} - N_{\ell\not\ell}^{\text{QMisId MC}}}$$

- predict fake yields in ee, $e\mu$ and $\mu\mu$ signal regions:

$$N_{\ell\ell}(\geq 5\text{jets}) = \theta_\ell \cdot N_{\ell\not\ell}(\geq 5\text{jets})$$

- closure test in $e\mu(\leq 4\text{jets})$: $\frac{\text{Data}}{\text{Pred.}} = 1.15 \pm 0.10(\substack{\text{stat.}\\ \text{data}}) \pm 0.22(\text{fakes, QMisId})$
- apply fake factors from 2ℓ**ss** on **ss** leptons in 3ℓ signal region

$$N_{x\ell\ell} = \theta_\ell \cdot N_{x\ell\not\ell}$$

Fakes in 2lSS1tau and 4l

2lSS1tau

- data-driven fake estimates from 2D side-band method (ABCD, A=SR)
- Event yields in regions A, B, C and D:

	2 tight leptons	1 tight and 1 loose lepton
$N_{\text{jet}} \geq 4$	A=SR	B
$N_{\text{jet}} = 2\|\|3$	C	D

- Prompt events subtracted from data, correction factor is applied to deal with tau compositions in signal region

$$k_{\text{corr}} = 1.02 \pm 0.29$$

- systematic uncertainties:
  - MC closure test
  - QMisId systematic
  - MC truth bias statistics
- estimate of fake processes in SR:

$$N^{\text{A}}_{\text{fake}} = \frac{N^{\text{C}}_{\text{Data-MC-QMisID}}}{N^{\text{D}}_{\text{Data-MC-QMisID}}} N^{\text{B}}_{\text{Data-MC-QMisID}} \cdot k_{\text{corr}}$$

4l

- Principle: two categories of fake source:
  - Z-like: fake leptons (mostly) coming from light-jets
  - top-like: fake leptons (mostly) coming from b-jets

$$N^{f,\text{CR}}_{\text{Data}} - N^{f,\text{CR}}_{\text{others}} = \lambda^{f}_{b} \cdot N^{f,\text{CR}}_{t\bar{t}} + \lambda^{f}_{l} \cdot N^{f,\text{CR}}_{Z+\text{jets}}$$