ATLAS measurements on ttH

Run 2 results, 13 TeV 13.2 fb^{-1}

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DESY LHC discussion on ttH

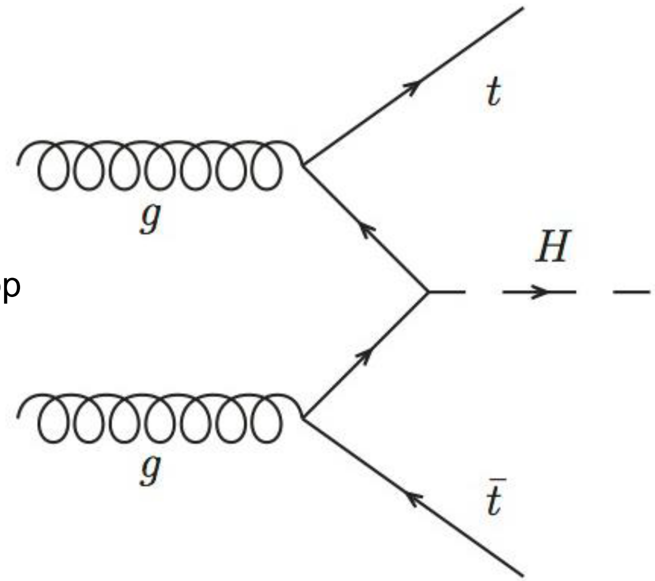
Motivation

Some open questions after the discovery of the Higgs boson:

- Does it obey the Standard Model?
- How does it couple to fermions?

ttH measurement:

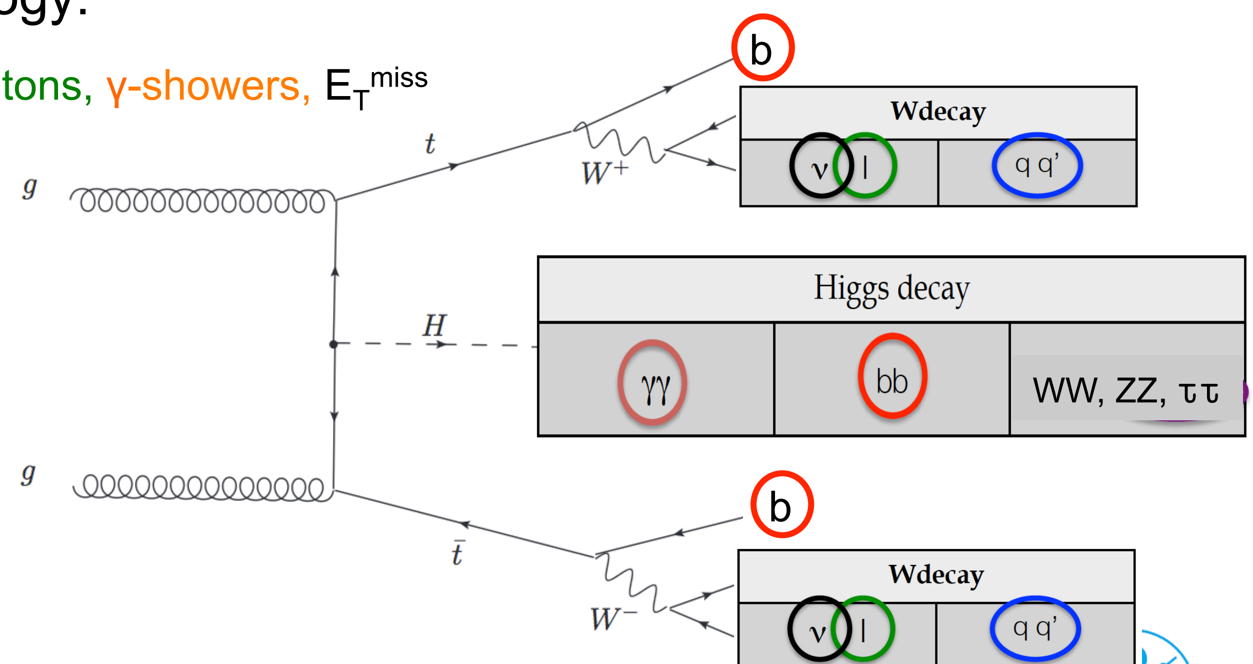
- Direct probe of Higgs-top Yukawa coupling y_{top}
  - Cross section proportional to y_{top}^2
  - Strongest Higgs to fermion coupling (SM $y_{top} \approx 1$)
- A deviation could indicate new physics
  - y_{top} linked to scale of new physics (arXiv:1411.1923)

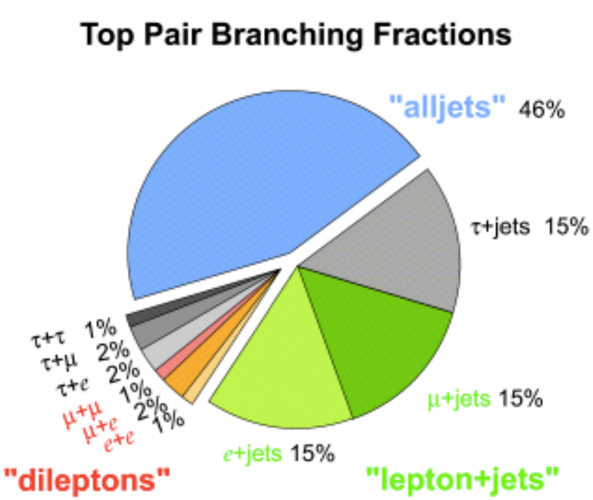


Search for ttH process

- ttH cross section at 13 TeV is 507 fb
  - Only ~1% of ggF Higgs production
  - Limited statistics is challenging
- Need to search in many Higgs decay modes, total ~89% BR
- Complex event topology:
  - B-jets, Non-b jets, Leptons, γ-showers, E_T^{miss}

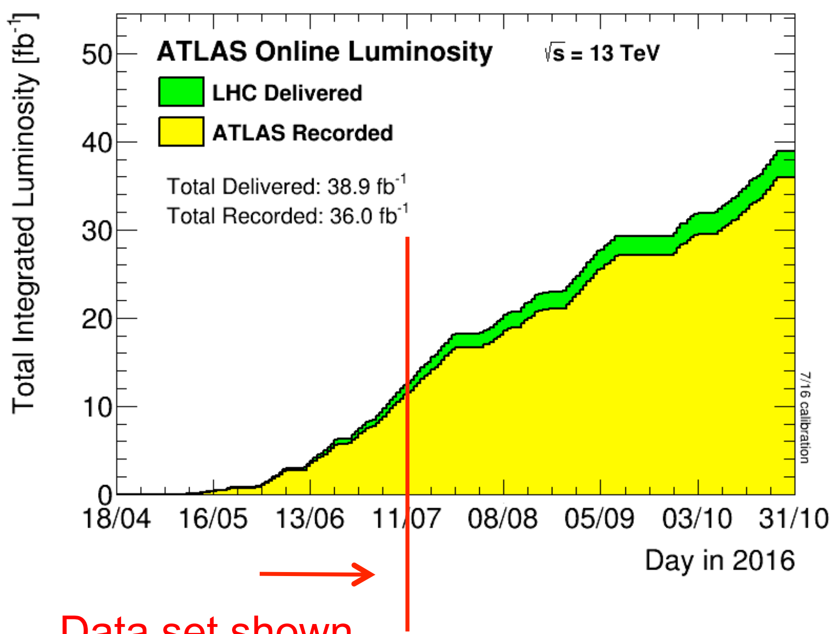
Higgs decay mode	Branching ratio [%]
H→ bb	58.1
H→ WW	21.5
H→ ττ	6.3
H→ ZZ	2.6
H→ γγ	0.23





Search for ttH process

- Search split into three analyses & combination
- Here I show the 13 TeV, 13.2 fb^{-1} results first shown at ICHEP2016



Data set shown

- Bulk of Run 2 still to come!

Higgs decay mode	Branching ratio [%]
$H \rightarrow bb$	58.1
$H \rightarrow WW$	21.5
$H \rightarrow \tau\tau$	6.3
$H \rightarrow ZZ$	2.6
$H \rightarrow \gamma\gamma$	0.23

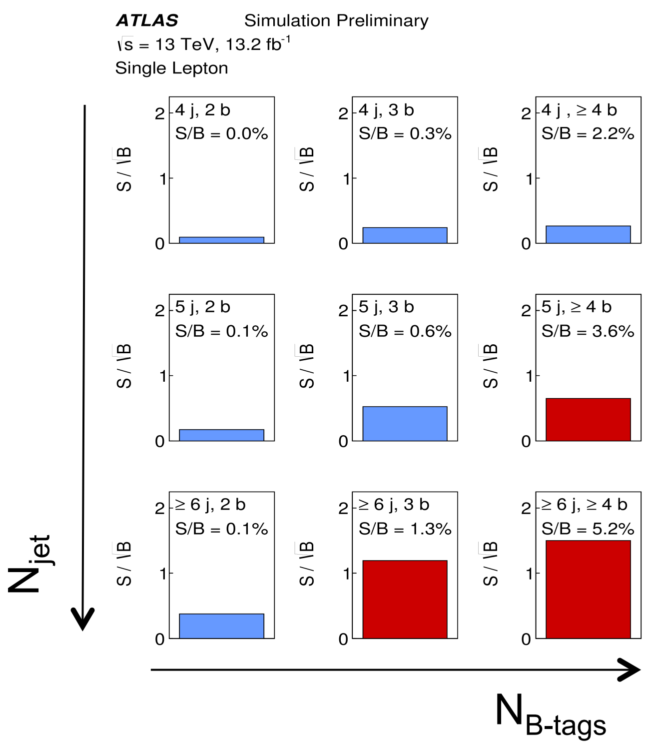
ttH, H to	Conference note
bb	ATLAS-CONF-2016-080
WW, ZZ, $\tau\tau$ (multi leptons)	ATLAS-CONF-2016-058
$\gamma\gamma$	ATLAS-CONF-2016-067
combination	ATLAS-CONF-2016-068

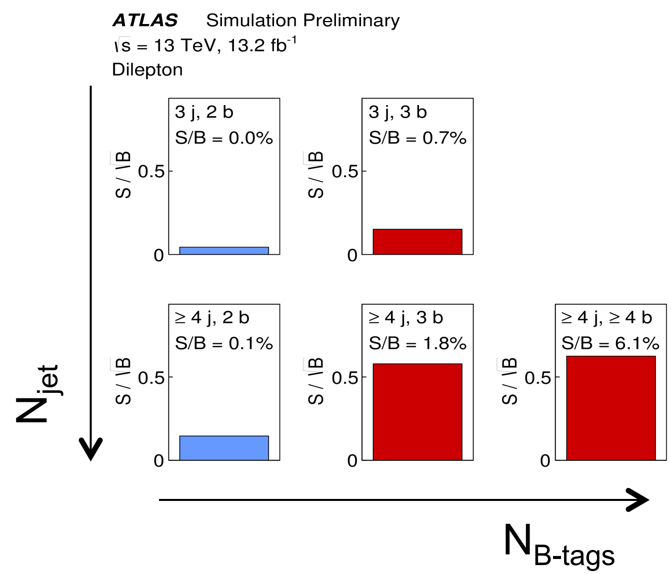
ttH (H->bb) Signal Regions

- ttH(bb) channel has largest branching ratio but large backgrounds
- Events selected by single lepton trigger
- Categorisation by # of reconstructed jets and # of b-tagged jets

Single lepton channel
- One tight electron or muon
- At least 4 jets
- At least 2 b-tagged jets

Di-lepton channel
- 2 tight opposite charge leptons (e or μ)
- At least 3 jets
- At least 2 b-tagged jets





Control region

Signal region

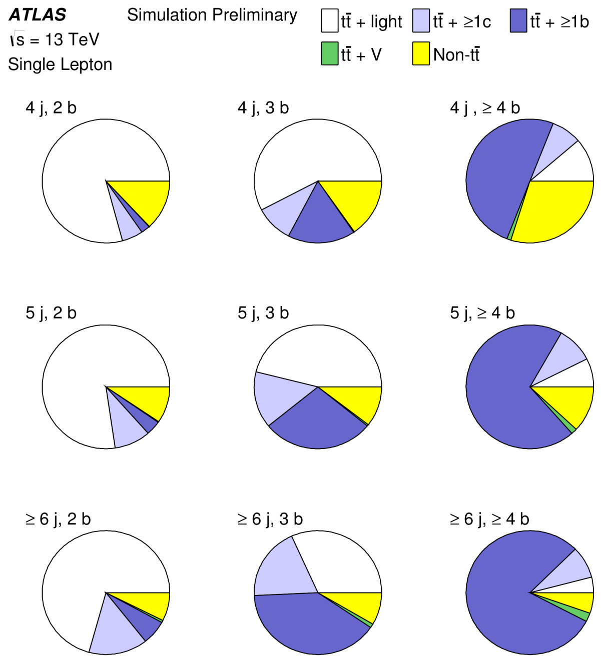
Anti-k_T , R=0.4 jets with p_T> 25 GeV
70% B-tag efficiency

ttH (H->bb) background composition

- Exploit different background compositions in simultaneous fit of all regions to reduce uncertainties and normalise backgrounds
- tt+≥1b-jet, tt+≥1c-jet and tt+light-jets are the dominant backgrounds

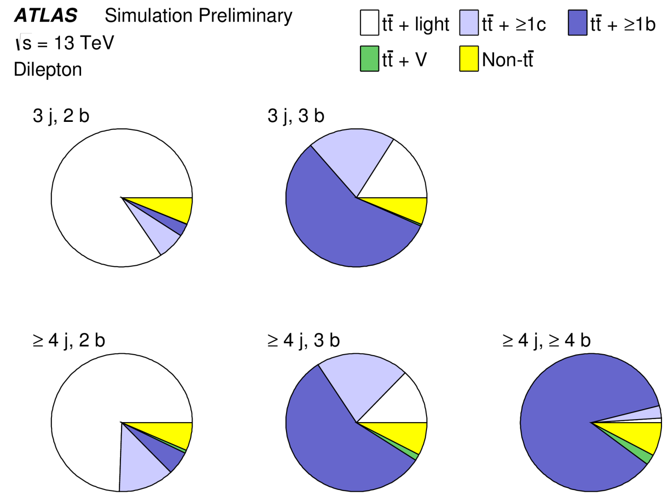
Single lepton channel

- One tight electron or muon
- At least 4 jets
- At least 2 b-tagged jets



Di-lepton channel

- 2 tight opposite charge leptons (e or μ)
- At least 3 jets
- At least 2 b-tagged jets

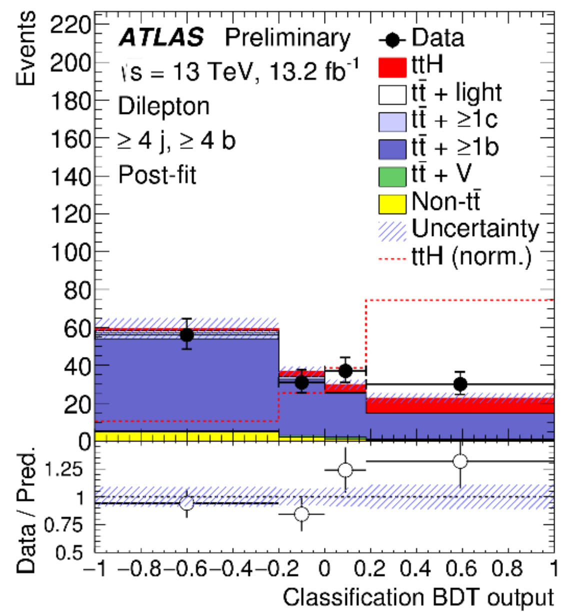


ttH (H->bb) Discriminating variables

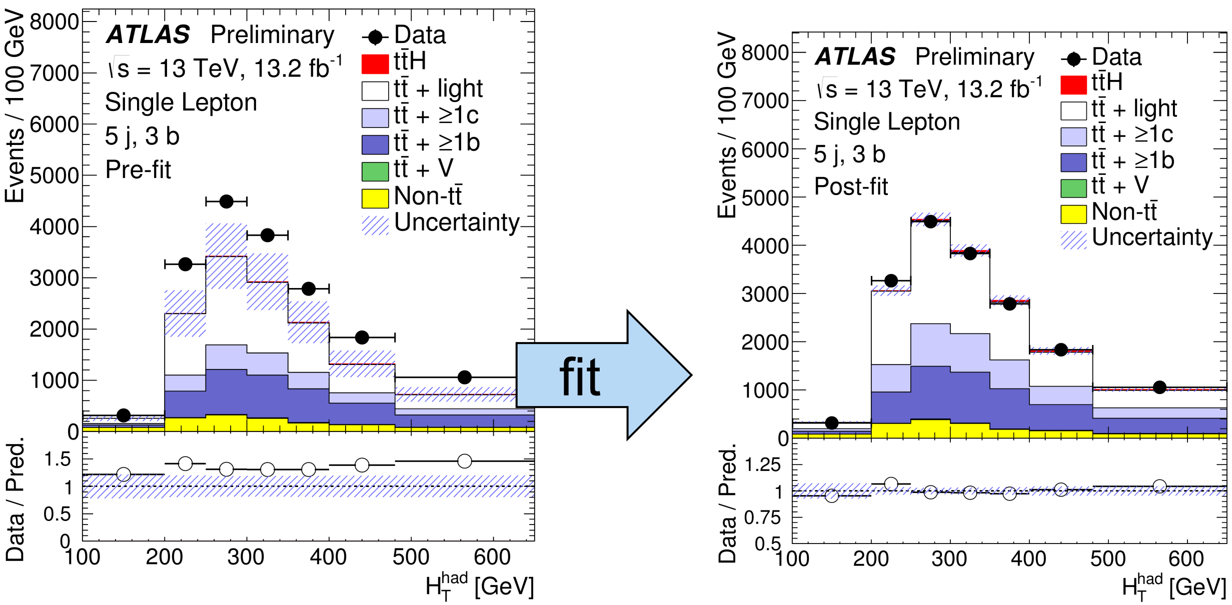
- H_t^{had} : scalar sum of all jets in single lepton channel
- H_t^{all} : scalar sum of jets +leptons in dilepton channel

} Control regions

- Two stage multivariate discriminate in signal regions
  - Reco BDT: match jet to Higgs and top decays
  - Classification BDT or NN: separate signal from background



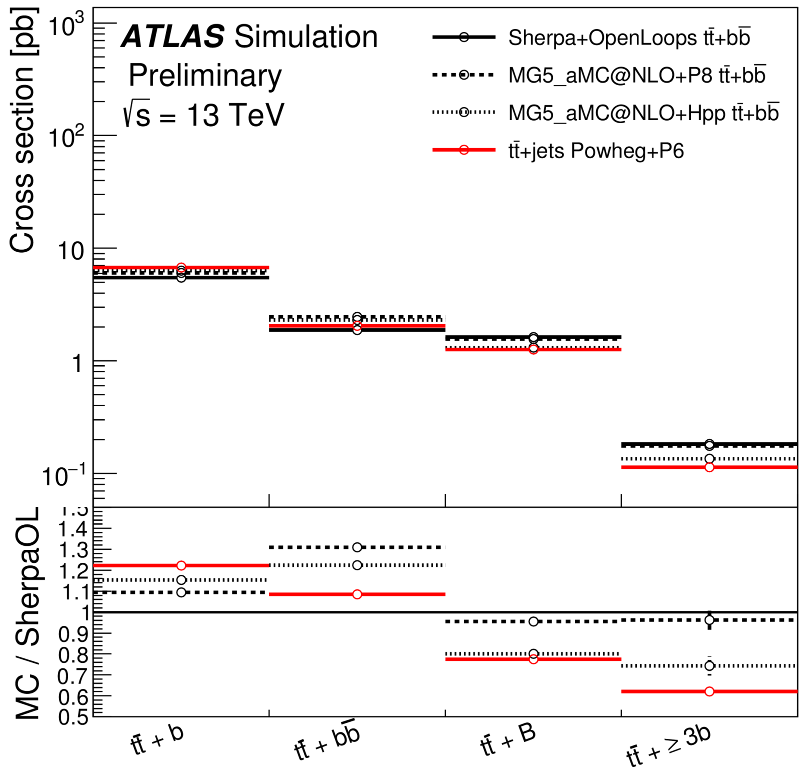
- Profile likelihood fit in all regions



ttH (H->bb): tt+jets background modelling

- tt+jets estimate is leading uncertainty
- Use PoPy6 NLO+PS
  - Correct p_T^{top} & p_T^{tt} at NNLO
- tt+≥1b corrected to 4-flavour scheme NLO tt+bb calculation with Sherpa+OpenLoops
- tt+≥1b and tt+≥1c normalisation treated as free parameters in the fit to data

Reweighting of PoPy6 to Sherpa+OpenLoops



tt+b: b-jet has a b-hadron matched to jet
tt+B: B-jet has two b-hadrons matched to one jet

ttH (H->bb): tt+jets uncertainties

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53
Jet flavour tagging	+0.26	−0.26
$t\bar{t}H$ modelling	+0.32	−0.20
Background model statistics	+0.25	−0.25
$t\bar{t}+\geq 1c$ modelling	+0.24	−0.23
Jet energy scale and resolution	+0.19	−0.19
$t\bar{t}$+light modelling	+0.19	−0.18
Other background modelling	+0.18	−0.18
Jet-vertex association, pileup modelling	+0.12	−0.12
Luminosity	+0.12	−0.12
$t\bar{t}Z$ modelling	+0.06	−0.06
Light lepton (e,μ) ID, isolation, trigger	+0.05	−0.05
Total systematic uncertainty	+0.90	−0.75
$t\bar{t}+\geq 1b$ normalisation	+0.34	−0.34
$t\bar{t}+\geq 1c$ normalisation	+0.14	−0.14
Statistical uncertainty	+0.49	−0.49
Total uncertainty	+1.02	−0.89

Dominant uncertainties:

- tt+jets background model

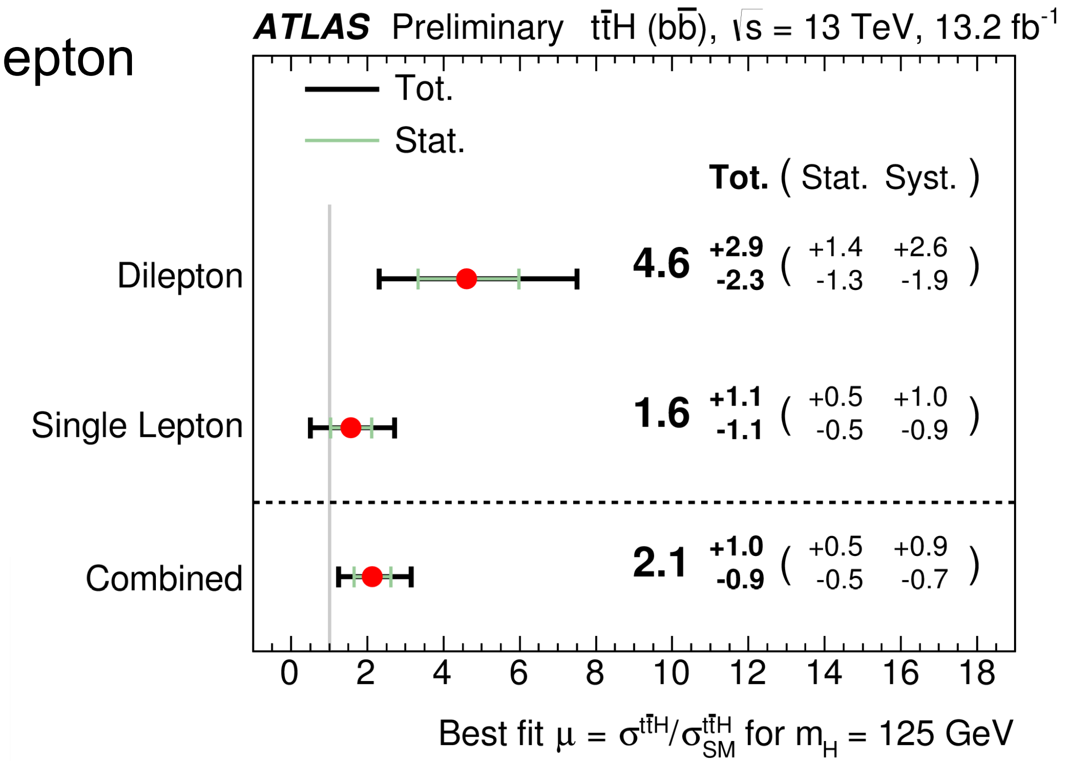
Main experimental uncertainties:

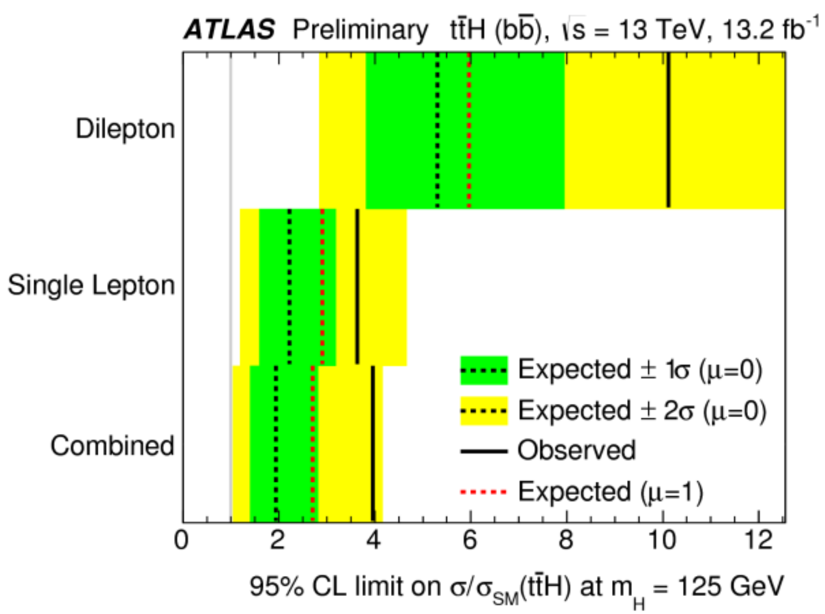
- Jet flavour tagging
- Jet energy scale and resolution

Systematically dominated with still large statistical limitation

ttH (H->bb) Results

- Combination driven by single lepton channel sensitivity
- Best fit at $\mu_{ttH}=2.1^{+1.0}_{-0.9}$





- Observed 95% C.L. upper limit is 4.0 times SM cross section

ttH multi-leptons (H->WW) or (H->ττ) or (H->ZZ)

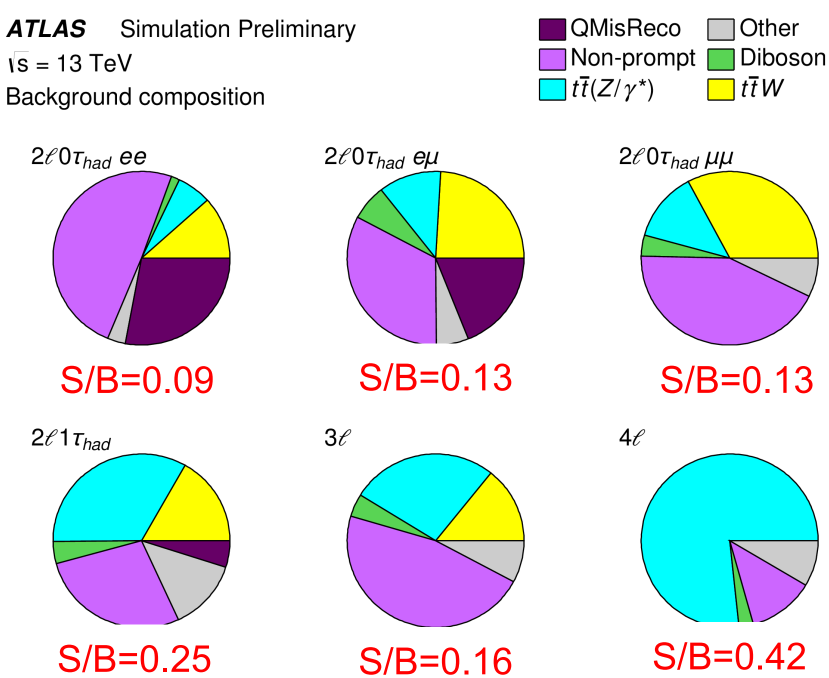
> ttH (multi. lep.) has small signal with small background

Categorised in 4 orthogonal channels with ≥1 b-jet :

2 same charge light leptons, no τ_{had}, ≥5j
2 same charge light leptons, one τ_{had}, ≥4j
3 light leptons, ≥3j
4 light leptons, ≥2j

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

τ_{had}: hadronic decay of a τ candidate from BDT on calorimeter and track info



Dominant background:

> ttV, VV (from MC)

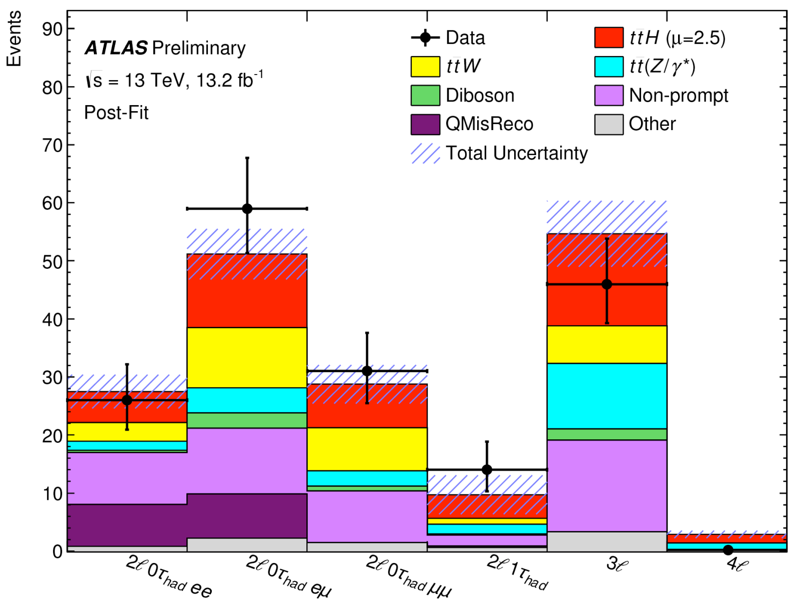
> Non-prompt leptons (estimated from data control regions)

> Electron charge mis-ID (Z+jets data)

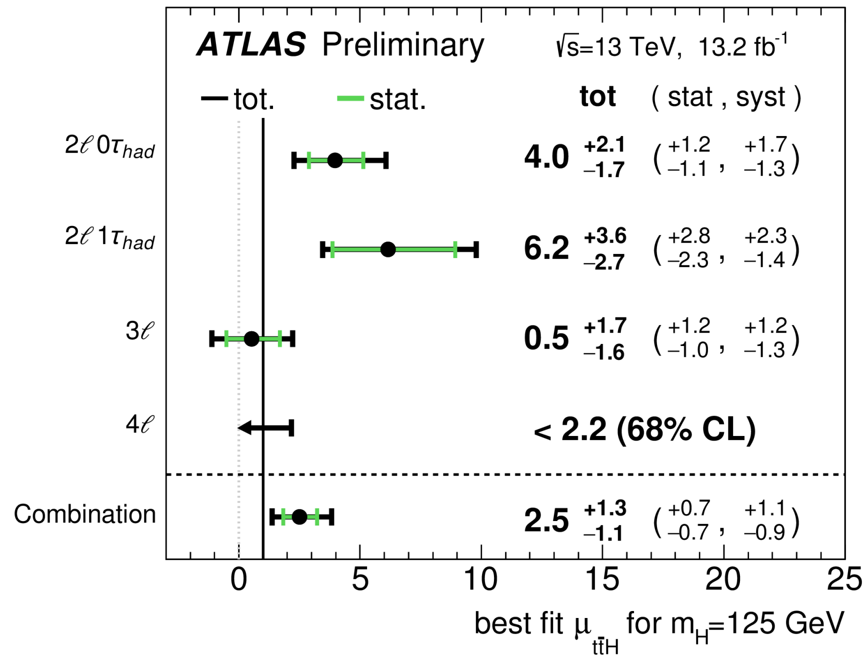
> τ_{had} mis-reco (MC normalised to data control regions)

ttH multi-leptons Results

- Cut and Count analysis in 6 categories + fit



Post-fit predicted yields vs data



Best fit values

- Systematic dominated by non-prompt background estimates
- 4 lep has zero observed events
- observed excess over background-only 2.2 σ

ttH (H->γγ)

- ttH (H->γγ) channel exploits high di-photon mass resolution of Higgs peak over background continuum
- Events selected: 2 tight, isolated photons with $E_T/m_{\gamma\gamma}$>0.35 (0.25) and …

Leptonic channel
- At least 1 tight lepton
- At least 2 jets
- At least 1 b-tagged jet
- Z veto (m_{ll} & $m_{e\gamma}$)
- E_t^{mis} >20 GeV for 1-tag events

Hadronic channel
- No tight lepton
- At least 5 jets
- At least 1 b-tagged jets

- Photon pair mass used as discriminating variable

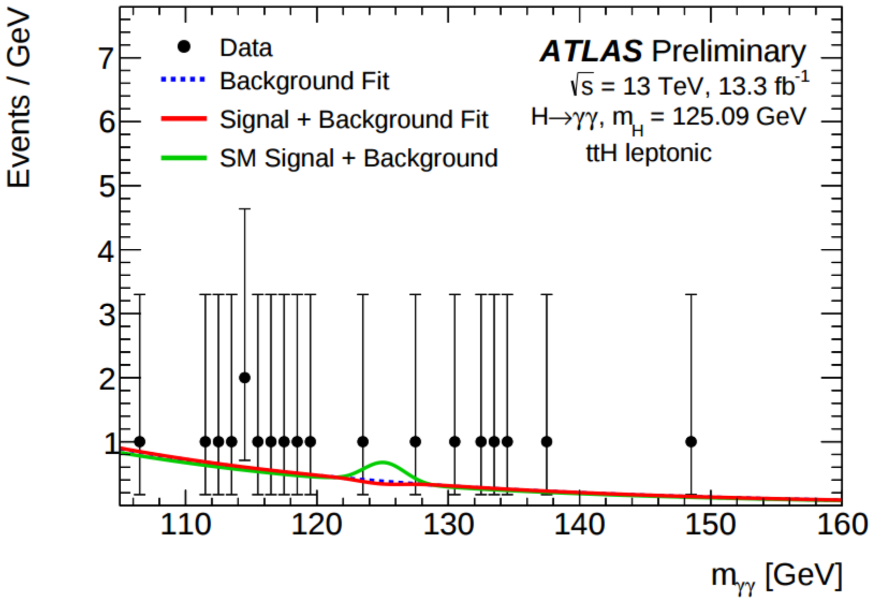
Channel	Region	$t\bar{t}H$ (S)	Bkgd (B)	$tHjb+WtH$	S/B	N_{Data}
$H \to \gamma\gamma$	all-hadronic	1.58	8.27	0.10	0.19	9
	leptonic	1.16	2.42	0.10	0.48	2

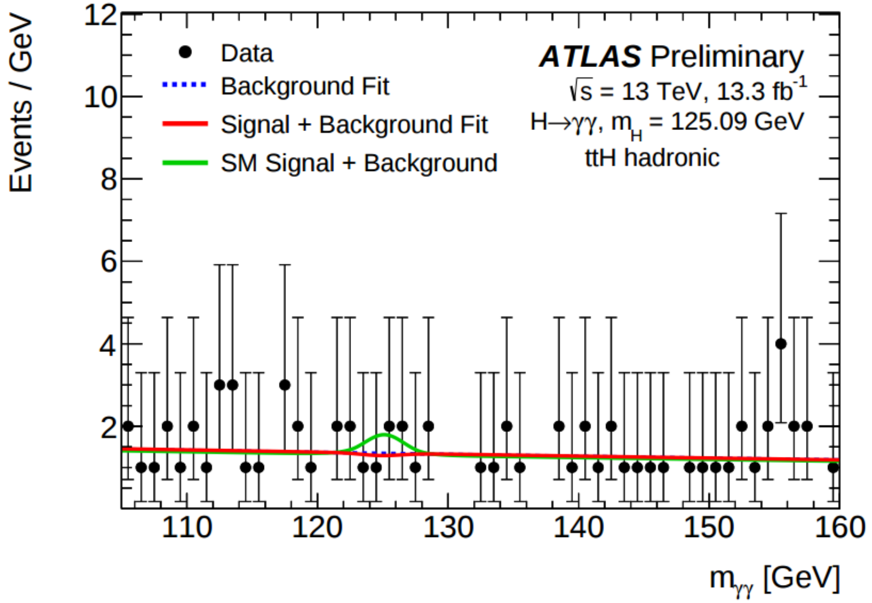
Mass window of $m_{\gamma\gamma}$ [105,160] GeV contains 90% of signal

As in all channels: tHjb and WtH are treated as backgrounds, with SM production

ttH (H->γγ) Results

- Background continuum is estimated from exponential curve, fitted to the data side-bands
- Signal described as 2 sided Crystal Ball function





- Measured signal strength is dominated by statistical uncertainties:

$$\mu_{t\bar{t}H} = -0.3\ ^{+1.2}_{-1.0}\ (\text{tot.})\ [\ ^{+1.2}_{-1.0}\ (\text{stat.})\ ]$$

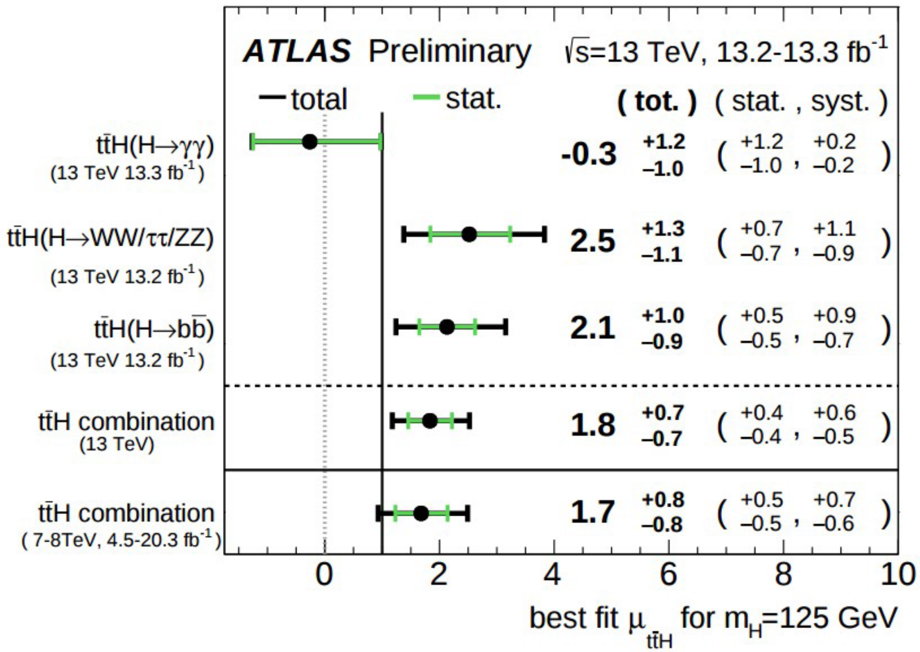
ttH Combination

- Summarise and repeat

	$H \to \gamma\gamma$		$H \to (WW, \tau\tau, ZZ)$				$H \to b\bar{b}$	
Analysis strategy	Narrow signal peak: fit to $m_{\gamma\gamma}$		Small signal and background: counting experiment				Moderate signal in large background: multivariate techniques	
Channels	leptonic	hadronic	2ℓSS	3ℓ	2ℓSS+1τ_{had}	4ℓ	single lepton	dilepton
Control regions	-		-				(4j,2bj) (5j,2bj) (4j,3bj) (4j,4bj) (≥ 6j,2bj) (5j,3bj)	(3j,2bj) (4j,2bj)
Signal regions	$m_{\gamma\gamma}$		(ee) (eμ) ($\mu\mu$) & (≥ 5j,≥ 1bj)	(3j,≥ 2bj OR ≥ 4j,≥ 1bj)	(≥ 4j,≥ 1bj)	(≥ 2j,≥ 1bj)	(5j,≥ 4bj) (≥ 6j,3bj) (≥ 6j,≥ 4bj)	(3j,3bj) (≥ 4j,3bj) (≥ 4j,≥ 4bj)

Channel	Region	$t\bar{t}H$ (S)	Bkgd (B)	$tHjb + WtH$	S/B	$\mathrm{N_{Data}}$
$H \to \gamma\gamma$	all-hadronic	1.58	8.27	0.10	0.19	9
	leptonic	1.16	2.42	0.10	0.48	2
$H \to (WW, \tau\tau, ZZ)$	2ℓSS ee	1.99 ± 0.51	22.2 ± 3.4	0.10 ± 0.03	0.09	26
	2ℓSS $e\mu$	4.82 ± 0.95	38.5 ± 5.1	0.26 ± 0.07	0.13	59
	2ℓSS $\mu\mu$	2.85 ± 0.58	21.2 ± 3.8	0.15 ± 0.04	0.13	31
	2ℓSS $+\tau_{\text{had}}$	1.43 ± 0.31	5.7 ± 1.7	0.11 ± 0.03	0.25	14
	3ℓ	6.2 ± 1.1	38.9 ± 5.3	0.30 ± 0.08	0.16	46
	4ℓ	0.59 ± 0.10	1.42 ± 0.24	0.014 ± 0.006	0.42	0
$H \to b\bar{b}$	ℓ+jets (≥ 6j,3bj)	119 ± 16	11250 ± 240	6.2 ± 1.5	0.011	11561
	ℓ+jets (5j,≥ 4bj)	11.8 ± 2.6	429 ± 28	0.91 ± 0.14	0.028	418
	ℓ+jets (≥ 6j,≥ 4bj)	44.9 ± 9.4	1191 ± 55	2.10 ± 0.50	0.038	1285
	dilepton (≥ 4j,3bj)	20.6 ± 4.2	1423 ± 45	0.71 ± 0.20	0.014	1467
	dilepton (≥ 4j,≥ 4bj)	6.6 ± 2.0	133 ± 12	0.171 ± 0.053	0.050	154

ttH combination Signal Strength



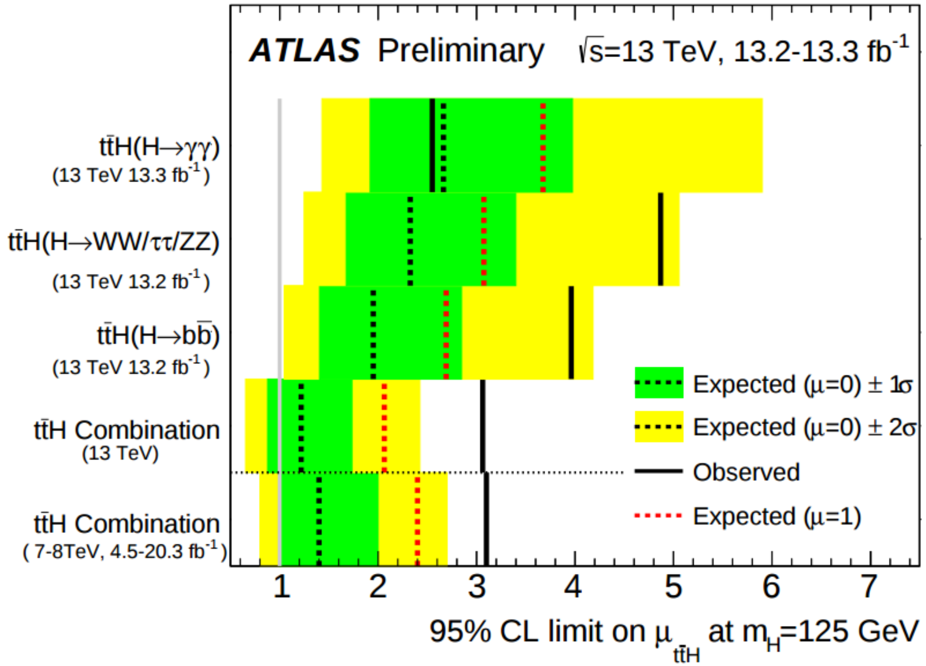
Uncertainty Source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.34	−0.33
Jet flavour tagging	+0.19	−0.19
Background model statistics	+0.18	−0.18
$t\bar{t}+\geq 1c$ modelling	+0.17	−0.17
Jet energy scale and resolution	+0.18	−0.18
$t\bar{t}H$ modelling	+0.20	−0.13
$t\bar{t}$+light modelling	+0.14	−0.14
Other background modelling	+0.16	−0.15
Fake lepton uncertainties	+0.11	−0.12
Jet-vertex association, pileup modelling	+0.09	−0.09
Luminosity	+0.09	−0.09
$t\bar{t}Z$ modelling	+0.08	−0.07
Light lepton (e,μ), photon, and τ ID, isolation, trigger	+0.04	−0.04
Total systematic uncertainty	+0.57	−0.54
$t\bar{t}+\geq 1b$ normalisation	+0.24	−0.24
$t\bar{t}+\geq 1c$ normalisation	+0.11	−0.11
Statistical uncertainty	+0.38	−0.38
Total uncertainty	+0.69	−0.66

Best fit of μ_{ttH} and uncertainty sources

- Higher sensitivity than Run 1 20 fb^{-1} results
- Compatible with SM ttH cross section as well as background-only hypothesis

- Orthogonally of channels ensured by common lepton definition
- Correlated systematics across channels: Xsec, BR, detector effects
- Uncorrelated systematics: leading bkg model uncertainties

ttH combination Significance & Limits



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

- Observed upper limit on μ_{ttH} = 3.1
- Expected limit (bkg only) = 1.4
- Combination is 50% better than dominated bb channel (expected)
- **Observed** (expected) significance is **2.8 σ** (1.8 σ)
- Result is above but still compatible with SM signal hypothesis

Conclusion

- ATLAS search for ttH production process performed in three channels ttH (bb), ttH (multi leptons) and ttH ($\gamma\gamma$)
- Results are shown for 13.3 fb^{-1}, 13 TeV pp collisions
- Best fit value of ttH signal strength w.r.t. SM prediction is 1.8 ± 0.7
  - Observed significance of 2.8 σ (SM expectation of 1.8 σ)
- Sensitivity exceeds Run 1 8 TeV results
- Stay tuned!
  - Greater precision with full 2016 dataset expected
  - ~3x more data from 2016 still to be analysed

Backup

Combination Signal Content

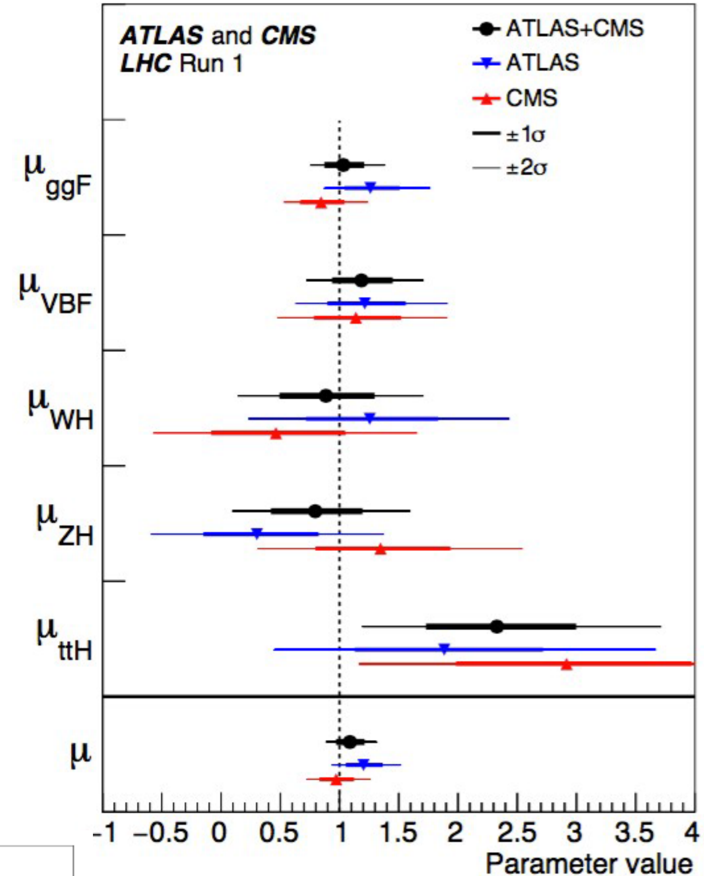
> Signal Region contributions from different sources

Channel	Region	WW	$\tau\tau$	ZZ	$b\bar{b}$	$\gamma\gamma$
$H \to \gamma\gamma$	all-hadronic	–	–	–	–	100%
	leptonic	–	–	–	–	100%
$H \to (WW, \tau\tau, ZZ)$	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%	–	–
$H \to b\bar{b}$	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%	–

Decays to cc, μμ, Zγ, gg are <1%

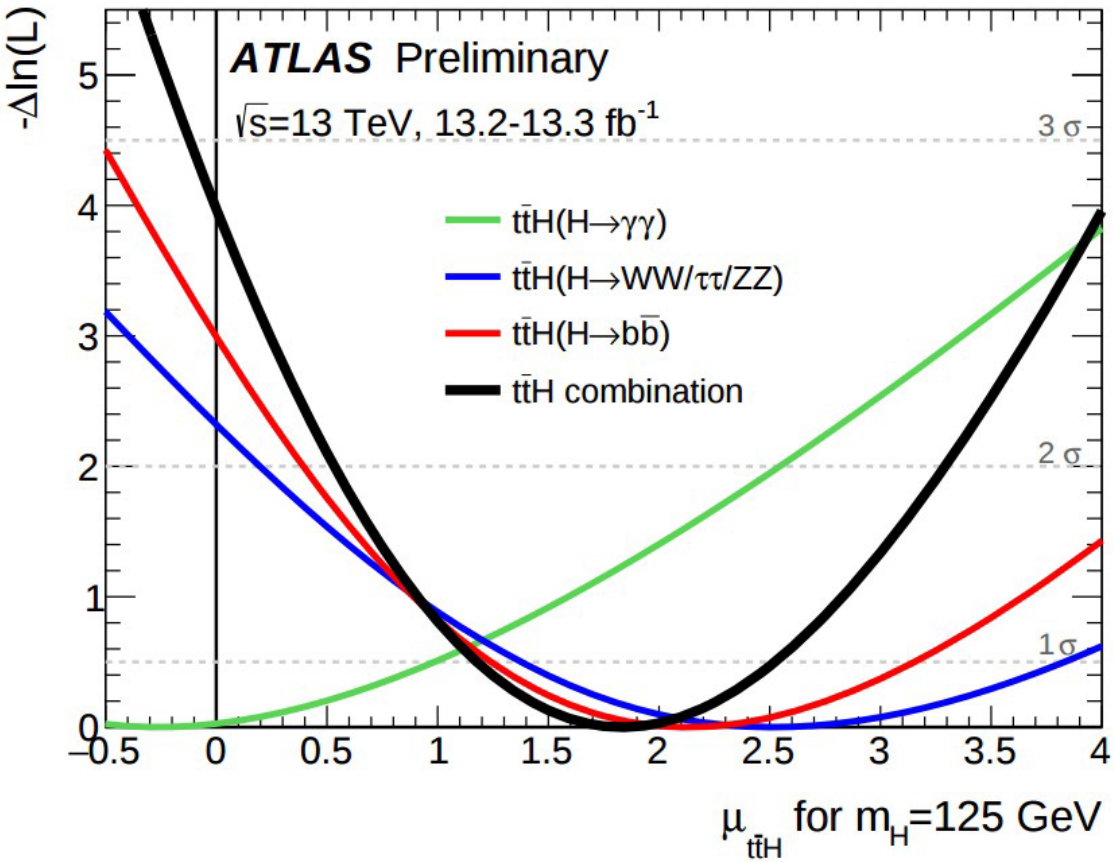
ttH Run 1

- Observed combined significance was found to be 4.4 σ (expected 1.5 σ)
- Assuming the SM prediction of the ttH production, the measurement is able to confirm the presence of ttH over the background estimate with a sensitivity of 2.0 σ.
- LHC Run2 analysis benefits from **large increase of ttH cross section**, though backgrounds increase at a comparable rate in the signal regions



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

ttH combination log likelihood



ttH signal MC

ttH signal MC in all channels:

- NLO QCD matrix element computed by MadGraph5_aMC@NLO (arXiv:1405.0301)
- matched to the Pythia8 parton shower (arXiv:0710.3820)
- SM cross section at 13 TeV of 507 fb taken from the NLO calculation in strong and electroweak couplings (ATLAS-COM-CONF-2016-052)

ttH (bb) tt background

Inclusive tt settings (p_T in centre of mass frame)

ME gen. PS/UE gen.	Powheg-Box Pythia 6.428	Powheg-Box Herwig++ 2.7.1	MG5_aMC Herwig++ 2.7.1	Powheg-Box Pythia 6.428	Powheg-Box Pythia 6.428
Ren. scale	$\sqrt{m_t^2 + p_{\mathrm{T},t}^2}$	$\sqrt{m_t^2 + p_{\mathrm{T},t}^2}$	$\sqrt{m_t^2 + \frac{1}{2}(p_{\mathrm{T},t}^2 + p_{\mathrm{T},\bar{t}}^2)}$	$\frac{1}{2} \cdot \sqrt{m_t^2 + p_{\mathrm{T},t}^2}$	$2 \cdot \sqrt{m_t^2 + p_{\mathrm{T},t}^2}$
Fact. scale	$\sqrt{m_t^2 + p_{\mathrm{T},t}^2}$	$\sqrt{m_t^2 + p_{\mathrm{T},t}^2}$	$\sqrt{m_t^2 + \frac{1}{2}(p_{\mathrm{T},t}^2 + p_{\mathrm{T},\bar{t}}^2)}$	$\frac{1}{2} \cdot \sqrt{m_t^2 + p_{\mathrm{T},t}^2}$	$2 \cdot \sqrt{m_t^2 + p_{\mathrm{T},t}^2}$
hdamp	m_t	m_t	–	$2 \cdot m_t$	m_t
ME PDF	CT10	CT10	CT10	CT10	CT10
PS/UE PDF	CTEQ6L1	CTEQ6L1	CTEQ6L1	CTEQ6L1	CTEQ6L1
Tune	P2012	UE-EE5	UE-EE5	P2012 radHi	P2012 radLo

tt+bb 4 flavour NLO setting

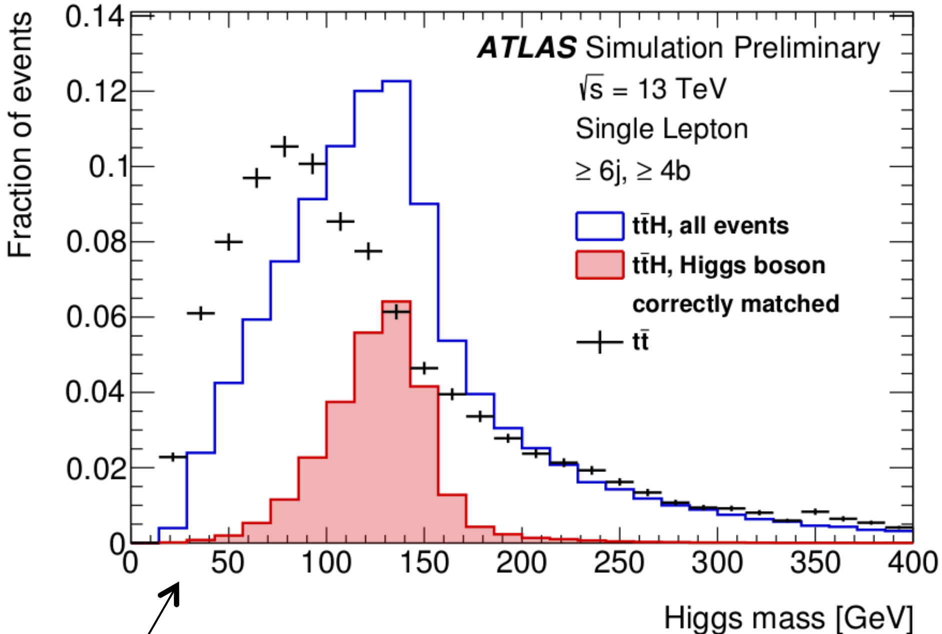
ME gen. PS/UE gen.	MG5_aMC Herwig++ 2.7.1	MG5_aMC Pythia 8.210	SherpaOL Sherpa
Renorm. scale	μ_{CMMPS}	μ_{CMMPS}	μ_{CMMPS}
Fact. scale	$H_{\mathrm{T}}/2$	$H_{\mathrm{T}}/2$	$H_{\mathrm{T}}/2$
Resumm. scale	$f_Q\sqrt{\hat{s}}$	$f_Q\sqrt{\hat{s}}$	$H_{\mathrm{T}}/2$
ME PDF	NNPDF3.0 4F	NNPDF3.0 4F	CT10 4F
PS/UE PDF	CTEQ6L1	NNPDF2.3	
Tune	UE-EE-5	A14	Author's tune

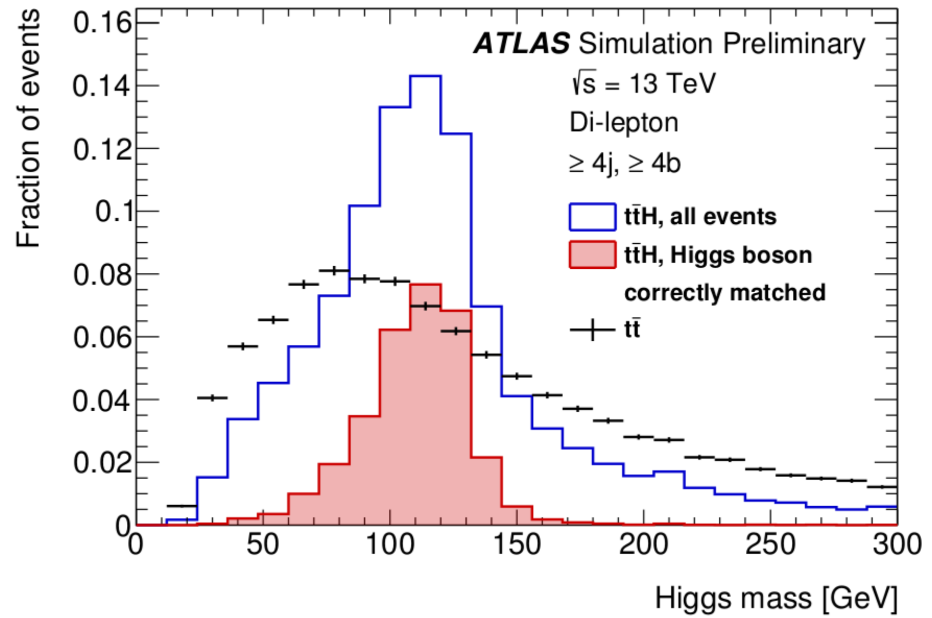
ttH (bb) tt+jets uncertainties

- For the tt + ≥1b background, the inclusive tt sample is reweighted to a NLO tt+bb prediction
- uncertainties on the inclusive sample are labeled residual, while those on the NLO prediction are labeled reweighting.

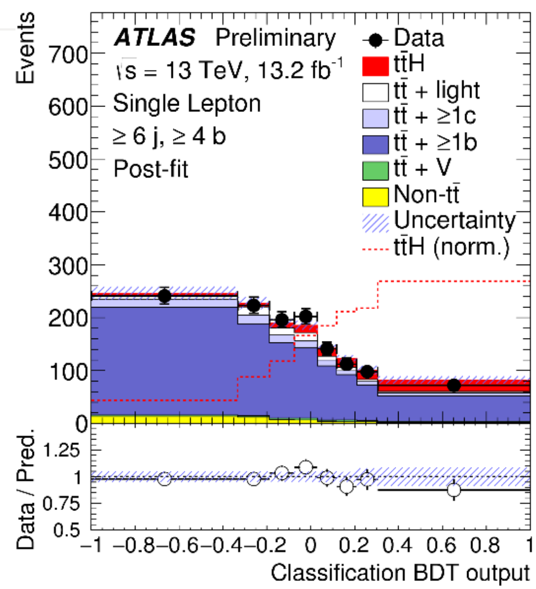
Systematic source	How evaluated	$t\bar{t}$ categories
$t\bar{t}$ cross-section	±6%	All, correlated
NLO generator (*residual*)	Powheg-Box + Herwig++ vs. MG5_aMC + Herwig++	All, uncorrelated
Radiation (*residual*)	Variations of μ_{R}, μ_{F}, and *hdamp*	All, uncorrelated
PS & hadronisation (*residual*)	Powheg-Box + Pythia 6 vs. Powheg-Box + Herwig++	All, uncorrelated
NNLO top & $t\bar{t}$ p_{T}	Maximum variation from any NLO prediction	$t\bar{t}+\geq1c$, $t\bar{t}$ +light, uncorr.
$t\bar{t}+b\bar{b}$ NLO generator *reweighting*	SherpaOL vs. MG5_aMC + Pythia8	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ PS & hadronis. *reweighting*	MG5_aMC + Pythia8 vs. MG5_aMC + Herwig++	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ renorm. scale *reweighting*	Up or down a by factor of two	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ resumm. scale *reweighting*	Vary μ_{Q} from $H_{\mathrm{T}}/2$ to μ_{CMMPS}	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ global scales *reweighting*	Set μ_{Q}, μ_{R}, and μ_{F} to μ_{CMMPS}	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ shower recoil *reweighting*	Alternative model scheme	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ PDF *reweighting*	CT10 vs. MSTW or NNPDF	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ MPI	Up or down by 50%	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ FSR	Radiation variation samples	$t\bar{t}+\geq1b$
$t\bar{t}+c\bar{c}$ ME calculation	MG5_aMC + Herwig++ inclusive vs. ME prediction	$t\bar{t}+\geq1c$

ttH (bb) BDT





Higgs mass after jet to parton matching
12 % full event reconstruction efficiency
30% efficient in reconstructing only the Higgs



Event classification
signal vs bkg

ttH (bb) classification BDT inputs 1 lepton

Variable	Definition	Region $\geq 6j, \geq 4b$	Region $\geq 6j$, 3b	Region 5j, $\geq 4b$
General kinematic variables				
$\Delta R^{\text{avg}}_{\text{bb}}$	Average ΔR for all b-tagged jet pairs	✓	✓	✓
$\Delta R^{\max p_T}_{bb}$	ΔR between the two b-tagged jets with the largest vector sum p_{T}	✓	–	–
$\Delta\eta^{\max}_{\text{jj}}$	Maximum $\Delta\eta$ between any two jets	✓	✓	✓
$m^{\min \Delta R}_{\text{bb}}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	✓	✓	–
$m^{\min \Delta R}_{\text{jj}}$	Mass of the combination of any two jets with the smallest ΔR	–	–	✓
$m^{\max p_T}_{\text{bj}}$	Mass of the combination of a b-tagged jet and any jet with the largest vector sum p_{T}	–	✓	–
$p^{\text{jet5}}_{\mathrm{T}}$	p_{T} of the fifth leading jet	✓	✓	✓
$\mathrm{N}^{\text{Higgs 30}}_{\text{bb}}$	Number of b-jet pairs with invariant mass within 30 GeV of the Higgs boson mass	✓	–	✓
$\mathrm{N}^{\text{jet}}_{40}$	Number of jets with $p_{\mathrm{T}} \geq 40$ GeV	–	✓	–
$H^{\text{had}}_{\mathrm{T}}$	Scalar sum of jet p_{T}	–	✓	✓
$\Delta R^{\min \Delta R}_{\text{lep-bb}}$	ΔR between the lepton and the combination of the two b-tagged jets with the smallest ΔR	–	–	✓
Aplanarity	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [41] built with all jets	✓	✓	✓
Centrality	Scalar sum of the p_{T} divided by sum of the E for all jets and the lepton	✓	✓	✓
$H1$	Second Fox–Wolfram moment computed using all jets and the lepton	✓	✓	✓
Variables from reconstruction BDT output				
BDT output		✓*	✓*	✓*
m_{H}	Higgs boson mass	✓	✓	✓
$m_{\mathrm{H},b_{\text{lep top}}}$	Mass of Higgs boson and b-jet from leptonic top	✓	–	–
$\Delta R_{\text{Higgs bb}}$	ΔR between b-jets from the Higgs boson	✓	✓	✓
$\Delta R_{\mathrm{H},t\bar{t}}$	ΔR between Higgs boson and $t\bar{t}$ system	✓*	✓*	✓*
$\Delta R_{\text{H,lep top}}$	ΔR between Higgs boson and leptonic top	✓	–	–
$\Delta R_{\mathrm{H},b_{\text{had top}}}$	ΔR between Higgs boson and b-jet from hadronic top	–	✓*	✓*

ttH (bb): tt+jets uncertainties

Systematic source	How evaluated	$t\bar{t}$ categories
$t\bar{t}$ cross-section	$\pm 6\%$	All, correlated
NLO generator (*residual*)	Powheg-Box + Herwig++ vs. MG5_aMC + Herwig++	All, uncorrelated
Radiation (*residual*)	Variations of μ_{R}, μ_{F}, and *hdamp*	All, uncorrelated
PS & hadronisation (*residual*)	Powheg-Box + Pythia 6 vs. Powheg-Box + Herwig++	All, uncorrelated
NNLO top & $t\bar{t}$ p_{T}	Maximum variation from any NLO prediction	$t\bar{t}+\geq 1c$, $t\bar{t}$ +light, uncorr.
$t\bar{t}+b\bar{b}$ NLO generator *reweighting*	SherpaOL vs. MG5_aMC+ Pythia8	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PS & hadronis. *reweighting*	MG5_aMC + Pythia8 vs. MG5_aMC + Herwig++	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ renorm. scale *reweighting*	Up or down a by factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ resumm. scale *reweighting*	Vary μ_{Q} from $H_{\mathrm{T}}/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ global scales *reweighting*	Set μ_{Q}, μ_{R}, and μ_{F} to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ shower recoil *reweighting*	Alternative model scheme	$t\bar{t}+\geq 1b$
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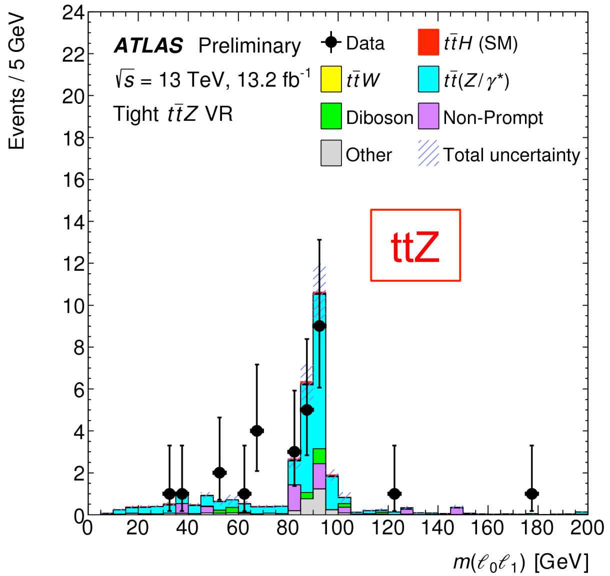
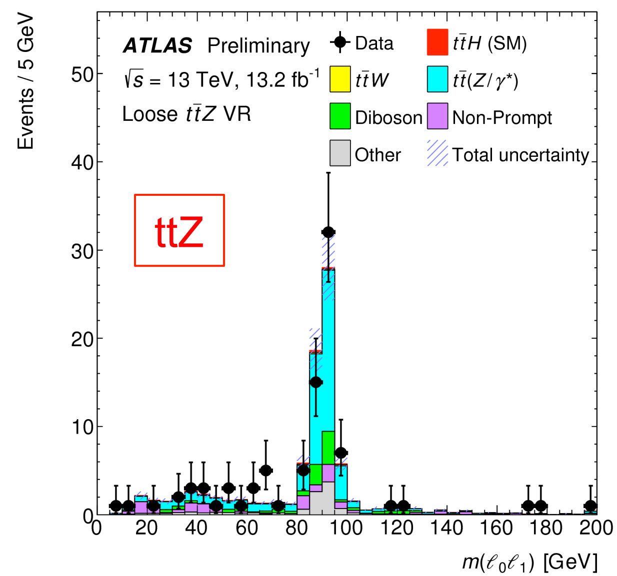
$t\bar{t}+b\bar{b}$ FSR	Radiation variation samples	$t\bar{t}+\geq 1b$
$t\bar{t}+c\bar{c}$ ME calculation	MG5_aMC + Herwig++ inclusive vs. ME prediction	$t\bar{t}+\geq 1c$

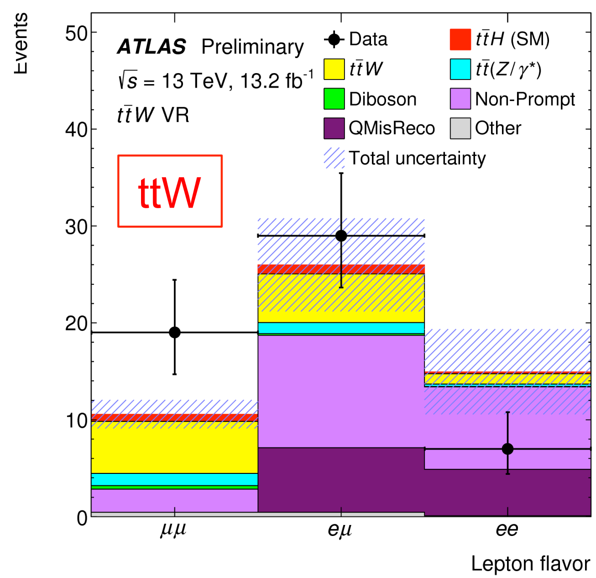
ttH (multi lepton) region definitions

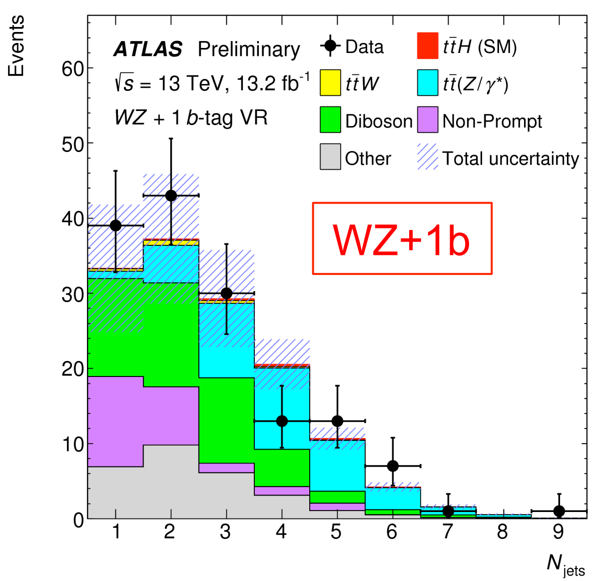
SR/VR	Channel	Selection criteria
SR	$2\ell 0\tau_{\mathrm{had}}$	Two tight light leptons with $p_{\mathrm{T}} > 25$, 25 GeV Sum of light lepton charges ± 2 Any electrons must have $\lvert\eta_e\rvert < 1.37$ Zero τ_{had} candidates $N_{\mathrm{jets}} \geq 5$ and $N_{b-\mathrm{jets}} \geq 1$
SR	$2\ell 1\tau_{\mathrm{had}}$	Two tight light leptons, with $p_{\mathrm{T}} > 25$, 15 GeV Sum of light lepton charges ± 2 Exactly one τ_{had} candidate, of opposite charge to the light leptons $\lvert m(ee) - 91.2\ \mathrm{GeV}\rvert > 10$ GeV for ee events $N_{\mathrm{jets}} \geq 4$ and $N_{b-\mathrm{jets}} \geq 1$
SR	3ℓ	Three light leptons; sum of light lepton charges ± 1 Two same-charge leptons must be tight and have $p_{\mathrm{T}} > 20$ GeV $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\ \mathrm{GeV}\rvert > 10$ GeV for all SFOC pairs $\lvert m(3\ell) - 91.2\ \mathrm{GeV}\rvert > 10$ GeV $N_{\mathrm{jets}} \geq 4$ and $N_{b-\mathrm{jets}} \geq 1$, or $N_{\mathrm{jets}} = 3$ and $N_{b-\mathrm{jets}} \geq 2$
SR	4ℓ	Four light leptons; sum of light lepton charges 0 All leptons pass "gradient" isolation selection $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\ \mathrm{GeV}\rvert > 10$ GeV for all SFOC pairs 100 GeV $< m(4\ell) <$ 350 GeV and $\lvert m(4\ell) - 125\ \mathrm{GeV}\rvert > 5$ GeV $N_{\mathrm{jets}} \geq 2$ and $N_{b-\mathrm{jets}} \geq 1$
VR	Tight $t\bar{t}Z$	3ℓ lepton selection %and trigger selection At least one $\ell^+\ell^-$ pair with $\lvert m(\ell^+\ell^-) - 91.2\ \mathrm{GeV}\rvert < 10$ GeV $N_{\mathrm{jets}} \geq 4$ and $N_{b-\mathrm{jets}} \geq 2$
VR	Loose $t\bar{t}Z$	3ℓ lepton selection %and trigger selection At least one $\ell^+\ell^-$ pair with $\lvert m(\ell^+\ell^-) - 91.2\ \mathrm{GeV}\rvert < 10$ GeV $N_{\mathrm{jets}} \geq 4$ and $N_{b-\mathrm{jets}} \geq 1$, or $N_{\mathrm{jets}} = 3$ and $N_{b-\mathrm{jets}} \geq 2$
VR	$WZ + 1$ b-tag	3ℓ lepton selection %and trigger selection At least one $\ell^+\ell^-$ pair with $\lvert m(\ell^+\ell^-) - 91.2\ \mathrm{GeV}\rvert < 10$ GeV $N_{\mathrm{jets}} \geq 1$ and $N_{b-\mathrm{jets}} = 1$
VR	$t\bar{t}W$	$2\ell 0\tau_{\mathrm{had}}$ lepton selection %and trigger selection $2 \leq N_{\mathrm{jets}} \leq 4$ and $N_{b-\mathrm{jets}} \geq 2$ $H_{\mathrm{T,jets}} > 220$ GeV for ee and $e\mu$ events $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV and ($m(ee) < 75$ or $m(ee) > 105$ GeV) for ee events

ttH multi-leptons Validation Regions









Validation of background modelling in enhanced regions for different processes

- Check normalisation and N_{jet} dependency

ttH (multileptons) uncertainties

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