Associated $t\bar{t}H$ production and search for CP violation in the ATLAS experiment

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8th International Workshop on the CKM Unitarity Triangle
– Vienna, 8th-12th September 2014 –

- Introduction
- $H \to b\bar{b}$
- $H \to \gamma\gamma$
- Combination
- CP Violation
- Summary and Discussion

Motivation: Why search for $t\bar{t}H$?

➔ after discovery of the Higgs Boson:

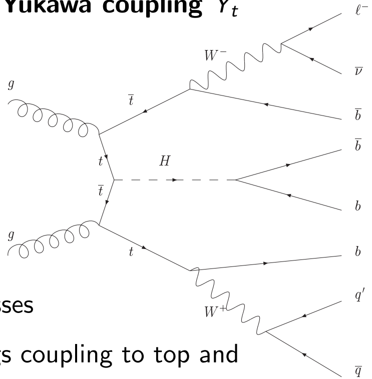
↪ what are its properties?

↪ is it really the SM particle?

➔ important: directly measure the **top-Higgs Yukawa coupling** Y_t

➔ top quark heaviest fermion:

↪ Y_t largest: ≈ 1



➔ any deviation would be sign for BSM processes

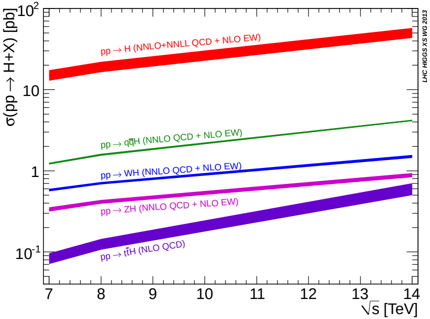
➔ get constraint on relative sign between Higgs coupling to top and W boson from tH process

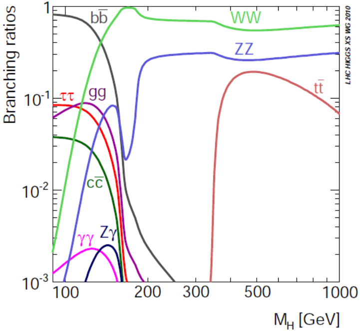
Higgs production at the LHC

Show two complementary approaches:

- $H \to bb$: highest branching ratio
- $H \to \gamma\gamma$: highest purity

$\Rightarrow$ Perform combination!



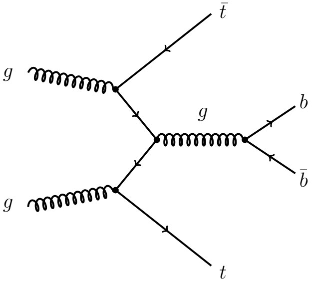


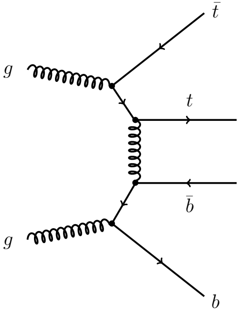
	σ(8 TeV)	σ(14 TeV)	$\frac{\sigma(14\,TeV)}{\sigma(8\,TeV)}$
ttH	0.1302 pb	0.6113 pb	4.7
ttbar	234 pb	920 pb	3.9

Why $t\bar{t}H\,(H \to b\bar{b})$?

Challenges:

- largest BR for Higgs decay, **but:**
- irreducible bkg from $t\bar{t}b\bar{b}$
- large uncertainties on $t\bar{t}$+HF





How to cope with irreducible bkg?

➔ exploit as much info as possible

➔ use a NN to get best possible S/B separation

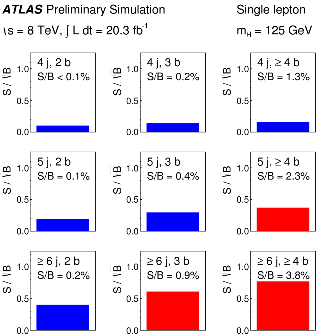
➔ use signal-depleted regions to constrain bkg and unc

➔ combined nuisance parameter fit to all regions

↪ analysis shown here: 8 TeV, 20.3 fb^{-1} ATLAS-CONF-2014-011

Lepton+jets channel

ATLAS-CONF-2014-011



Event selection

- ➔ 1 isolated lepton (25 GeV)
- ➔ at least 4 jets, 2 *b*-tagged jets
- ➔ MVA based *b*-tagging
- ➔ **no** cut on MET/$m_{T,W}$
- ➔ ttbar modelling with Powheg

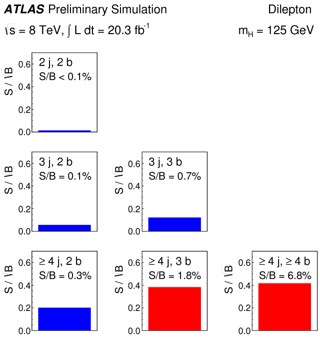
Discriminating variables

- signal-depleted regions: H_T^{had}
- signal-enriched regions: MVA output

  ↪ input to MVA are 10 variables per region (backup)

Dilepton channel

ATLAS-CONF-2014-011



Event selection

➔ 2 isolated leptons (25/15 GeV), opposite sign

➔ at least 2 jets, 2 *b*-tagged jets

➔ MVA based *b*-tagger

➔ cut on *Z*-mass window

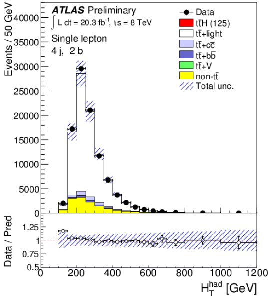
➔ $H_T > 130$ GeV ($e\mu$)

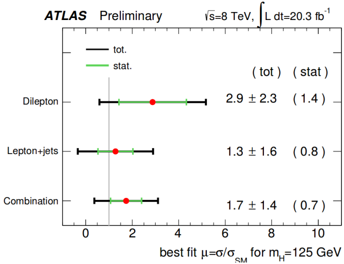
Discriminating variables

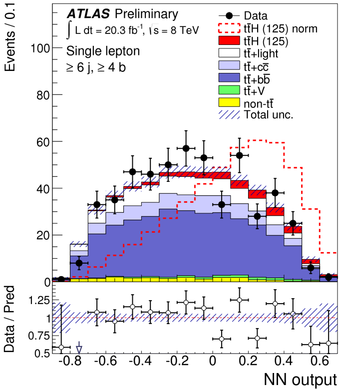
- signal-depleted regions: H_T
- signal-enriched regions: MVA output

  ↪ input to MVA are 10 variables per region (backup)

Results $t\bar{t}H\,(H \to b\bar{b})$







Final results:

➔ $\sigma < 4.1\ (2.6)\ \sigma_{\mathrm{SM}}$ obs. (exp.) @ 95 % C.L.

➔ Best fit signal strength: $\mu = 1.7 \pm 1.4$

Systematic uncertainties

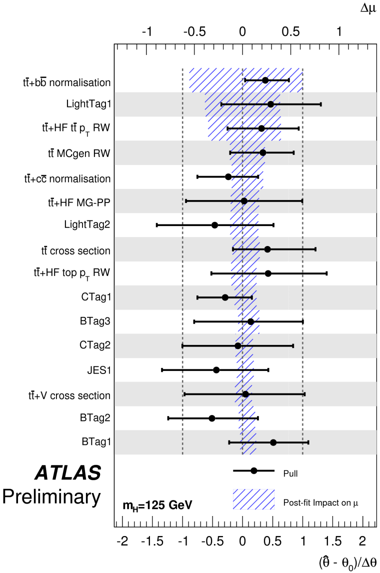
Dominant uncertainties:

- heavy flavour modelling

  ↪ need a good understanding about modelling of ttbar+HF

- *b*-tagging uncertainties

- Jet energy scale components

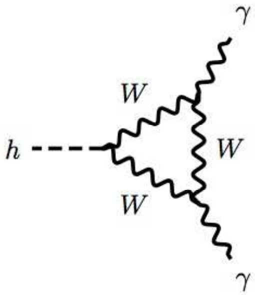


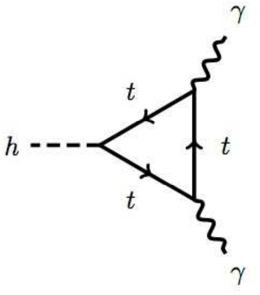
- Introduction
- $H \to b\bar{b}$
- **$H \to \gamma\gamma$**
- Combination
- CP Violation
- Summary and Discussion

Why search for $t\bar{t}H(\to \gamma\gamma)$? ▸ ATLAS-CONF-2014-043

Challenges/Features

- small branching ratoi: $O(10^{-3})$
- good mass resolution
- small background contribution





Analysis setup:

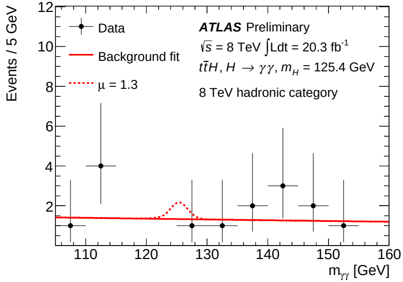
- both 7 and 8 TeV (4.5/20.3 fb^{-1})
- leptonic/hadronic channels
- get backgrounds from sideband in diphoton mass spectrum

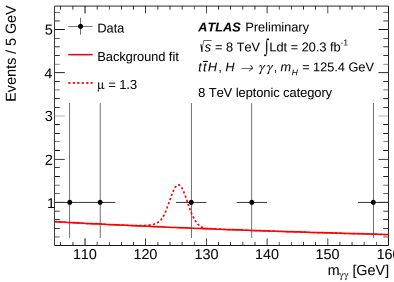
  $\hookrightarrow$ exponential fit

$t\bar{t}H(\to \gamma\gamma)$: optimise event selection

Leptonic: very loose cuts

- at least 1 e/μ
- at least 1 b-jet
- MET > 20 GeV
- 2 photons: $p_T > 0.35/0.25\ m_{\gamma\gamma}$





Hadronic:

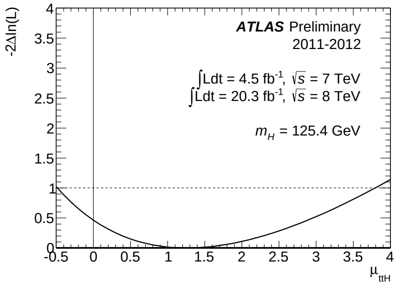
- no e/μ, 2 photons as above
- ≤ 6 jets with ≤ 2 b-tags
- or: ≤ 5 jets with ≤ 2 b-tags
- or: ≤ 6 jets with ≤ 1 b-tags

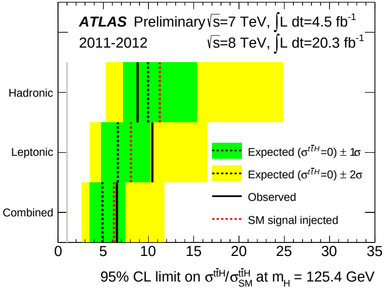
$\hookrightarrow$ different b-tagging working points

Search for $t\bar{t}H(\to \gamma\gamma)$: Results

Main systematics:

- MC Modelling
- Theory
- Jets/ETmiss





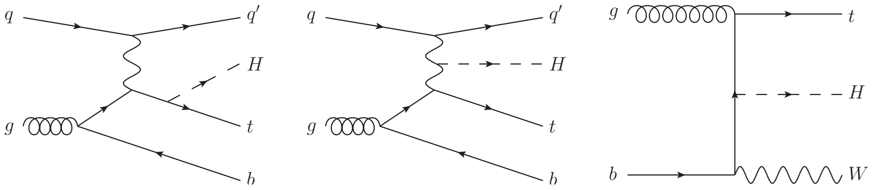
Limit:

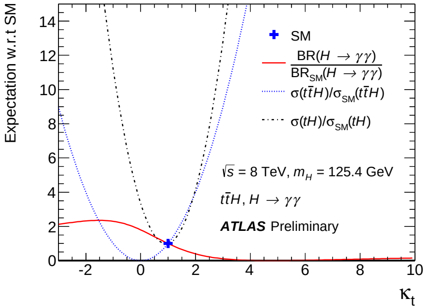
$\sigma < 6.5\ (4.9)\ \sigma_{\mathrm{SM}}$ obs. (exp.) @ 95% CL

Best fit signal strength:

$$\mu_{ttH} = 1.3^{+2.0}_{-1.4}(\mathrm{stat.})^{+0.6}_{-0.3}(\mathrm{syst.})$$

Set Limit on Yukawa-coupling via tH





➔ look at tH production:

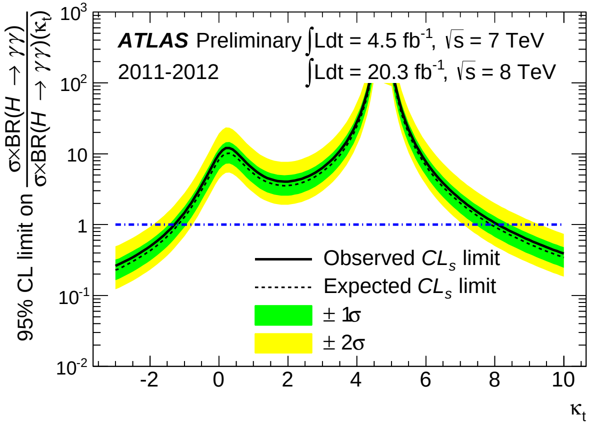
➔ sensitive to relative sign of Y_t

➔ define $Y_t = \kappa_t Y_t^{SM}$

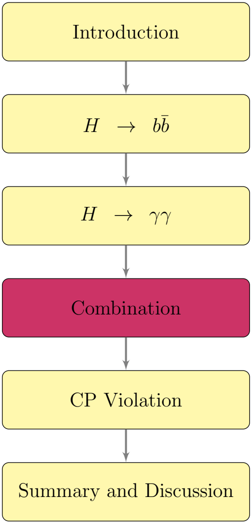
➔ if $\kappa_t < 0$: fast increase of σ_{tH}

➔ if κ not 1:
$\hookrightarrow$ modifications to BEH-mechanism

Set Limit on Yukawa-coupling via tH



- ➔ tH production sensitive to relative sign of Y_t
- ➔ -1.3 $< \kappa_t <$ 8.1 at 95 % CL
- ➔ constrain mainly models with negative sign


Introduction
$H \to b\bar{b}$
$H \to \gamma\gamma$
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CP Violation
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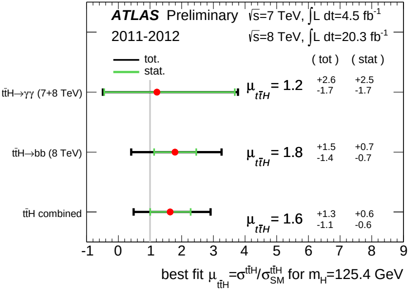
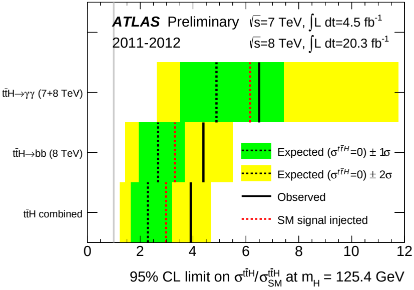
Preliminary combination

Complementary measurements:

- $H \to b\bar{b}$
  $\hookrightarrow$ large BR, large bkg
- $H \to \gamma\gamma$
  $\hookrightarrow$ tiny BR, clean signal





Combination:

- Limit: $\sigma < 3.9$ (2.3) σ_{SM} obs. (exp.) at 95 % CL
- Best fit signal strength: $\mu_{t\bar{t}H} = 1.6^{+1.3}_{-1.1}$

Introduction

↓

$H \to b\bar{b}$

↓

$H \to \gamma\gamma$

↓

Combination

↓

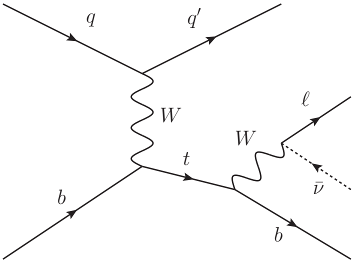
CP Violation

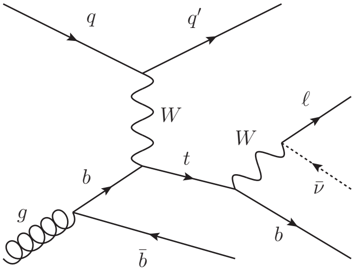
↓

Summary and Discussion

Search for CP violation in single top events ATLAS-CONF-2013-032

- CP violation observed in Kaon and B-meson decays
- does not explain the size of baryon asymmetry
- look for new sources of **direct** CP violation
- here: investigate the *Wtb*-vertex



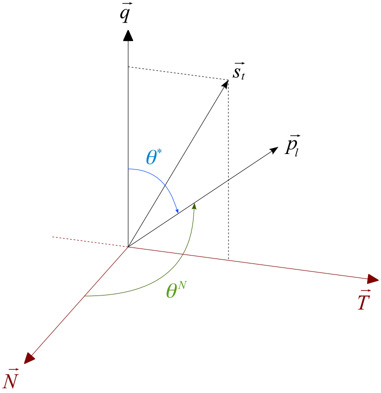


Search for CP-violation in single top events [1]

The *Wtb*-vertex:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_{\rm L}P_L + V_{\rm R}P_R\right)t\; W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_{\rm L}P_L + g_{\rm R}P_R\right)t\; W_{\mu}^{-} + \text{h.c.}$$

Look at angular asymmetries:



$$A_z = \frac{N_{evt}(\cos\theta^N > z) - N_{evt}(\cos\theta^N < z)}{N_{evt}(\cos\theta^N > z) + N_{evt}(\cos\theta^N < z)}$$

$$A_{FB}^N \approx 0.64\, P\, \text{Im}(g_R)$$

➔ high polarisation: P $\approx$ 0.9

➔ EW corr: $g_R = (-7.17 - 1.23\text{i})\, 10^{-3}$

[1] Eur.Phys.J. C50, 519 (2007), Nucl. Phys. B840(2010) 349, JHEP 1107 (2011) 094

Event selection/reconstruction

Preselection:

- 1 high p_T lepton
- 2 jets $p_T > 30$ GeV, $|\eta| < 4.5$
- 1 jet with b-tag
- $E_T^{miss} > 30$ GeV
- $m_T^W > 30$ GeV

Final selection:

- forward light jet
- additional cut on H_T
- cut on top mass window
- low stat (ca. 1200 events)

  ↪ just use two bins

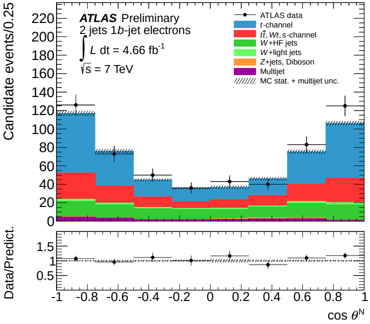
Reconstruction:

- reconstruct W:

  ↪ from lepton and E_T^{miss}

  ↪ get p_z^ν from m_W constraint
- reconstruct top:

  ↪ W+b-tagged jet



Results

Method:

➔ subtract background

➔ unfold to parton level

➔ set limit on $\mathrm{Im}(g_R)$

Main systematics:

➔ t-channel generator

➔ $t\bar{t}$ generator + PS

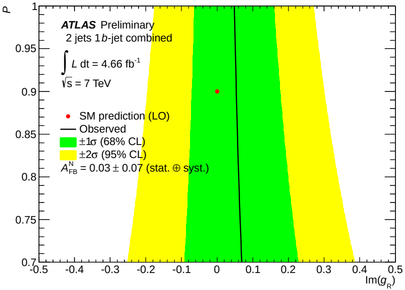
➔ background norm.

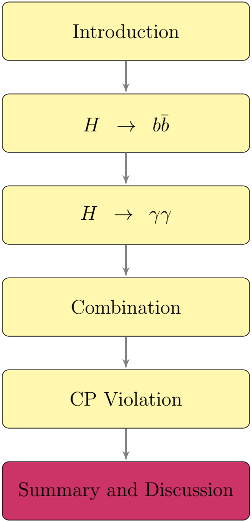
➔ JER/JES

$$A_{FB} = 0.031 \pm 0.065(\text{stat.})^{+0.029}_{-0.031}(\text{syst.})$$

$\Rightarrow [-0.20, 0.30]$ @ 95% CL

➔ consistent with CP invariance




Introduction
$H \rightarrow b\bar{b}$
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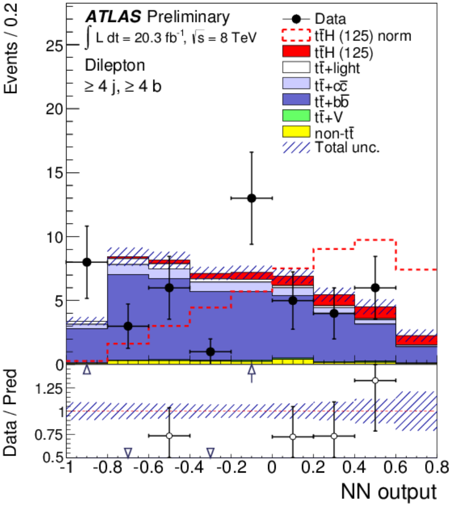
Summary

- $t\bar{t}H$ is only process to directly study the top-Higgs Yukawa-coupling
- search performed in $H \rightarrow b\bar{b}$ and $H \rightarrow \gamma\gamma$
- very complementary, combined limit yields 3.9 (2.3) obs. (exp.)
- ratio ttbar/ttH will improve at 13/14 TeV
- will also gain from boosted topology in Run2
- other channels like multilepton have good potential
- search for CP-violation in top-sector

  $\hookrightarrow$ no evidence found, A_{FB} consistent with 0

Backup


ATLAS Preliminary
∫ L dt = 20.3 fb⁻¹, √s = 8 TeV
Dilepton
≥ 4 j, ≥ 4 b
Data
tt̄H (125) norm
tt̄H (125)
tt̄+light
tt̄+cc̄
tt̄+bb̄
tt̄+V
non-tt̄
Total unc.
Events / 0.2
Data / Pred
NN output

Variable	Definition
$m_{b\bar{b}}$	Mass of the two b jets from the Higgs candidate system
H_{T}	Scalar sum of jet p_{T} and lepton p_{T}
$p_{\mathrm{T}}^{\mathrm{jet3}}$	3rd Leading jet p_{T}
Cent	Sum of p_{T} divided by sum of E for all jets
$\mathrm{Apla_j}$	$1.5\lambda_2$ (Second eigenvalue of the momentum tensor constructed from jets)
$H4$	Fifth Fox-Wolfram Moment
$\Delta R_{\mathrm{hl}}^{\mathrm{MaxdR}}$	Maximum ΔR between the Higgs candidate and the two leptons
$\Delta R_{\mathrm{hl}}^{\mathrm{MindR}}$	Minimum ΔR between the Higgs candidate and the two leptons
NHiggs 30	Number of Higgs candidates within 30 GeV of the defined Higgs mass (e.g. 125 GeV)
$M_{\mathrm{jj}}^{\mathrm{closest}}$	Dijet mass closest to the defined Higgs mass
$\Delta\eta_{\mathrm{jj}}^{\mathrm{Max}\Delta\eta}$	Maximum $\Delta\eta$ between two jets in the event
$M_{\mathrm{jj}}^{\mathrm{MinM}}$	Minimum di-jet mass
$M_{\mathrm{jj}}^{\mathrm{MaxPt}}$	Mass of the two jet system with maximum p_{T} in the event
$M_{\mathrm{bb}}^{\mathrm{MindR}}$	Mass of the two b-jet system with minimum ΔR in the event
$\Delta R_{\mathrm{lj}}^{\mathrm{MindR}}$	Minimum ΔR between leptons and untagged jets
$\Delta R_{\mathrm{bb}}^{\mathrm{MaxPt}}$	ΔR between the b-jet pair with maximum p_{T} in the event
$\Delta R_{\mathrm{bb}}^{\mathrm{MaxM}}$	ΔR between the b-jet pair with maximum mass in the event

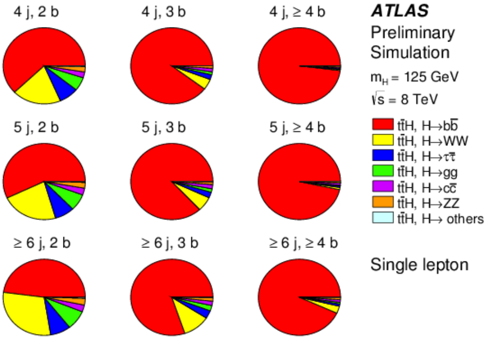
Table 11: The variables considered for use within the dilepton Neural Network analysis.

	4j4b	4j3b	3j3b
$\Delta\eta_{jj}^{\mathrm{Max}\Delta\eta}$	1	1	1
M_{bb}^{MindR}	2	8	-
$m_{b\bar{b}}$	3	-	-
$\Delta R_{hl}^{\mathrm{MindR}}$	4	5	-
NHiggs30	5	2	5
$\Delta R_{bb}^{\mathrm{MaxPt}}$	6	4	8
Apla_{j}	7	7	-
M_{jj}^{MinM}	8	3	2
$\Delta R_{hl}^{\mathrm{MaxdR}}$	9	-	-
$M_{jj}^{\mathrm{closest}}$	10	-	10
H_{T}	-	6	3
$\Delta R_{bb}^{\mathrm{MaxM}}$	-	9	-
$\Delta R_{lj}^{\mathrm{MindR}}$	-	10	-
Cent	-	-	7
M_{jj}^{MaxPt}	-	-	9
$H4$	-	-	4
$p_{\mathrm{T}}^{\mathrm{jet3}}$	-	-	6

Table 12: Best variables found in the region and their NB ranking in the dilepton channel

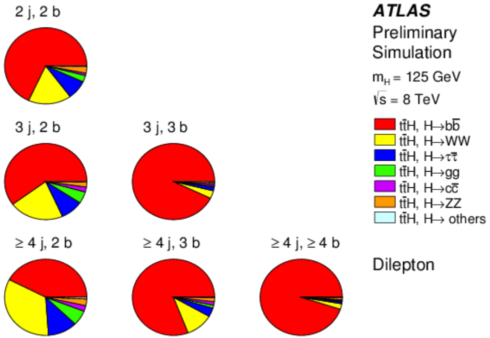
Variable	Definition
Cent	Sum of p_{T} divided by sum of E for all jets and lepton
$H1$	2nd Fox-Wolfram moment
$M_{\mathrm{bb}}^{\mathrm{MindR}}$	mass of the combination between two tagged jets with the smallest ΔR
N_{40}^{jet}	number of jets with $p_{\mathrm{T}} \geq 40$ GeV
$\Delta R_{\mathrm{ave}}^{\mathrm{bb}}$	average ΔR for all tagged jet pairs
$M_{\mathrm{jj}}^{\mathrm{MaxPt}}$	mass of the combination between any two jets with the largest vector sum p_{T}
$\mathrm{Apla_b}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the 3-dimensional linear momentum tensor built with only tagged jets
$H_{\mathrm{T}}^{\mathrm{had}}$	Scalar sum of jet p_{T}
$M_{\mathrm{jj}}^{\mathrm{MindR}}$	mass of the combination between any two jets with the smallest ΔR
$\Delta R_{lep-bb}^{\mathrm{MindR}}$	ΔR between the lepton and two tagged jets with the smallest ΔR
$M_{\mathrm{bj}}^{\mathrm{MindR}}$	mass of the combination between a tagged jet and any jet with the smallest ΔR
$M_{\mathrm{bj}}^{\mathrm{MaxPt}}$	mass of the combination between a tagged jet and any jet with the largest vector sum p_{T}
M^{Whad}	Mass of the closest in ΔR pair of untagged jets
$p_{\mathrm{T}}^{\mathrm{jet5}}$	Fifth leading jet p_{T}
$\Delta R_{\mathrm{bb}}^{\mathrm{MaxPt}}$	ΔR between two tagged jets with the largest vector sum p_{T}
M_{bb}^{MaxM}	mass of the combination between two tagged jets with the largest invariant mass
p_{T}^{Whad}	scalar sum of the p_{T}'s of the pair of untagged jets closest in ΔR
M_{jjj}	Mass of the jet triplets with the largest vectorial sum p_{T}
ΔR^{Whad}	ΔR of the closest in ΔR pair of untagged jets
$M_{\mathrm{bb}}^{\mathrm{MaxPt}}$	mass of the combination between two tagged jets with the largest vector sum p_{T}

Table 9: The variables considered for use within the Neural Network analysis in the single lepton channel.


4 j, 2 b
4 j, 3 b
4 j, ≥ 4 b
5 j, 2 b
5 j, 3 b
5 j, ≥ 4 b
≥ 6 j, 2 b
≥ 6 j, 3 b
≥ 6 j, ≥ 4 b
ATLAS
Preliminary
Simulation
m_H = 125 GeV
√s = 8 TeV
tt̄H, H→bb̄
tt̄H, H→WW
tt̄H, H→ττ̄
tt̄H, H→gg
tt̄H, H→cc̄
tt̄H, H→ZZ
tt̄H, H→ others
Single lepton

Variable	$\geq$ 6 jet $\geq$ 4 b	$\geq$ 6 jet 3 b	5j $\geq$ 4 b	5 j 3 b
$\Delta R^{\rm bb}_{\rm ave}$	1	5	5	-
$M^{\rm MindR}_{\rm bb}$	2	9	3	1
Cent	3	2	1	-
$H1$	4	3	2	-
$p^{\rm jet5}_{\rm T}$	5	8	-	-
$\rm Apla_b$	6	-	7	-
$M^{\rm Whad}$	7	7	-	2
$\Delta R^{\rm MaxPt}_{\rm bb}$	8	-	-	-
$\Delta R^{\rm MindR}_{lep-bb}$	9	10	10	-
$M^{\rm MaxPt}_{\rm bj}$	10	6	-	-
$N^{\rm jet}_{40}$	-	1	4	-
$M^{\rm MindR}_{\rm bj}$	-	4	-	-
$M^{\rm MaxPt}_{\rm jj}$	-	-	6	-
$H^{\rm had}_{\rm T}$	-	-	8	-
$M^{\rm MindR}_{\rm jj}$	-	-	9	-
$M^{\rm MaxM}_{bb}$	-	-	-	3
$p^{\rm Whad}_{T}$	-	-	-	4
M_{jjj}	-	-	-	5
$\Delta R^{\rm Whad}$	-	-	-	6
$M^{\rm MaxPt}_{\rm bb}$	-	-	-	7

Table 10: The lists and rankings of the variables in each of the regions in the singel lepton channel.



2 j, 2 b
3 j, 2 b
3 j, 3 b
≥ 4 j, 2 b
≥ 4 j, 3 b
≥ 4 j, ≥ 4 b
ATLAS
Preliminary
Simulation
m_H = 125 GeV
$\sqrt{s}$ = 8 TeV
$t\bar{t}H$, $H \to b\bar{b}$
$t\bar{t}H$, $H \to WW$
$t\bar{t}H$, $H \to \tau\bar{\tau}$
$t\bar{t}H$, $H \to gg$
$t\bar{t}H$, $H \to c\bar{c}$
$t\bar{t}H$, $H \to ZZ$
$t\bar{t}H$, $H \to$ others
Dilepton

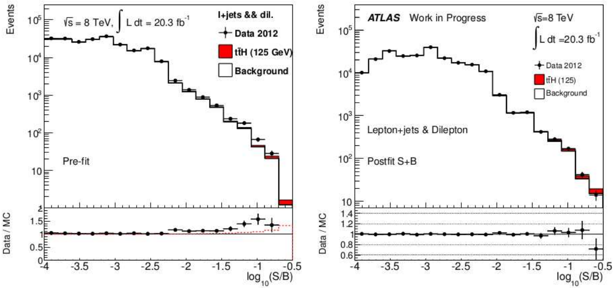


Figure 23: Prefit and postfit yields per bin, ordered by log(S/B), for all bins used in the combined fit of the single lepton and dilepton channels. For postfit yields, signal is normalized to the fitted value of signal strength.

Region	2 b-tags	3 b-tags	$\geq 4b$-tags
4 jets	H_T^{had}	H_T^{had}	H_T^{had}
5 jets	H_T^{had}	NNHF	NN
$\geq$ 6 jets	H_T^{had}	NN	NN

Table 6: A summary of discriminants used in analysis regions in the single lepton channel

Region	2 b-tags	3 b-tags	$\geq 4b$-tags
2 jets	H_T		
3 jets	H_T^{had}	NN	
$\geq$ 4 jets	H_T	NN	NN

Table 7: A summary of discriminants used in analysis regions in the dilepton channel

Region	2 b-tags	3 b-tags	$\geq 4b$-tags
4 jets	H_T^{had}	H_T^{had}	H_T^{had}
5 jets	H_T^{had}	NNHF	NN
$\geq$ 6 jets	H_T^{had}	NN	NN

Table 6: A summary of discriminants used in analysis regions in the single lepton channel

Region	2 b-tags	3 b-tags	$\geq 4b$-tags
2 jets	H_T		
3 jets	H_T^{had}	NN	
$\geq$ 4 jets	H_T	NN	NN

Table 7: A summary of discriminants used in analysis regions in the dilepton channel

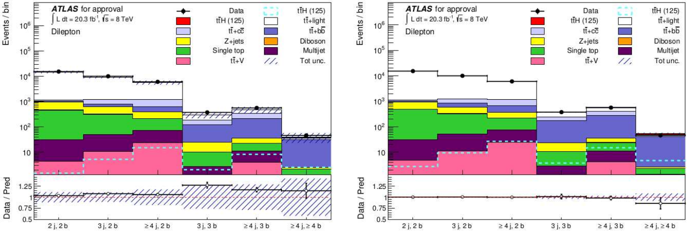


Figure 22: Prefit and postfit plots for the yields in all analysis regions in the dilepton channel.

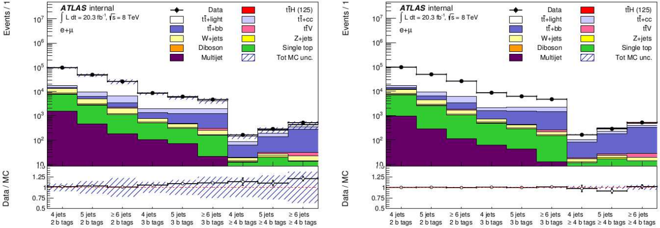
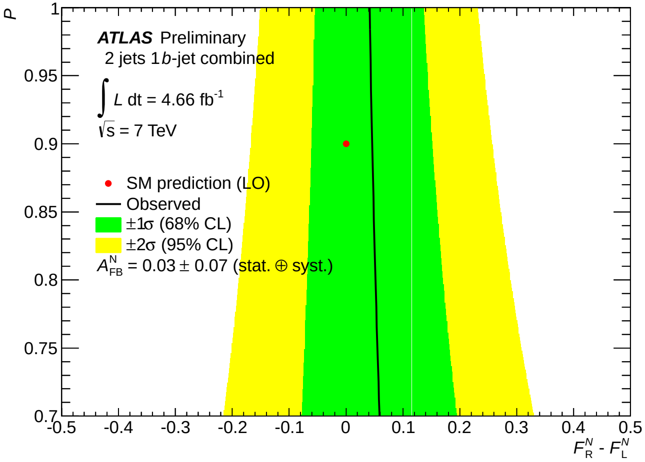


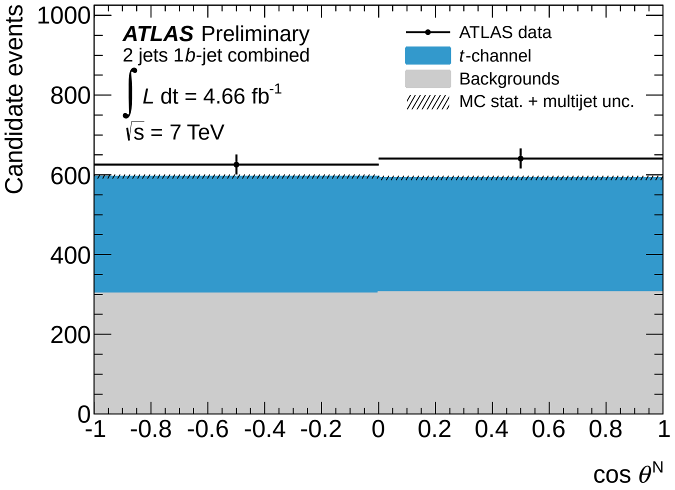
Figure 19: Prefit and postfit plots for the yields in all analysis regions in the single lepton channel.

Category	N_H	ggF	VBF	WH	ZH	$t\bar{t}H$	$tHqb$	WtH	N_B
8 TeV leptonic	0.59	1.0%	0.2%	8.1%	2.3%	80.3%	5.5%	2.7%	$0.9^{+0.6}_{-0.4}$
8 TeV hadronic	0.50	7.3%	1.0%	0.7%	1.3%	84.3%	3.4%	2.0%	$2.7^{+0.9}_{-0.7}$
7 TeV leptonic	0.10	0.6%	0.1%	14.9%	4.0%	72.8%	5.0%	2.4%	$0.5^{+0.5}_{-0.3}$
7 TeV hadronic	0.07	10.5%	1.3%	1.3%	1.4%	81.1%	2.5%	1.8%	$0.5^{+0.5}_{-0.3}$

	$t\bar{t}H$ [%]		$tHqb$ [%]		WtH [%]		ggF [%]	WH [%]
	had.	lep.	had.	lep.	had.	lep.	had.	lep.
Luminosity	±2.8							
Photons	±3.3							
Leptons	< 0.1	±0.6	< 0.1	±0.5	< 0.1	±0.5	< 0.1	±0.6
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±7.4	±0.7	±16	±1.9	±11	±2.1	±29	±10
Bkg. modeling	0.24 evt.	0.16 evt.	applied on the sum of all Higgs boson production processes					
Theory ($\sigma \times$ BR)	+10,-13		+10,-9		+24,-19		+11,-11	+5.5,-5.4
MC Modeling	±11	±3.3	±13	±13	±12	±4.6	±130	±100



ATLAS Preliminary
2 jets 1b-jet combined
∫ L dt = 4.66 fb-1
√s = 7 TeV
SM prediction (LO)
Observed
±1σ (68% CL)
±2σ (95% CL)
A^N_FB = 0.03 ± 0.07 (stat. ⊕ syst.)
P
1
0.95
0.9
0.85
0.8
0.75
0.7
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
F^N_R - F^N_L



Candidate events
1000
800
600
400
200
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
cos θ^N
ATLAS Preliminary
2 jets 1b-jet combined
∫ L dt = 4.66 fb^-1
√s = 7 TeV
ATLAS data
t-channel
Backgrounds
MC stat. + multijet unc.

Source	ΔA_{FB}^{N}
t-channel generator	+0.024 / −0.024
$t\bar{t}$ generator and parton shower	+0.010 / −0.010
Background normalisation	+0.008 / −0.008
Jet energy resolution	+0.007 / −0.007
Jet energy scale	+0.005 / −0.009
Lepton id, reco., trigger and scale	+0.004 / −0.006
PDFs	+0.003 / −0.003
Unfolding	+0.003 / −0.003
E_{T}^{miss}	+0.002 / −0.004
b-tagging	+0.002 / −0.002
W+jets shape	+0.001 / −0.001
ISR/FSR	+0.001 / −0.001
Jet reconstruction efficiency	+0.001 / −0.001
Luminosity	+0.001 / −0.001
Jet vertex fraction	<0.001 / <0.001
Total systematic	+0.029 / −0.031