Evidence for ttH production at the ATLAS detector

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

Paul Glaysher (DESY)
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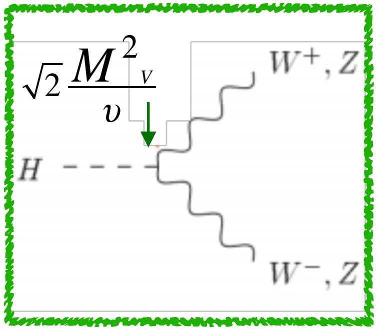
LHC discussion, DESY, Hamburg

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**

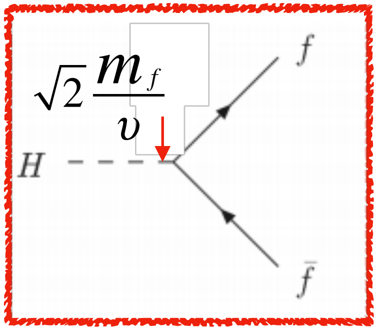
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi + |D_\mu\phi|^2 - V(\phi) + \bar{\psi}_i y_{ij}\psi_j\phi + h.c.$$

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

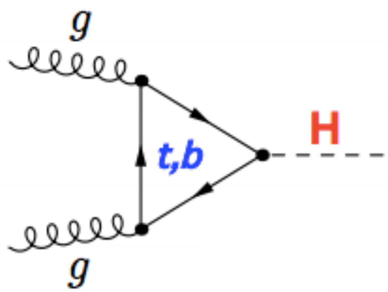
$$\boxed{\lambda_t = \sqrt{2}\frac{m_t}{v} \approx \sqrt{2}\frac{173\ \text{GeV}}{246\ \text{GeV}} \approx 0.99 \approx 1.}$$

Top quark Yukawa coupling

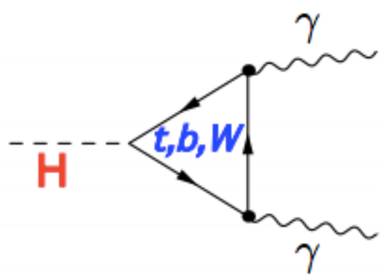
➡Run 1 (ATLAS+CMS) results: top-Higgs coupling (κ_t) = 0.87 (+0.15, -0.15) is consistent with the SM JHEP 08 (2016) 045

➡Determined indirectly from loop processes

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

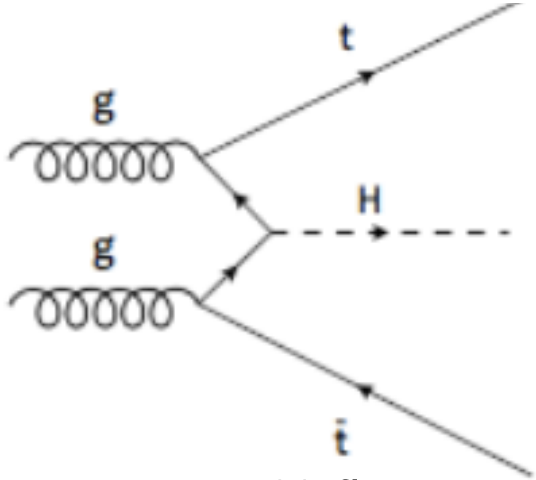


σ_{ggF} = 44 pb



➡ 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!

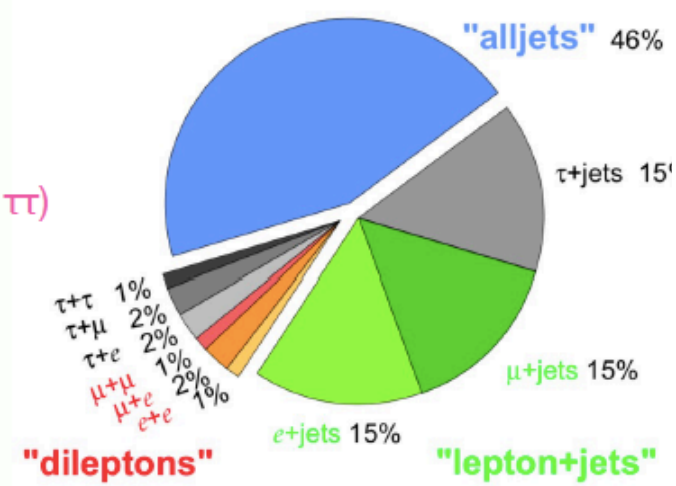
Experimental Challenge

- 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

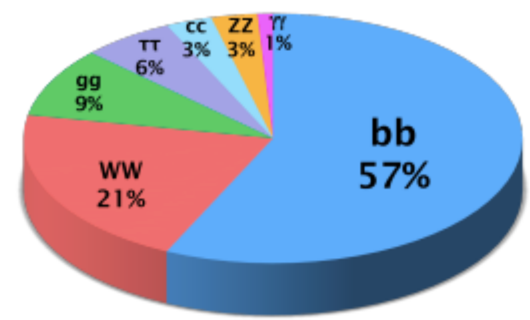
Channels

- 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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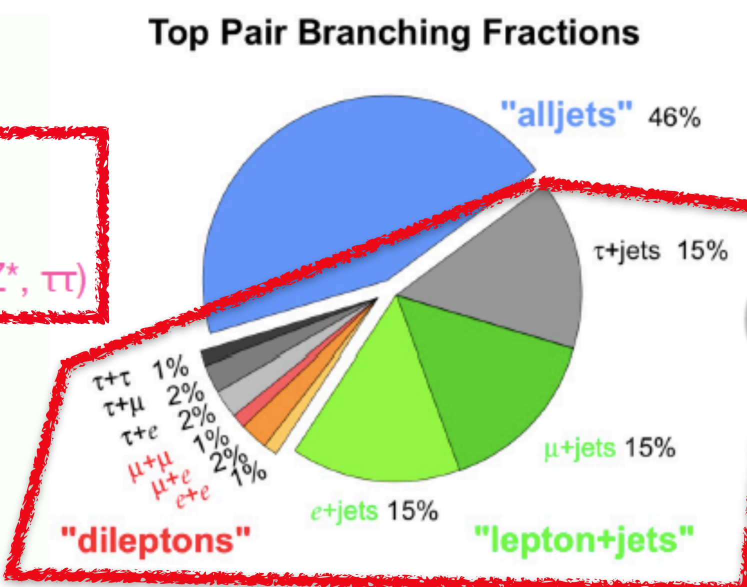
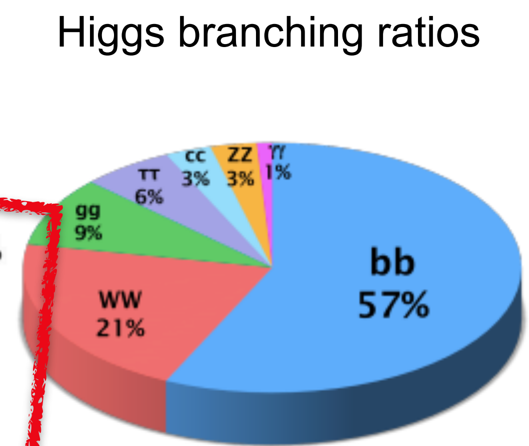
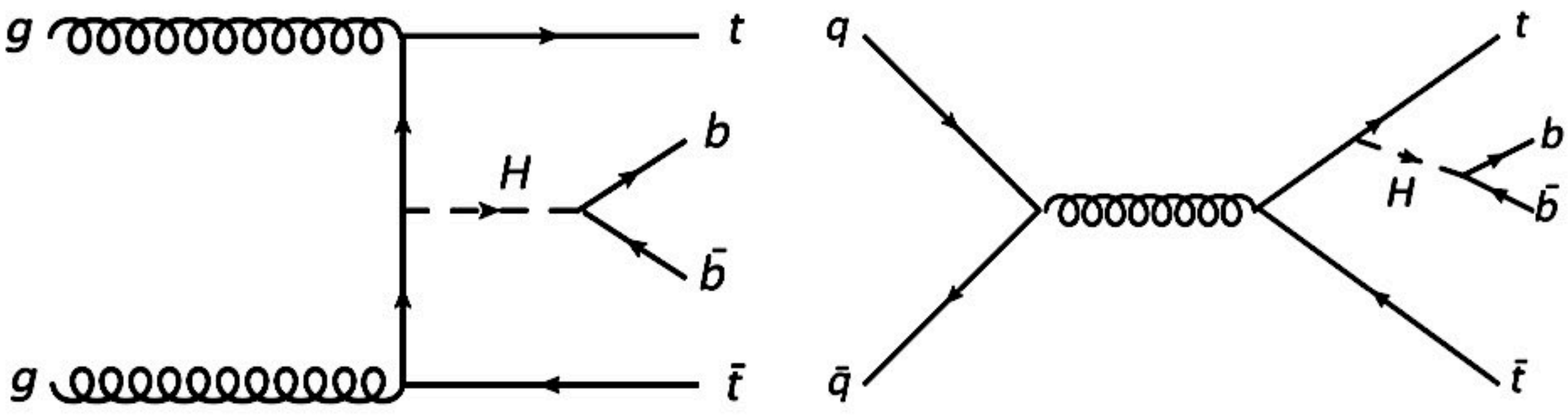




- Complex final states: γ, e, μ, τ-hadronic, jets, b-jets
- Sensitivity enhanced by dedicated channels
- Large background from tt+jets and tt+V
- Identification of non-prompt leptons in multi-lepton channel
- High combinatorics of b-jets in bb channel

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



ttH(bb)

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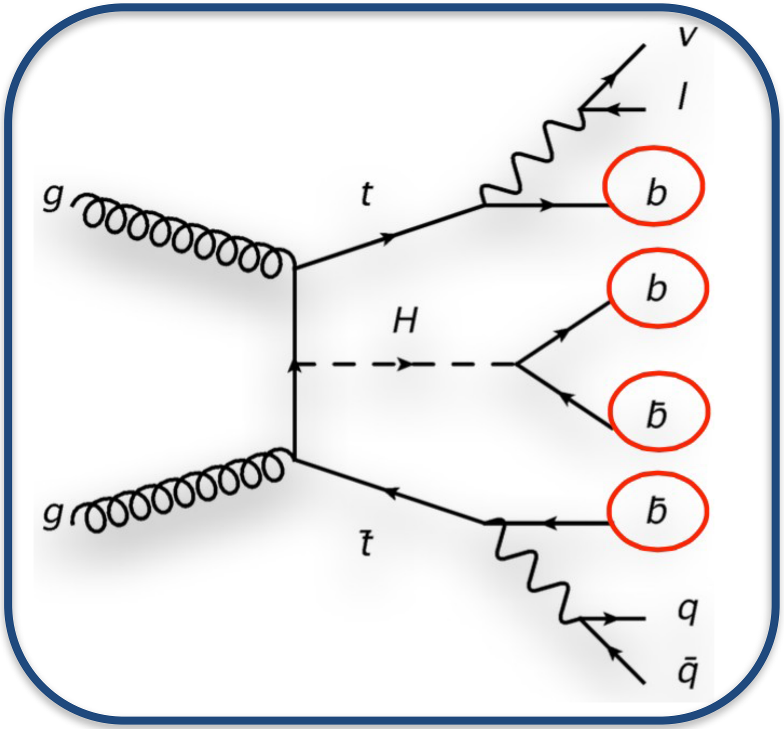
Search for ttH (H->bb) process

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

event selection

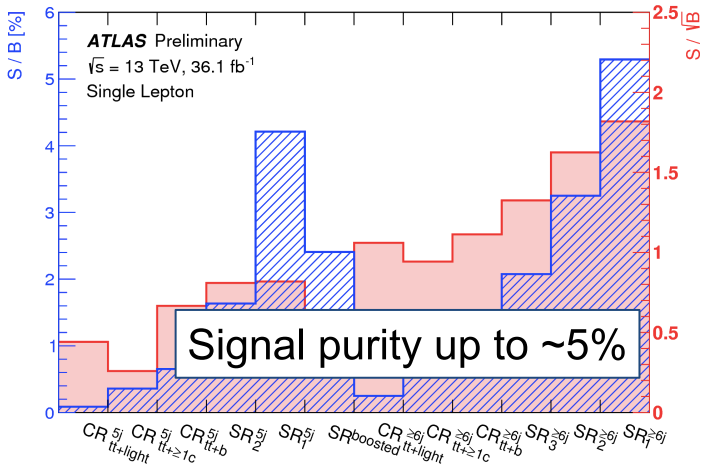
Semi-leptonic channel
(one leptonic W decay)
- one electron or muon
- at least 5 jets
- at least 4 b-tagged jets

di-lepton channel
(two leptonic W decay)
- Two opposite charge light leptons (electron or muon)
- at least 3 jets
- at least 3 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 $\mu_{ttH} = \sigma_{measured}/\sigma_{SM}$

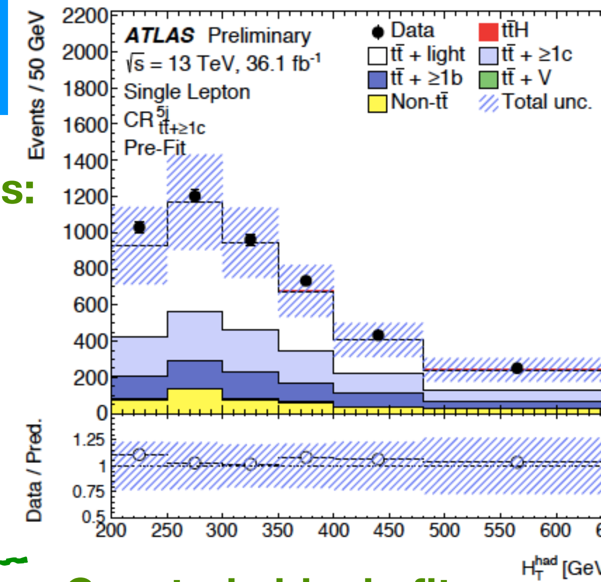
ttH(bb) Signal extraction



Background rich regions:

HT distribution

or one bin

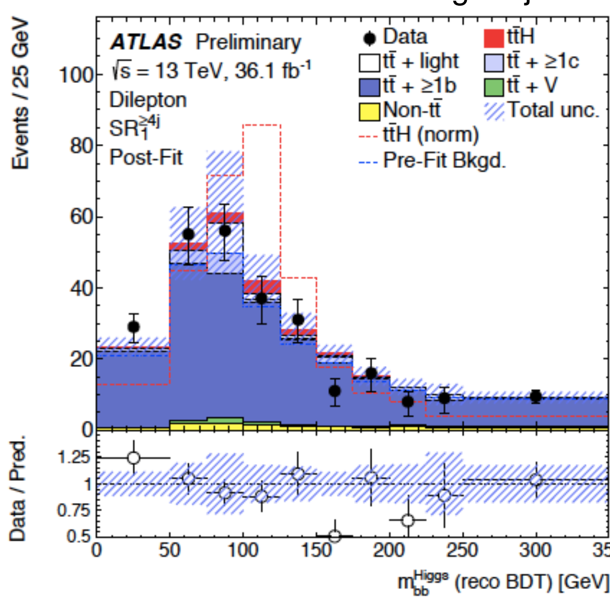


Signal rich regions

Constrain bkg in fit

Reconstruction BDT

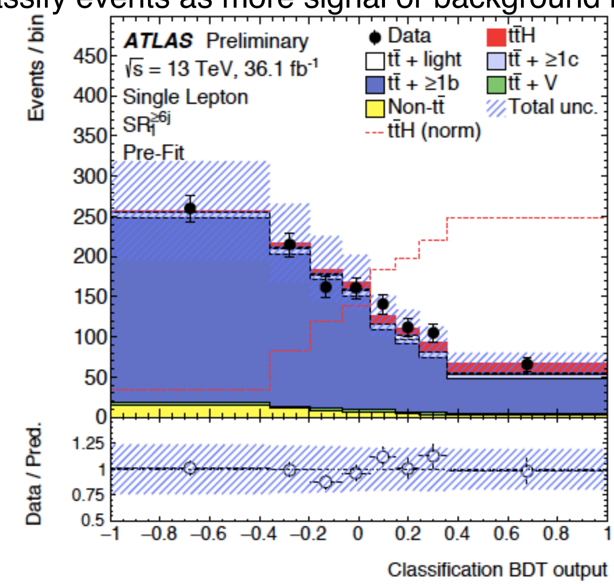
Match jets to Higgs or top decays, allows for Higgs reconstruction from large b-jet combinatorics



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

Classification BDT

classify events as more signal or background like



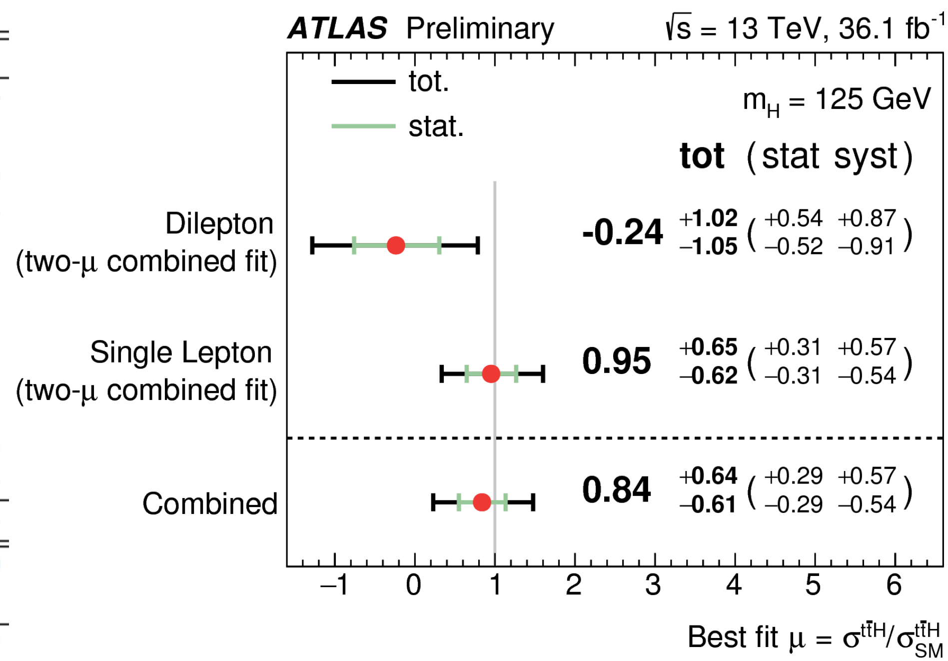
Training inputs

In total: Fit 9 SR and 10 CR

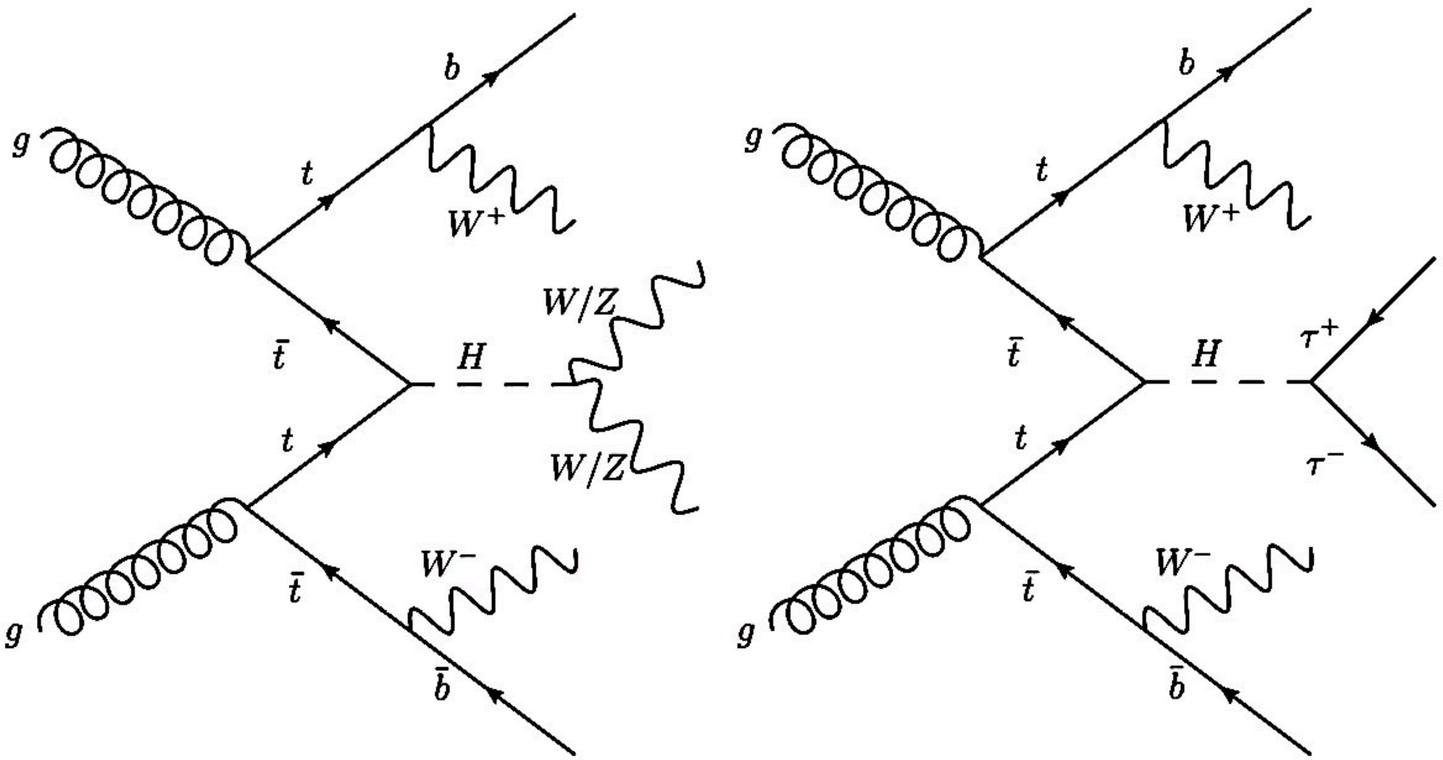
ttH(bb) results

- 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 multilepton

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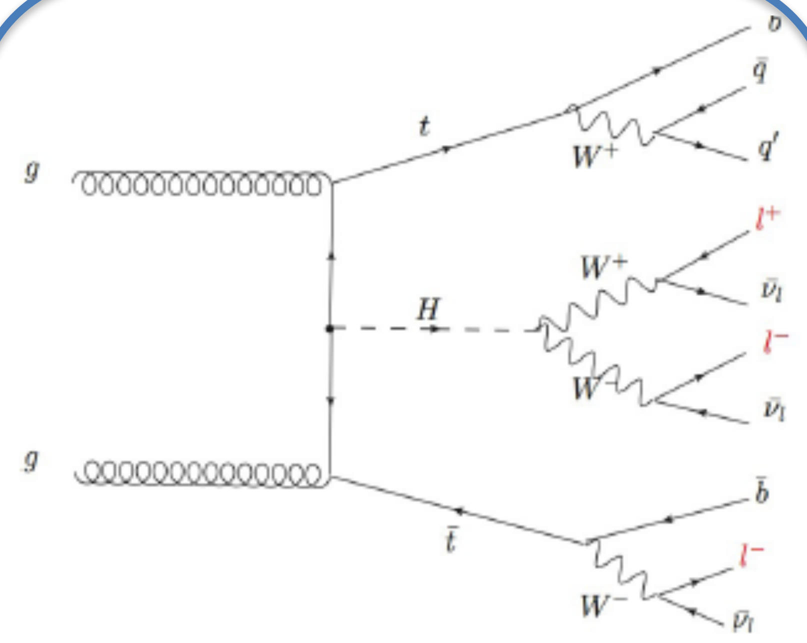
Search for the ttH (multi leptons) process

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

Many possible final states

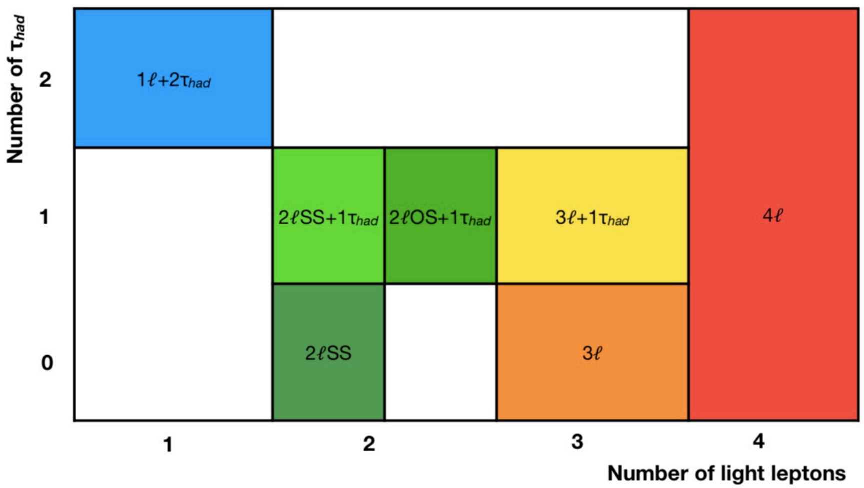
- Focus on those with clean signature and low background
- Select electron/muon from H and top decay
- Requiring same-sign leptons or 3leptons with charge sum ±1 reduces large tt background
- H→WW most sensitive channel
- H→ττ next sensitive
  - Hadronic τ reconstruction has larger uncertainties

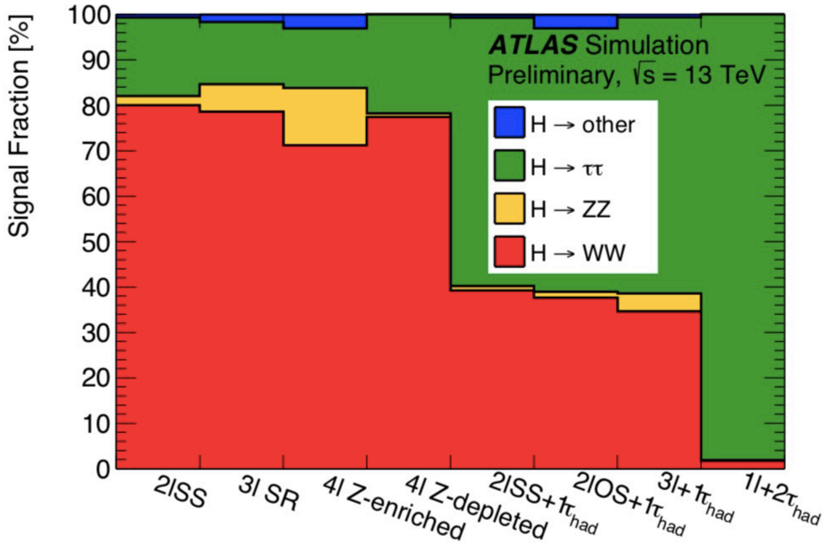


H→WW, 3-leptons

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



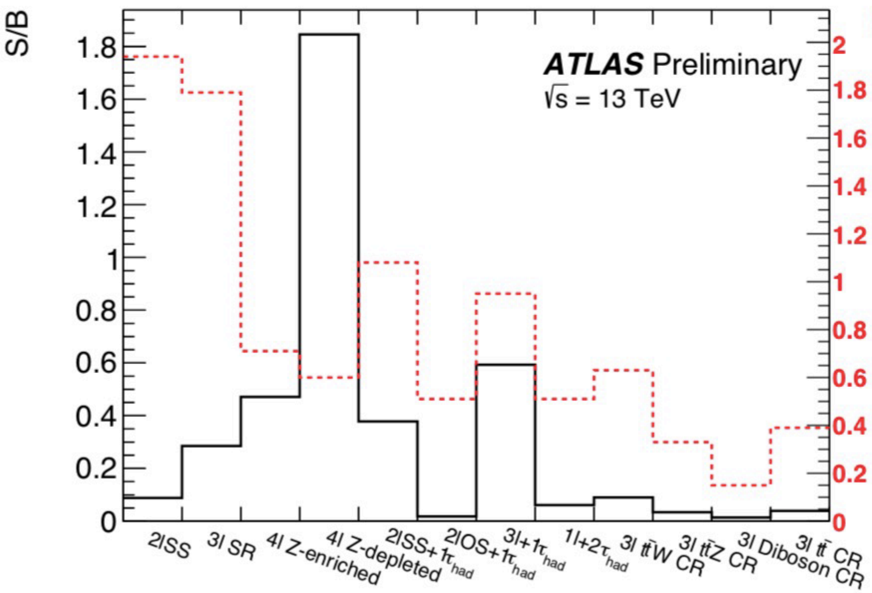


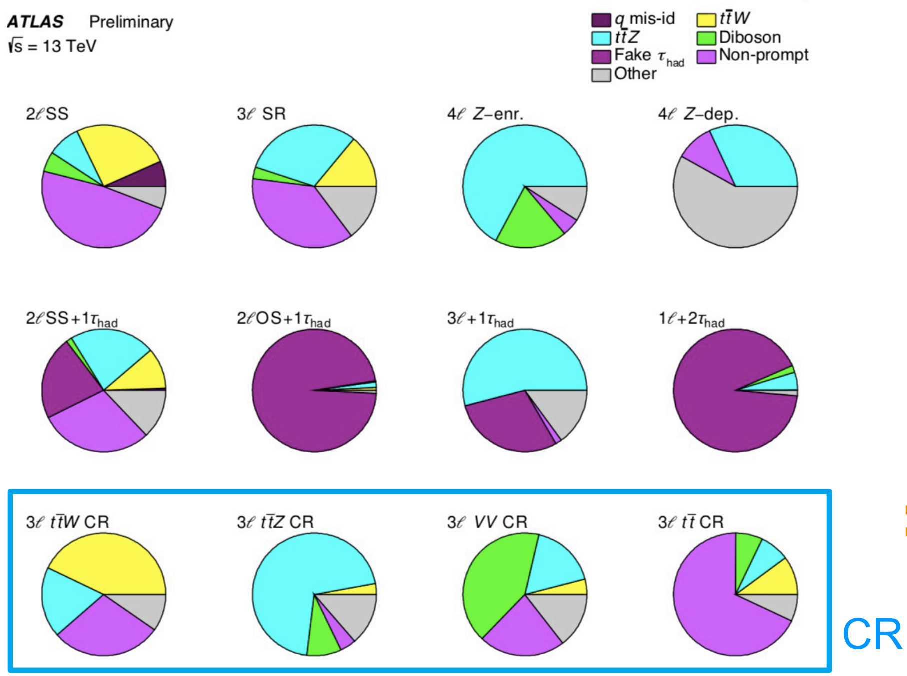
- Common jet selection: $N_{jet} \geq 2$ and $N_{b\text{-}jet} \geq 1$
- Optimised lepton selection in each category
  - Isolation requirement
  - BDTs to reject backgrounds

- 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

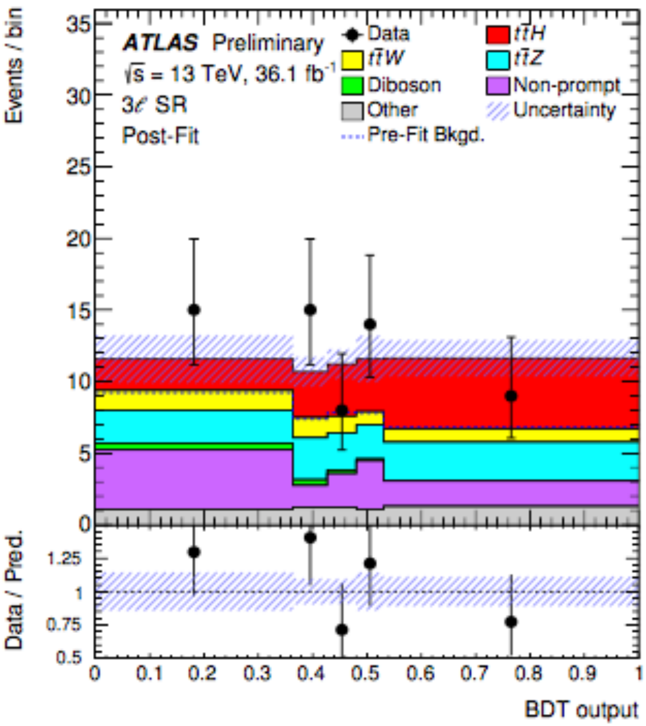


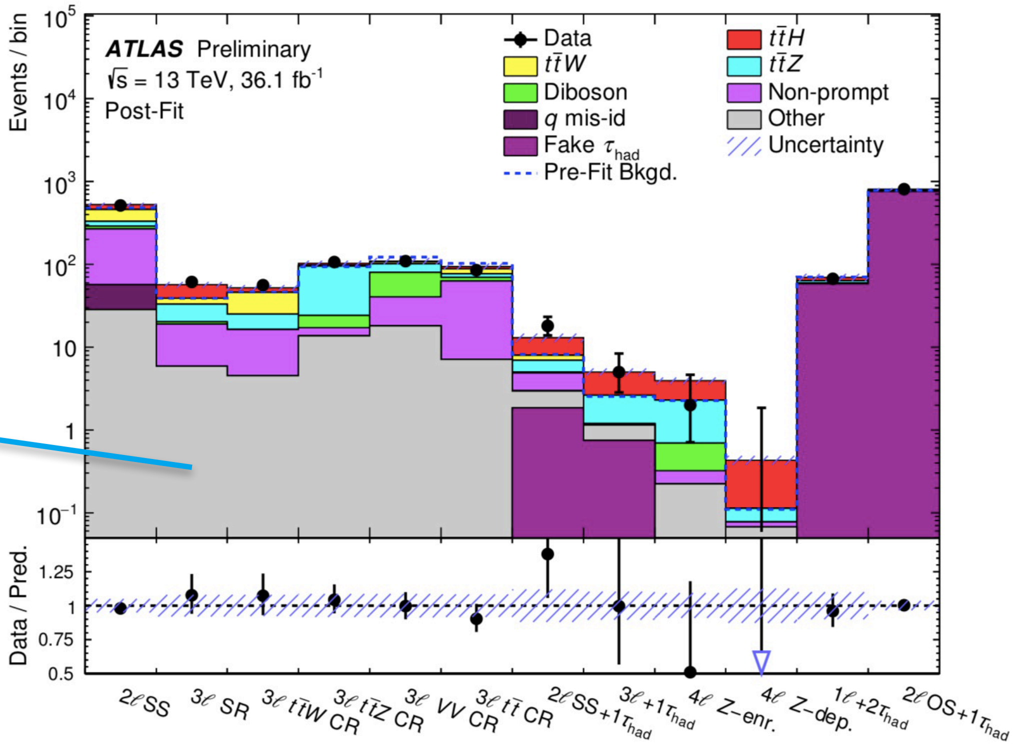


- S/B upto ~1.8
- MVA techniques used in most categories to suppress backgrounds
- Different background components in regions:
  - ttW, ttZ, VV, NonPrompt, fake τ
- NonPrompt and fake τ backgrounds estimated from control regions using data driven methods
  - NonPrompt: mainly tt+nonPrompt leptons from 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+$2\tau_{\mathrm{had}}$	2ℓSS+$1\tau_{\mathrm{had}}$	2ℓOS+$1\tau_{\mathrm{had}}$	3ℓ+$1\tau_{\mathrm{had}}$
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	-	-	-	-	-

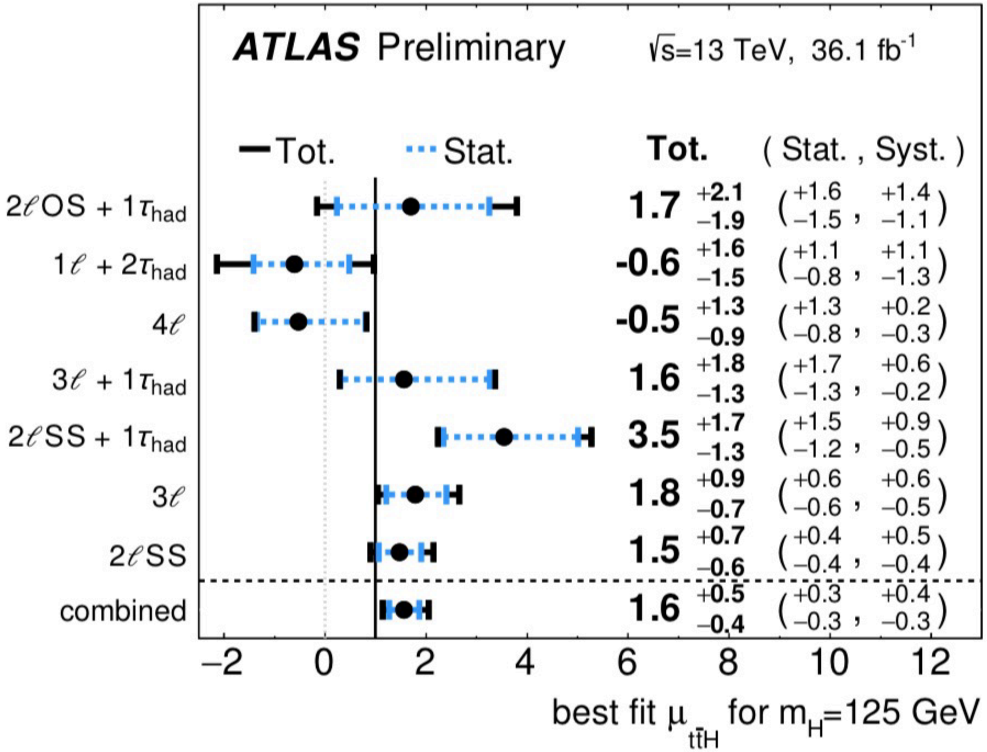




- Profile likelihood fit in all sub-channels simultaneously
- Fit BDT discriminant or single bin in low stat regions

ttH(ML) results

Channel	Significance Observed	Significance Expected
2ℓOS+1τ_{had}	0.9σ	0.5σ
1ℓ+2τ_{had}	-	0.6σ
4ℓ	-	0.8σ
3ℓ+1τ_{had}	1.3σ	0.9σ
2ℓSS+1τ_{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

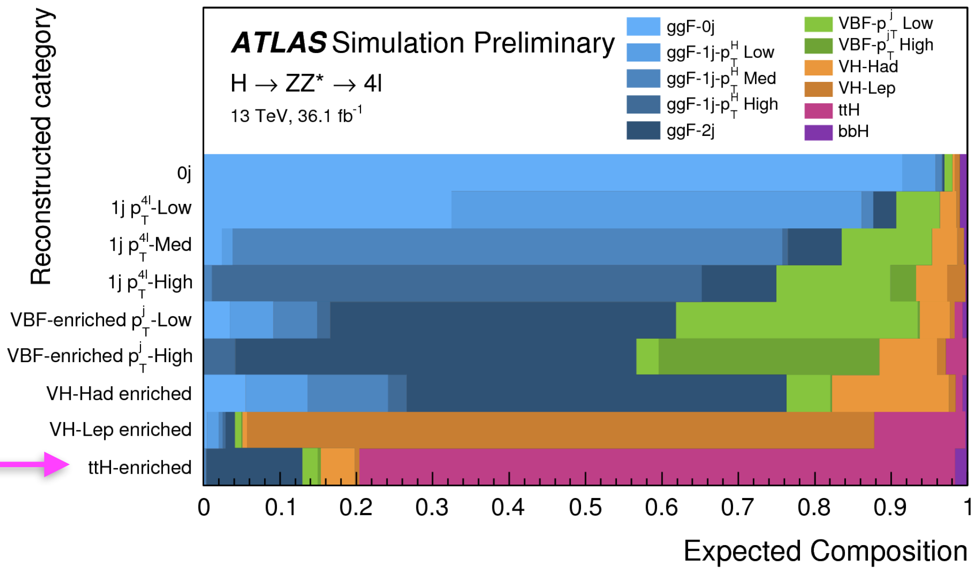
- Largest impact from ttH modelling scale uncertainty
- Jet energy resolution, largest experimental uncertainty
- Non prompt estimation suffers from low statistics in control region
- Sizeable ttV scale uncertainty

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

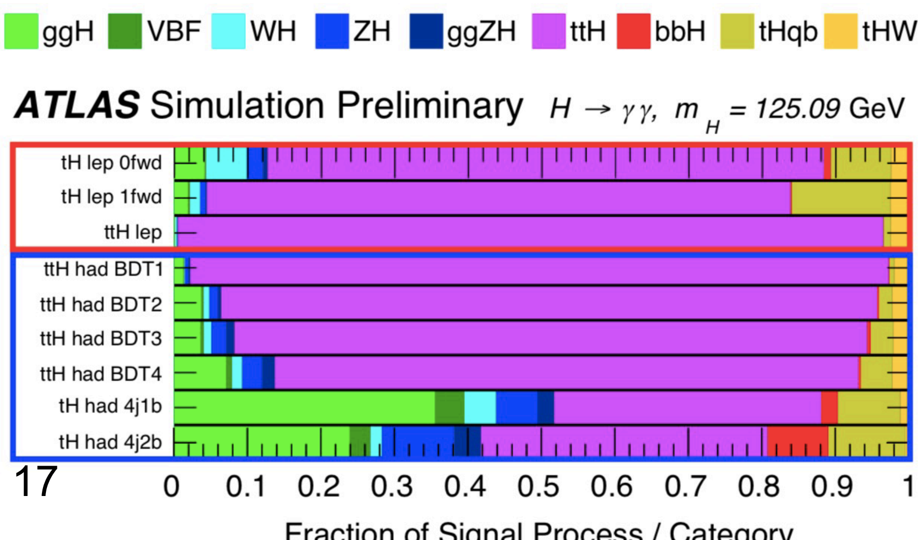
ttH(ZZ→4l) and ttH(γγ)

> 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

CERN-EP-2017-206

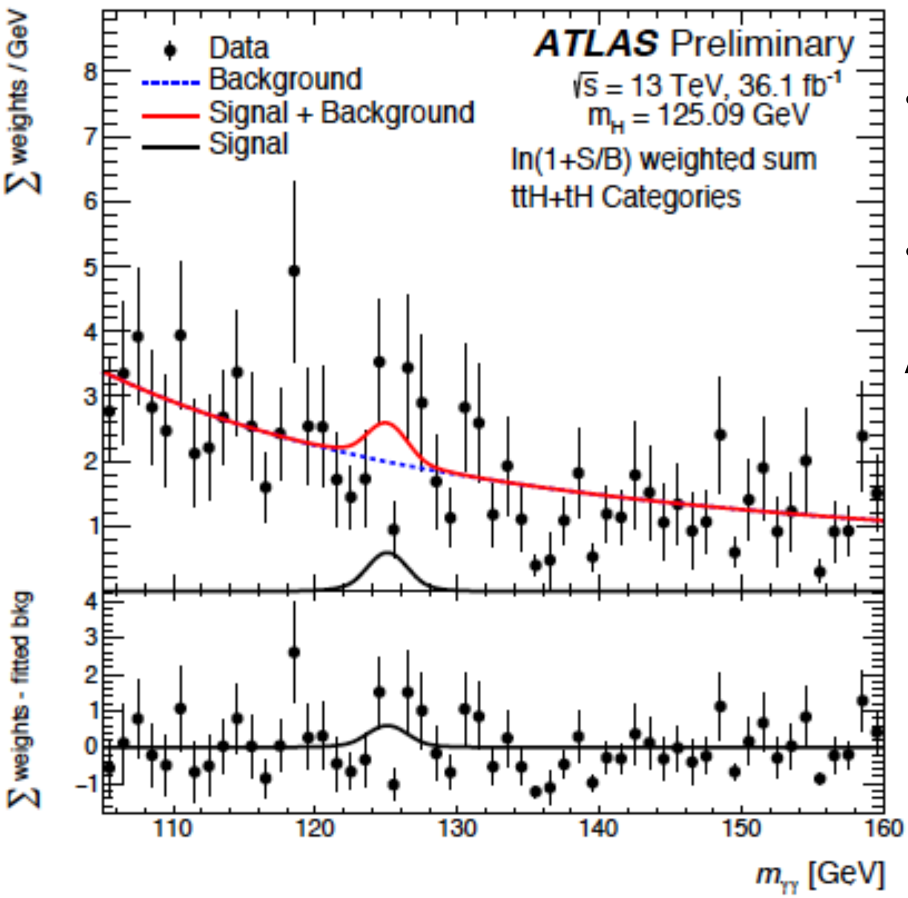


- H→γγ , ttH and tH categories in leptonic and hadronic channels

ATLAS-CONF-2017-045

tH + ttH (H->γγ)

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



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

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Signal model: double-sided Crystal Ball

Background model: data driven by inverting γ ID or isolation, or removing b-tagging; shape+normalisation from fit to $m_{\gamma\gamma}$

ttH results, combined

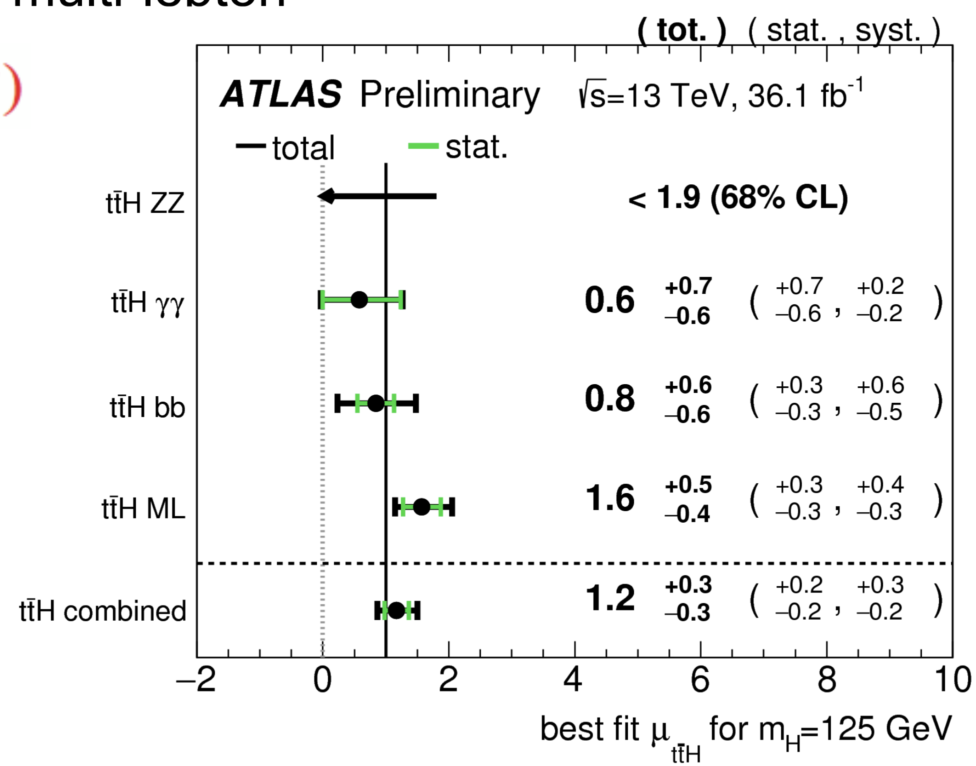
- Combination of bb with multi-lepton(WW & $\tau\tau$), ZZ→4l and γγ channels for best possible sensitivity
- Common systematics correlated across channels
  - Large overlap between bb and multi-lepton

ATLAS-CONF-2017-077

Significance : 4.2σ (expected : 3.8σ)

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

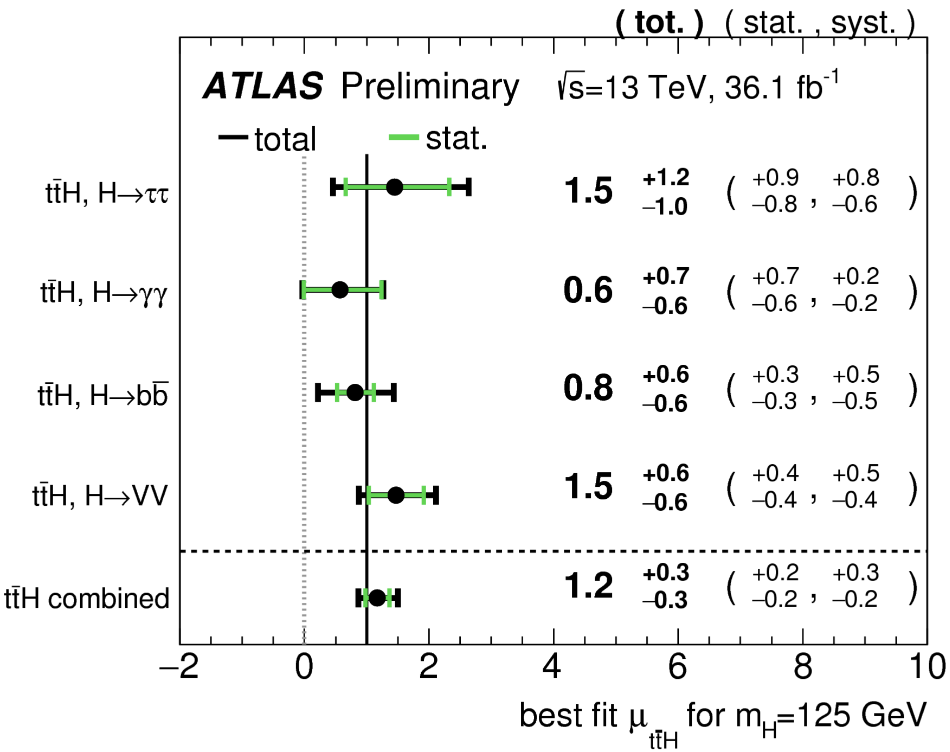
Uncertainty Source	$\Delta\mu$	
$t\bar{t}$ modelling in $H \to bb$ analysis	+0.15	−0.14
$t\bar{t}H$ modelling (cross section)	+0.13	−0.06
Non-prompt light-lepton and fake τ_{had} estimates	+0.09	−0.09
Simulation statistics	+0.08	−0.08
Jet energy scale and resolution	+0.08	−0.07
$t\bar{t}V$ modelling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

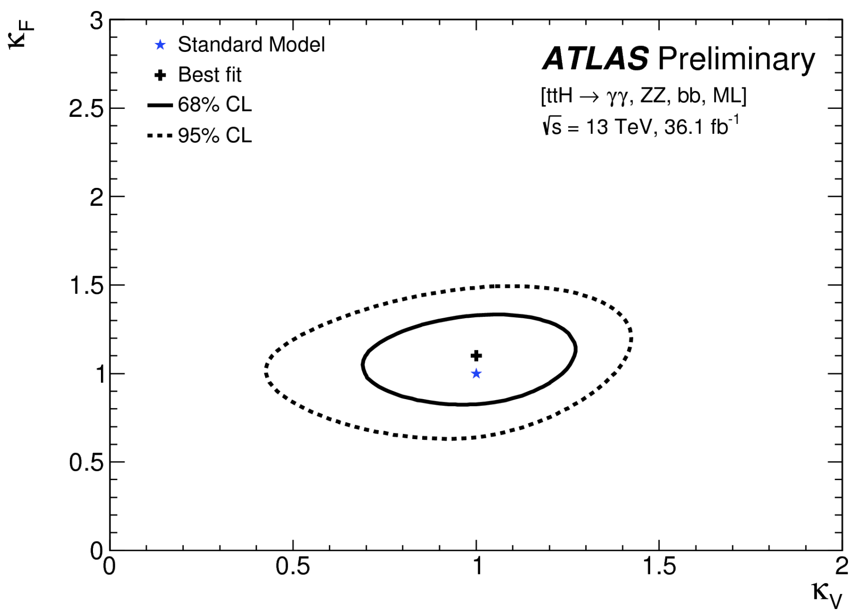


tH processes are treated as SM background

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.

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

ttH bb yields

Sample	$SR_3^{\geq 6j}$ Pre-fit	$SR_3^{\geq 6j}$ Post-fit	$SR_2^{\geq 6j}$ Pre-fit	$SR_2^{\geq 6j}$ Post-fit	$SR_1^{\geq 6j}$ Pre-fit	$SR_1^{\geq 6j}$ Post-fit
$t\bar{t}H$	85 ± 10	71 ± 52	81 ± 10	68 ± 50	62 ± 11	51 ± 38
$t\bar{t}$ + light	750 ± 370	586 ± 98	210 ± 210	96 ± 33	14 ± 10	12.1 ± 5.8
$t\bar{t} + \geq 1c$	880 ± 350	1330 ± 190	350 ± 100	473 ± 99	53 ± 33	44 ± 20
$t\bar{t} + \geq 1b$	2100 ± 420	2290 ± 170	1750 ± 370	1850 ± 130	1010 ± 240	1032 ± 59
$t\bar{t} + V$	51.2 ± 7.4	50.8 ± 5.9	40.8 ± 5.7	40.3 ± 4.8	25.8 ± 3.7	25.3 ± 3.2
Non-$t\bar{t}$	303 ± 82	267 ± 63	155 ± 52	134 ± 46	75 ± 20	58 ± 17
Total	4140 ± 850	4590 ± 110	2550 ± 510	2657 ± 82	1220 ± 250	1223 ± 42
Data	4698		2641		1222	

Sample	SR_2^{5j} Pre-fit	SR_2^{5j} Post-fit	SR_1^{5j} Pre-fit	SR_1^{5j} Post-fit	$SR^{boosted}$ Pre-fit	$SR^{boosted}$ Post-fit
$t\bar{t}H$	40.1 ± 5.1	34 ± 25	15.9 ± 2.1	13.3 ± 9.8	16.9 ± 1.9	14 ± 10
$t\bar{t}$ + light	500 ± 210	393 ± 67	15 ± 33	12.5 ± 9.3	180 ± 120	112 ± 32
$t\bar{t} + \geq 1c$	436 ± 92	610 ± 100	30 ± 17	28 ± 14	168 ± 70	235 ± 39
$t\bar{t} + \geq 1b$	1230 ± 200	1450 ± 110	273 ± 53	335 ± 25	236 ± 89	229 ± 33
$t\bar{t} + V$	19.9 ± 2.9	19.7 ± 2.4	6.4 ± 1.3	6.4 ± 1.2	16.1 ± 2.9	16.6 ± 2.4
Non-$t\bar{t}$	269 ± 64	220 ± 52	54 ± 11	28.1 ± 8.4	104 ± 30	101 ± 26
Total	2440 ± 390	2724 ± 70	371 ± 68	423 ± 23	710 ± 200	708 ± 40
Data	2798		426		740	

ttH bb ttbar background

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 $t\bar{t}+\geq 1c$ normalization	$t\bar{t}+\geq 1c$
$k(t\bar{t}+\geq 1b)$	Free-floating $t\bar{t}+\geq 1b$ normalization	$t\bar{t}+\geq 1b$
SHERPA5F vs. nominal	Related to the choice of NLO event generator	All, uncorrelated
PS & hadronization	POWHEG+HERWIG 7 vs. POWHEG+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+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 tuned parameters for the underlying event	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 3b$ normalization	Up or down by 50%	$t\bar{t}+\geq 1b$

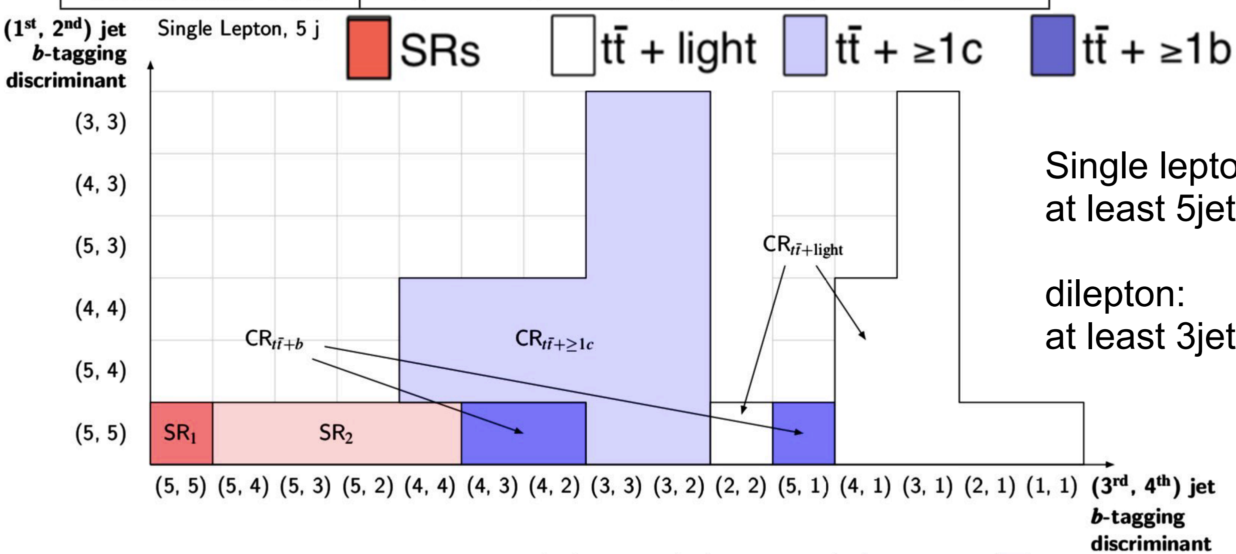
ttH(bb) regions

- 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

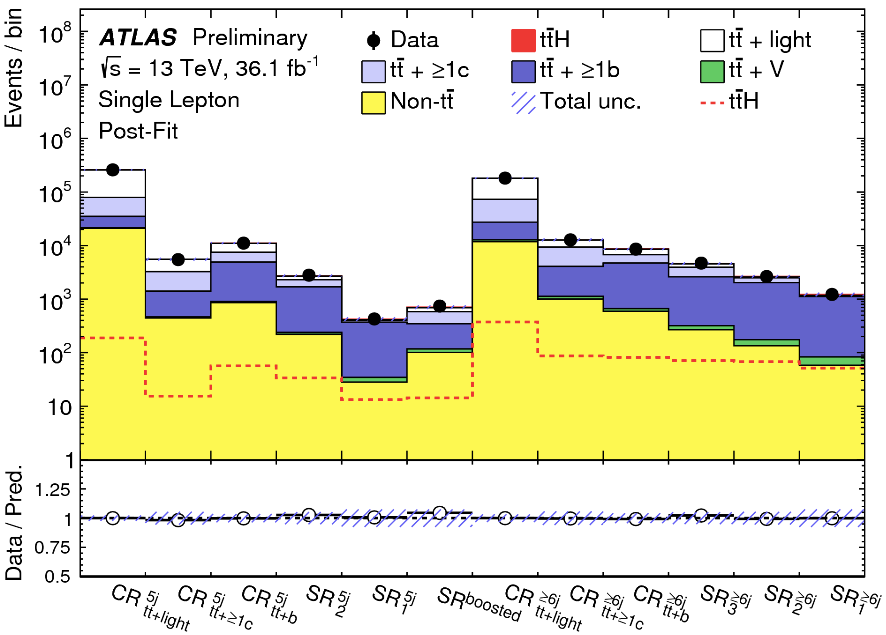
	none	*loose*	*medium*	*tight*	*very-tight*
Efficiency	-	85%	77%	70%	60%
Discriminant value	1	2	3	4	5

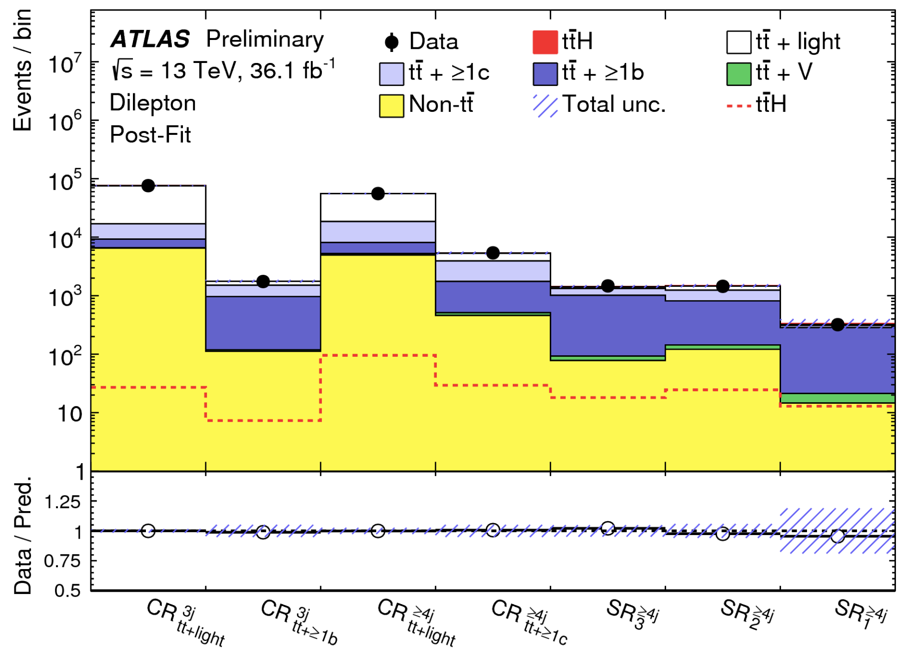


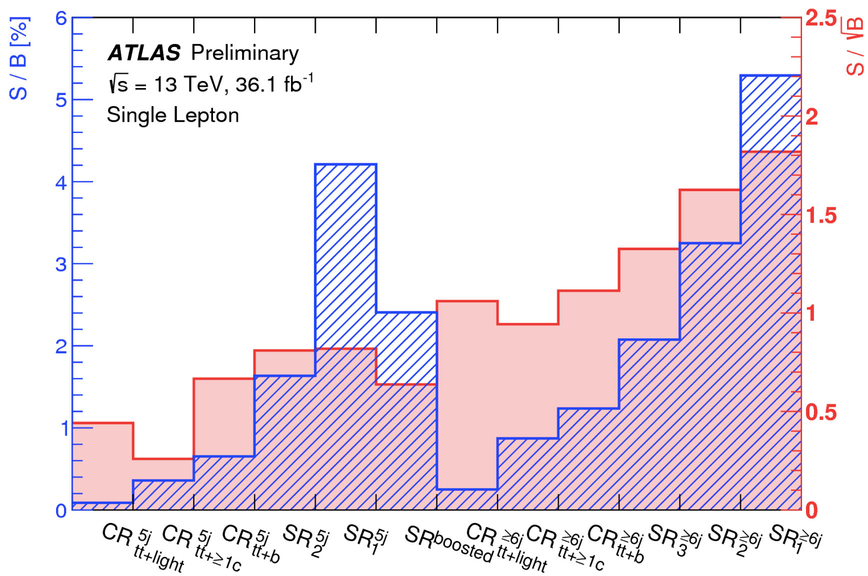
Single lepton:
at least 5jets, 2 very tight or 3 medium b-jets

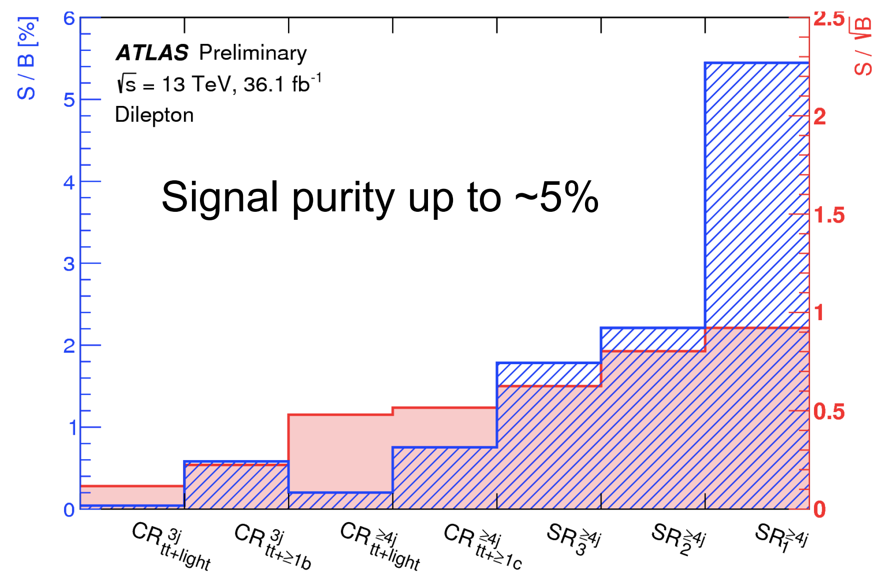
dilepton:
at least 3jets, 2 medium b-jets

Single lepton and dilepton region summary



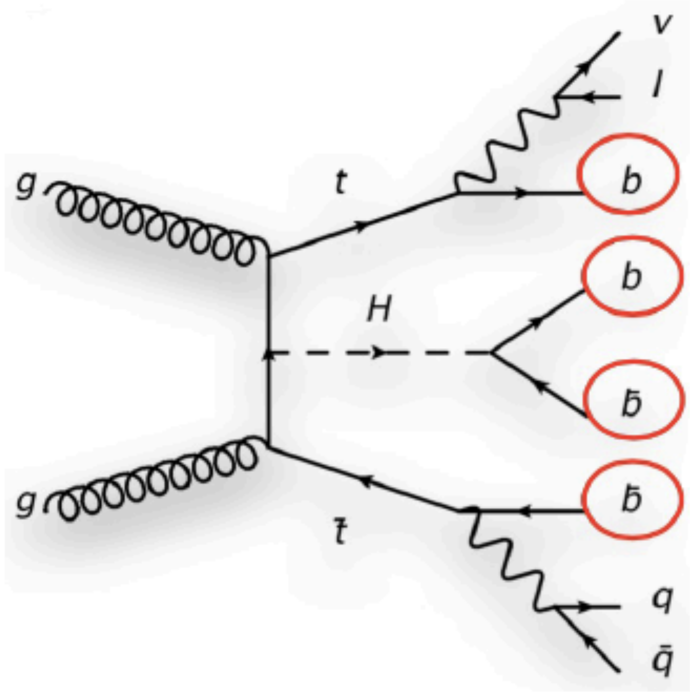




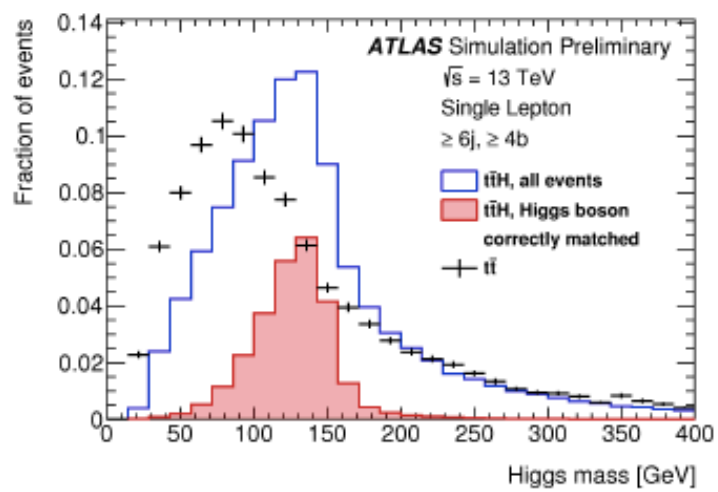


Higgs reconstruction

- 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.



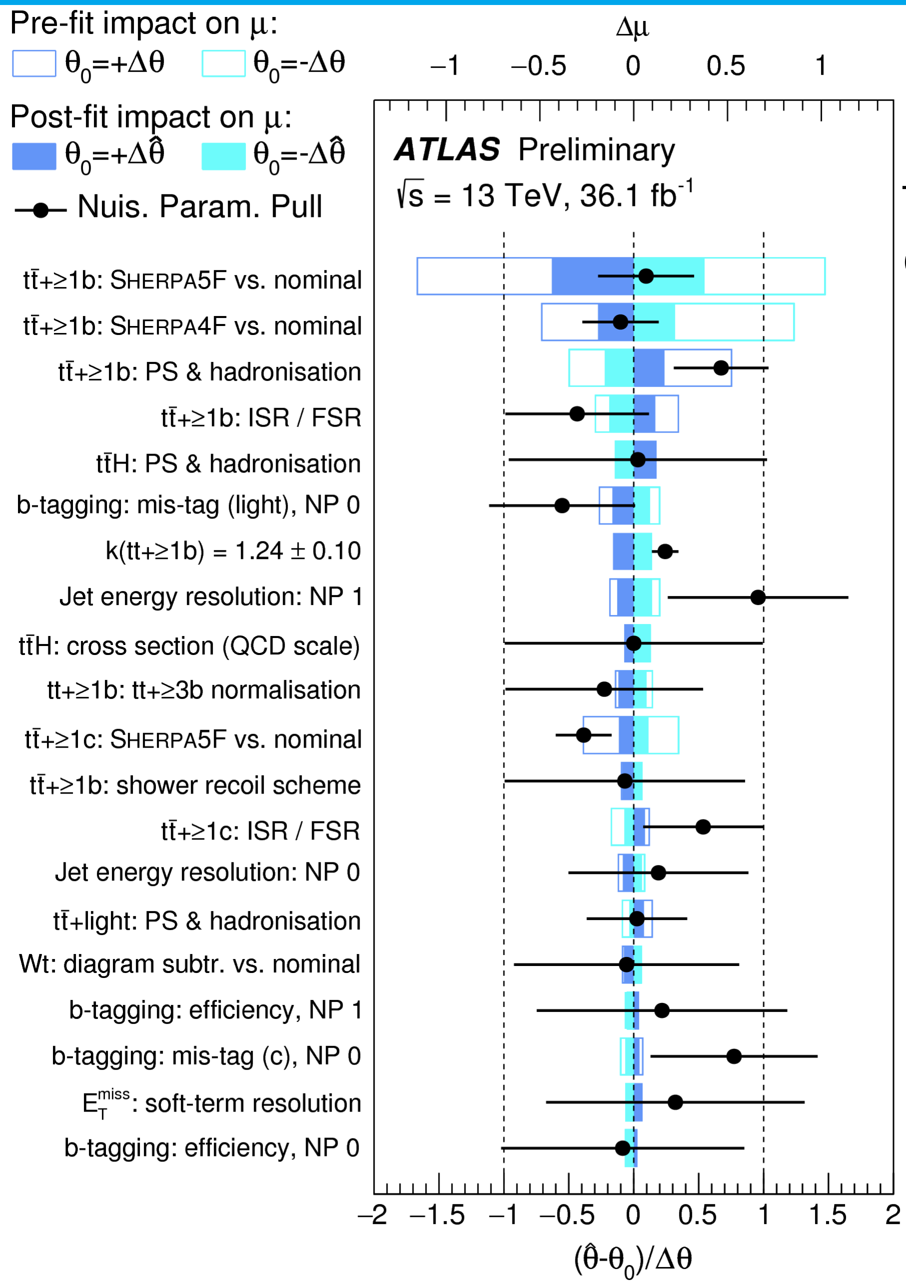
Other tools used in some regions:
Likelihood Discriminant & Matrix Element play minor role

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 $H_{\mathrm{T}}/2$ 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

ttH multilepton selection

Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
2ℓSS	Two very tight light leptons with $p_{\text{T}} > 20$ GeV
	Same-charge light leptons
	Zero medium τ_{had} candidates
	$N_{\text{jets}} \geq 4$ and $N_{b\text{-jets}} < 3$
3ℓ	Three light leptons with $p_{\text{T}} > 10$ GeV; sum of light-lepton charges ± 1
	Two same-charge leptons must be very tight and have $p_{\text{T}} > 15$ GeV
	The opposite-charge lepton must be loose, isolated and pass the non-prompt BDT
	Zero medium τ_{had} candidates
	$m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\ \text{GeV}\rvert > 10$ GeV for all SFOC pairs
	$\lvert m(3\ell) - 91.2\ \text{GeV}\rvert > 10$ GeV

….

ttH multilepton yields

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

ttH multilepton MC

Process	Event generator	ME order	Parton Shower	PDF	Tune
$t\bar{t}H$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO [70]	A14
	(MG5_aMC)	(NLO)	(Herwig++)	(CT10 [71])	(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	NLO	Pythia 8	NNPDF 3.0 NLO	A14
	(Sherpa 2.1.1)	(LO multileg)	(Sherpa)	(NNPDF 3.0 NLO)	(Sherpa default)
$t\bar{t}(Z/\gamma^* \to ll)$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO	A14
	(Sherpa 2.1.1)	(LO multileg)	(Sherpa)	(NNPDF 3.0 NLO)	(Sherpa default)
tZ	MG5_aMC	LO	Pythia 6	CTEQ6L1	Perugia2012
tWZ	MG5_aMC	NLO	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}t$, $t\bar{t}t\bar{t}$	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 [72]	NLO	Pythia 8	NNPDF 3.0 NLO	A14
$t\bar{t}\gamma$	MG5_aMC	LO	Pythia 8	NNPDF 2.3 LO	A14
s-, t-channel, Wt single top	Powheg-BOX v1 [73–75]	NLO	Pythia 6	CT10	Perugia2012
$VV(\to llXX)$, $qqVV$, VVV	Sherpa 2.1.1	MEPS NLO	Sherpa	CT10	Sherpa default
$Z \to l^+l^-$	Sherpa 2.2.1	MEPS NLO	Sherpa	NNPDF 3.0 NLO	Sherpa default