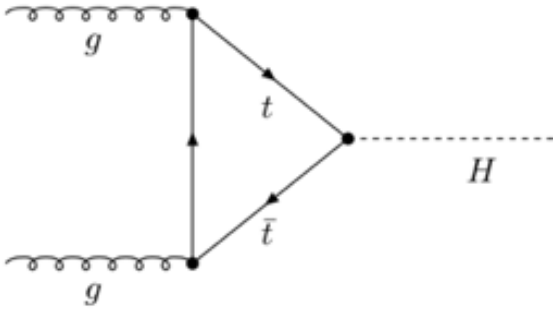
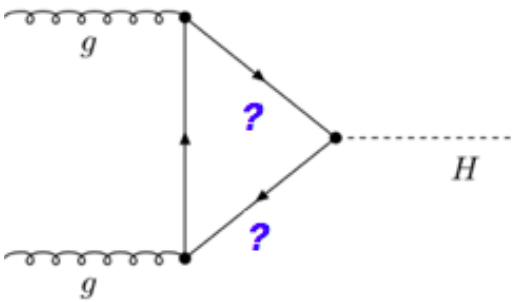
Search for the SM Higgs boson in the ttH production channel using the ATLAS detector.

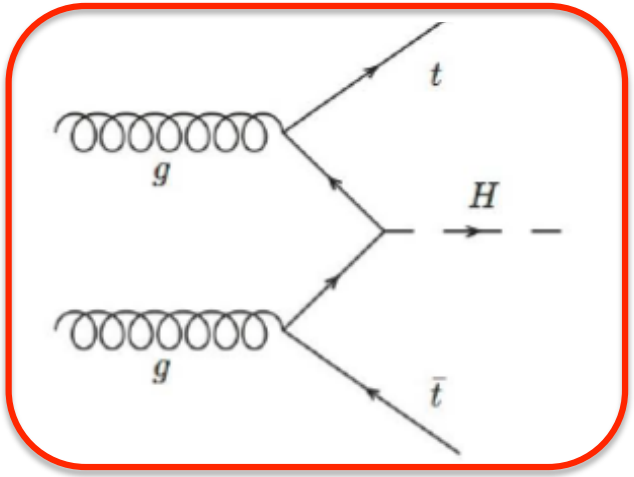
Judith Katzy (DESY)
On Behalf of the ATLAS Collaboration

Motivation

ttH cross section directly proportional to Yukawa Coupling y_t







σ_{ggF} = 44 pb

$\sigma_{ttH}/\sigma_{ggF}$ ~ 0.01

σ_{ttH} = 508 fb

Top associated Higgs production not yet observed

-> production cross section at 13 TeV 3.8 times higher than at 8 TeV

Searches for the ttH process with the ATLAS detector

$$N_{events} = L \cdot \sigma_{ttH} \cdot \mathcal{B}(H) \cdot \mathcal{B}(ttbar) \cdot \varepsilon \cdot A$$

σ_{ttH} = 508 fb

Results with L = 13.6 fb^{-1}

New results with L = 36 fb^{-1}

Higgs decay mode	B. ratio
H->bb	58.1 %
H->WW	21.5 %
H->ττ	6.3 %
H->γγ	0.23 %
H->ZZ ->4 leptons (e,μ)	0.0124 %

ttbar decay mode	B.Ratio
Di-lepton (e,μ)	4%
Single lepton (e,μ) + jets	30%
All jets	44%

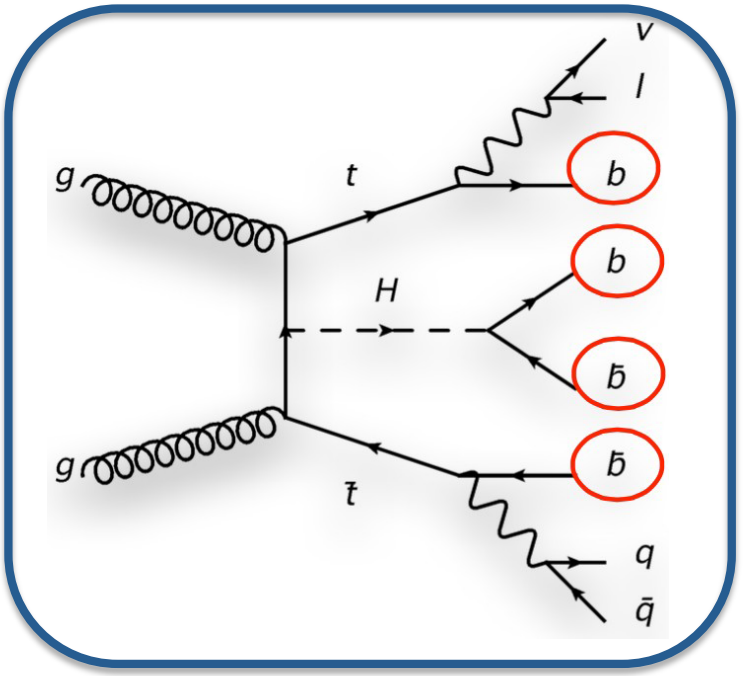
Search for the ttH (H→bb) process

- Largest branching ratio (58.1%)
- Large irreducible background ttbb

event selection

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

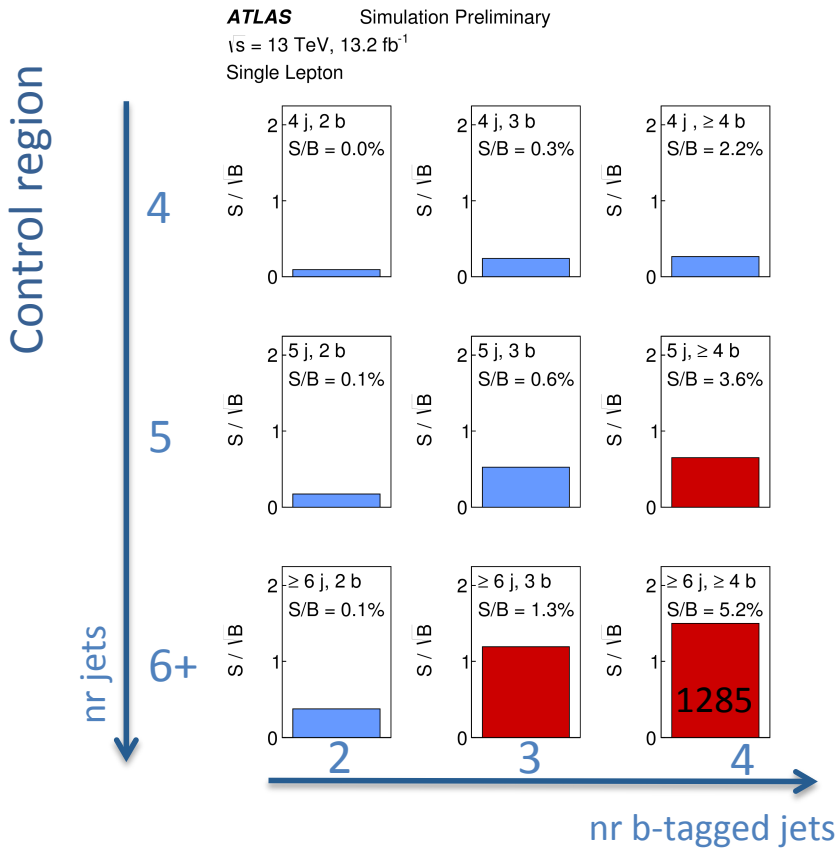
di-lepton channel
(two leptonic W decay)
- Two opposite charge light leptons (electron or muon)
- at least 3 jets
- at least 2 b-tagged jets

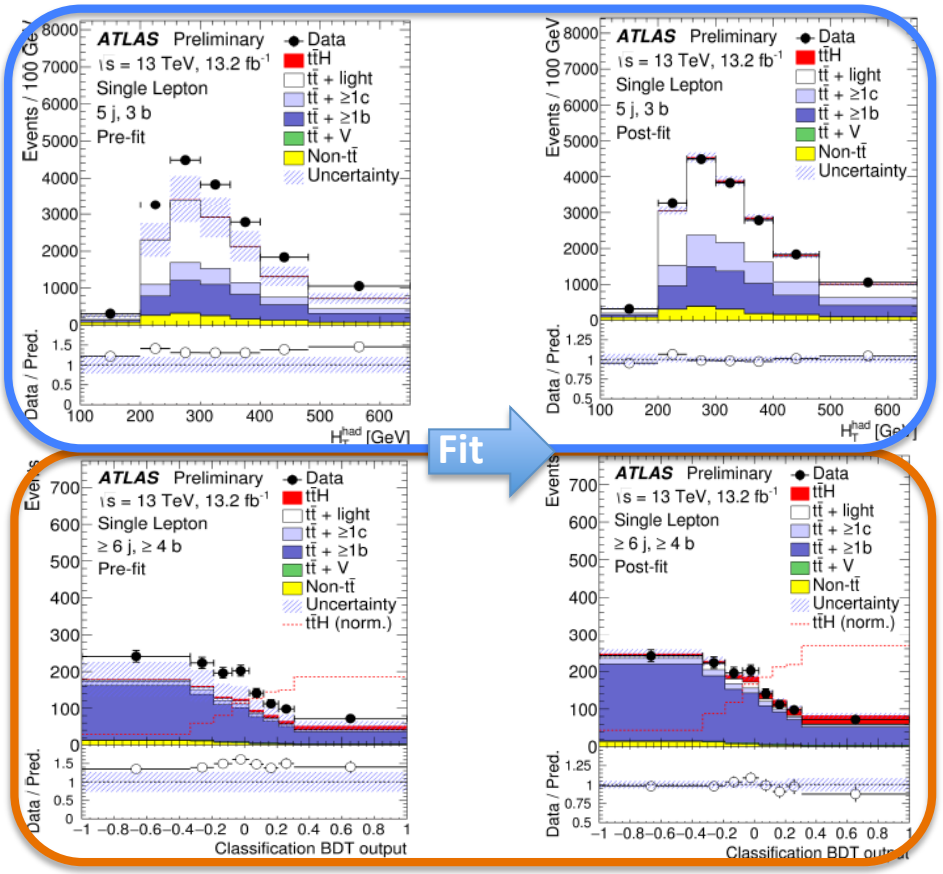


ttH(bb): Analysis strategy

example: single-lepton channel

Signal and background



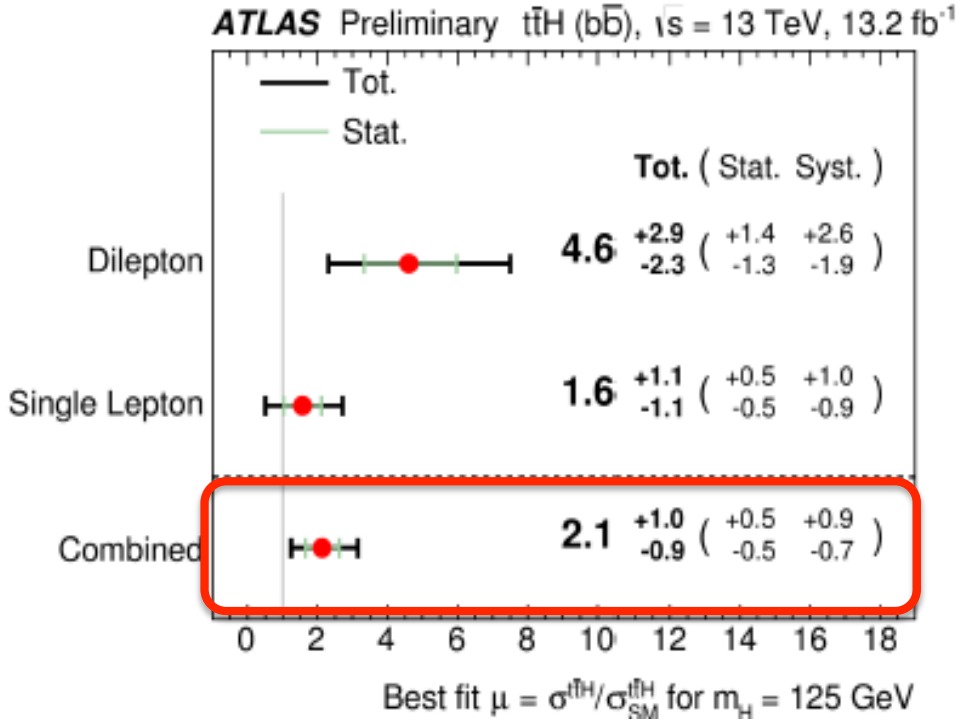


Simultaneous fit of all regions to reduce uncertainties:

- signal regions: try to separate ttH signal from background
- control regions: exploit different background compositions (tt+light, tt+c, tt+b)

Di-lepton channel similar but only 5 regions, best region has 6.1% S/B and 124 events

ttH(H->bb) signal strength



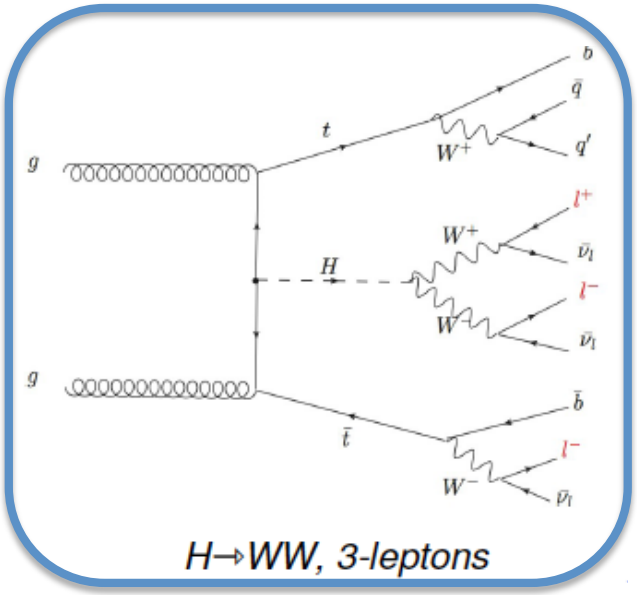
Uncertainty of the measurement is dominated by the normalisation and modeling of the tt+b/jet background.

Upper limit on ttH signal strength at 95% CL

	Observed	Expected (μ = 0) Median	+/-1σ	+/-2σ	Expected (μ = 1)
Dilepton	10.1	5.3	[3.8, 7.9]	[2.8, 12.6]	6.0
Single lepton	3.6	2.2	[1.6, 3.2]	[1.2, 4.7]	2.9
Combined	4.0	1.9	[1.4, 2.8]	[1.0, 4.2]	2.7

Search for the ttH (multi leptons) process

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



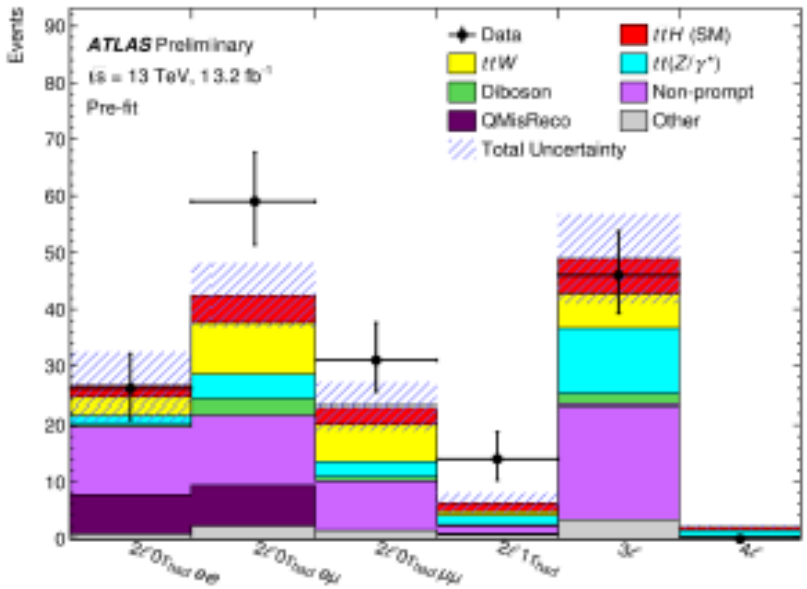
Many possible final states

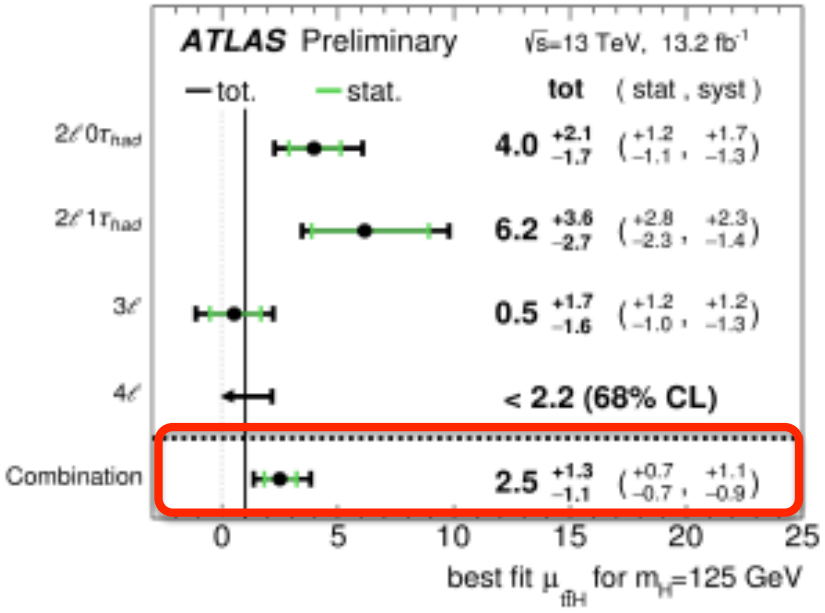
- Focus on those with clean signature and low background
- 6 categories: 2l0τ(μμ, ee,eμ), 2l1τ, 3l and 4l
- Perform cut & count analysis

channel	2l0τ	2l1τ	3l	4l
Light leptons	2 (SS)	2(SS)	3	4
jets	>=5	>=4	>=4 or >=3	>=2
b-jets	>=1	>=1	>=1 or >= 2	>=1
τ_{had}	0	1	-	-

	Higgs boson decay mode				$A \times \epsilon$	Data	S/B
Category	WW^*	$\tau\tau$	ZZ^*	Other	$(\times 10^{-4})$		
$2\ell 0\tau_{had}$	77%	17%	3%	3%	14	116	0.1
$2\ell 1\tau_{had}$	46%	51%	2%	1%	2.2	14	0.23
3ℓ	74%	20%	4%	2%	9.2	46	0.13
4ℓ	72%	18%	9%	2%	0.88	0	0.29

Results on ttH(multi-lepton)



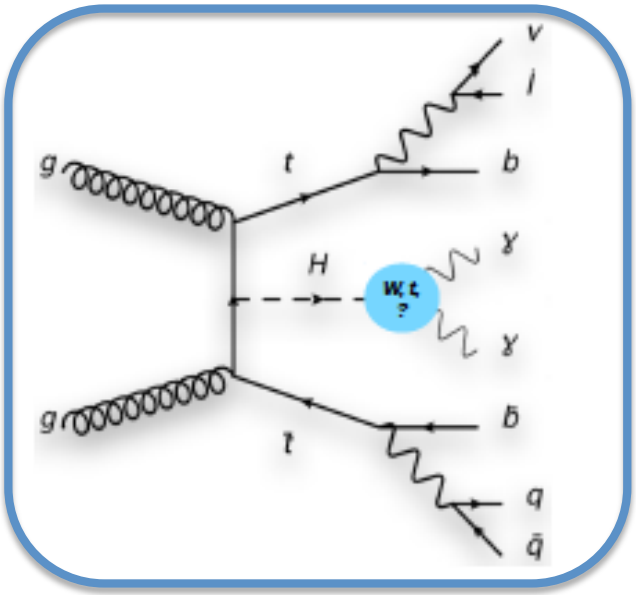


Profile likelihood fit on all channels simultaneously.
Systematic uncertainty is dominated by non-prompt background estimates in the 2l0τ, 2l1τ and 3l channels

ttH (H->γγ)

new

Higgs decay mode	Branching ratio
H->bb	58.1 %
H->WW	21.5 %
H->ττ	6.3 %
H->γγ	0.23 %
H->ZZ->4 leptons	0.0124 %

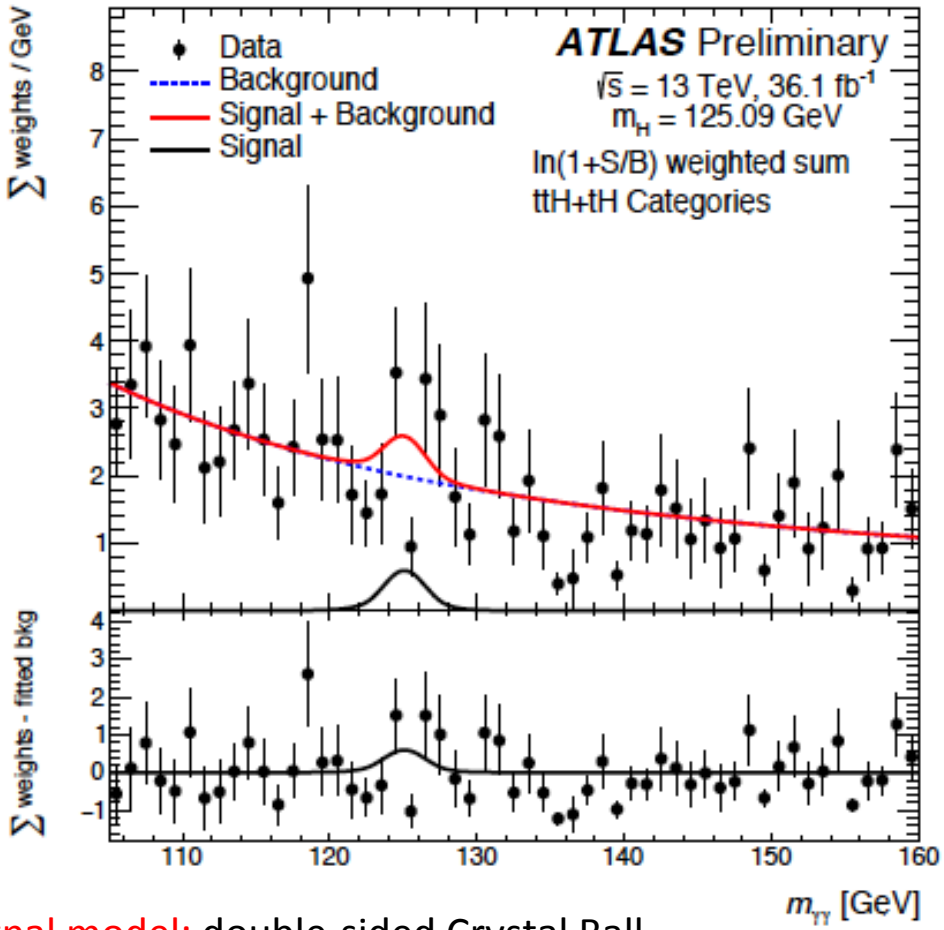


- 9 event categories for ttH and tH in all top pair decay channels (all had, single- or di-lepton)
- 80-96% ttH signal event fractions in the different categories
- BDT used to separate ttH in all hadronic top decays from ggH and multi-jet background
- 16 ttH and 2.7 tH events expected in total of 36 fb^{-1}
- Results presented in ttH categories combined with tH (σ_{ttH} ~ 508 fb, σ_{tH} ~ 74 fb)

ATLAS-CONF-2017-045

tH+ttH (H->γγ)

new



Max likelihood fit for each event category

Signal strength $\mu_{top} = \mu(ttH+tH)$

			Total	Stat	Syst	Theo
μ_{top}	=	0.5	$^{+0.6}_{-0.6}$	$[^{+0.6}_{-0.5}$	$^{+0.1}_{-0.1}$	$^{+0.1}_{-0.0}]$

Expected loc. significance: 1.8 σ
Observed loc. significance: 1.0 σ

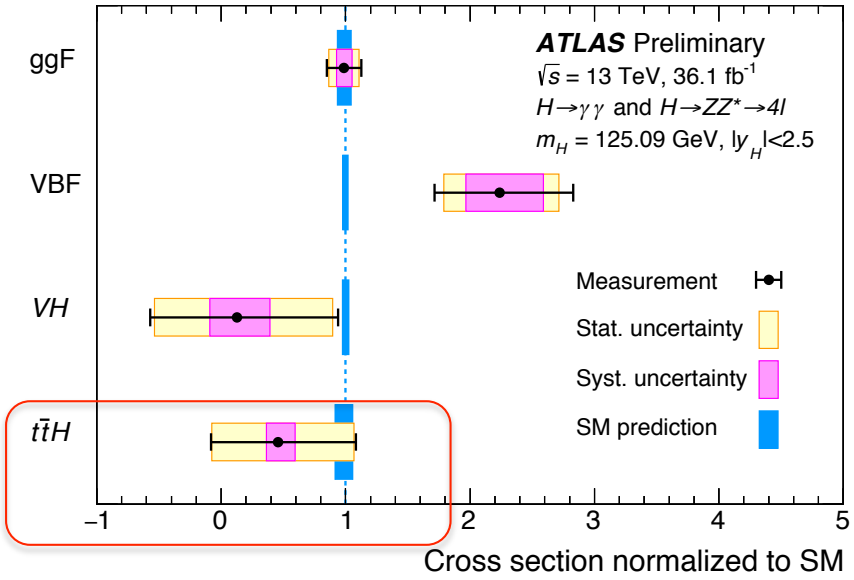
Expected limit (μ=1): 2.3
Expected limit (μ=0): 1.2
Observed limit: 1.7

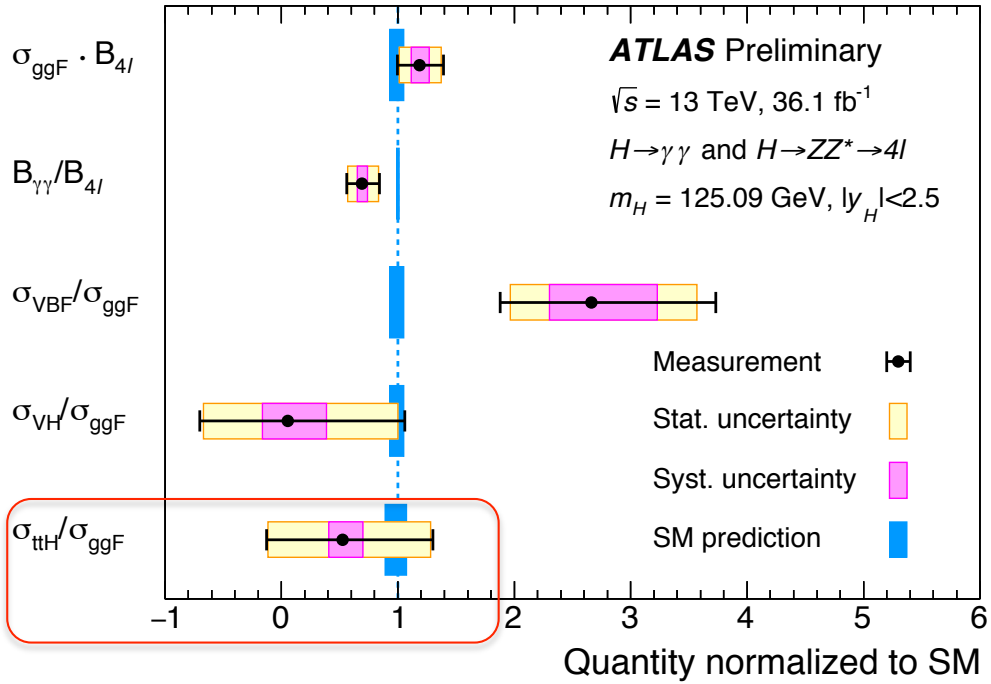
Signal model: double-sided Crystal Ball
Background model: data driven by reverting γ id or isolation, or removing b-tagging; shape+normalisation from fit to $m_{\gamma\gamma}$

tH+ttH (H->γγ) and (H->ZZ*) combined

new

Higgs decay mode	Branching ratio
H->γγ	0.23 %
H->ZZ->4 leptons	0.0124 %





$\sigma_{ttH}/\sigma_{ggF}[10^{-2}] = 0.7^{+1.0}_{-0.9}$ theo: $1.3^{+0.1}_{-0.2}$

Process ($\lvert y_H \rvert < 2.5$)	Result [pb]	Uncertainty [pb] Total	Stat.	Exp.	Th.	SM prediction [pb]
$t\bar{t}H$	0.27	$^{+0.37}_{-0.32}$	$\left(^{+0.36}_{-0.31}\right.$	$^{+0.06}_{-0.05}$	$\left.^{+0.05}_{-0.02}\right)$	$0.59^{+0.03}_{-0.05}$

Submitted to JHEP, on arXiv

Flavour changing neutral currents in t->qH with H->γγ

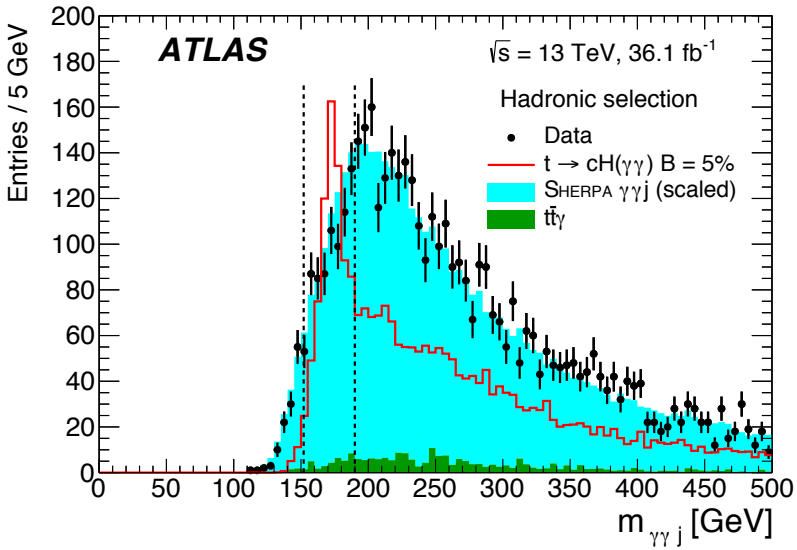
new

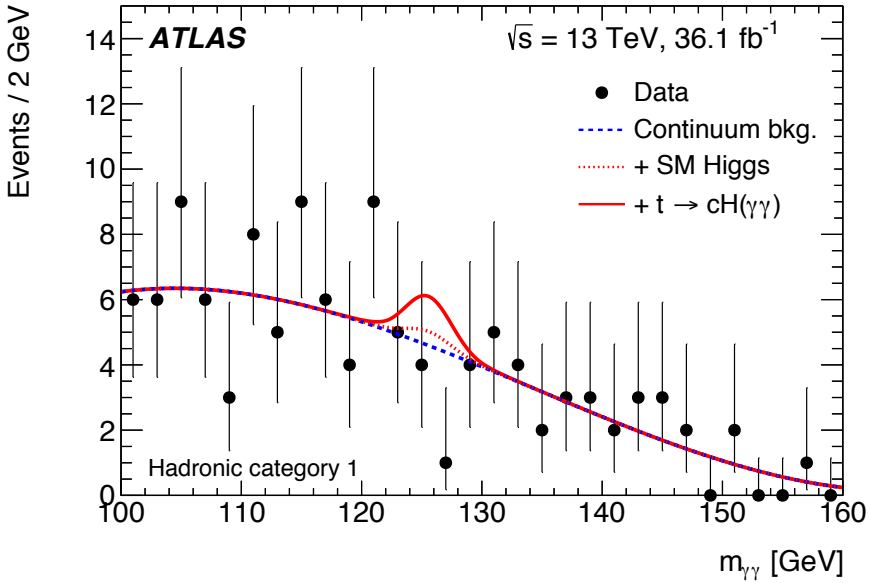
Search performed in top pair production events with t->Wb and t->qH(H->γγ)

- Allowed in SM only at loop level with $\mathcal{B}$~$3 \cdot 10^{-15}$

Selection	Hadronic		Leptonic	
Category	1	2	1	2
Signal $t \to cH$	2.4	3.7	0.82	0.23
SM Higgs boson resonant background	1.1	3.1	0.24	0.22
Other background	16	63	0.14	0.29
Total background	17	66	0.38	0.51
Data	14	69	2	1

>= 2γ with p_T>40GeV (p_T>30GeV) 100<$m_{\gamma\gamma}$<160 GeV
+ hadronic (leptonic) top decay selection
+ reconstruct masses of both top decay chains
$M_{\gamma\gamma j}$,M_{jjj}($M_{jl\nu}$)





Limit: $\mathcal{B} < 2.2 \cdot 10^{-3}$ at 95%CL

Summary

- ttH measurement performed for 5 different Higgs decay modes in data sets of 13.6 fb^{-1} and 36 fb^{-1}

- Signal strength μ_{ttH} observed between $2.1^{+1.0}_{-0.9}$, $2.5^{+1.3}_{-1.1}$ for ttH in H->bb and H->multileptons, and $0.5^{+0.6}_{-0.6}$ in H->$\gamma\gamma$ for the combined ttH+tH. The combined production cross section of ttH+tH and decay into either H->$\gamma\gamma$ or ZZ* is $0.27^{+0.37}_{-0.32}$ pb corresponding to μ= 0.45.

- The cross section ratio of $\sigma_{ttH}/\sigma_{ggF}$ is measured to be $(0.7^{+1.0}_{-0.9})\cdot 10^{-2}$ in agreement with the SM prediction of $1.3 \cdot 10^{-2}$.

- Significant improvements expected with full 2015+2016 data set for the ttH multi-lepton and the tttH(H->bb) analysis.

- Un upper limit of the branching ratio of t->Hq is set to $2.2 \cdot 10^{-3}$, indicating the absence of FCNC

Back-up

ttH(H->γγ) object & event selection

General H->γγ selection of photons:

E_T > 25 GeV

$|\eta|$ <2.37, excluding 1.37 < $|\eta|$ < 1.52

Leading γ: E_T >0.35 $m_{\gamma\gamma}$, sub-leading γ: E_T>0.25 $m_{\gamma\gamma}$

Isolation (Σp_T(charged particles in ΔR<0.2) / $p_{T\gamma}$ < 5%)

Event selection:

At least 2 photons

⇒ 332 030 events with 105 GeV < $m_{\gamma\gamma}$ < 160 GeV.

ttH production channel:

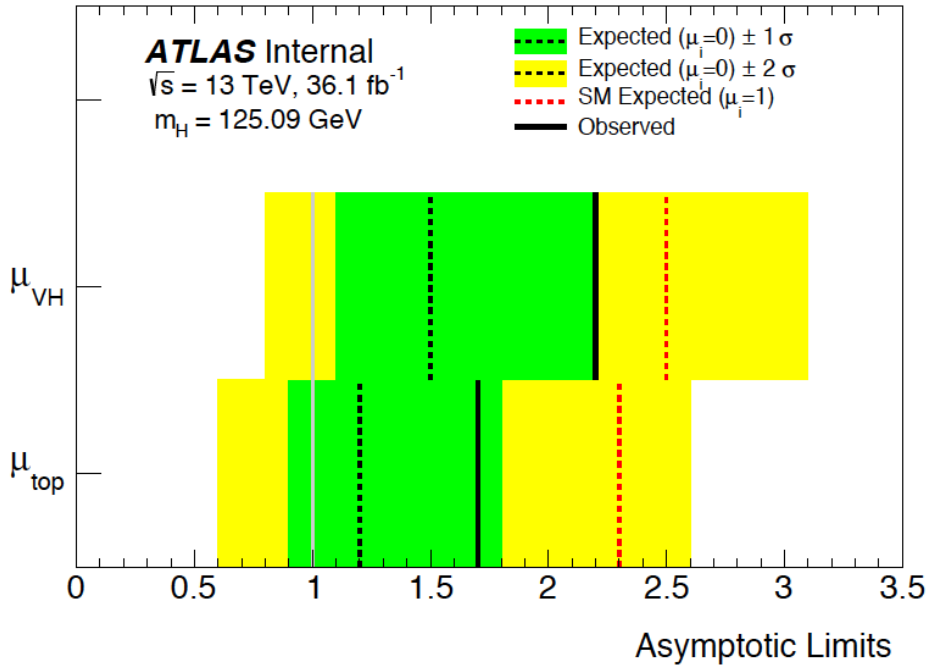
Jet pT>25 GeV

>=1 b-jet, pT>25 GeV

Electron: p_T>10 GeV, $|\eta|$<2.47, muon: p_T>10 GeV, $|\eta|$<2.7 (fiducial xs: >15 GeV)

Limits on ttH+tH(H->γγ)

Measurement	Observed	Exp. Limit ($\mu = 1$)	Exp. Limit ($\mu = 0$)	$+2\sigma$	$+1\sigma$	-1σ	-2σ
μ_{VH}	2.2	2.5	1.5	3.1	2.2	1.1	0.8
μ_{top}	1.7	2.3	1.2	2.6	1.8	0.9	0.6

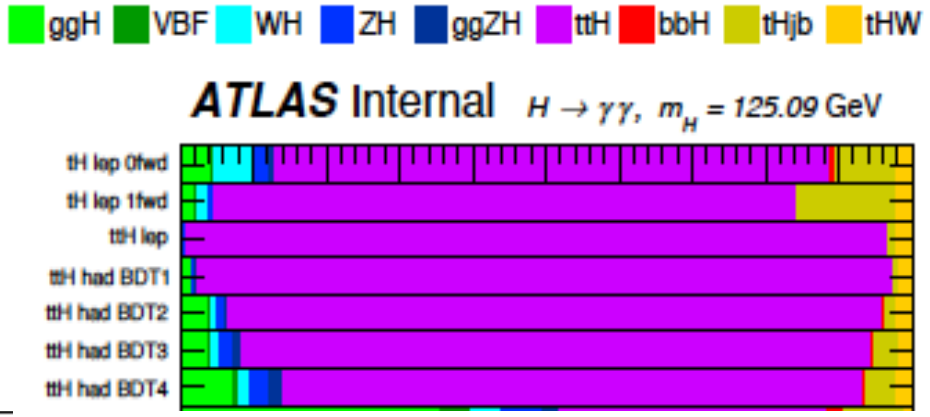


ttH(H->γγ) - details

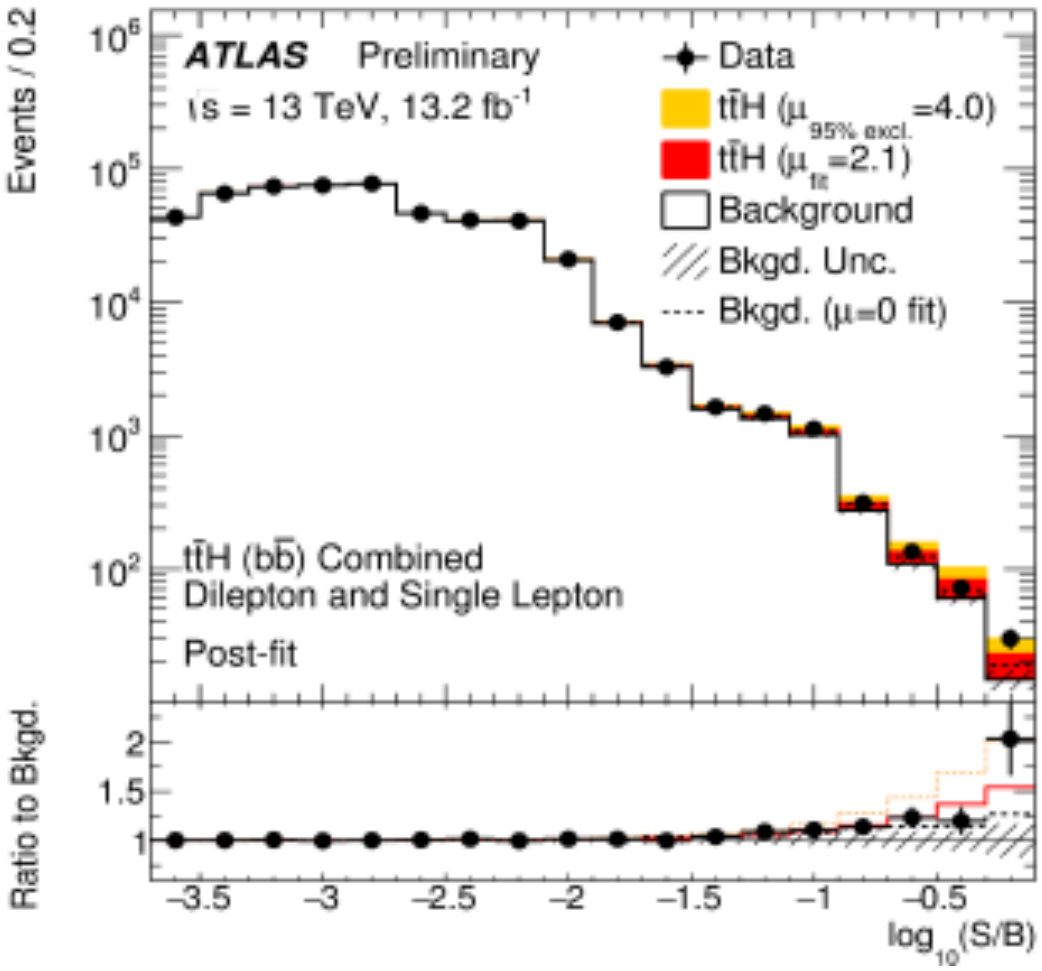
BDT

- Input variables: H_t^{had} (scalar sum of jet pT), mass of all jets, N(jets), N(central jets),N(b-jets)
- Training of ttH against ggH and data driven multi-jet background
- Data driven multi-jet background from events with γγ+3jets with >=1γ failing isolation or identification requirement
- Working points at 95, 89, 86, 79% fraction of ttH / (all H->γγ)

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



ttH(H->bb)
Data vs Predictions in all bins



Ordered by S/B

ttH(multi-lepton) event yields

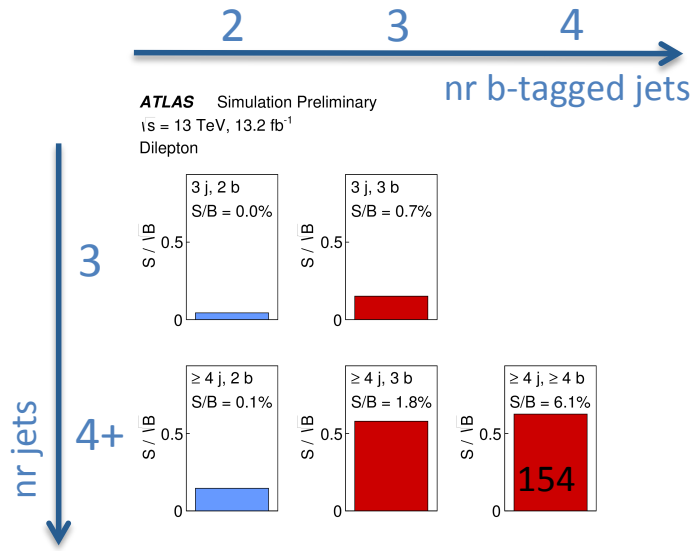
Table 7: Expected and observed yields in the six signal region categories in 13.2 fb^{-1} of data at $\sqrt{s}$ = 13 TeV. Uncertainties in the background expectations due to systematic effects and MC statistics are shown. "Other" backgrounds include tZ, tWZ, $tHqb$, tHW, $t\bar{t}t\bar{t}$, $t\bar{t}WW$, and triboson production. Values are obtained pre-fit, i.e., using the initial values of background systematic uncertainty nuisance parameters.

	$2\ell 0\tau_{\text{had}}$ ee	$2\ell 0\tau_{\text{had}}$ $e\mu$	$2\ell 0\tau_{\text{had}}$ $\mu\mu$	$2\ell 1\tau_{\text{had}}$	3ℓ	4ℓ
$t\bar{t}W$	2.9 ± 0.7	9.1 ± 2.5	6.6 ± 1.6	0.8 ± 0.4	6.1 ± 1.3	—
$t\bar{t}(Z/\gamma^*)$	1.55 ± 0.29	4.3 ± 0.9	2.6 ± 0.6	1.6 ± 0.4	11.5 ± 2.0	1.12 ± 0.20
Diboson	0.38 ± 0.25	2.5 ± 1.4	0.8 ± 0.5	0.20 ± 0.15	1.8 ± 1.0	0.04 ± 0.04
Non-prompt leptons	12 ± 6	12 ± 5	8.7 ± 3.4	1.3 ± 1.2	20 ± 6	0.18 ± 0.10
Charge misreconstruction	6.9 ± 1.3	7.1 ± 1.7	—	0.24 ± 0.03	—	—
Other	0.81 ± 0.22	2.2 ± 0.6	1.4 ± 0.4	0.63 ± 0.15	3.3 ± 0.8	0.12 ± 0.05
Total background	25 ± 6	38 ± 6	20 ± 4	4.8 ± 1.4	43 ± 7	1.46 ± 0.25
$t\bar{t}H$ (SM)	2.0 ± 0.5	4.8 ± 1.0	2.9 ± 0.6	1.43 ± 0.31	6.2 ± 1.1	0.59 ± 0.10
Data	26	59	31	14	46	0

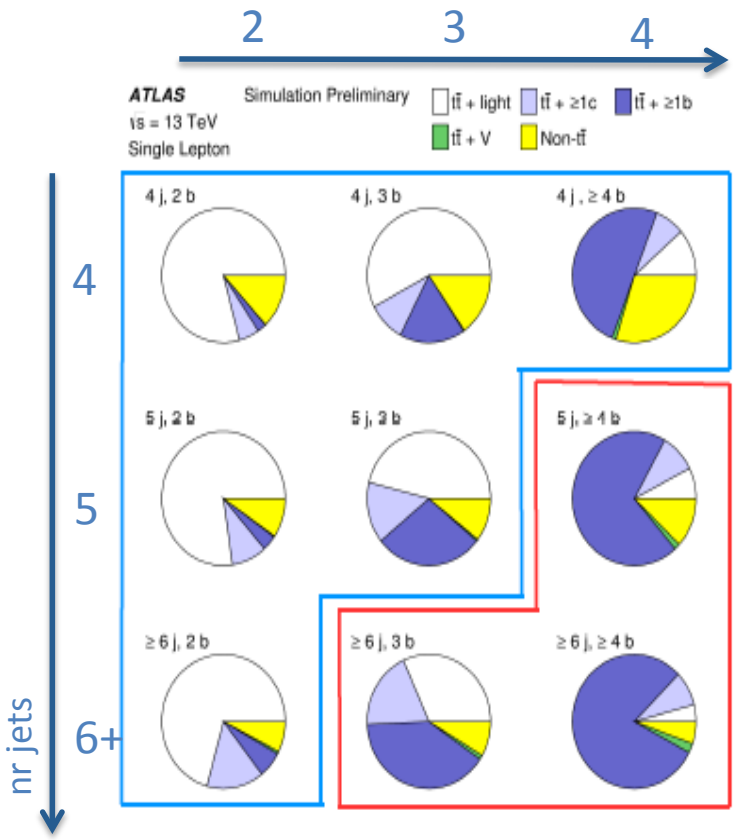
ttH(bb): di-lepton analysis

control regions

Signal regions

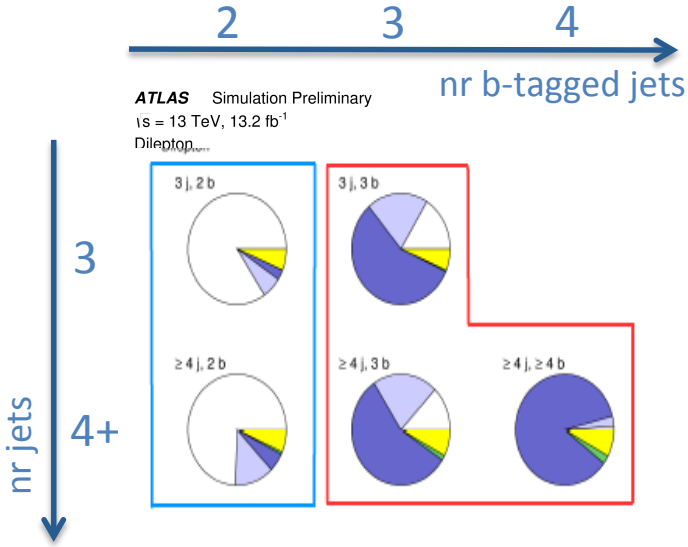


ttH(bb):background composition

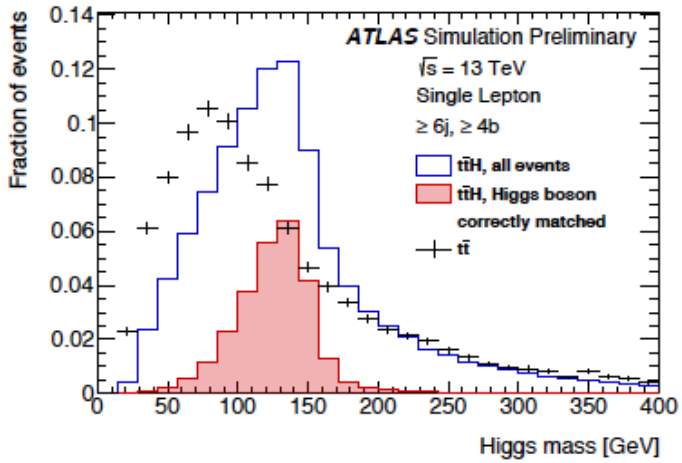


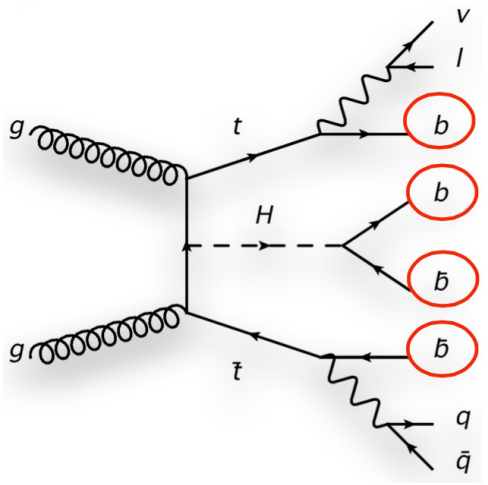
control regions

Signal regions



Reconstruction of H in ttH (H→bb) process





H->ZZ*->4leptons selection & yields

Event selection

Leptons and jets	
Muons:	$p_T > 5$ GeV, $\|\eta\| < 2.7$
Electrons:	$p_T > 7$ GeV, $\|\eta\| < 2.47$
Jets:	$p_T > 30$ GeV, $\|y\| < 4.4$
Jet-lepton overlap removal:	$\Delta R(\text{jet}, \ell) > 0.1$ (0.2) for muons (electrons)
Lepton selection and pairing	
Lepton kinematics:	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12}):	SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair (m_{34}):	remaining SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection (at most one quadruplet per channel)	
Mass requirements:	$50 < m_{12} < 106$ GeV and $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1$ (0.2) for same- (different-) flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	115 GeV $< m_{4\ell} <$ 130 GeV

Reconstructed m_H from 4 lepto

ttH category:

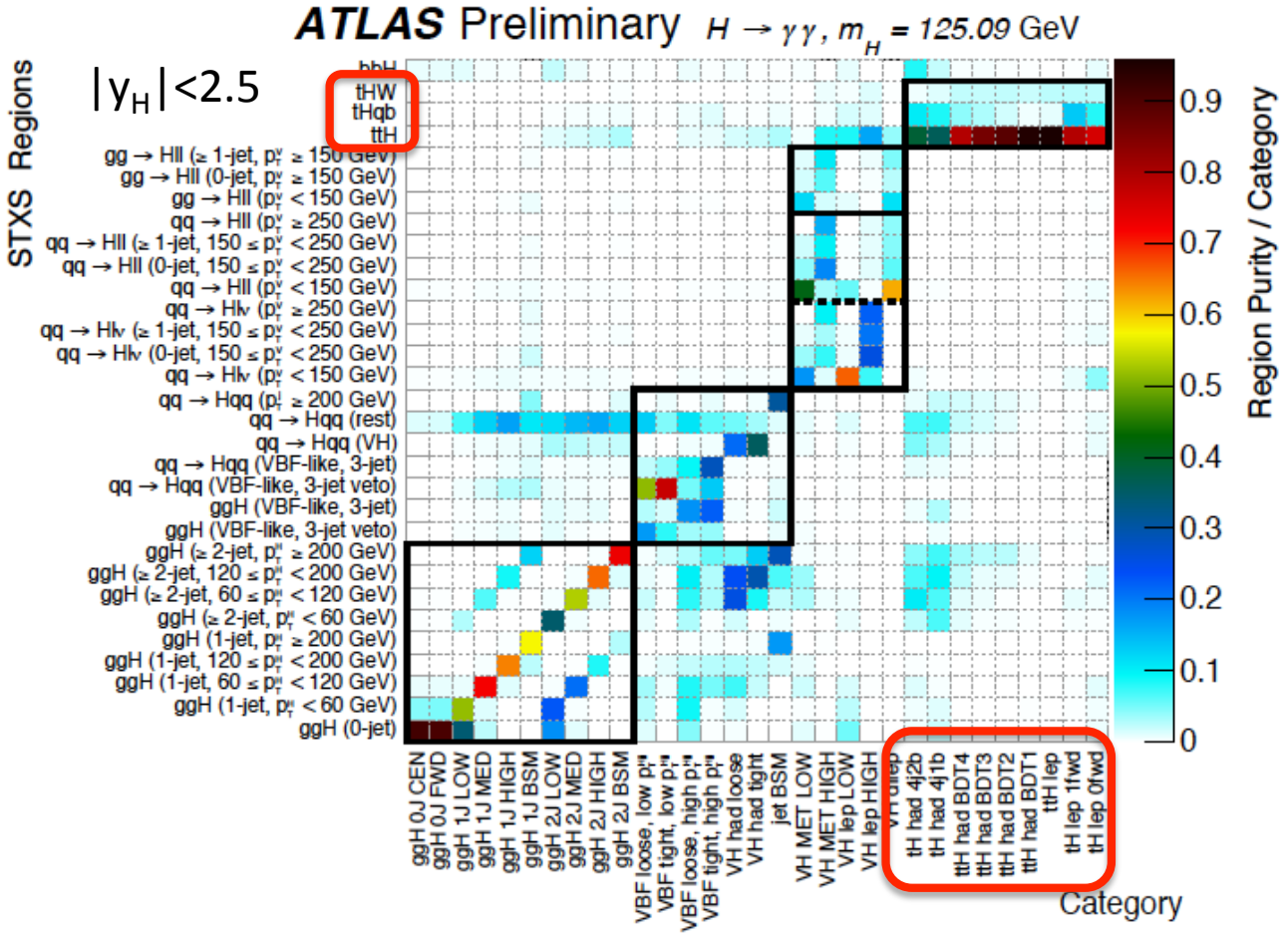
- >=1 b-tagged jet
- >= 4 jets

  or 1 add.l (e,μ) + >=2jets

Final state	SM Higgs	ZZ^*	Z + jets, $t\bar{t}$ WZ, ttV, VVV	Expected	Observed
4μ	20.1 ± 2.1	9.8 ± 0.5	1.3 ± 0.3	31.2 ± 2.2	33
$4e$	10.6 ± 1.2	4.4 ± 0.4	1.3 ± 0.2	16.3 ± 1.3	16
$2e2\mu$	14.2 ± 1.4	7.1 ± 0.4	1.0 ± 0.2	22.3 ± 1.5	32
$2\mu2e$	10.8 ± 1.2	4.6 ± 0.4	1.4 ± 0.2	16.8 ± 1.3	21
Total	56 ± 6	25.9 ± 1.5	5.0 ± 0.6	87 ± 6	102

Event yields

Simplified template xs Matrix



Flavour changing neutral currents in t->qH with H->γγ

Search performed in top pair production events with t->Wb and t->Hq

- Reconstruct top mass from decay products for both top quarks $M_{\gamma\gamma j}$,M_{jjj}($M_{jl\nu}$)
- 152 GeV < $M_{\gamma\gamma j}$ < 190 GeV, 120 GeV<M_{jjj}<220 GeV
- Category 1: both top quark masses reconstructed, category 2: no cut on M_{jjj} ($M_{jl\nu}$)

	>= 2γ with p_T>40GeV (p_T>30GeV)	
hadronic	0 leptons >=4 jets >=1 b-jet	1 lepton (e,m) >=2jets m_T>30GeV leptonic