Search for the SM Higgs boson in the ttH production channel using the ATLAS detector

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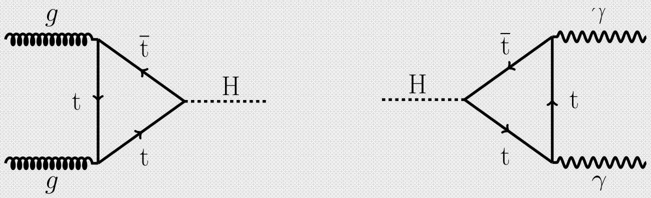
Motivation

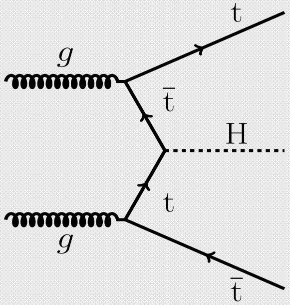
- Study of the Higgs properties is crucial for Standard Model validation and understanding of electroweak symmetry breaking
- Top-Higgs Yukawa coupling y_t is one of the key features to measure
  - ✓ It's the biggest in SM: y_t~0.94
  - ✓ Top loop contribution to the Higgs mass is dominant
  - ✓ Mandatory to understand stability of electroweak vacuum
  - ✓ Direct coupling measurement may give insight into scale of new physics

	7TeV	8TeV	13TeV
ttH x-sec(fb)	89	133	507

- y_t can be constrained indirectly via loop contributions in ggF and H→γγ processes



- ttH production gives direct access to y_t



- ATLAS+CMS Run 1 combination:

$$\mu_{ttH} = \frac{\sigma_{ttH}}{\sigma_{ttH}^{SM}} = 2.3^{+0.7}_{-0.6}$$

$$k_t = \frac{y_t}{y_t^{SM}} = 0.87^{+0.14}_{-0.15} \text{ (SM only)}$$

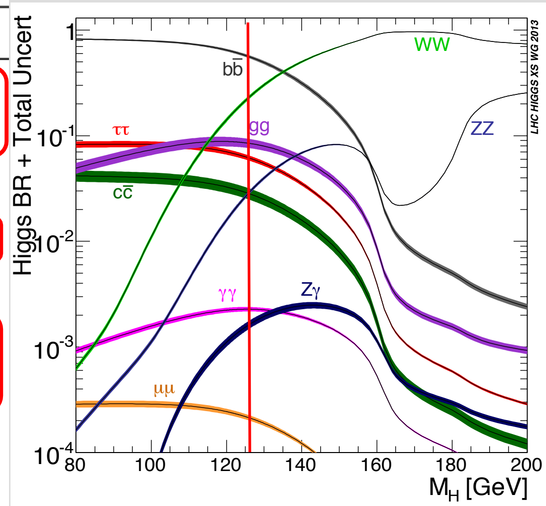
Current presentation: 36.1 fb^{-1} data collected in 2015+2016 at 13 TeV

Higgs and top quark features

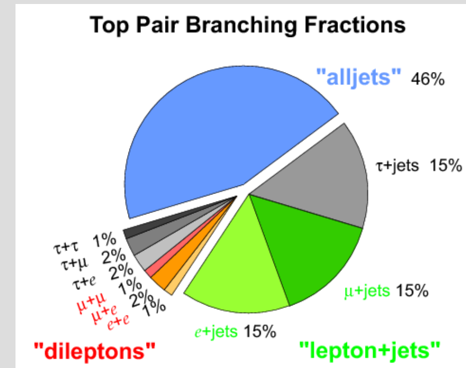
13TeV ttH production cross-section ~507fb (cf. ggF ~49pb)

SM Higgs decay branching ratios(M=125.09GeV)

Decay channel	Branching ratio [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001



Top quark pair
decay branching fractions



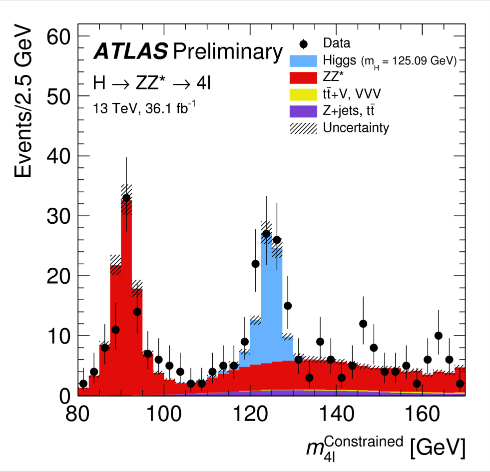
ttH experimental challenges

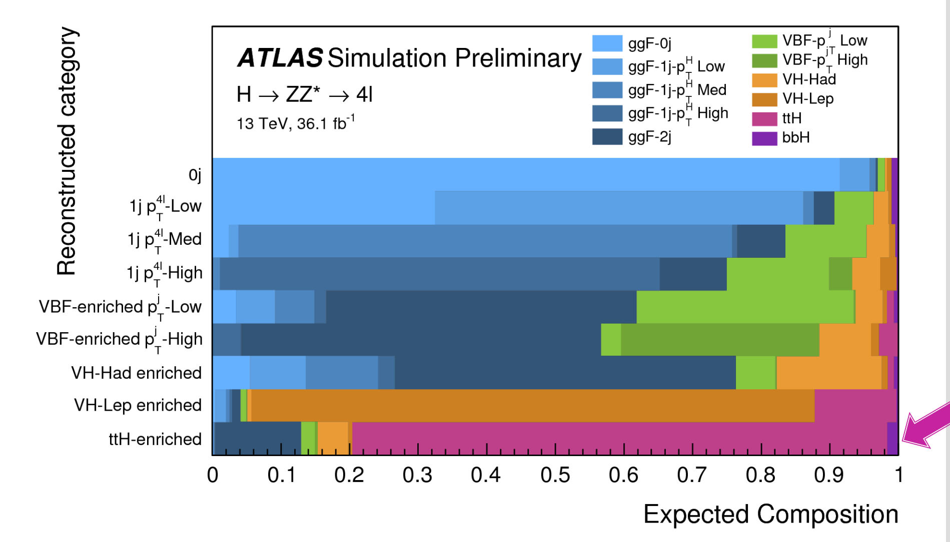
- Small cross section as compared to other Higgs production channels
- Many different final states/experimental signatures (γ, μ, e, τ, jets, b-jets, MET) depending on chosen Higgs and top quark decay modes
- Different final states have similar sensitivities to the ttH contribution
  - ✓ H→bb: dominant, but large background
  - ✓ H→γγ: experimentally clean, but tiny
- Combination of channels is necessary to observe this small production process

ttH(→ZZ*→4ℓ)

ATLAS-CONF-2017-043

- Prominent inclusive Higgs invariant mass peak in selected 4ℓ events
- Analysis strategy: select Higgs candidates 118 GeV < $M_{4\ell}$ < 129 GeV and categorize them according to topological and kinematical event features.
- ttH-enriched category:
  - ✓ ≥ 4 jets, ≥ 1 b-jet
  - ✓ ≥ 2 jets, ≥ 1 b-jet, ≥ 1 lepton.





Reconstructed category	Signal	ZZ*	Other backgrounds	Total expected	Observed
ttH-enriched	0.39±0.04	0.014±0.006	0.07±0.04	0.47±0.05	0

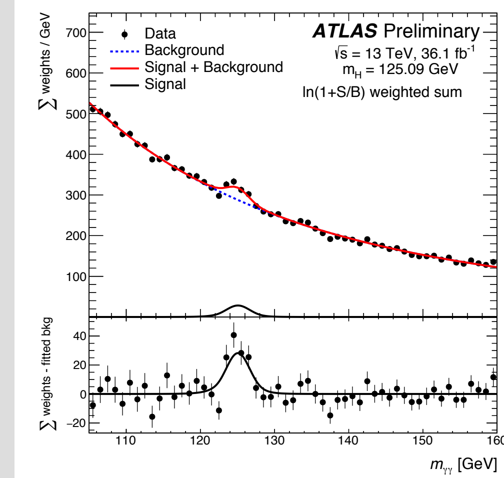
Production bin	cross section(σBr)		Observed signal μ (95% CL_s)
	Observed	SM	
ttH	<120 fb	15.4 fb	< 7.7

ttH(→γγ)

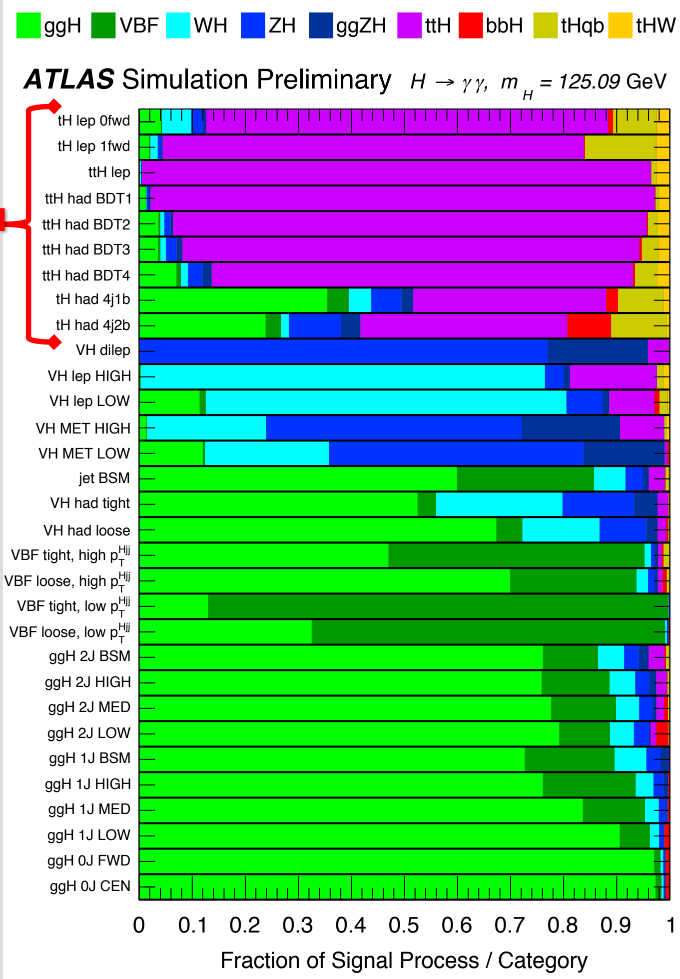
ATLAS-CONF-2017-045

- **Prominent Higgs mass peak in two good γ's invariant mass spectrum**
- **Similar to 4ℓ, select Higgs candidate events in 105 GeV<$M_{\gamma\gamma}$<160 GeV and categorize them based on topological and kinematical features to maximise sensitivity to different production modes. In total 31 categories.**

All selected γγ pair masses. Events are weighted by *ln(1+S_{90}/B_{90})* where S_{90} and B_{90} are expected signal and background



topH



"Top" categories target ttH, tHW, tHqb and bbH production channels. They are dominated by ttH.

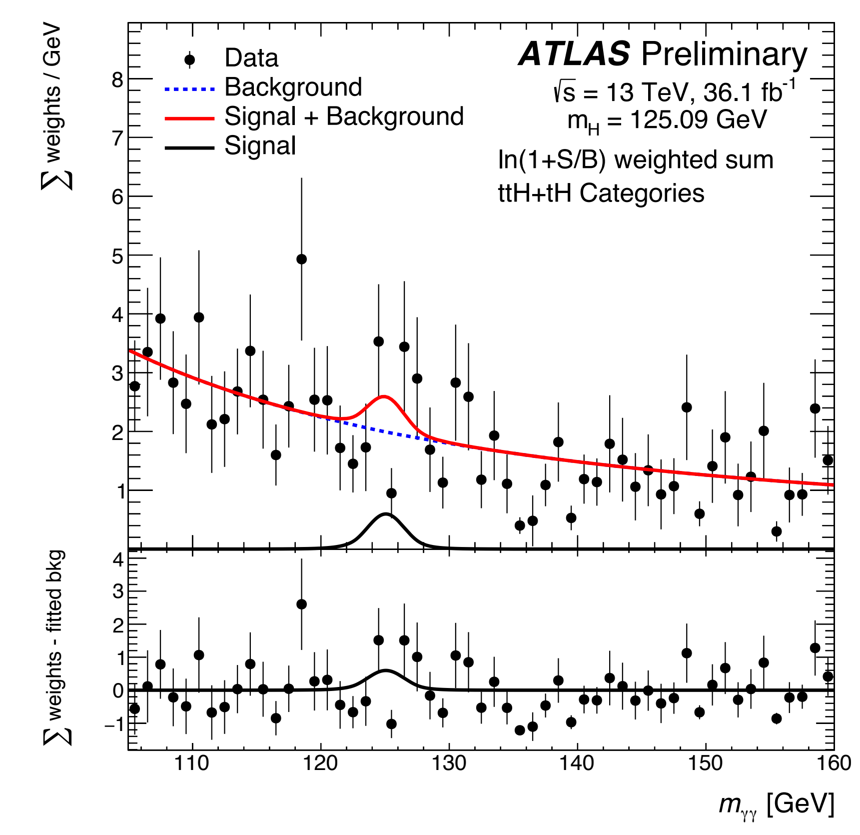
Category	Selection
tH lep 0fwd	$N_{\text{lep}} = 1,\ N_{\text{jets}}^{\text{cen}} \leq 3,\ N_{\text{b-tag}} \geq 1,\ N_{\text{jets}}^{\text{fwd}} = 0\ (p_T^{\text{jet}} > 25\,\text{GeV})$
tH lep 1fwd	$N_{\text{lep}} = 1,\ N_{\text{jets}}^{\text{cen}} \leq 4,\ N_{\text{b-tag}} \geq 1,\ N_{\text{jets}}^{\text{fwd}} \geq 1\ (p_T^{\text{jet}} > 25\,\text{GeV})$
ttH lep	$N_{\text{lep}} \geq 1,\ N_{\text{jets}}^{\text{cen}} \geq 2,\ N_{\text{b-tag}} \geq 1,\ Z_{\ell\ell}$ veto $(p_T^{\text{jet}} > 25\,\text{GeV})$
ttH had BDT1	$N_{\text{lep}} = 0,\ N_{\text{jets}} \geq 3,\ N_{\text{b-tag}} \geq 1,\ \text{BDT}_{\text{ttH}} > 0.92$
ttH had BDT2	$N_{\text{lep}} = 0,\ N_{\text{jets}} \geq 3,\ N_{\text{b-tag}} \geq 1,\ 0.83 < \text{BDT}_{\text{ttH}} < 0.92$
ttH had BDT3	$N_{\text{lep}} = 0,\ N_{\text{jets}} \geq 3,\ N_{\text{b-tag}} \geq 1,\ 0.79 < \text{BDT}_{\text{ttH}} < 0.83$
ttH had BDT4	$N_{\text{lep}} = 0,\ N_{\text{jets}} \geq 3,\ N_{\text{b-tag}} \geq 1,\ 0.52 < \text{BDT}_{\text{ttH}} < 0.79$
tH had 4j1b	$N_{\text{lep}} = 0,\ N_{\text{jets}}^{\text{cen}} = 4,\ N_{\text{b-tag}} = 1\ (p_T^{\text{jet}} > 25\,\text{GeV})$
tH had 4j2b	$N_{\text{lep}} = 0,\ N_{\text{jets}}^{\text{cen}} = 4,\ N_{\text{b-tag}} \geq 2\ (p_T^{\text{jet}} > 25\,\text{GeV})$

Hadronic ttH selection exploits BDT trained to identify ttH against ggF and multi-jet events

Higgs signal strength is extracted by fitting the $m_{\gamma\gamma}$ in each analysis category. Higgs peak is modelled by Crystal Ball function, while background shapes are defined for each analysis category using high statistics MC or data in background enriched control regions

ttH(→γγ)

Observed γγ masses in ttH+tH categories.
Events are weighted by $ln(1+S_{90}/B_{90})$ where S_{90} and B_{90} are expected signal and background



Observed $\mu_{top}=\mu_{ttH+tH}$ signal strength and limit

$$\mu_{\rm top} = 0.5\ ^{+0.6}_{-0.6} = 0.5\ ^{+0.6}_{-0.5}\,(\text{stat.})\ ^{+0.1}_{-0.1}\,(\text{exp.})\ ^{+0.1}_{-0.0}\,(\text{theory})$$

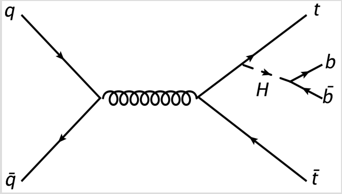
	Limits		
	Observed	Expected(μ=0)	Expected(μ=1)
μ_{top}	1.7	1.2	2.3

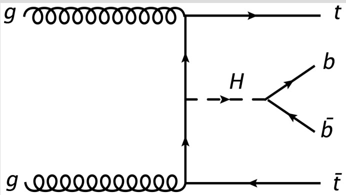
ttH(→bb)

ATLAS-CONF-2017-076

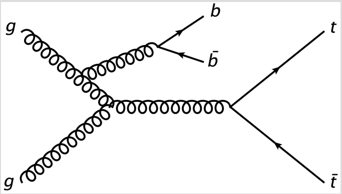
- **No visible H(→bb) peak due to limited mass resolution and high background including combinatorial one**
- **Analysis strategy: categorize events into different signal and control regions to enhance signal sensitivity and constrain different background components**
- **Dilepton channel:**
  - Exactly two opposite sign leptons, Z-veto, no hadronic τ
  - ≥ 3 jets, ≥ 2 *medium* b-tagged jets
- **Single lepton channel:**
  - Exactly one lepton, ≤ 1 hadronic τ
  - "Boosted" category
    - One boosted Higgs and one boosted top candidates, R=1.0
    - ≥1 *loose* b-jet
  - "Resolved" category
    - ≥ 5 jets
    - ≥ 2 *very-tight* b-jets or ≥ 3 *medium* b-jets

ttH signal





Dominant background: **tt+bb**



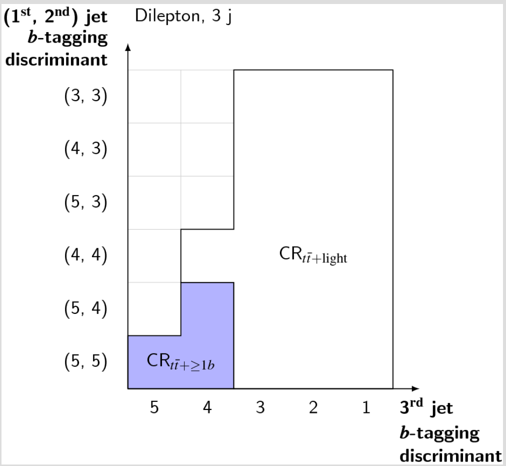
B-tagging is crucial for this analysis.

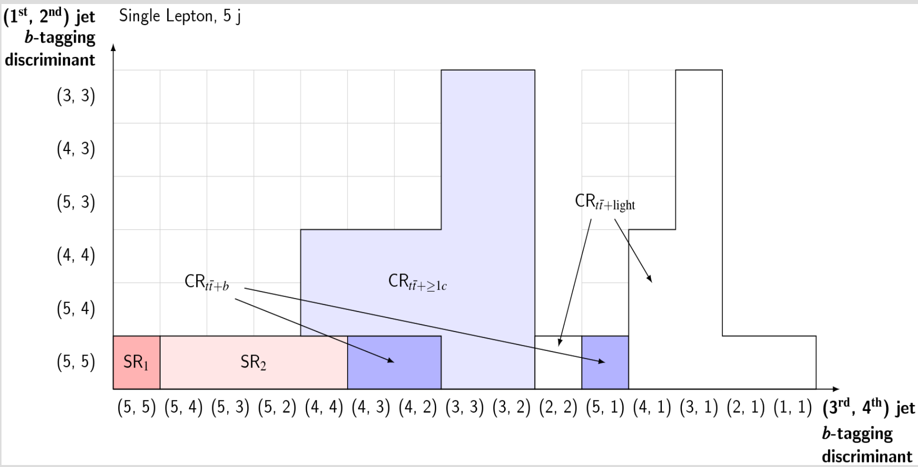
B-tagging selection	-	*loose*	*medium*	*tight*	*very-tight*
Efficiency	100%	85%	77%	70%	60%
B-tagging discriminant	1	2	3	4	5

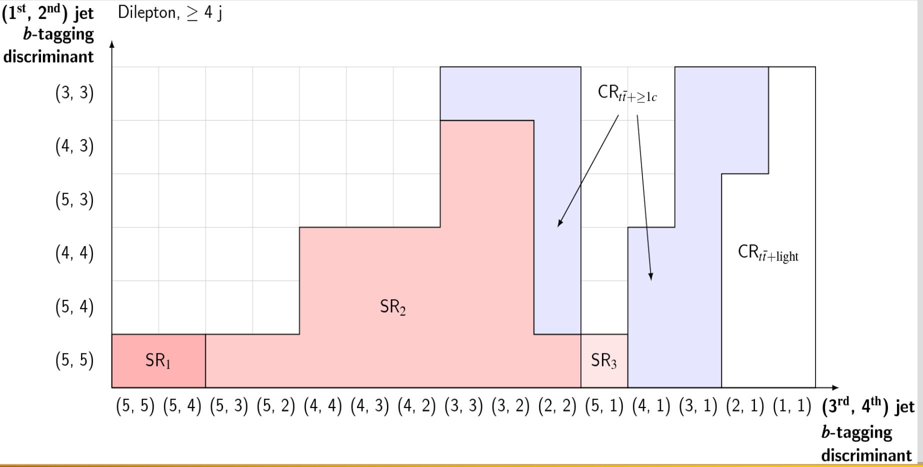
Dilepton and single lepton channels sub-categorization

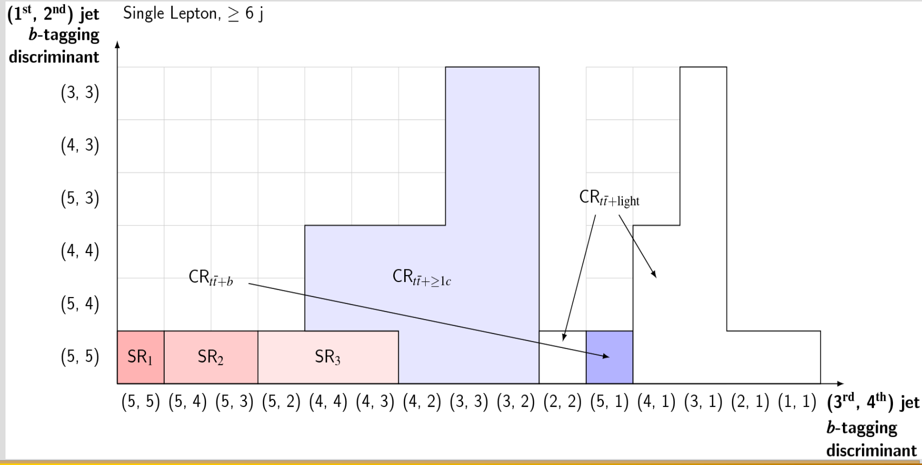
Events are classified based on number of jets and b-tagging discriminants as presented

- Categories with enhanced ttH and tt+bb content are labelled "signal regions"(SR), in these multivariate techniques are used
- Other categories are labelled "control regions"(CR), they are used to constrain backgrounds and systematic errors. No multivariate techniques are applied

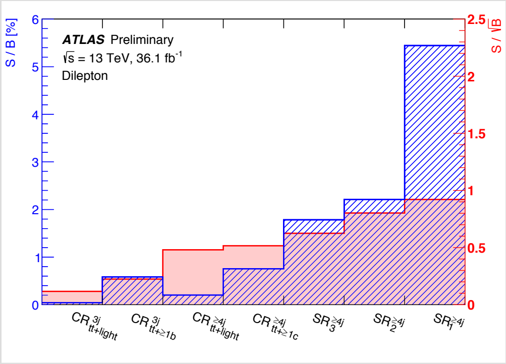




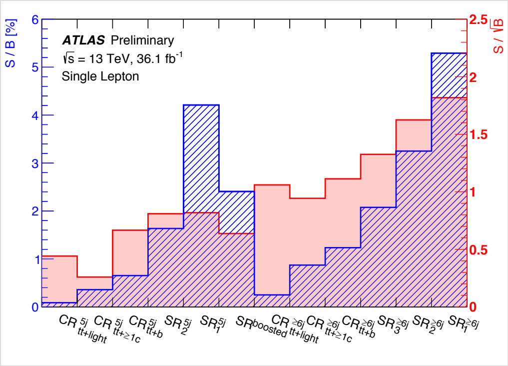




ttH(→bb)



S/B (≤5.3% in the best case) and S/sqrt(B) in the defined categories



Multivariate analysis

Reconstruction BDT:

- Dilepton and resolved single lepton channels
- Attempt to assign jets to top and Higgs decays
- Train BDT on simulated ttH events to distinguish correct and wrong assignments
- Use masses, $\Delta\varphi$ and ΔR separations, P_Ts

Likelihood discriminant(LHD):

- Resolved single lepton channel
- PDFs for masses, angles, MET from jets and lepton for signal and backgrounds
- Two backgrounds: tt+1 b-jet and tt+ ≥2 b-jets, weighted according to relative fractions
- P^{sig} and P^{bkg} are PDFs products averaged over all jet permutations weighted with the b-tagging information
- Final discriminant: $LHD=P^{sig}/(P^{sig}+P^{bkg})$

Matrix Element(MEM):

- Most sensitive $SR_1^{\geq 6j}$ single lepton region
- LO ME using MadGraph5_aMC@NLO for ttH(→bb) signal and tt+bb background
- Final discriminant: $MEM=\log_{10}(L_S)-\log_{10}(L_B)$

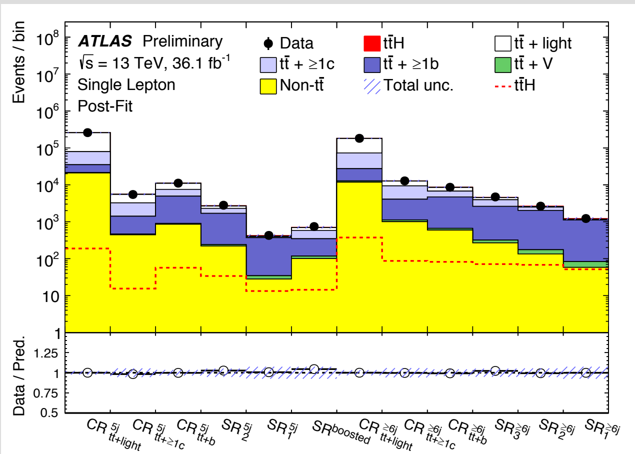
Classification BDT:

- RecoBDT+LHD+MEM (+related variables)
- General kinematic variables
- B-tagging discriminants
- Jet constituents in boosted category
- 20/23/8 variables in dilepton/single lepton/boosted

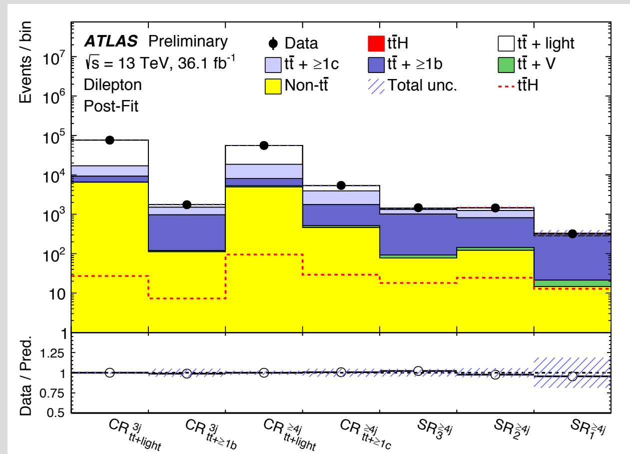
ttH(→bb)

Discriminant distributions from signal regions and normalisations from control regions are combined in a profile likelihood fit to measure the ttH signal strength

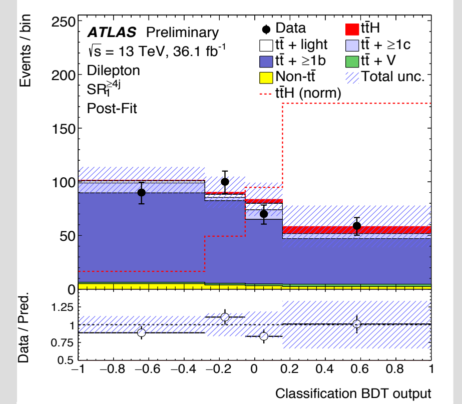
N_{ev} single lepton post-fit

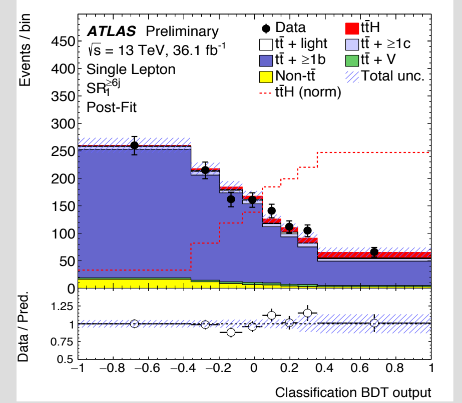


N_{ev} dilepton post-fit

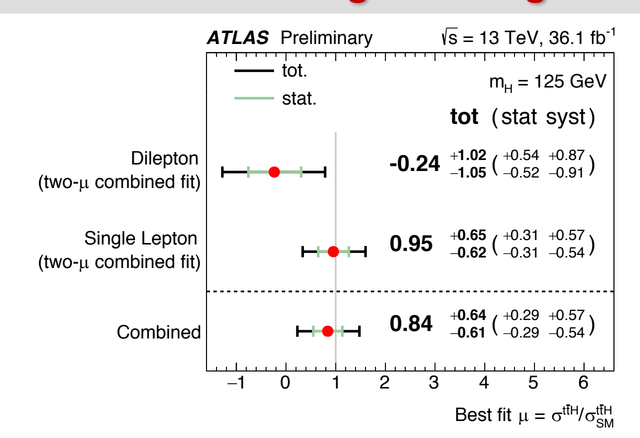


Post-fit classification BDT output in the most sensitive regions.
Dashed - ttH prediction normalized to background





Measured ttH signal strength



95% CL upper limits

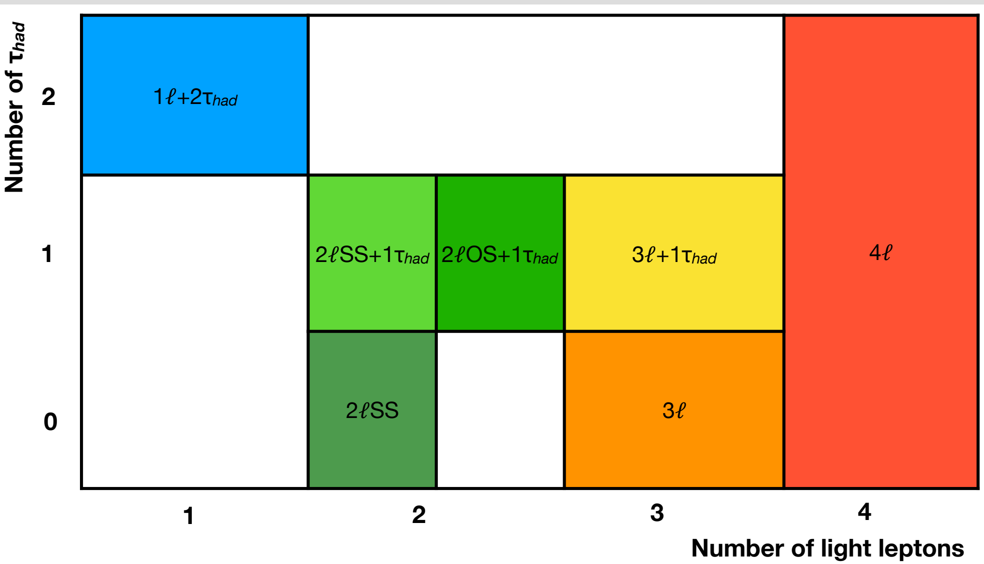
	Observed	Expected(μ=0)	Expected(μ=1)
Dilepton	2.64	2.74	3.63
Single lepton	1.95	1.40	2.27
Dilepton(2μ fit)	1.84	2.47	3.39
Single lepton(2μ fit)	2.09	1.26	2.13
Combined	1.96	1.24	2.12

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.46	−0.46
Background model statistics	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+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
JVT, 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

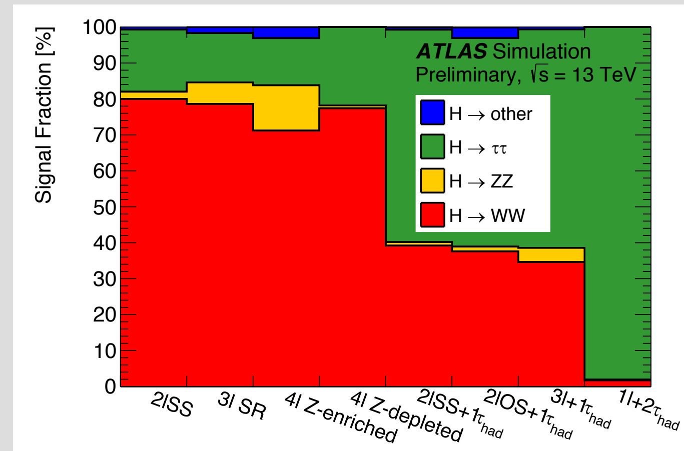
ttH multilepton(ML)

ATLAS-CONF-2017-077

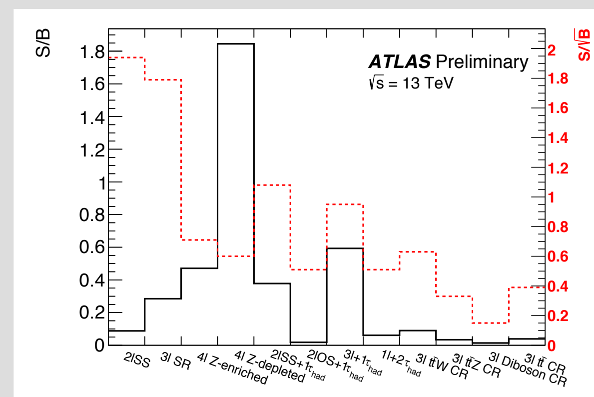
- **No Higgs mass peak due to missing neutrinos**
- **Targets H→WW*, ZZ*, $\tau\tau$ → leptons channels**
  - ✓ Overlap with H→4ℓ analysis is removed
- **7 different categories to maximise sensitivity**



Higgs decay mode composition in the selected signal categories



S/B and S/sqrt(B) in the signal and control regions



Selection details

	2ℓSS	3ℓ	4ℓ	1ℓ+$2\tau_{\rm had}$	2ℓSS+$1\tau_{\rm had}$	2ℓOS+$1\tau_{\rm had}$	3ℓ+$1\tau_{\rm had}$
Light lepton	2T*	1L*, 2T*	2L, 2T	1T	2T*	2L†	1L†, 2T
$\tau_{\rm had}$	0M	0M	–	1T, 1M	1M	1M	1M
$N_{\rm jets}$, $N_{b-{\rm jets}}$	$\geq 4, =1,2$	$\geq 2, \geq 1$	$\geq 2, \geq 1$	$\geq 3, \geq 1$	$\geq 4, \geq 1$	$\geq 3, \geq 1$	$\geq 2, \geq 1$

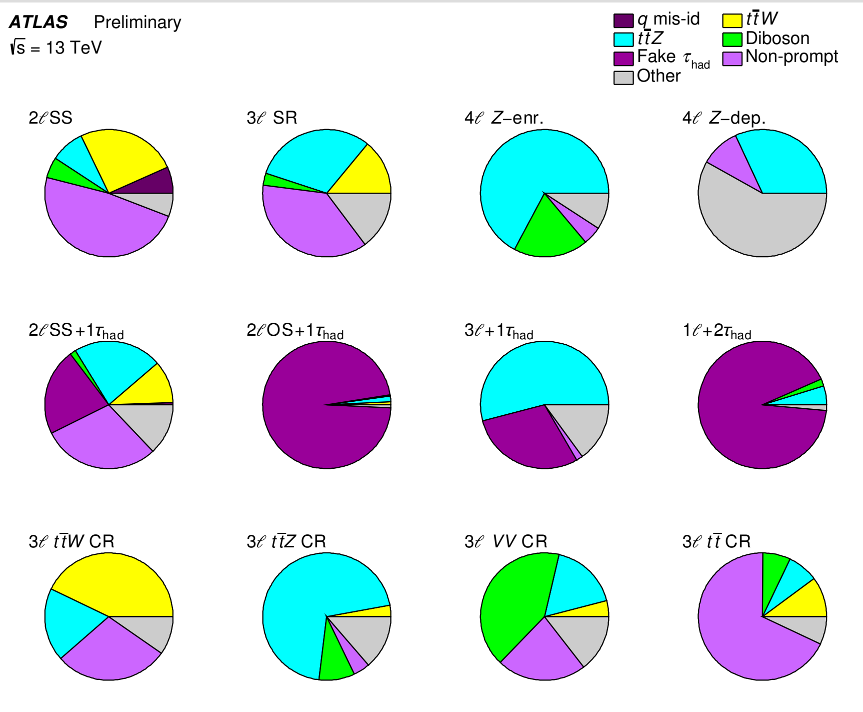
OS/SS – opposite/same sign

Light lepton selection: L-loose, L†-loose isolated, L/M/T* +non-prompt BDT loose/medium/tight*

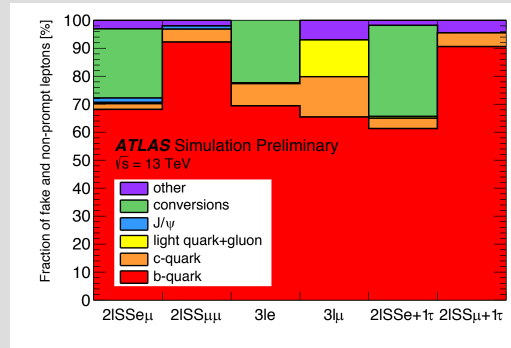
Tau selection: M-medium, T-tight

ttHML vs ttH(bb): better purity, but similar S/sqrt(B) due to smaller statistics

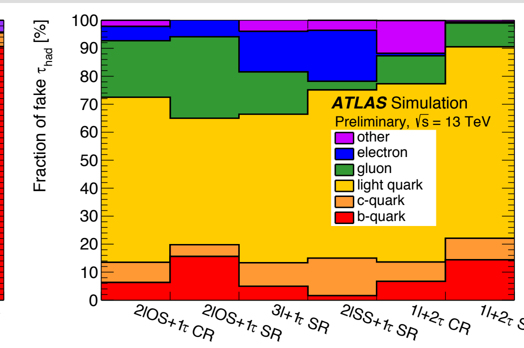
Major problem – light lepton and τ fakes



Light lepton fake origin



τ fake origin



Fake lepton estimate strategies

	2ℓSS	3ℓ	4ℓ	1ℓ+$2\tau_{\rm had}$	2ℓSS+$1\tau_{\rm had}$	2ℓOS+$1\tau_{\rm had}$	3ℓ+$1\tau_{\rm had}$
Non-prompt lepton strategy	DD (MM)	DD (MM)	semi-DD (SF)	MC	DD (FF)	MC	MC
Fake tau strategy	–	–	–	DD (SS data)	semi-DD (SF)	DD (FF)	semi-DD (SF)
Control Region Selection							
Light lepton	1T*, 1L		3L	1T	1T*, 1L	2L†	–
$\tau_{\rm had}$	0M			1T, 1M	$\leq$ 1M	1L	–
$N_{\rm jets}$	$2 \leq N_{\rm jets} \leq 3$		$1 \leq N_{\rm jets} \leq 2$	≥ 3	$2 \leq N_{\rm jets} \leq 3$	≥ 3	–
$N_{b-\rm jets}$	≥ 1					$= 0$	–

DD - data driven, MM - matrix method, SF - scale factor, FF - fake factor(ABCD)

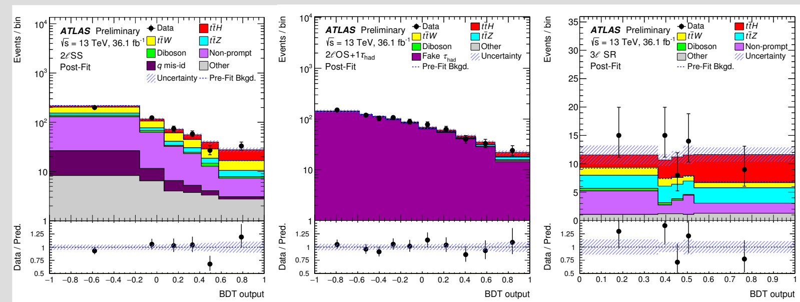
ttH ML

Summary of analysis strategies in different categories

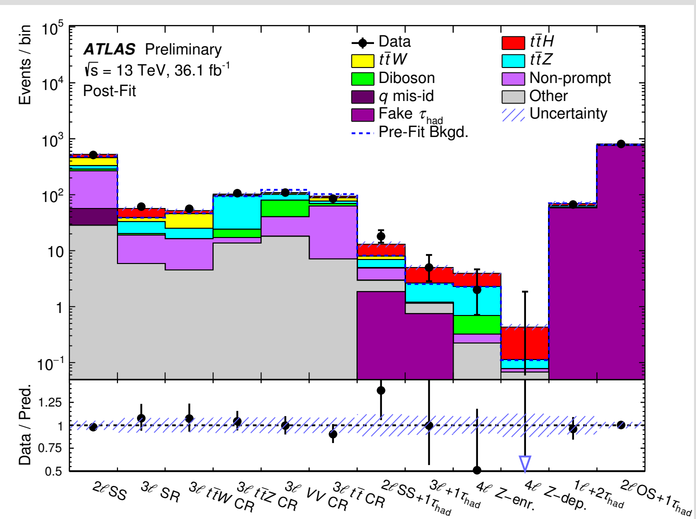
	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{had}$	2ℓSS$+1\tau_{had}$	2ℓOS$+1\tau_{had}$	$3\ell+1\tau_{had}$
BDT trained against	Fakes and $t\bar{t}V$	$t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, VV	$t\bar{t}Z$ / -	$t\bar{t}$	all	$t\bar{t}$	-
Discriminant	2×1D BDT	5D BDT	Event count	BDT	BDT	BDT	Event count
Number of bins	6	5	1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

BDT: 2x1D - scatter plot of 2 usual BDTs, 5D – five-class BDT

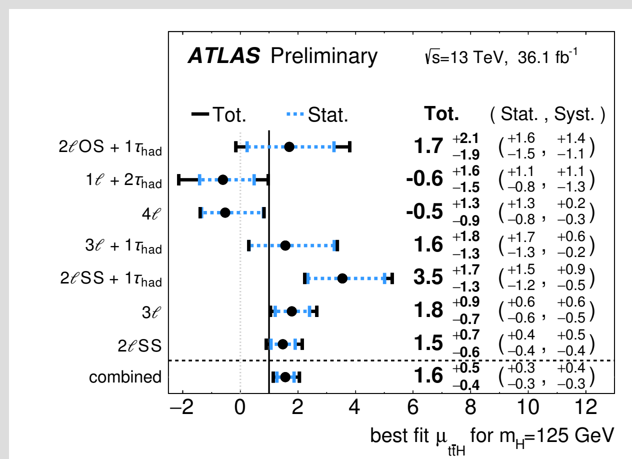
Data description examples in different analysis regions



7 signal regions and 4 control regions are used in profile likelihood fit



ttH multilepton states analysis results

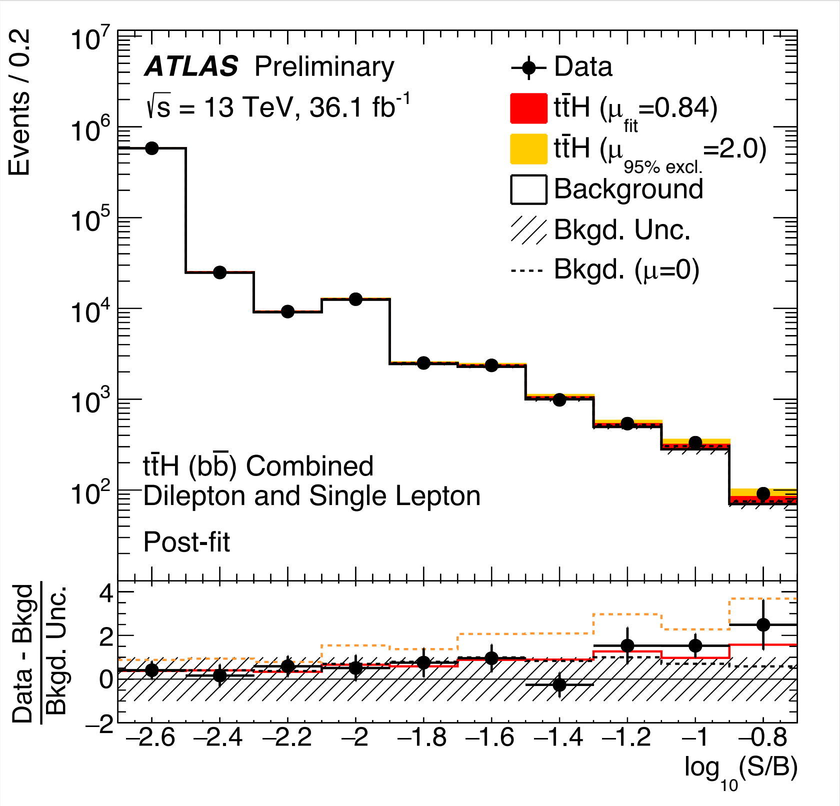


Channel	Significance	
	Observed	Expected
2l OS+1τ_{had}	0.9σ	0.5σ
2l OS+2τ_{had}	-	0.6σ
4l	-	0.8σ
3l+1τ_{had}	1.3σ	0.9σ
2l SS+1τ_{had}	3.4σ	1.1σ
3l	2.4σ	1.5σ
2l SS	2.7σ	1.9σ
Combined	4.1σ	2.8σ

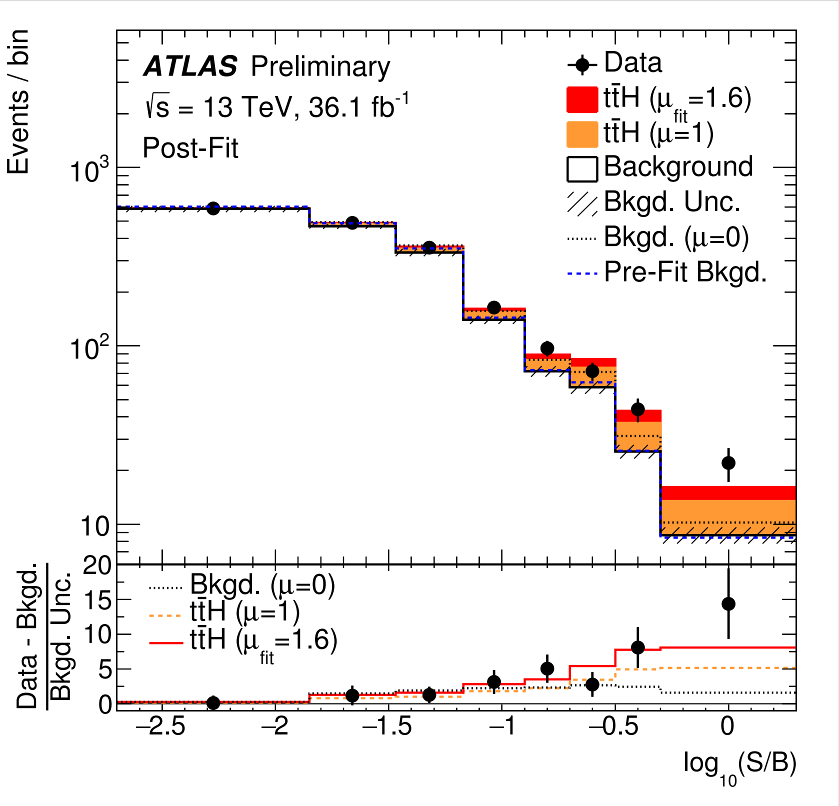
ttH(bb)+ttH ML

In order to visualise the ttH signal presence in data both ttH ML and ttH(→bb) analyses combine all used events into bins of $\log_{10}$(S/B) for background(B), SM 125GeV Higgs signal(S) and data.

ttH(→bb)



ttH multilepton



Dotted black line – background only data fit, full red line – nominal signal+background data fit

Some excess of data over background-only fit in the most sensitive to the ttH presence bins is observed in both ttH(bb) and ttH ML analyses

13 TeV ttH combination

ATLAS-CONF-2017-077

- **The ttH-enriched categories from H→γγ and H→ZZ*→4ℓ analyses were combined with the ttH(→bb) and ttH ML analyses to extract the ttH signal strength. Combined likelihood was obtained as a product of likelihoods of individual analyses.**
- **Non-ttH Higgs production cross sections and Higgs decay branching ratios were set to SM expectations.**
- **Similar nuisance parameters were correlated**
  - Background uncertainties(except for tt model in ttH(→bb))
  - Experimental uncertainties

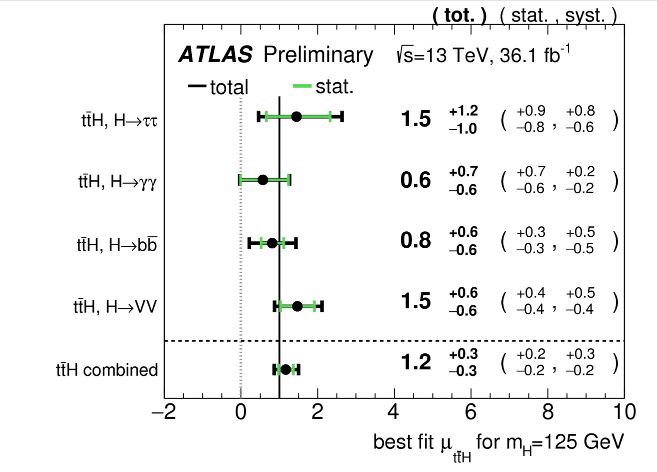
Uncertainty Source	$\Delta\mu$	
$t\bar{t}$ modelling in $H \to bb$ analysis	+0.15	−0.14
$t\bar{t}H$ modelling (cross section)	+0.13	−0.06
Non-prompt light-lepton and fake τ_{had} estimates	+0.09	−0.09
Simulation statistics	+0.08	−0.08
Jet energy scale and resolution	+0.08	−0.07
$t\bar{t}V$ modelling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

Individual analyses and combination results

Channel	Best fit μ	Significance	
		Observed	Expected
Multilepton	$1.6^{+0.5}_{-0.4}$	4.1σ	2.8σ
H→bb	$0.8^{+0.6}_{-0.6}$	1.4σ	1.6σ
H→γγ	$0.6^{+0.7}_{-0.6}$	0.9σ	1.7σ
H→4ℓ	<1.9	-	0.6σ
Combined	$1.2^{+0.3}_{-0.3}$	4.2σ	3.8σ
Cross section	590^{+160}_{-150}fb (SM: 507^{+35}_{-50}fb)		

The compatibility of the individual analyses signal strengths with the combined value of μ is 38%

Best fit μ for Higgs boson decay modes



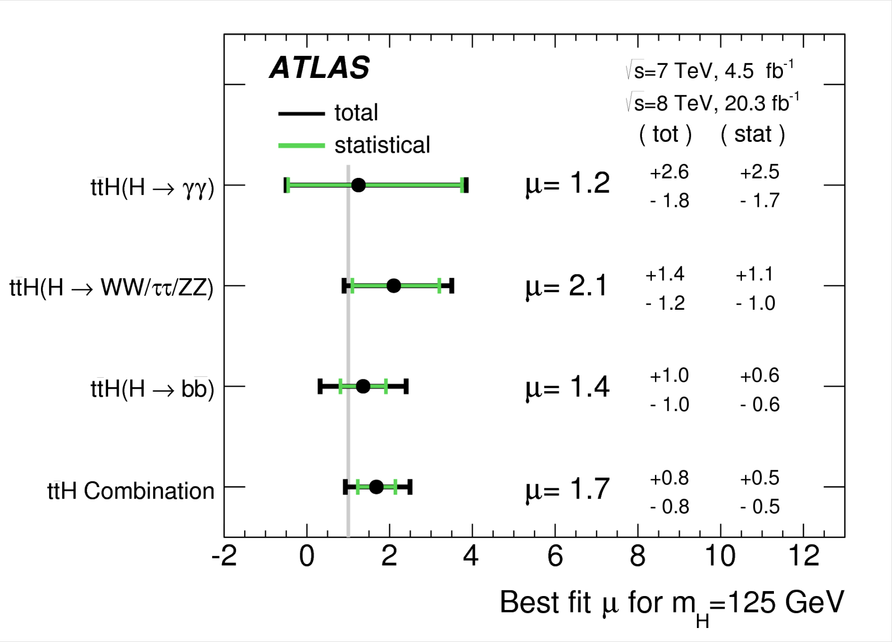
Summary

- ttH search has been performed by the ATLAS collaboration using 13 TeV data delivered by LHC in 2015+2016 and corresponding to 36.1 fb^{-1}.
- The accomplished ttH(→γγ), ttH(→4ℓ), ttH(→bb), ttH ML(→WW*, ZZ*, $\tau\tau$) analyses target different Higgs boson decay modes.
- Advanced and complex analysis methods have been exploited to obtain maximal sensitivity to the Higgs signal.
- The ATLAS collaboration has made a combination of the ttH searches. The observed best fit value is $\mu_{ttH}=1.2^{+0.3}_{-0.3}$. This corresponds to an observed significance 4.2 standard deviations as compared to 3.8 expected.
- This combination provides an evidence for the associated production of the Higgs boson and a top quark pair.

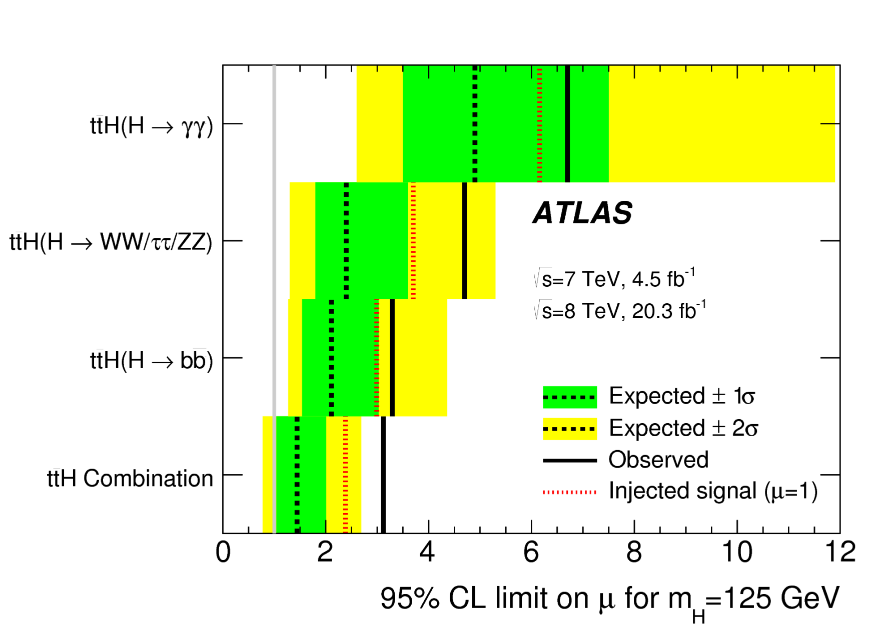
ATLAS ttH 7+8TeV combination

arXiv:1604.03812 *(submitted: 2016/04/13)*

Best fit ttH 7+8TeV



Combined 95% CL limits ttH 7+8TeV



Best combined 7+8TeV ttH fit:
$\mu/\mu_{SM} = 1.7 \pm 0.8$

Combined 7+8TeV 95% CL ttH limit:
3.1(1.4) obs.(exp.)

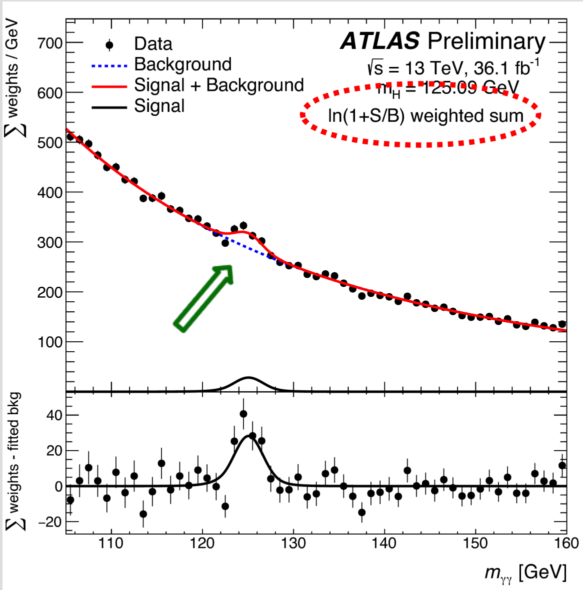
The combination includes following channels:

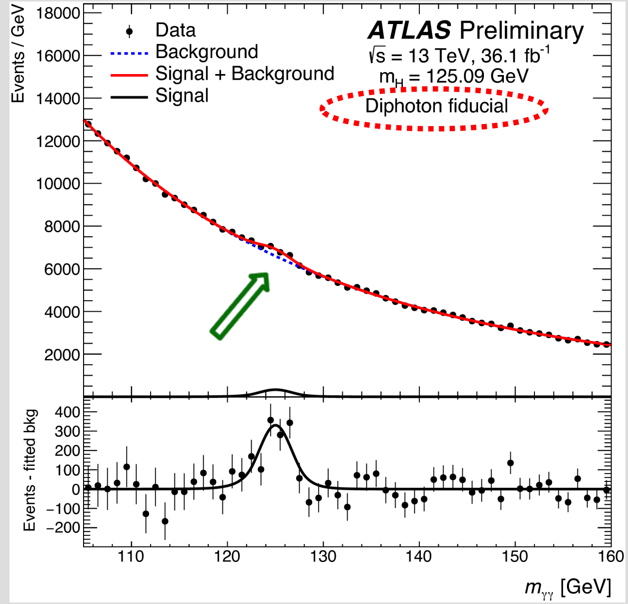
- ✓ ttH($\rightarrow\gamma\gamma$)
- ✓ ttH($\rightarrow WW^*, ZZ^*, \tau\tau$)
- ✓ ttH($\rightarrow$bb) leptonic
- ✓ ttH($\rightarrow$bb) hadronic

Backup: H→γγ

ln(1+S_{90}/B_{90}) transformation

All selected γγ mass





Observed γγ mass in ttH categories