Evidence for ttH production at the ATLAS detector

13 TeV, 36 fb^{-1} Run 2 results

Paul Glaysher (DESY)

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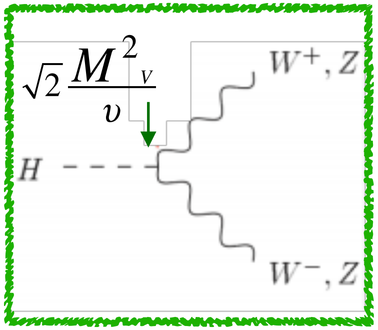
Higgs boson in the Standard Model

- ➡ Through spontaneous symmetry breaking, the **Higgs mechanism** provides masses to bosons
- ➡ The Higgs discovery allows the exploration of a new sector of the SM Lagrangian
- ➡ In the SM the coupling between the Higgs field and the fermions is described by the **Yukawa interaction**

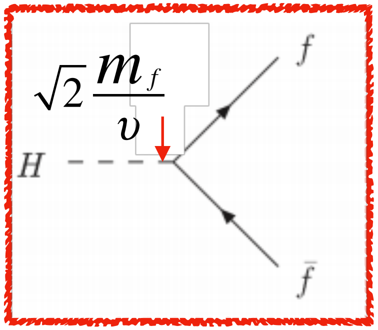
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi + |D_\mu\phi|^2 - V(\phi) + \bar{\psi}_i y_{ij}\psi_j\phi + h.c.$$

coupling to Bosons



Two type of tree-level coupling

coupling to Fermions



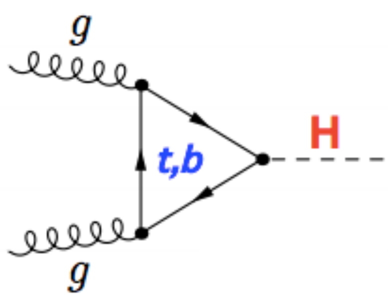
- ➡ Yukawa coupling is proportional to the mass of the fermion
- ➡ Top quark is the heaviest particle in the SM

$$\lambda_t = \sqrt{2}\frac{m_t}{v} \approx \sqrt{2}\frac{173\text{ GeV}}{246\text{ GeV}} \approx 0.99 \approx 1.$$

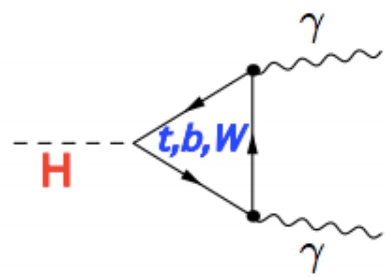
Top quark Yukawa coupling

- Run 1 (ATLAS+CMS) results: top-Higgs coupling (κ_t) = 0.87 (+0.15, -0.15) is consistent with the SM JHEP 08 (2016) 045
  - Determined indirectly from loop processes

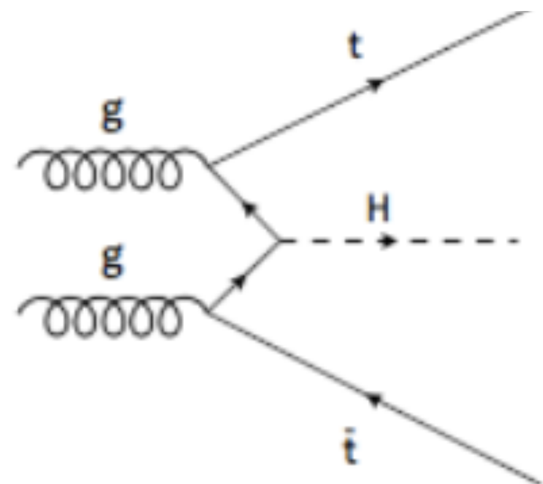
$$\kappa_i^2 = \frac{\lambda^i}{\lambda^i_{SM}}$$



σ_{ggF} = 44 pb



- ttH production gives a direct way to probe the top quark Yukawa coupling
- Tree-level process, cross-section proportional to λ_t^2



σ_{ttH} = 508 fb

Any deviation could hint for new physics!

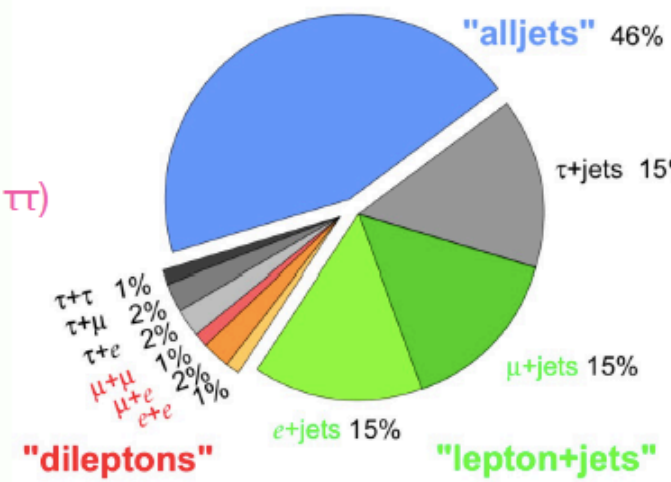
Experimental Challenge

- ttH cross section only 508 fb, ~1% of total Higgs boson cross-section at 13 TeV
- Need to target all Higgs and top decay modes

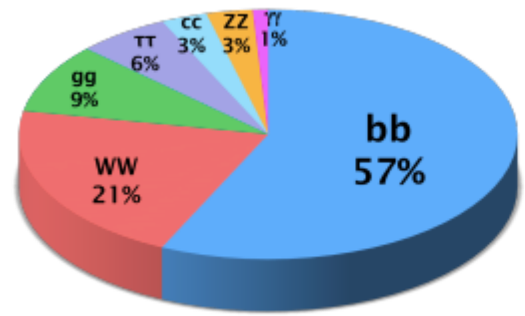
Channels

- tt(1-2 e/μ) + H(bb)
- tt(1-2 e/μ/τ-had) + H(WW, ZZ*, ττ)
- tt(0-2 e/μ) + H(ZZ*)
- tt(0-2 e/μ) + H(γγ)

Top Pair Branching Fractions



Higgs branching ratios



- Complex final states: γ, e, μ, τ-hadronic, jets, b-jets
- Sensitivity enhanced by dedicated channels

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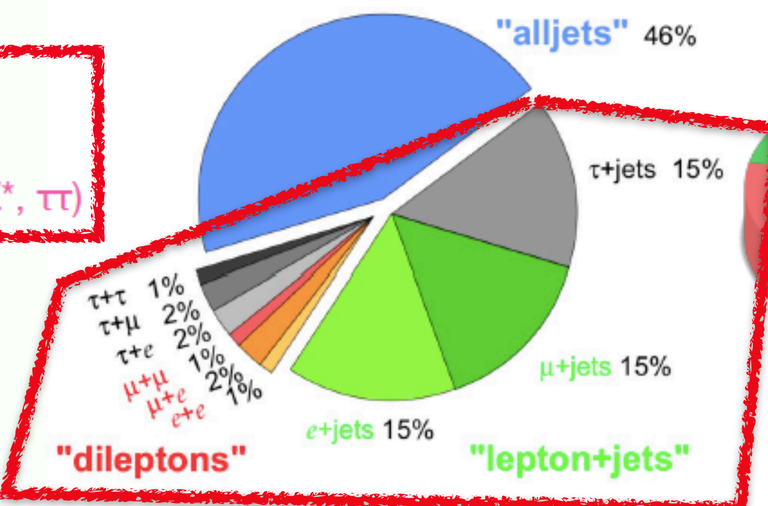
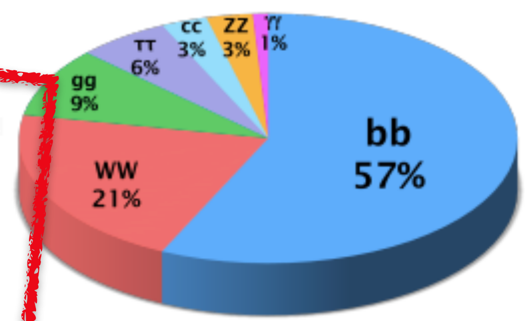


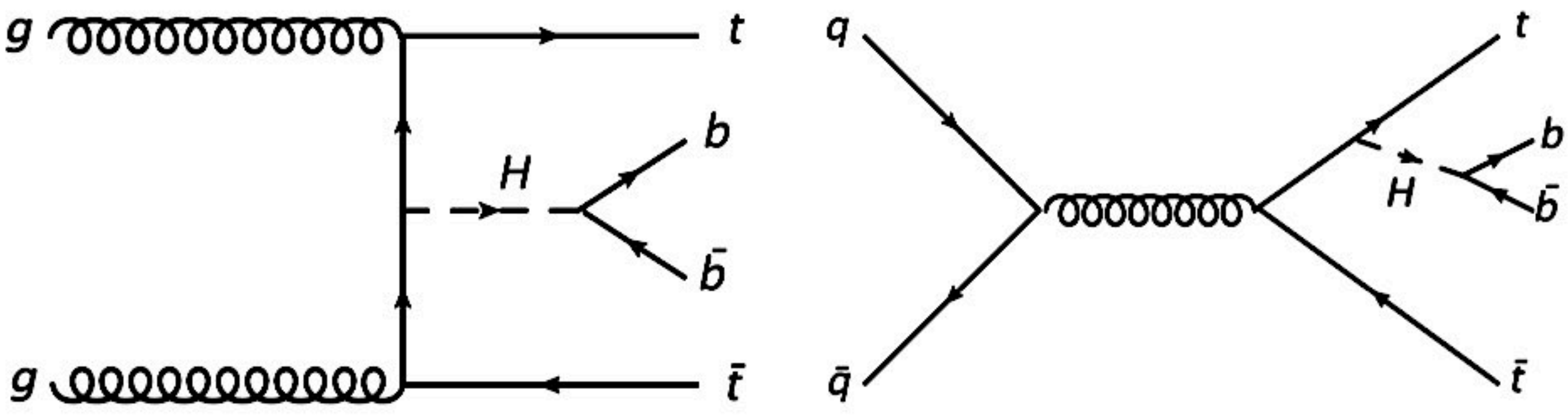
Higgs branching ratios



- Complex final states: γ, e, μ, τ-hadronic, jets, b-jets
- Sensitivity enhanced by dedicated channels
- Large background from tt+jets and tt+V
- Identification of non-prompt leptons in multi-lepton channel
- High combinatorics of b-jets in bb channel

Will focus on recent **bb** and **multi-lepton** results, and the **combination**.

ttH(bb)



ttH(bb)

ATLAS-CONF-2017-076

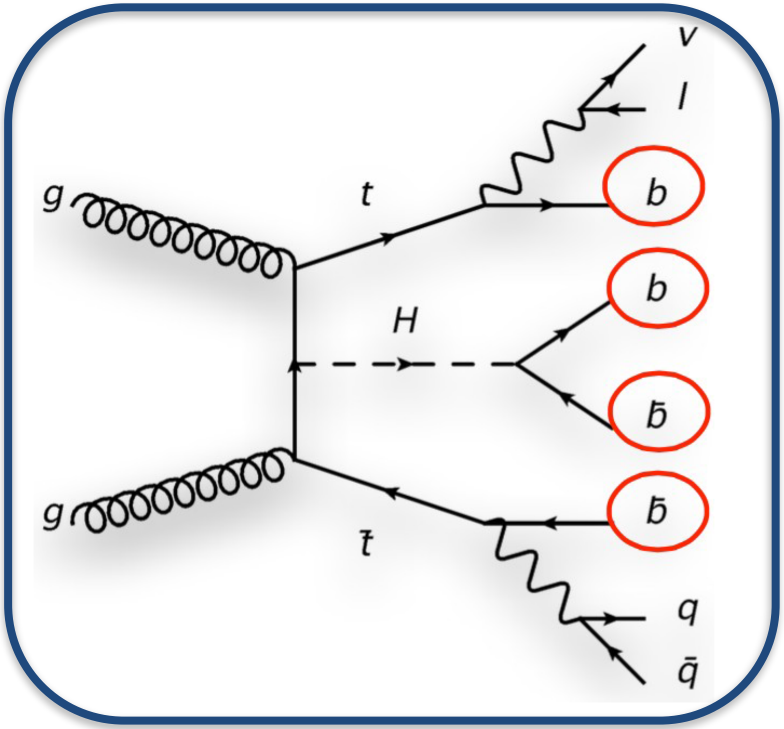
Search for ttH (H->bb) process

- Largest H->bb branching ratio of 58.1%
- Suffers from large irreducible background tt+ b-jet

event selection

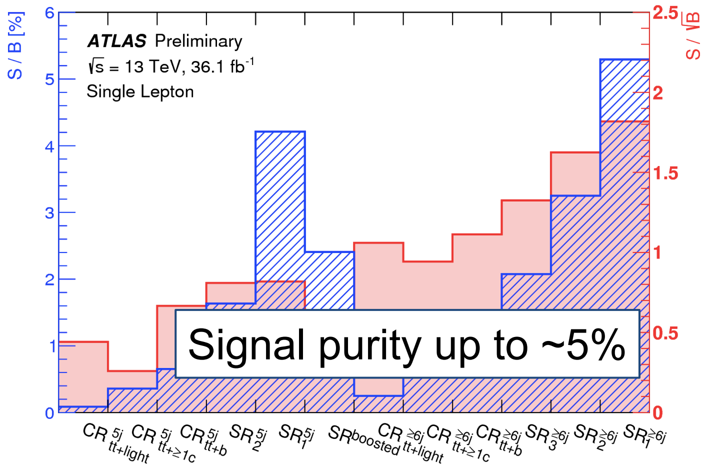
Semi-leptonic channel
(one leptonic W decay)
- one electron or muon
- at least 4 jets
- at least 2 b-tagged jets

di-lepton channel
(two leptonic W decay)
- Two opposite charge light leptons (electron or muon)
- at least 3 jets
- at least 2 b-tagged jets



- Define signal rich and background rich regions based on b-tagging discriminants
- Two stage Boosted Decision Tree for event reconstruction and classification
- Profile likelihood Fit over all regions, control background and systematic uncertainties
- Obtain signal strength $\mu_{ttH} = \sigma_{measured}/\sigma_{SM}$

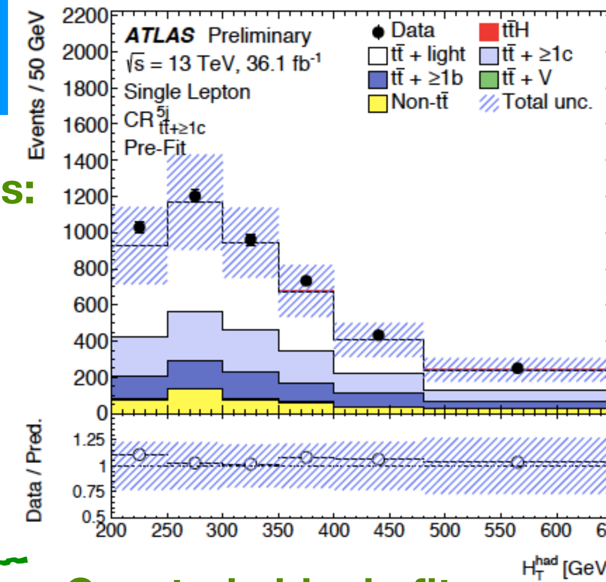
ttH(bb) Signal extraction



Background rich regions:

HT distribution

or one bin

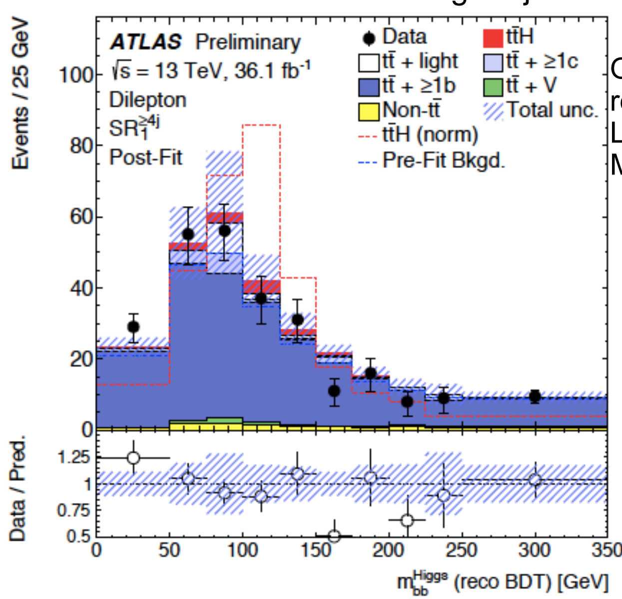


Signal rich regions

Constrain bkg in fit

Reconstruction BDT

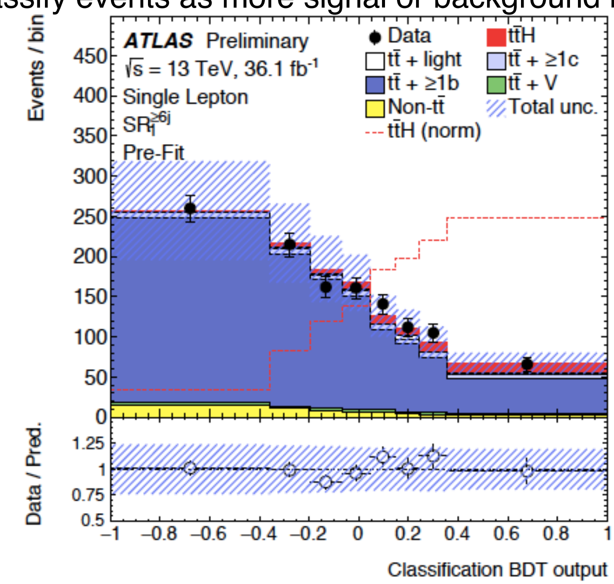
Match jets to Higgs or top decays, allows for Higgs reconstruction from large b-jet combinatorics



Other tools used in some regions:
Likelihood Discriminant & Matrix Element Method

Classification BDT

classify events as more signal or background like



Training inputs

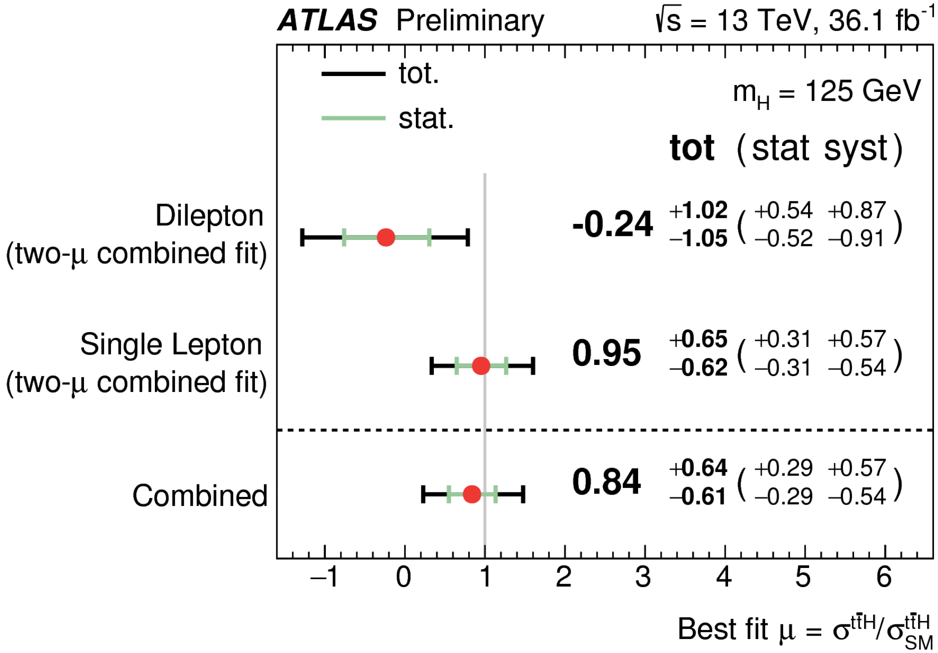
In total: Fit 9 SR and 10 CR

ttH(bb) results

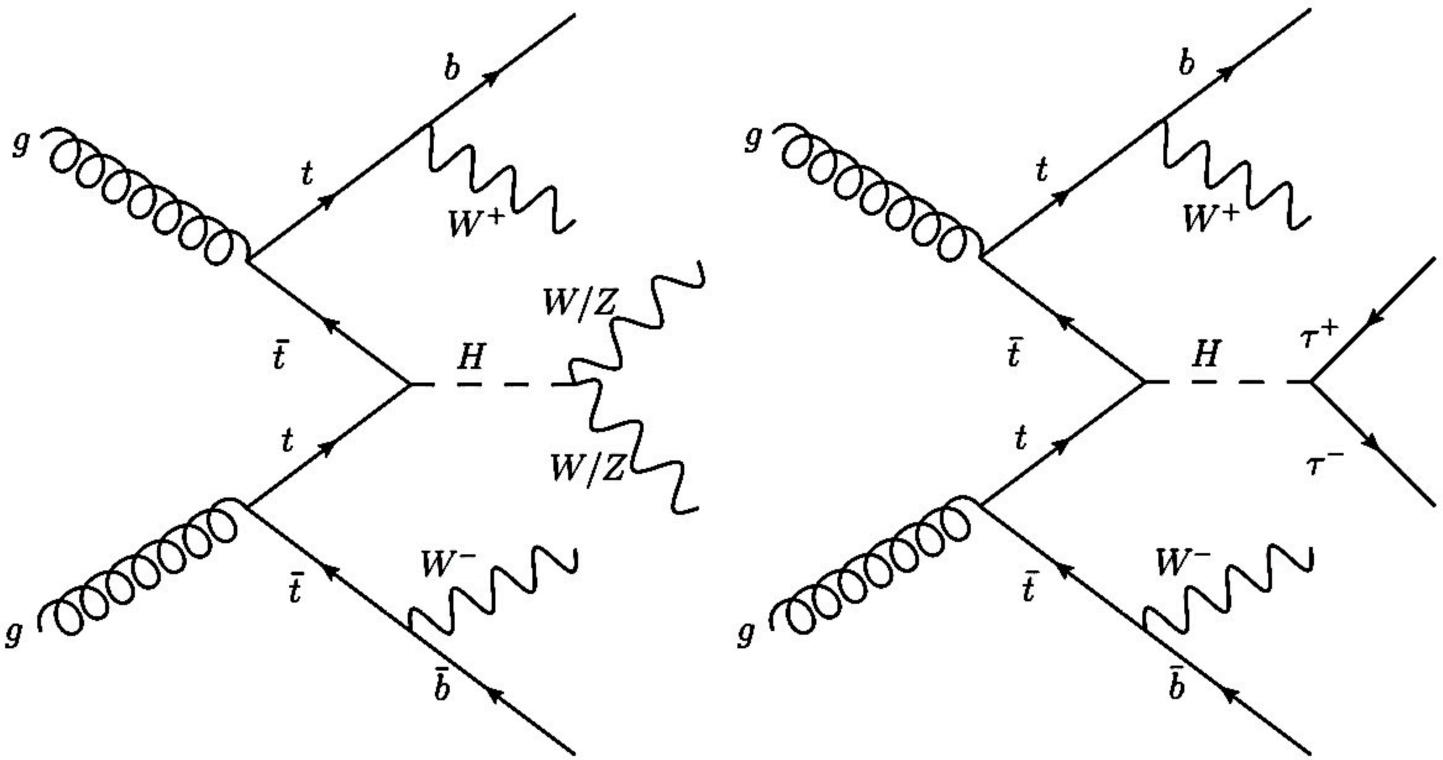
- Best fit value of signal strength μ= $\sigma_{measured}/\sigma_{SM}$ is determined
- Upper limit μ > 2.0 excluded at 95% C.L.
- Significance: 1.4σ (1.6σ exp)
- tt+b modelling uncertainty is the limiting factor

Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modelling	+0.46	−0.46
Background model statistics	+0.29	−0.31
Jet flavour tagging	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modelling	+0.22	−0.05
$t\bar{t} + \geq 1c$ modelling	+0.09	−0.11
Jet-vertex association, pileup modelling	+0.03	−0.05
Other background modelling	+0.08	−0.08
$t\bar{t}$ + light modelling	+0.06	−0.03
Luminosity	+0.03	−0.02
Light lepton (e, μ) ID, isolation, trigger	+0.03	−0.04
Total systematic uncertainty	+0.57	−0.54
$t\bar{t} + \geq 1b$ normalisation	+0.09	−0.10
$t\bar{t} + \geq 1c$ normalisation	+0.02	−0.03
Statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61

Impact of systematic uncertainties on ttH signal strength μ



ttH(ML)



ttH multilepton

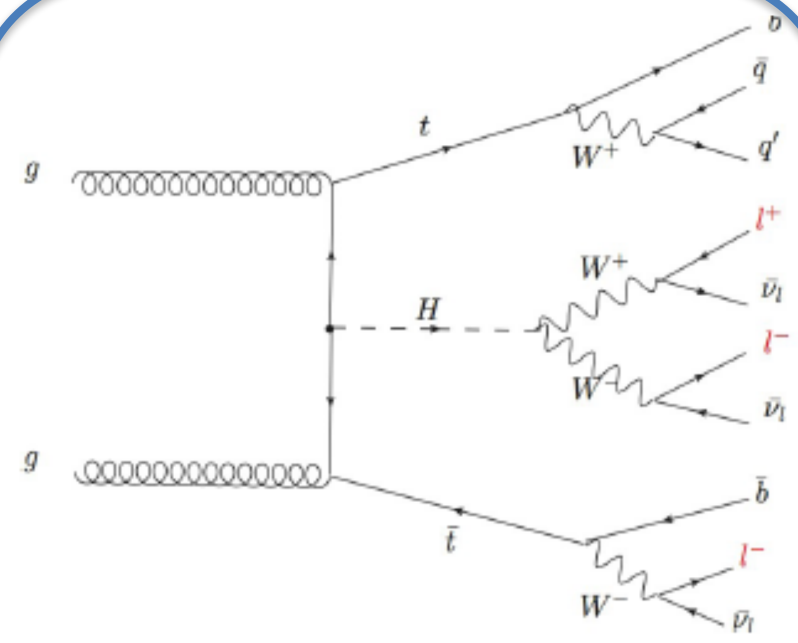
ATLAS-CONF-2017-077

Search for the ttH (multi leptons) process

Higgs decay mode	Branching ratio
H->WW	21.5 %
H->ττ	6.3 %

Many possible final states

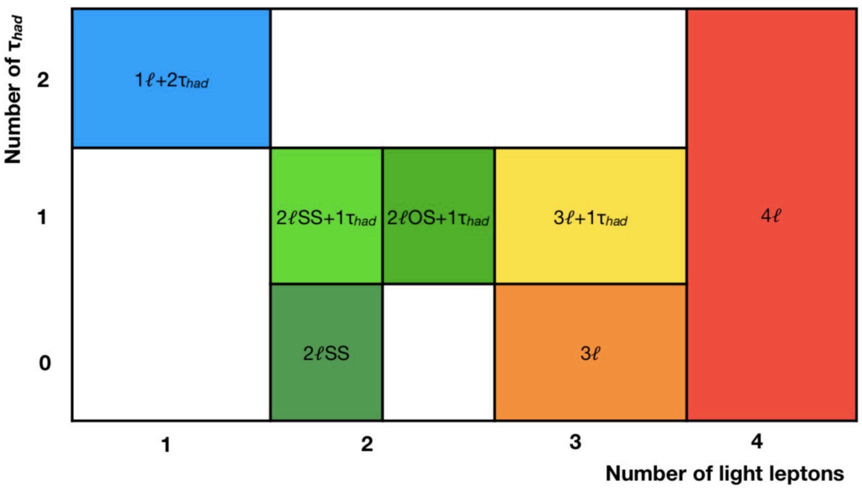
- Focus on those with clean signature and low background
- Select electron/muon from H and top decay
- Requiring same-sign leptons or 3leptons with charge sum ±1 reduces large tt background
- H→WW most sensitive channel
- H→ττ next sensitive
    - Hadronic τ reconstruction has larger uncertainties

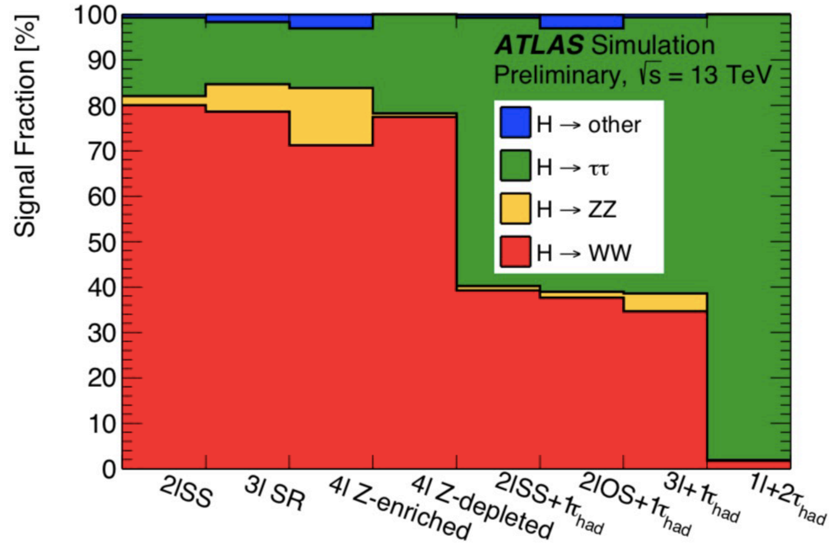


H→WW, 3-leptons

ttH(ML)

- High lepton multiplicity suppresses background
- Main background from $t\bar{t}$ + fake leptons
- Analysis split in 7 sub categories by number of hadronic tau and light leptons



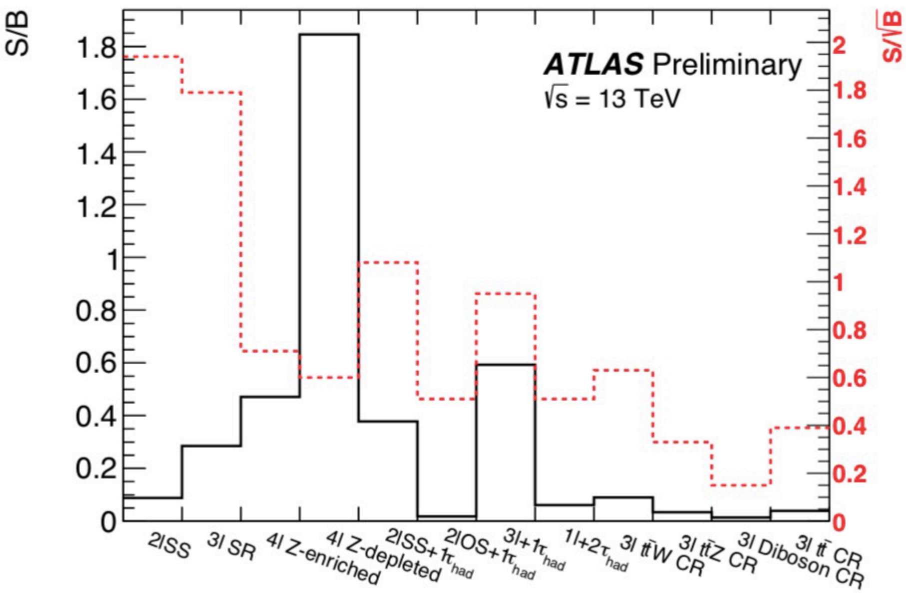


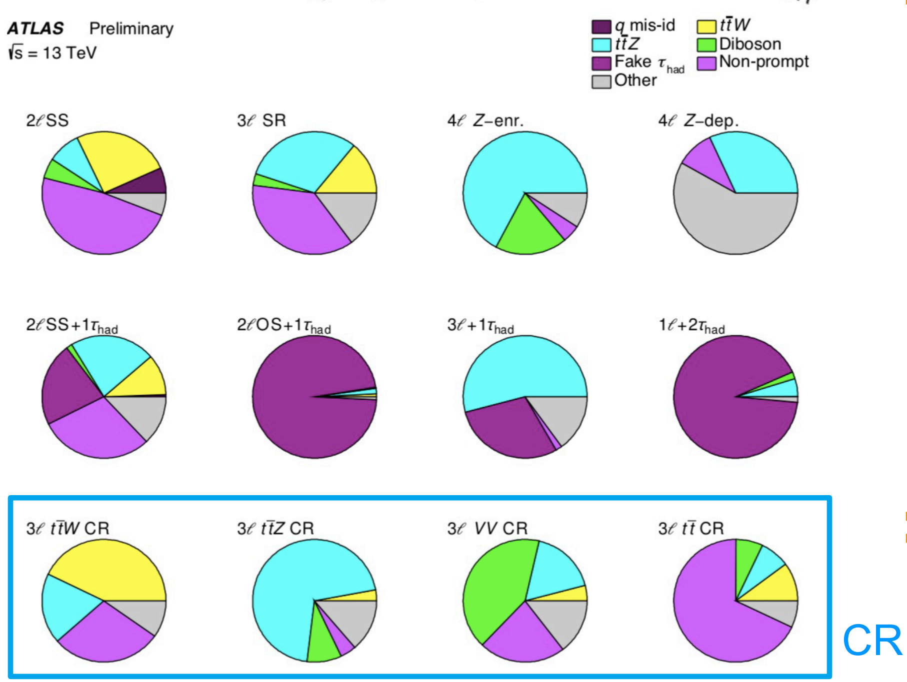
- Common jet selection: $N_{jet} \geq 2$ and $N_{b\text{-}jet} \geq 1$
- Optimised lepton selection in each category
  - Isolation requirement
  - BDTs to reject backgrounds

- H→WW most sensitive
- $H \rightarrow \tau\tau$ dominant in hadronic τ channels

SS: same sign leptons
OS: opposite sign leptons

ttH(ML) sub channels

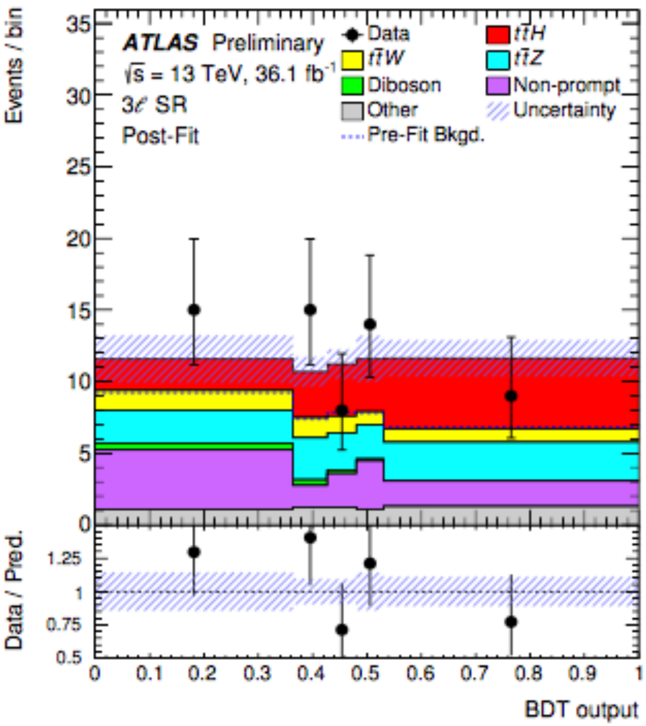


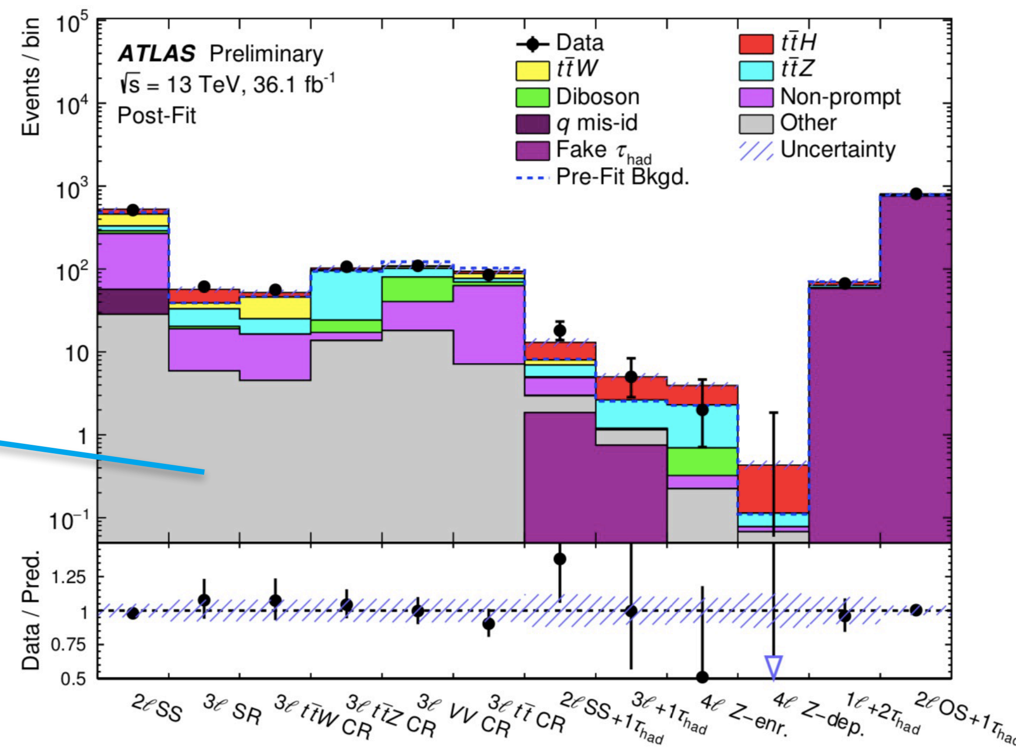


- S/B upto ~1.8
- MVA techniques used in most categories to suppress backgrounds
- Different background components in regions:
  - ttW, ttZ, VV, NonPrompt, fake τ
- NonPrompt and fake τ backgrounds estimated from a low jet multiplicity region using data driven methods
  - NonPrompt: mainly tt+nonPrompt leptons from b-hadron decay
  - Fake τ : mainly from tt and ttV with mis-reconstructed τ_{had}
- Control regions to constrain MC estimated backgrounds in fit

ttH(ML) Fit

	2ℓSS	3ℓ	4ℓ	1ℓ+$2\tau_{\text{had}}$	2ℓSS+$1\tau_{\text{had}}$	2ℓOS+$1\tau_{\text{had}}$	3ℓ+$1\tau_{\text{had}}$
BDT trained against	Fakes and $t\bar{t}V$	$t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, VV	$t\bar{t}Z$ / -	$t\bar{t}$	all	$t\bar{t}$	-
Discriminant	2×1D BDT	5D BDT	Event count	BDT	BDT	BDT	Event count
Number of bins	6	5	1 / 1	2	2	10	1
Control regions	-	4	-	-	-	-	-

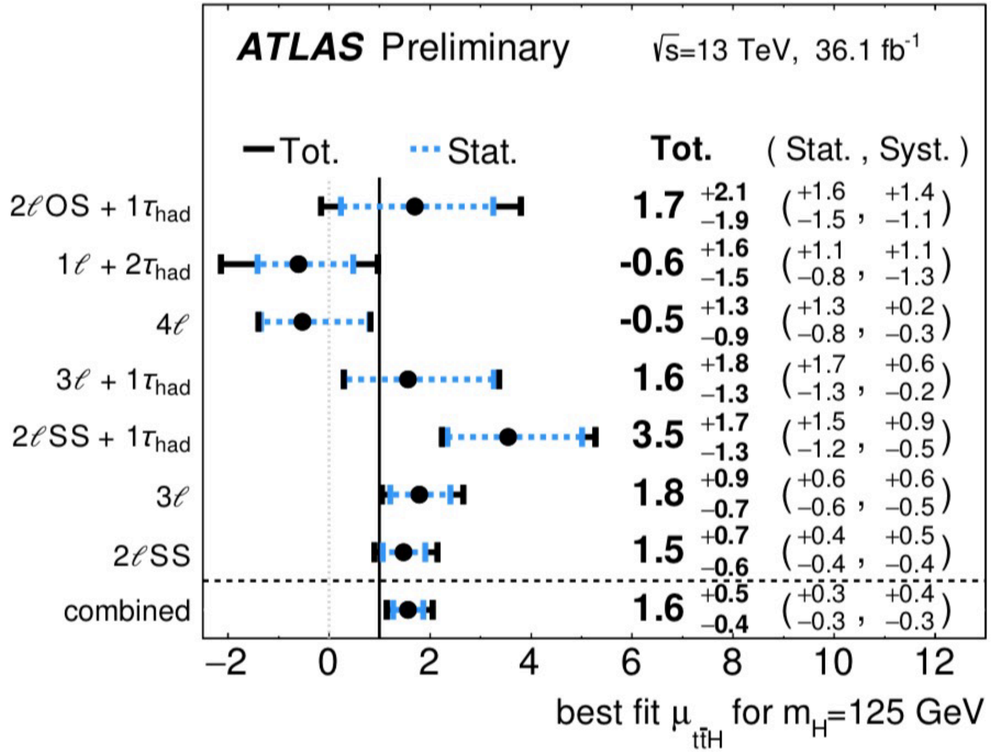




- Profile likelihood fit in all sub-channels simultaneously
- Fit BDT discriminant or single bin in low stat regions

ttH(ML) results

Channel	Significance	
	Observed	Expected
2ℓOS+1$\tau_{\rm had}$	0.9σ	0.5σ
1ℓ+2$\tau_{\rm had}$	-	0.6σ
4ℓ	-	0.8σ
3ℓ+1$\tau_{\rm had}$	1.3σ	0.9σ
2ℓSS+1$\tau_{\rm had}$	3.4σ	1.1σ
3ℓ	2.4σ	1.5σ
2ℓSS	2.7σ	1.9σ
Combined	4.1σ	2.8σ



- Measured signal strength $\mu = 1.6^{+0.5}_{-0.4}$
- Significance wrt. to background-only hypothesis 4.1σ (expected 2.8σ)
- Cross section extrapolated to inclusive phase space

$$\sigma(t\bar{t}H) = 790^{+230}_{-210}\ \text{fb (the SM prediction } 507^{+35}_{-50}\ \text{fb)}$$

ttH(ML) Systematic uncertainties

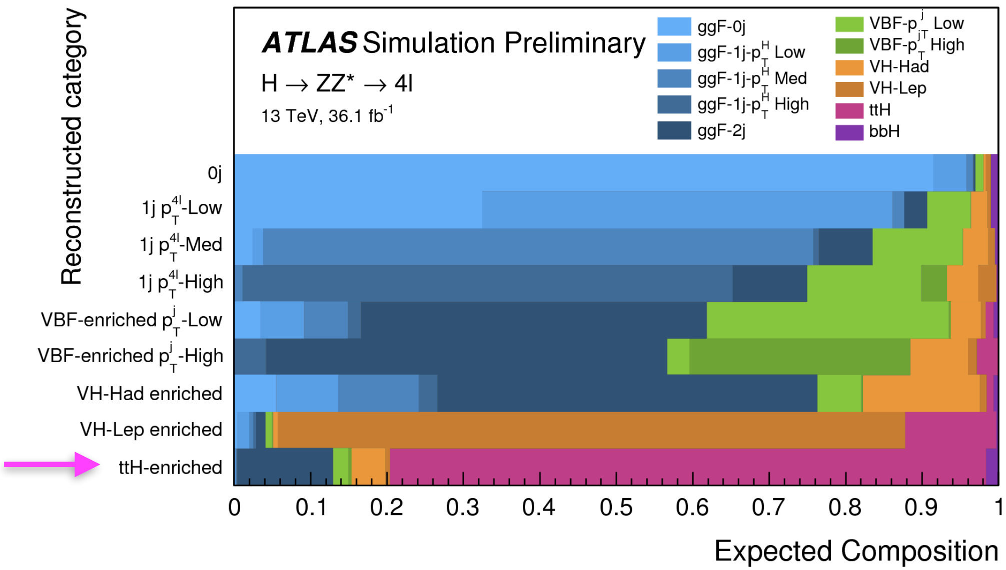
- Largest impact from ttH modelling scale uncertainty
- Jet energy resolution, largest experimental uncertainty
- Non prompt estimation suffers from low statistics in control region
- Sizeable ttV scale uncertainty

Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modelling (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 flavour tagging and τ_{had} identification	+0.11	−0.09
$t\bar{t}W$ modelling	+0.10	−0.09
$t\bar{t}Z$ modelling	+0.08	−0.07
Other background modelling	+0.08	−0.07
Luminosity	+0.08	−0.06
$t\bar{t}H$ modelling (acceptance)	+0.08	−0.04
Fake τ_{had} estimates	+0.07	−0.07
Other experimental uncertainties	+0.05	−0.04
Simulation statistics	+0.04	−0.04
Charge misassignment	+0.01	−0.01
Total systematic uncertainty	+0.39	−0.30

Impact of systematic uncertainties on ttH signal strength μ

ttH(ZZ→4l) and ttH(γγ)

- Consider ttH enriched regions from inclusive studies of H→ZZ→4l and H→γγ searches for the ttH combination



- Add ttH, H→ZZ resonant region
  - 118 < m_{4l} < 129 GeV
- Orthogonal to 4l ML (ZZ veto)
- Very rare but clean channel
- Zero events observed, 0.39 ttH (0.08 Bkg) expected
- Upper limit on μ_{ttH} of 1.9 at 68% C.L.
- Will become more important as more data is gathered

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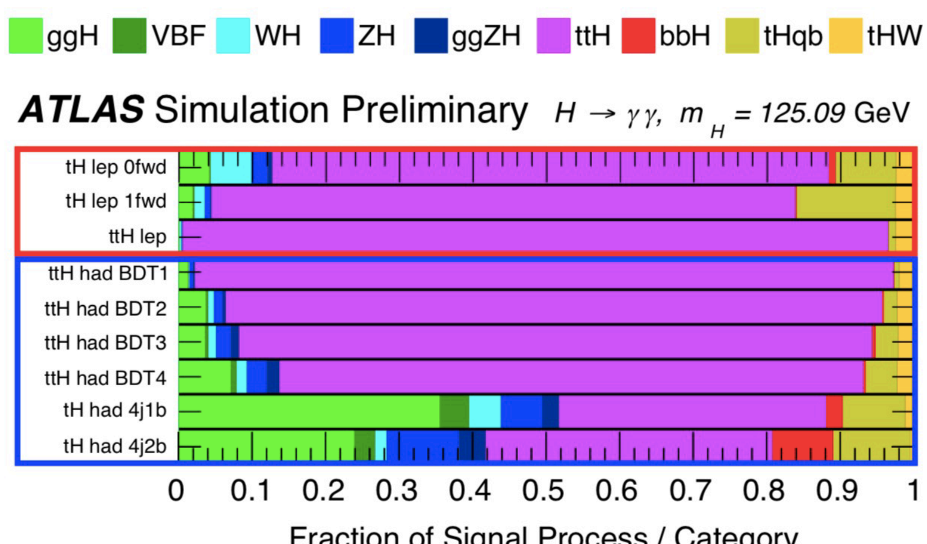
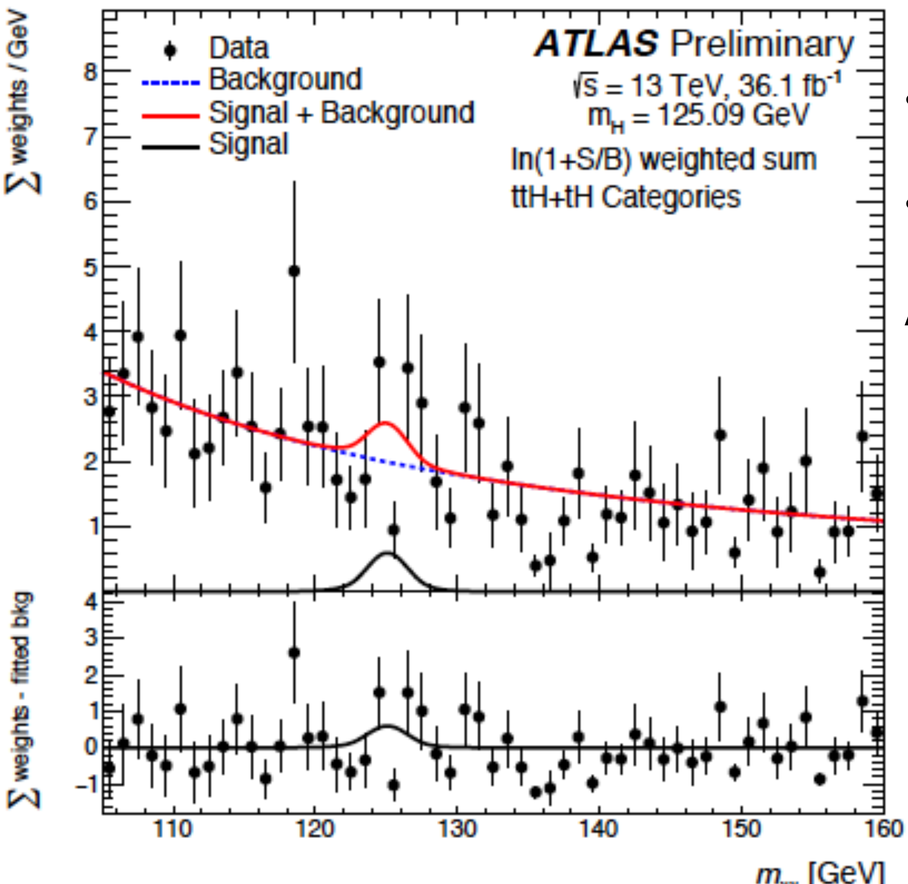


- H→γγ , ttH and tH categories in leptonic and hadronic channels
- μ_{ttH} =0.5±0.6, significance 1σ (exp.1.8σ)

ATLAS-CONF-2017-045

tH +ttH (H->ɣɣ)

> Different trigger, event selection approach. Select events based on $m_{\gamma\gamma}$ + b-jets.



- Employs BDT to isolate ttH from ggH production
- $\mu_{tH,\, ttH}$ =0.5±0.6, significance 1σ (exp.1.8σ)

ATLAS-CONF-2017-045

Signal model: double-sided Crystal Ball
Background model: data driven by reverting γ id or isolation, or removing b-tagging; shape+normalisation from fit to $m_{\gamma\gamma}$

ttH results, combined

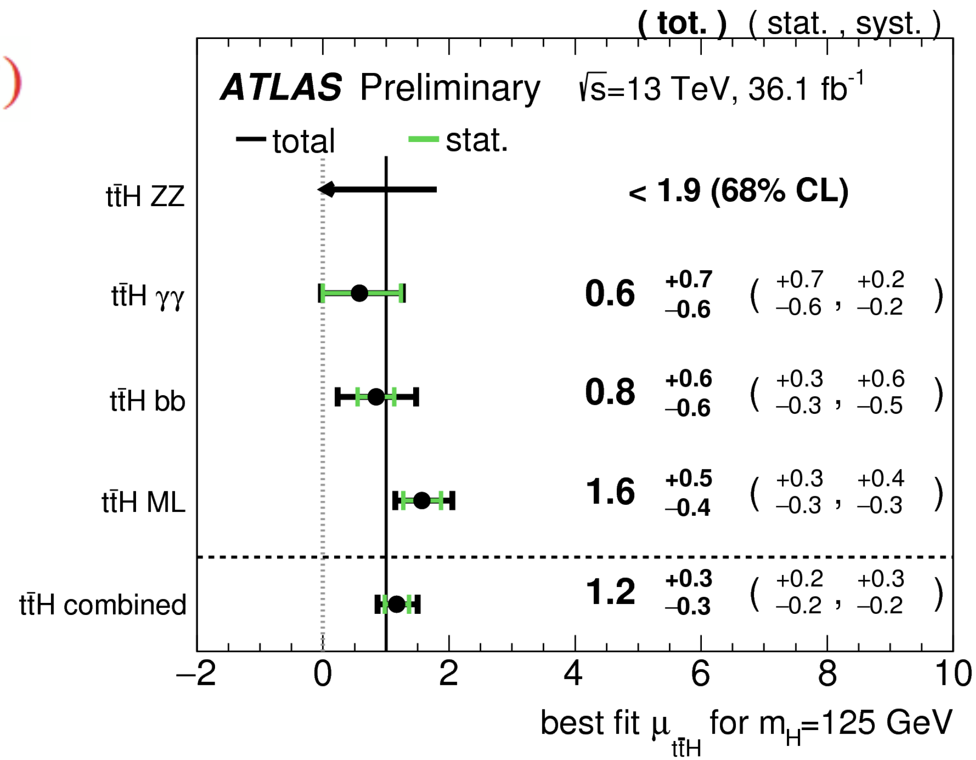
- Combination of bb with multi-lepton(WW & $\tau\tau$), $ZZ\rightarrow 4l$ and $\gamma\gamma$ channels for best possible sensitivity
- Common systematics correlated across channels
  - Large overlap between bb and multi-lepton

ATLAS-CONF-2017-077

$$\text{Significance}: 4.2\sigma\,(\text{expected}: 3.8\sigma)$$

$$\sigma_{t\bar{t}H} = 590^{+160}_{-150}\,fb$$

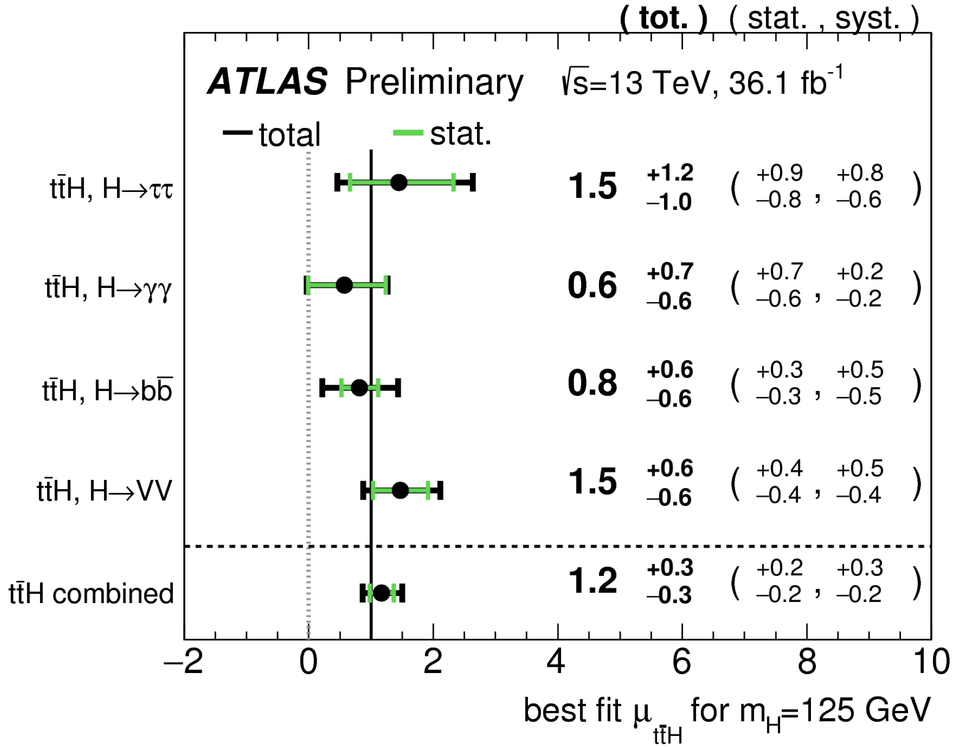
Uncertainty Source	$\Delta\mu$	
$t\bar{t}$ modelling in $H \to bb$ analysis	+0.15	−0.14
$t\bar{t}H$ modelling (cross section)	+0.13	−0.06
Non-prompt light-lepton and fake τ_{had} estimates	+0.09	−0.09
Simulation statistics	+0.08	−0.08
Jet energy scale and resolution	+0.08	−0.07
$t\bar{t}V$ modelling	+0.07	−0.07
$t\bar{t}H$ modelling (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 flavour tagging	+0.03	−0.02
Modelling 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

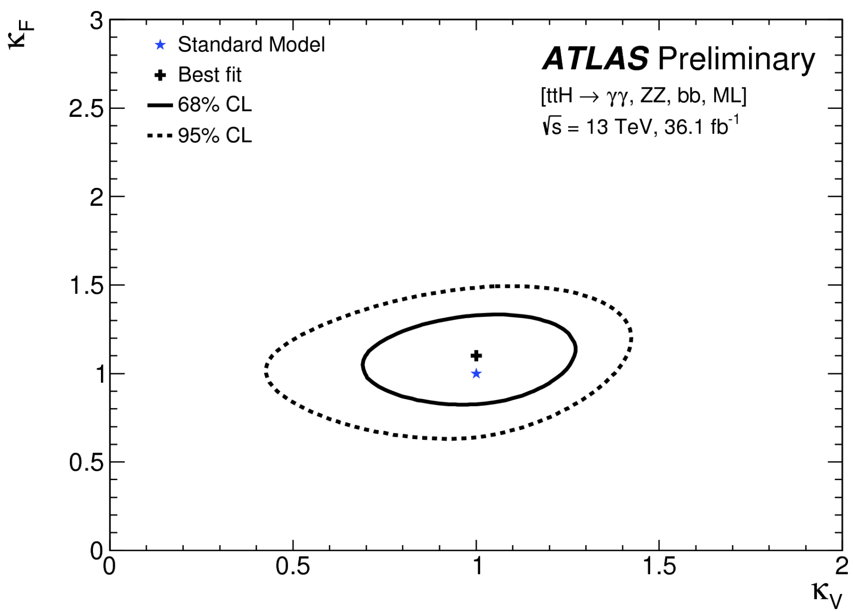


tH processes are treated as SM background

ttH coupling

- Determine individual signal strength and thus coupling in combined fit
- ttH analysis is sensitive to Htt, Hbb, H$\tau\tau$, HWW, HZZ coupling and H$\gamma\gamma$ effective coupling





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Likelihood scan in κ_F - κ_V is in good agreement with the SM: κ_F, κ_V=1.

κ_F < 0 is excluded at 95% C.L.

Summary

- The search for ttH production has been performed at ATLAS using a 36.1 fb^{-1} 13 TeV dataset
- Most recent results in the **bb** and **multi-lepton channels** are shown together with the combination, which excludes the background-only hypothesis at 4.2σ (with an expectation of 3.8σ).
  - We therefore see evidence for ttH production at ATLAS !
- For 125 GeV Higgs boson the measured signal strength is

$$\mu = 1.17 \pm 0.19\ (\text{stat})\ ^{+0.27}_{-0.23}\ (\text{syst})$$

- The measured ttH cross section is $590\ ^{+160}_{-150}$ fb in good agreement with the SM prediction 507^{+35}_{-50} fb (NLO).

Backup

Previous results

	Signal strength $\mu_{t\bar{t}H}$	Obs. (exp.) significance
Run1 ATLAS+CMS (~25 fb^{-1})	2.3 +0.7/-0.6	4.4σ (2.2σ)
Run2 ATLAS preliminary (13.2 fb^{-1})	1.8 ± 0.7	2.8σ (1.8σ)
Run2 CMS preliminary (35.9 fb^{-1})	1.5 ± 0.5	3.3σ (2.5σ)

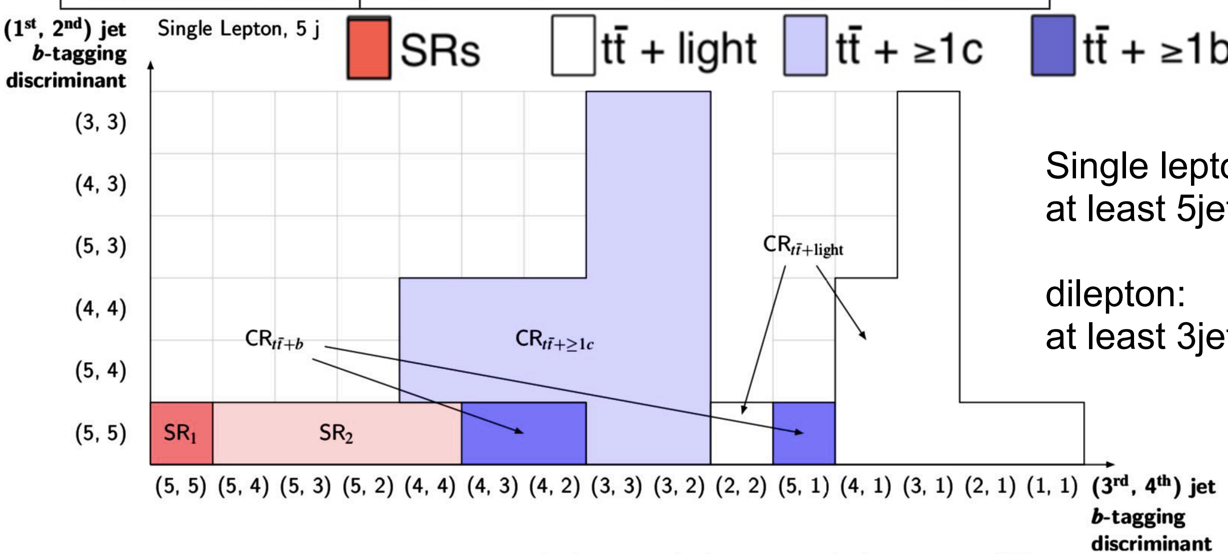
ttH(bb) regions

- take advantage of large BR(H->bb)
    - suffers from large $t\bar{t}$ + b-jets background
- Split channels by $t\bar{t}$ decays: **single lepton and dilepton**
    - Includes dedicated lepton+jets boosted region

- Create **regions** enriched in ttH, tt+b, tt+c and tt+light
    - Defined by jet multiplicity and number of b-tagged jets
- Use all b-tag working points in region definition:

B-tagging rejection factors:
c-jets 3->35; light jets 30->1500

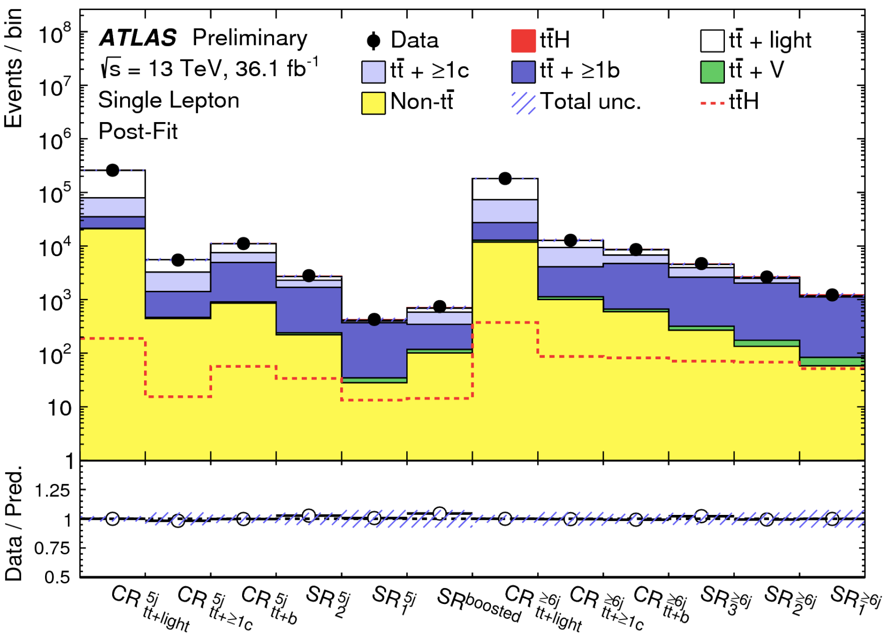
	none	*loose*	*medium*	*tight*	*very-tight*
Efficiency	-	85%	77%	70%	60%
Discriminant value	1	2	3	4	5

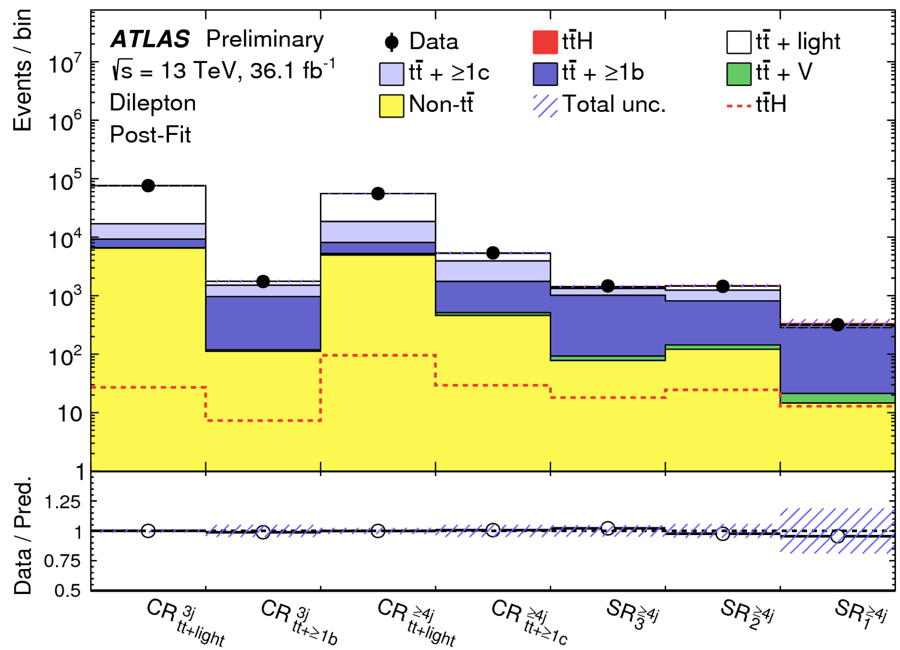


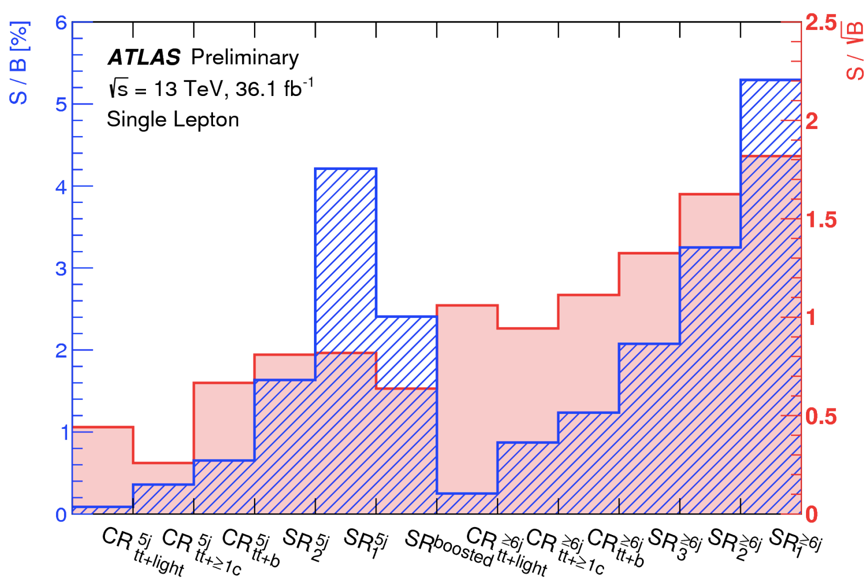
Single lepton:
at least 5jets, 2 very tight or 3 medium b-jets

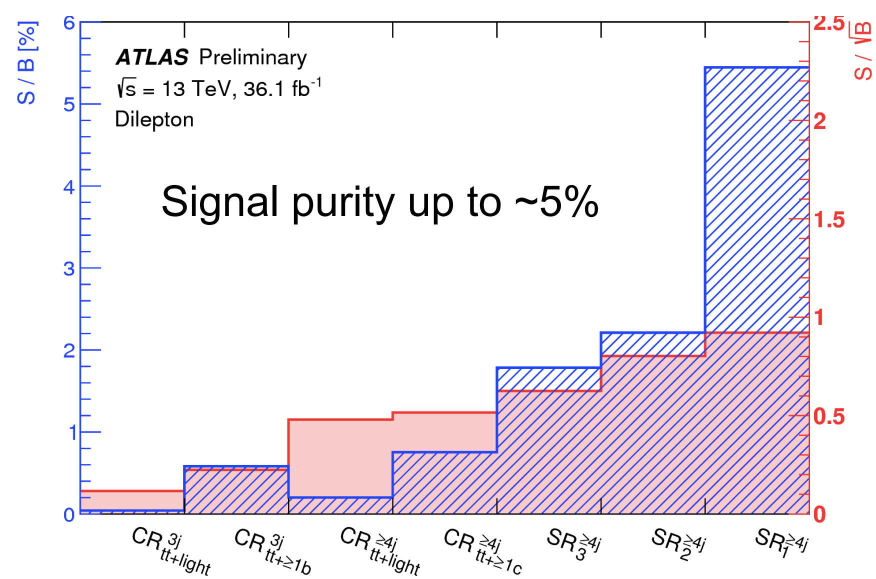
dilepton:
at least 3jets, 2 medium b-jets

Single lepton and dilepton region summary



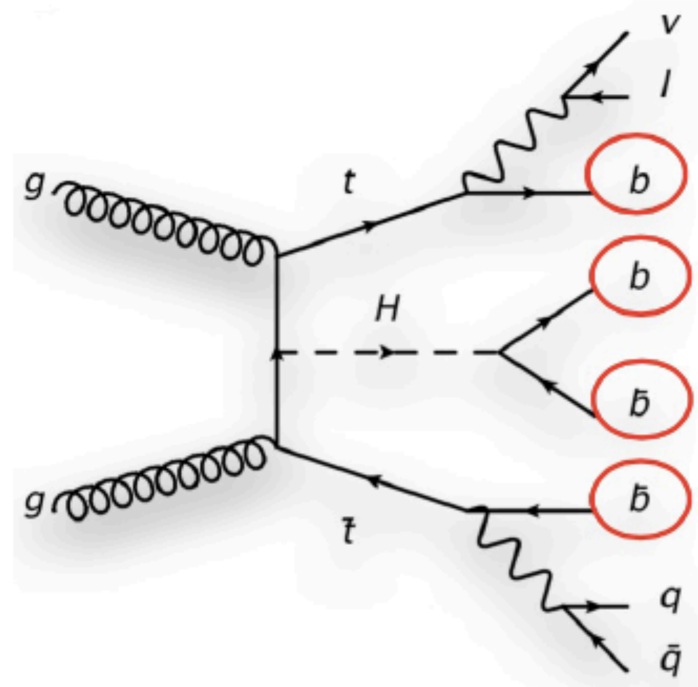




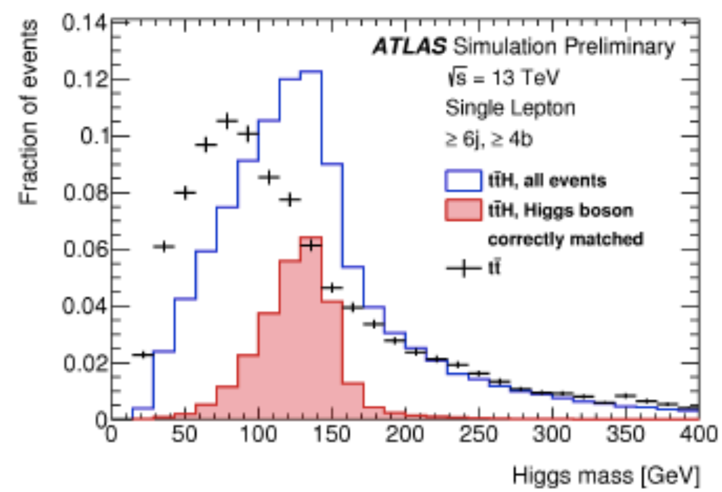


Higgs reconstruction

- the **Reconstruction BDT** is the most important event reconstruction tool
- A BDT matches b-jets to final state partons from **Higgs or top decays**
- Allows for reconstruction of Higgs mass from large combinatorics of b-jets
- Train on ~ 10 well modelled topological variables in ttH MC
- 42% of all ttH events are reconstructed correctly



Normalised reconstructed mass of Higgs candidate from ttH MC and fraction of events correctly matched, compared to $t\bar{t}$ background.



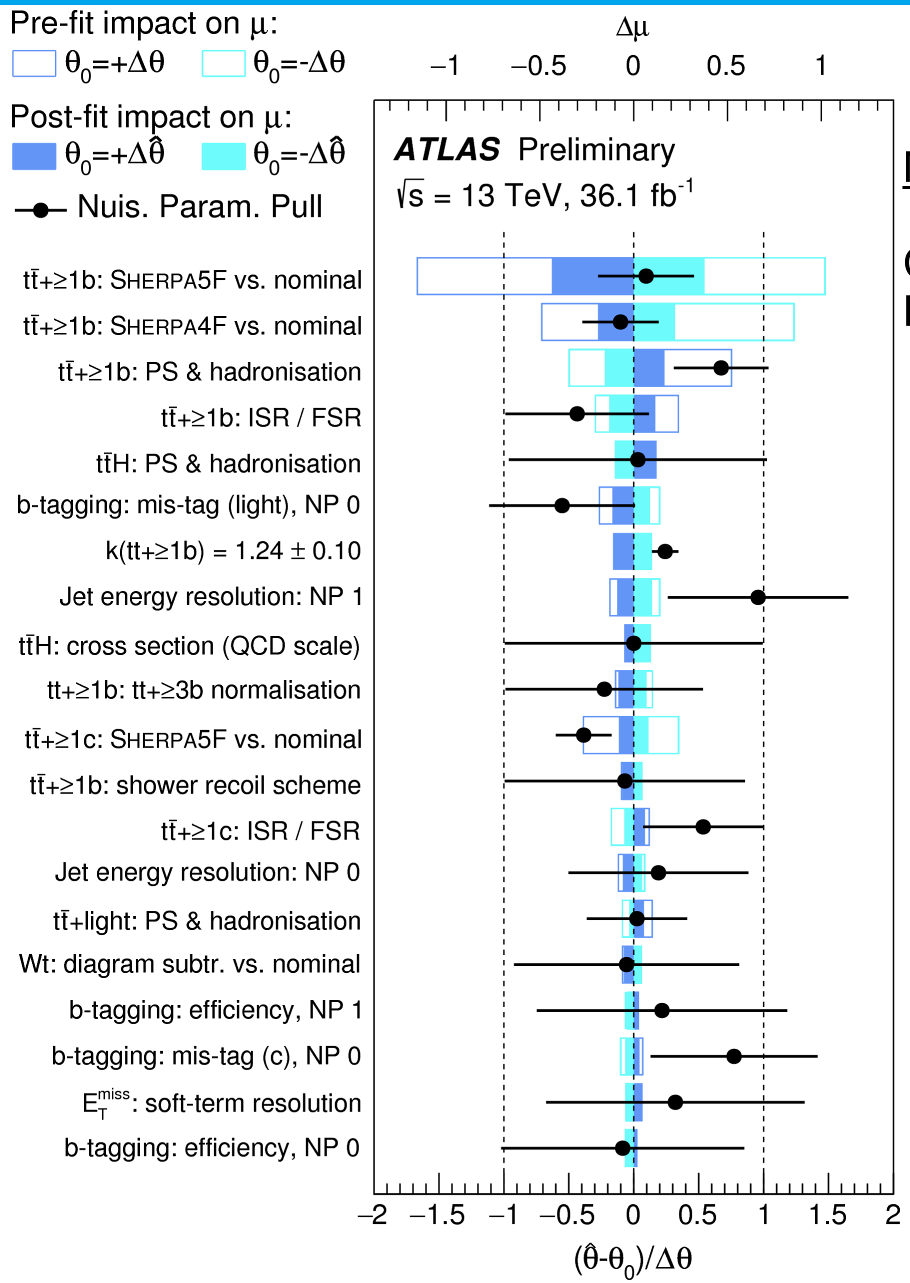
Other tools used in some regions:
Likelihood Discriminant & Matrix Element play minor role

tt+jets background modelling

- tt+heavy-flavour jets modelling relies on Powheg+Pythia8 simulation. The cross section is normalised to NNLO+NNLL prediction.
- tt+ ≥1b reweighted to state-of-the-art ttbb NLO+PS prediction: Sherpa+OpenLoops, 4FS including b-quark mass, additions b-jet described by ME
- tt+ ≥1b, tt+ ≥1c normalisations are determined in data from the fit.
- Large set of systematic uncertainties are evaluated, account for various variations

Systematic source	Description	$t\bar{t}$ categories
$t\bar{t}$ cross-section	Up or down by 6%	All, correlated
$k(t\bar{t}+\geq 1c)$	Free-floating $t\bar{t}+\geq 1c$ normalisation	$t\bar{t}+\geq 1c$
$k(t\bar{t}+\geq 1b)$	Free-floating $t\bar{t}+\geq 1b$ normalisation	$t\bar{t}+\geq 1b$
SHERPA5F vs. nominal	Related to the choice of the NLO generator	All, uncorrelated
PS & hadronisation	POWHEG-BOX+HERWIG 7 vs. POWHEG-BOX+PYTHIA 8	All, uncorrelated
ISR / FSR	Variations of μ_R, μ_F, h_{damp} and A14 Var3c parameters	All, uncorrelated
$t\bar{t}+\geq 1c$ ME vs. inclusive	MG5_aMC@NLO+HERWIG++: ME prediction (3F) vs. incl. (5F)	$t\bar{t}+\geq 1c$
$t\bar{t}+\geq 1b$ SHERPA4F vs. nominal	Comparison of $t\bar{t}+b\bar{b}$ NLO (4F) vs. POWHEG-BOX+PYTHIA 8 (5F)	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ renorm. scale	Up or down by a factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ resumm. scale	Vary μ_Q from $H_T/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ global scales	Set μ_Q, μ_R, and μ_F to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ shower recoil scheme	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ PDF (MSTW)	MSTW vs. CT10	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ PDF (NNPDF)	NNPDF vs. CT10	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ UE	Alternative set of tunable parameters for the underlying event	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 3b$ normalisation	Up or down by 50%	$t\bar{t}+\geq 1b$

ttH(bb) ranking



<u>Main issue: tt+b generator uncertainty</u>

Choice of the NLO generator PP8 vs Sherpa5F
Reweighting uncert. (or 5F vs 4F) PP8 vs Sherpa4F