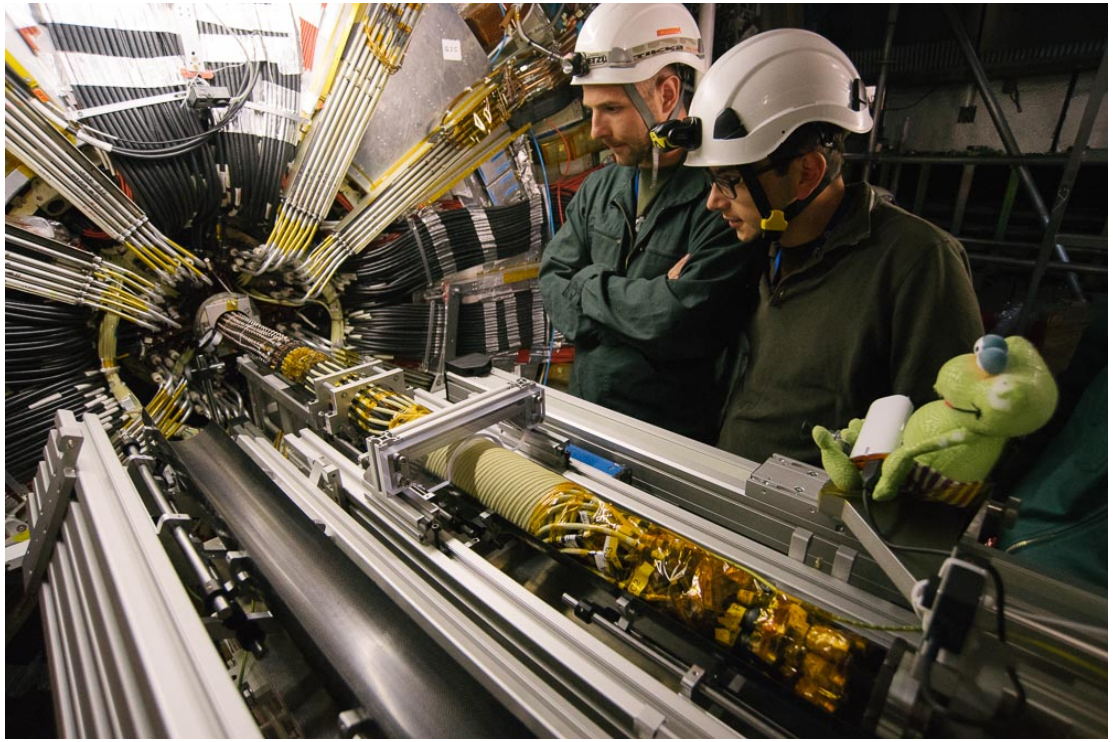
Search for the Higgs boson in the $t\bar{t}H$ production mode using the ATLAS detector



Rustem Ospanov (University of Pennsylvania)
on behalf of the ATLAS collaboration

Large Hadron Collider Physics Conference, June 2nd, 2014

Introduction

- Higgs boson with $m \approx 125$ GeV discovered via $\gamma\gamma$, ZZ, WW decays
- Higgs boson Yukawa couplings probe flavor structure of the SM
- Higgs Yukawa couplings accessible at LHC: τ, μ, b and top quark
- Strong evidence for $H \to \tau\tau$: 4.1σ for ATLAS and 3.2σ for CMS

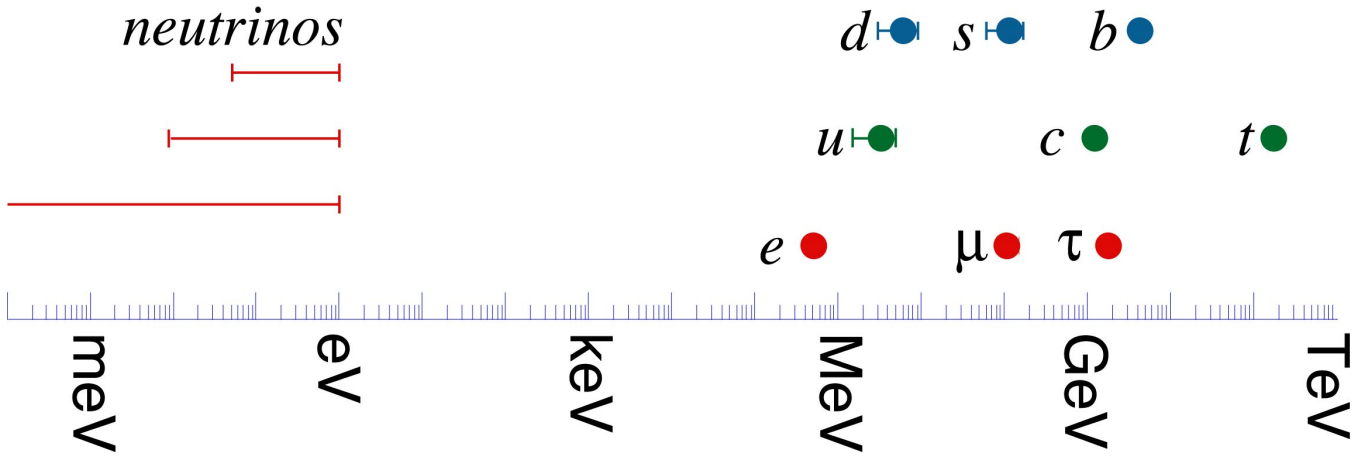


Figure by Hitoshi Murayama

Evidently the Higgs system knows something that we do not know: the difference between the generations - Martinus Veltman.

Higgs-top quark coupling

$t\bar{t}H$ coupling

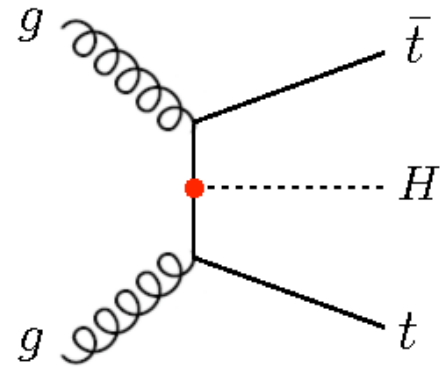
- Drives SM properties at high energy scale
- Indirect measurement via gluon fusion production
- Direct measurement via $t\bar{t}H$ production

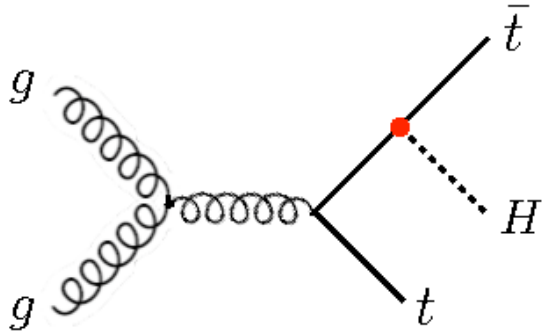
$t\bar{t}H$ production:

- $\sigma(t\bar{t}H) \approx 130$ fb for $m_H = 125$ GeV at $\sqrt{s} = 8$ TeV
- ≈ 2600 events with 20.3 fb^{-1}
- Main background is $t\bar{t} +$ jets with $\sigma \approx 250$ pb

Decay modes:

- $B(H \to b\bar{b}) = 0.58$ - dominant mode
- $B(H \to \gamma\gamma) = 2.3 \times 10^{-3}$ - clean resonance signature
- $B(H \to WW, ZZ, \tau\tau) \approx 0.3$ - multi-lepton final states





$t\bar{t}H \rightarrow t\bar{t} + b\bar{b}$ analysis strategy

- Tag $t\bar{t}$ decay by 1-lepton and 2-lepton
- Categorize by number jets and b-jets
- Increase sensitivity with different S/B
- Constrain systematic uncertainty by fitting regions with low S/B

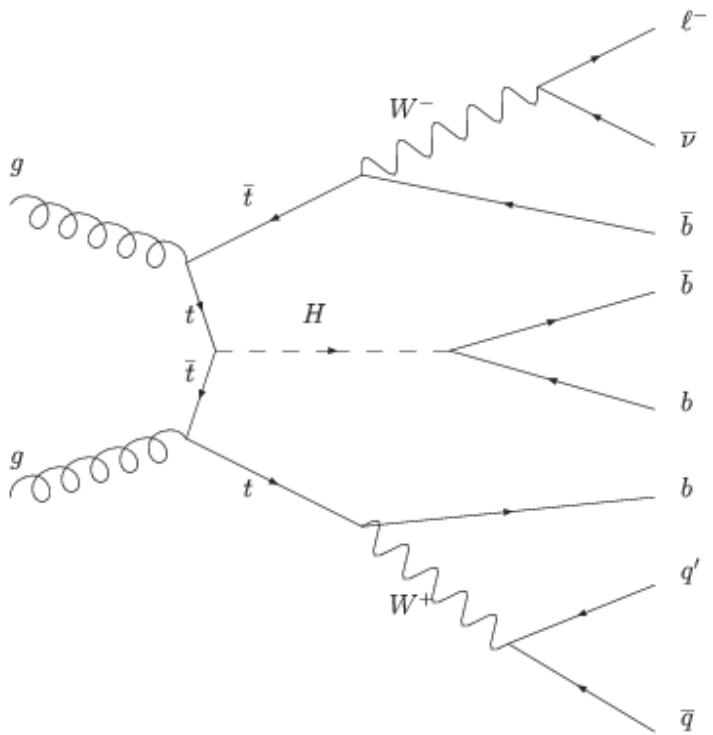
1-lepton:

- $t\bar{t}H \rightarrow$ 6 jets 4 b-jets
- 1 electron or muon
- $\geq$ 4 jets
- $\geq$ 2 b-jets

2-lepton:

- $t\bar{t}H \rightarrow$ 4 jets 4 b-jets
- 2 electron or muon
- $\geq$ 2 jets
- $\geq$ 2 b-jets

$t\bar{t}H \rightarrow$ 6 jets 4 b-jets



- $t\bar{t}H$ signal $> 90\%$

$t\bar{t}H \rightarrow t\bar{t} + b\bar{b}$ analysis strategy

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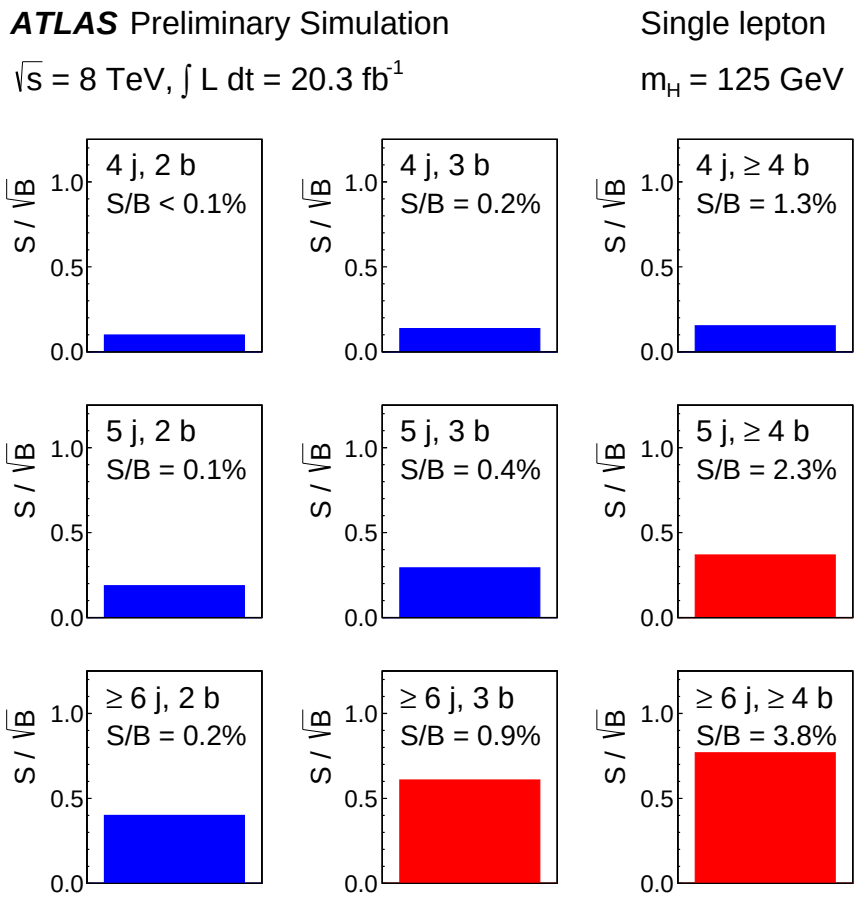
- 1 electron or muon
- $\geq$ 4 jets
- $\geq$ 2 b-jets

2-lepton:

- $t\bar{t}H \rightarrow$ 4 jets 4 b-jets
- 2 electron or muon
- $\geq$ 2 jets
- $\geq$ 2 b-jets

1-lepton



$S/\sqrt{B}$ for control regions

$S/\sqrt{B}$ for signal regions

$t\bar{t}H \rightarrow t\bar{t} + b\bar{b}$ analysis strategy

- Tag $t\bar{t}$ decay by 1-lepton and 2-lepton
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1-lepton:

- $t\bar{t}H \rightarrow$ 6 jets 4 b-jets
- 1 electron or muon
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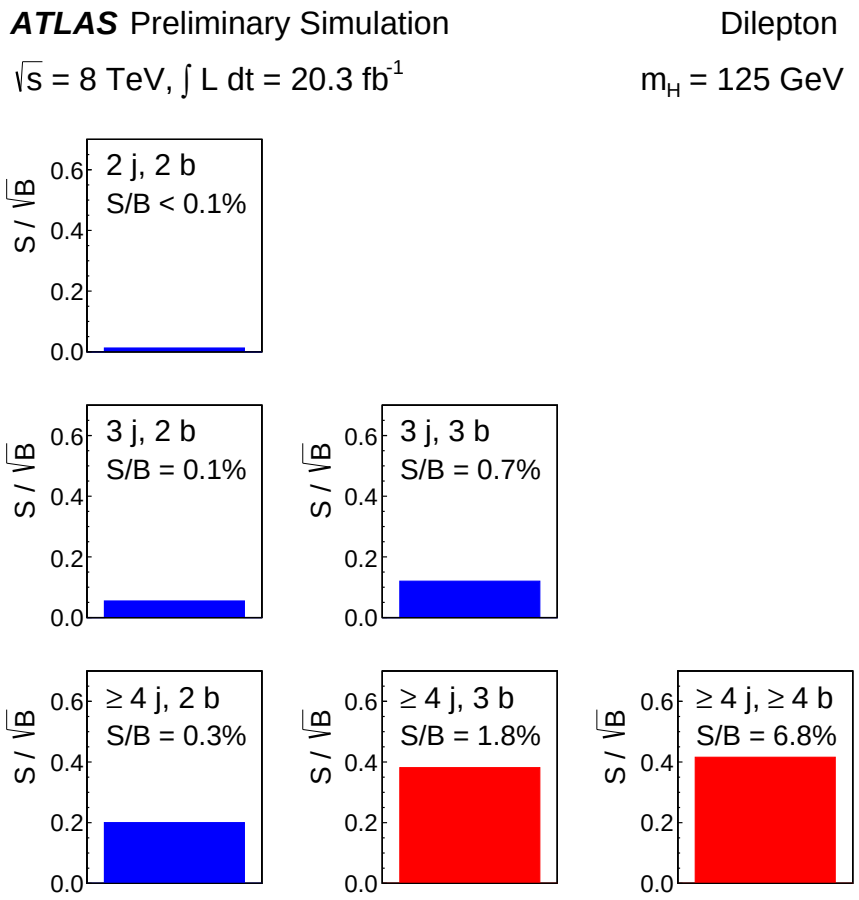
- $\geq$ 2 b-jets

2-lepton:

- $t\bar{t}H \rightarrow$ 4 jets 4 b-jets
- 2 electron or muon
- $\geq$ 2 jets
- $\geq$ 2 b-jets

2-lepton



$S/\sqrt{B}$ for control regions

$S/\sqrt{B}$ for signal regions

$t\bar{t}H \to t\bar{t} + b\bar{b}$: backgrounds

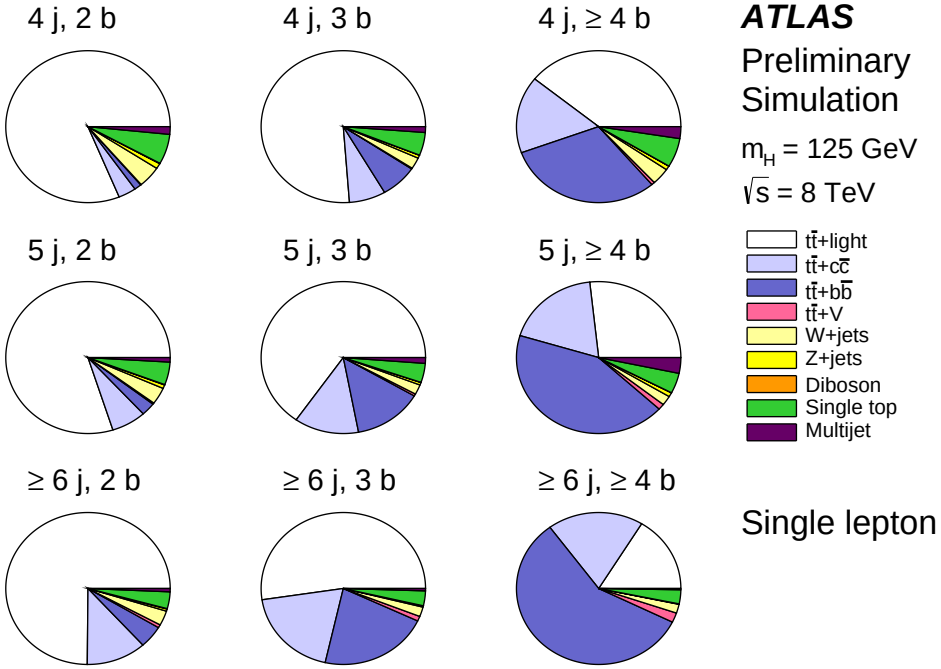
$t\bar{t}$ + jets

- Dominant background
- $+5\%$ -6% uncertainty
- Modeled with Powheg+Pythia
- Difference between Powheg and Madgraph is taken as uncertainty
- $p_T^{t\bar{t}}$ and p_T^t are re-weighted to unfolded 7 TeV data
- $t\bar{t} + b\bar{b}$ same final state as signal

Other backgrounds:

- $t\bar{t}W/Z$ - Madgraph+Pythia
- W/Z+jets - Alpgen+Pythia
- Diboson - Alpgen+Herwig
- QCD multi-jet - data-driven

1-lepton background composition



$t\bar{t}H \to t\bar{t} + b\bar{b}$: backgrounds

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Other backgrounds:

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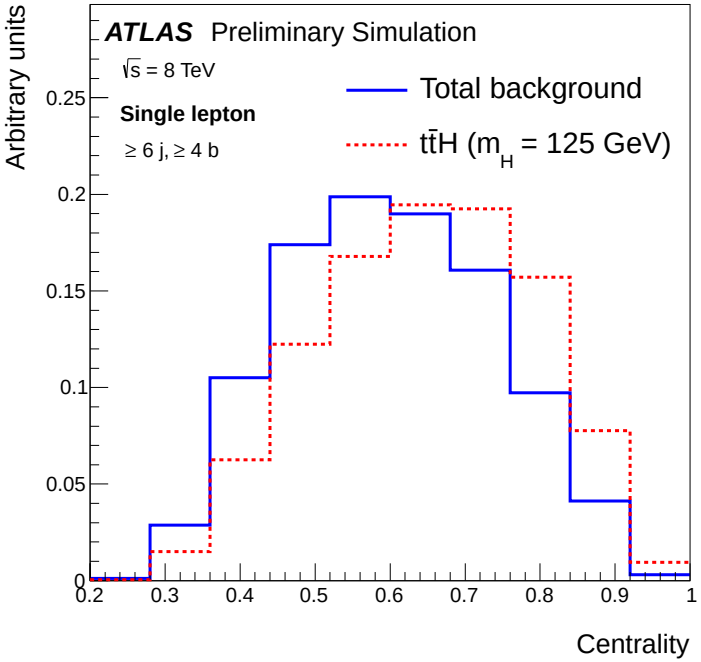
1-lepton yields - post-fit

	5 jets, $\geq$ 4 b-tags	$\geq$ 6 jets, 3 b-tags	$\geq$ 6 jets, $\geq$ 4 b-tags
$t\bar{t}H$ (125)	$11 \pm 1 \pm 9$	$69 \pm 3 \pm 57$	$28 \pm 2 \pm 23$
$t\bar{t}$+ light	78 ± 9	2380 ± 130	78 ± 11
$t\bar{t} + c\bar{c}$	45 ± 12	750 ± 190	75 ± 19
$t\bar{t} + b\bar{b}$	149 ± 20	1160 ± 170	300 ± 40
$t\bar{t} + V$	3.3 ± 1.0	44 ± 13	8.9 ± 2.7
non-$t\bar{t}$	23.2 ± 2.5	218 ± 23	18.8 ± 2.2
Total	309 ± 11	4620 ± 80	507 ± 27
Data	283	4671	516

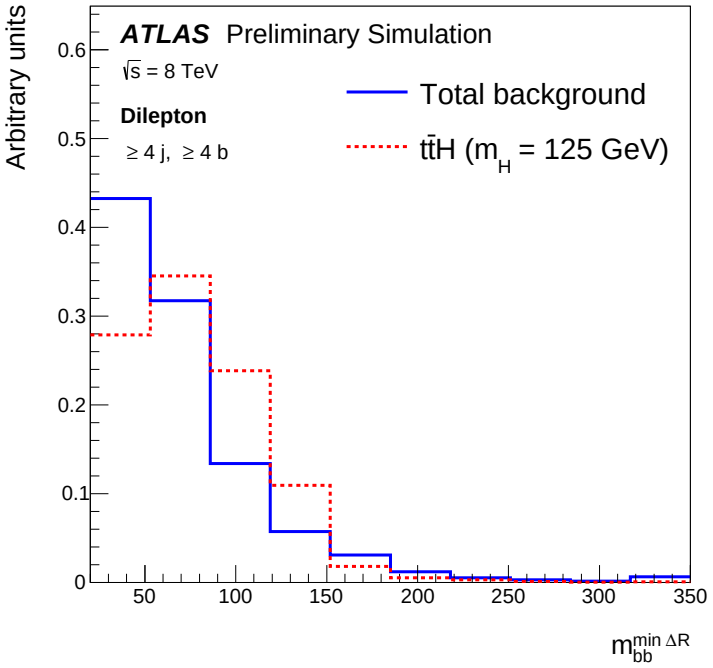
$t\bar{t}H \to t\bar{t} + b\bar{b}$: multi-variate discriminant inputs

- Event shape variables: event centrality, ...
- Object pair properties: $m_{b\bar{b}}^{min\Delta R}$, ...
- Object kinematics: p_T^{jet5}, ...
- Event kinematics: H_T^{had}, $N_{p_T>40\ \mathrm{GeV}}$, ...
- Modeling of variables and correlations checked in signal depleted regions

1-lepton centrality$=\sum p_T / \sum E$



2-lepton $m_{b\bar{b}}^{min\Delta R}$

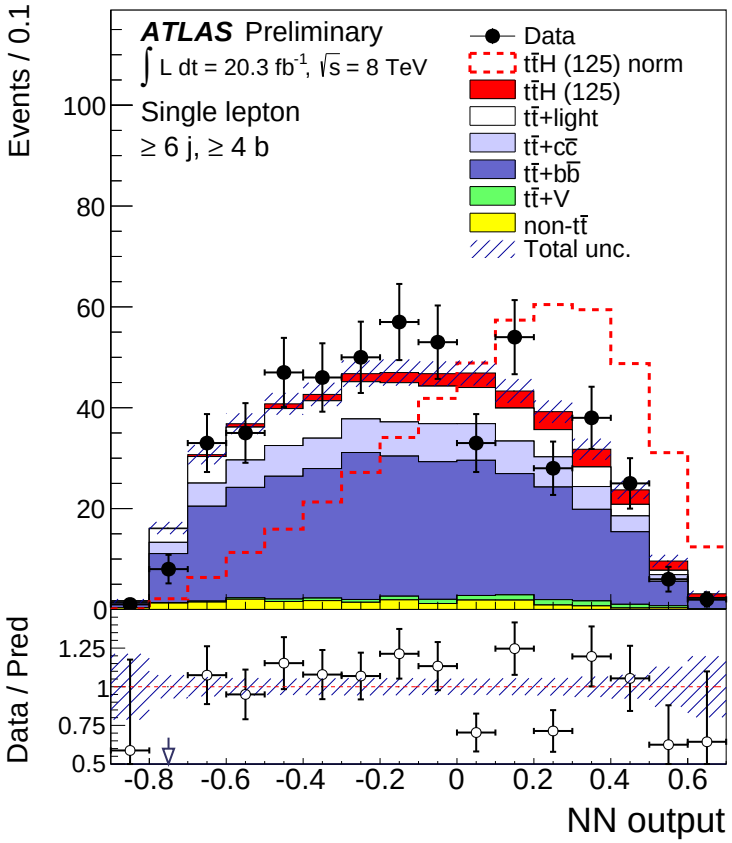


$t\bar{t}H \rightarrow t\bar{t} + b\bar{b}$: multi-variate discriminant output

- Neural Network trained in each signal region
- Select 10 highest rank variables with NeuroBayes
- Use all MC events - weight light jets with b-jet mistag rate maps

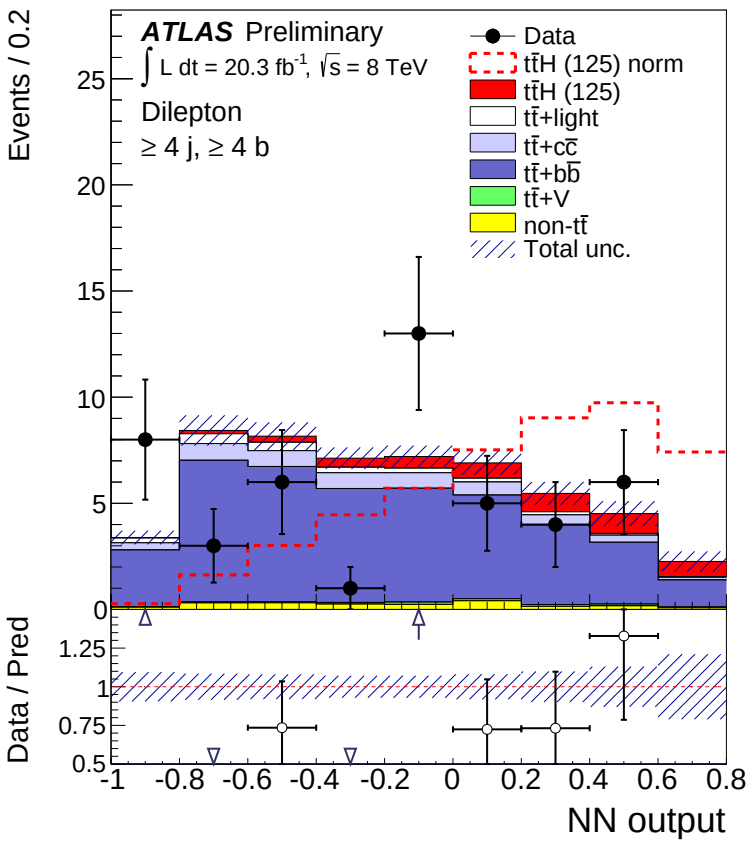
1-lepton

$t\bar{t}H \rightarrow$ 6 jets 4 b-jets



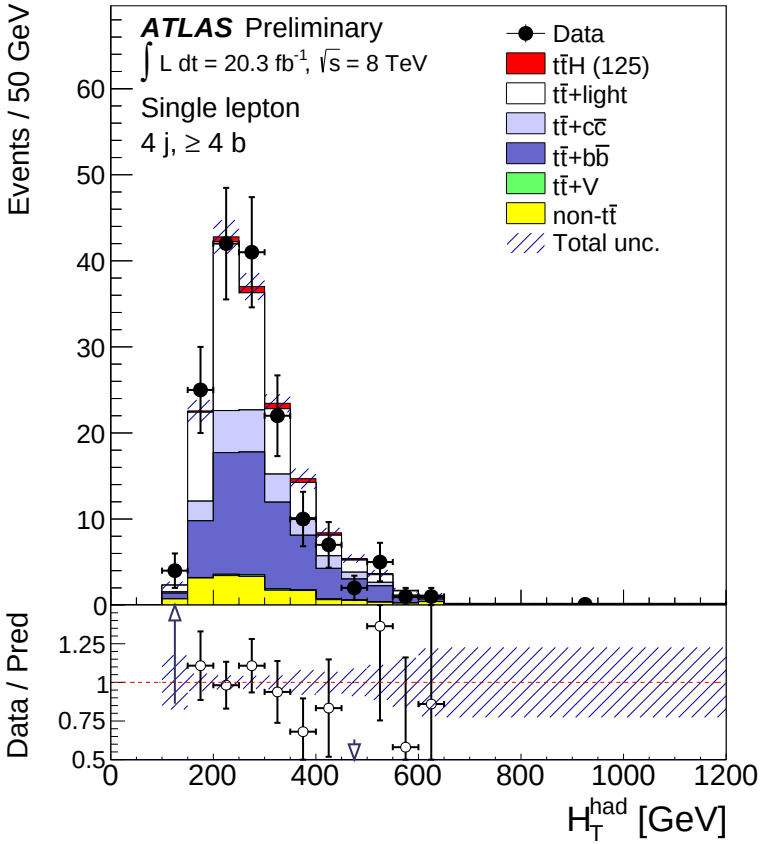
2-lepton

$t\bar{t}H \rightarrow$ 4 jets 4 b-jets



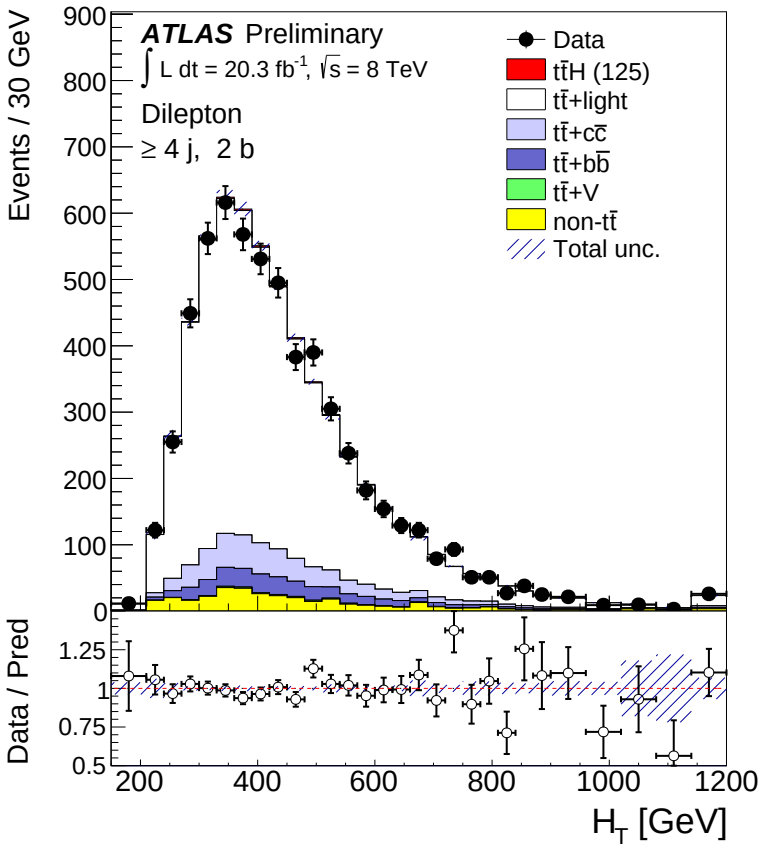
$t\bar{t}$ + jets control regions

1-lepton 4 jet ≥4 b



$$H_T^{had} = \sum p_T^{jet}$$

2-lepton ≥4 jet 2 b

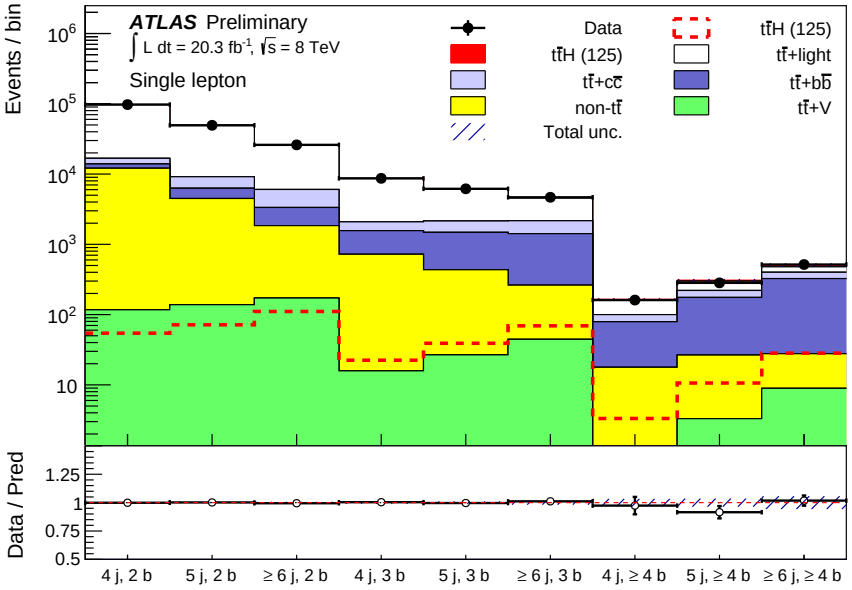


$$H_T = \sum p_T^{jet} + \sum p_T^{lepton}$$

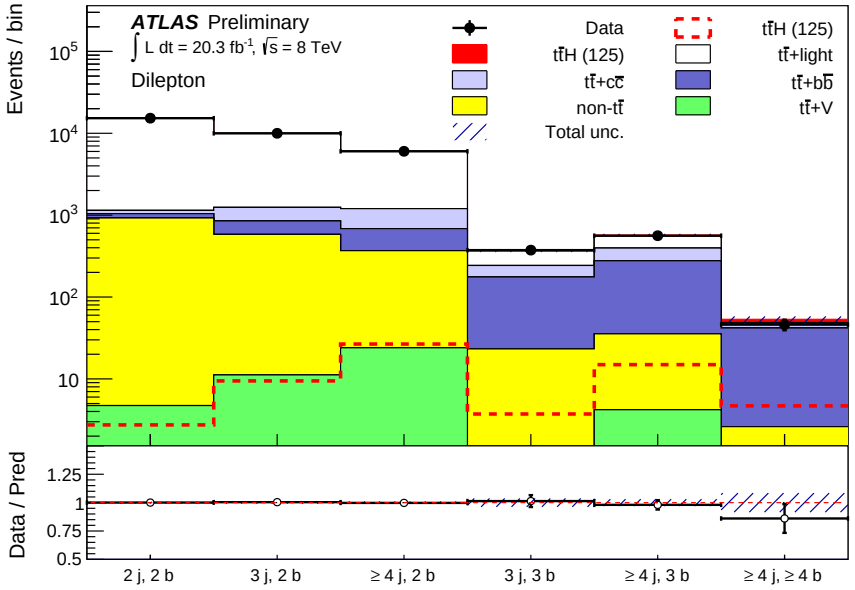
- $t\bar{t} + b\bar{b}$ and $t\bar{t} + c\bar{c}$ are constrained from fits to signal depleted regions

Signal and control region yields

1-lepton yields post-fit



2-lepton yields post-fit



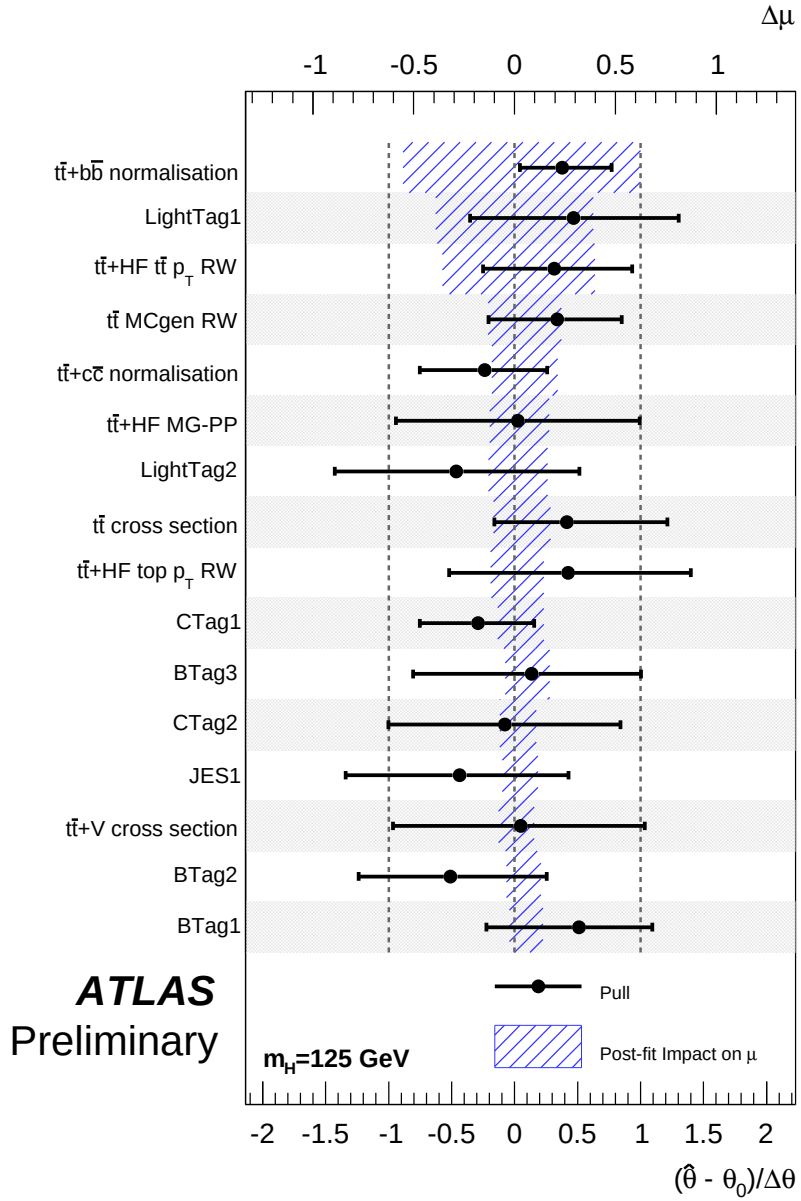
- Simultaneous binned likelihood fit to 6 signal and 9 control regions
- Measure $t\bar{t}H$ signal strength μ and background normalization
- $\mu = 1$ corresponds to SM $t\bar{t}H$ prediction

$t\bar{t}H \to t\bar{t} + b\bar{b}$: systematic uncertainties

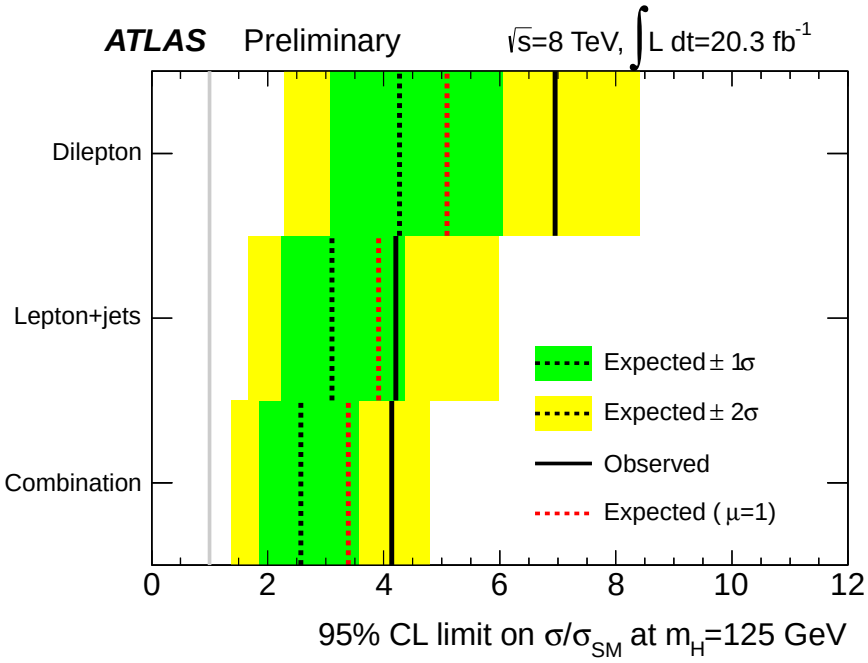
Main systematic uncertainties

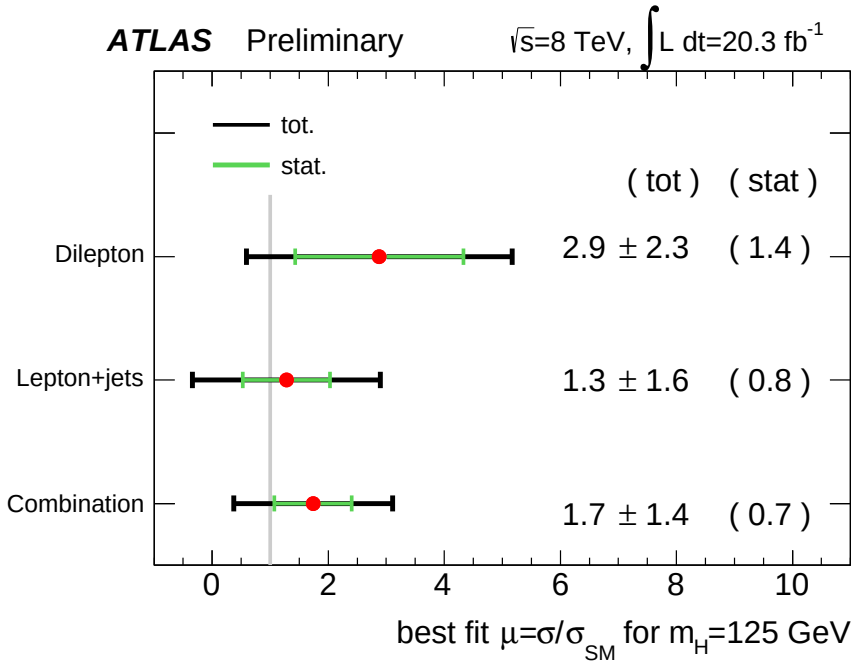
- $t\bar{t}$+heavy flavor normalization
- Jet flavor tagging
- $t\bar{t}$ re-weighting to data and Madgraph
- $t\bar{t}$ theoretical uncertainties
- Reduced by fitting data

	$t\bar{t}$ + light	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$
Total pre-fit	± 30	± 57	± 56
Total post-fit	± 14	± 25	± 14



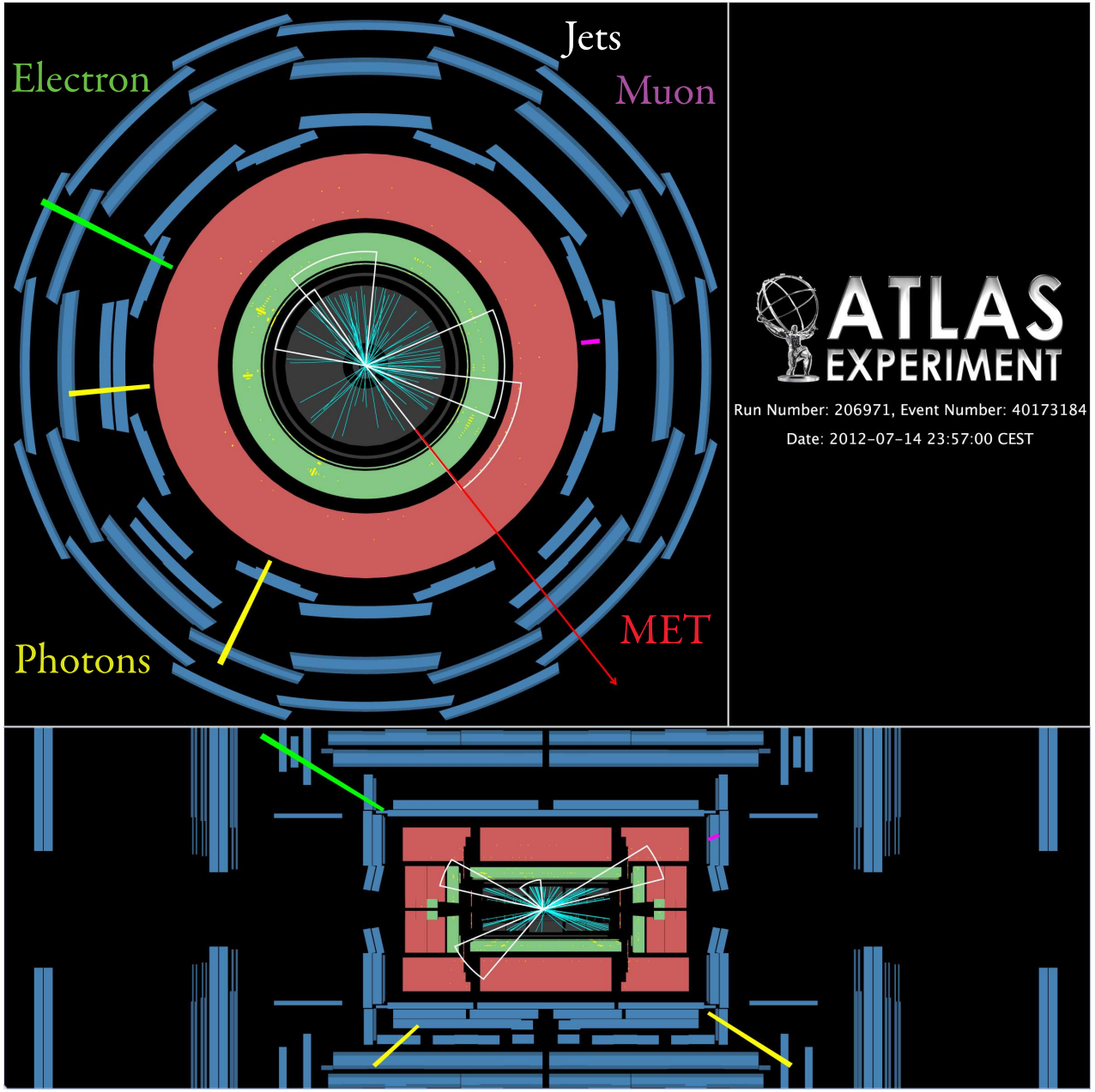
$t\bar{t}H \to t\bar{t} + b\bar{b}$: results





- Observed (expected) 95% CL limit 4.1×SM (2.6×SM) for $m_H = 125$ GeV
- Best fit $\mu = 1.7 \pm 1.4$
- ATLAS-CONF-2014-011

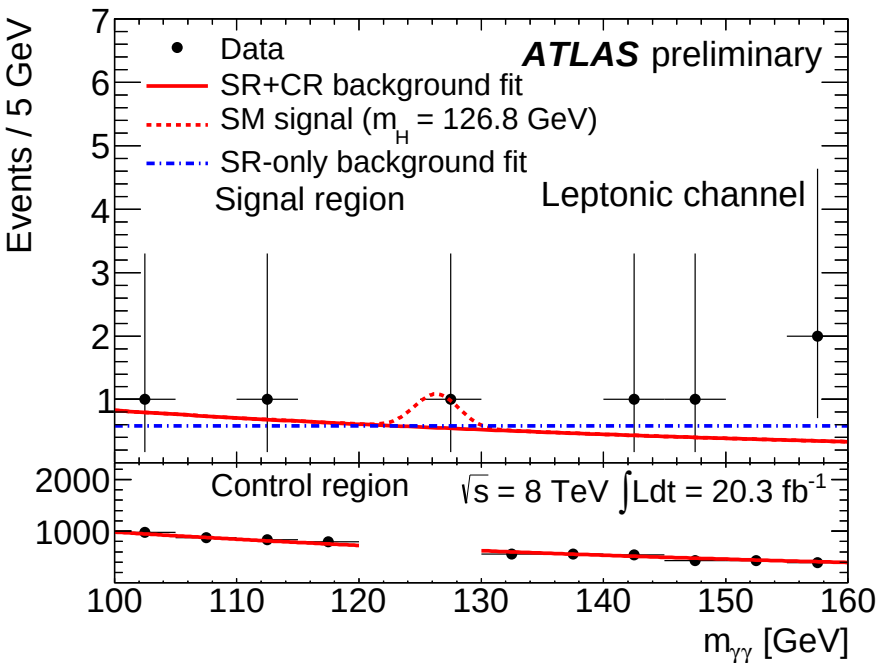
$t\bar{t}H \to t\bar{t} + \gamma\gamma$ candidate event



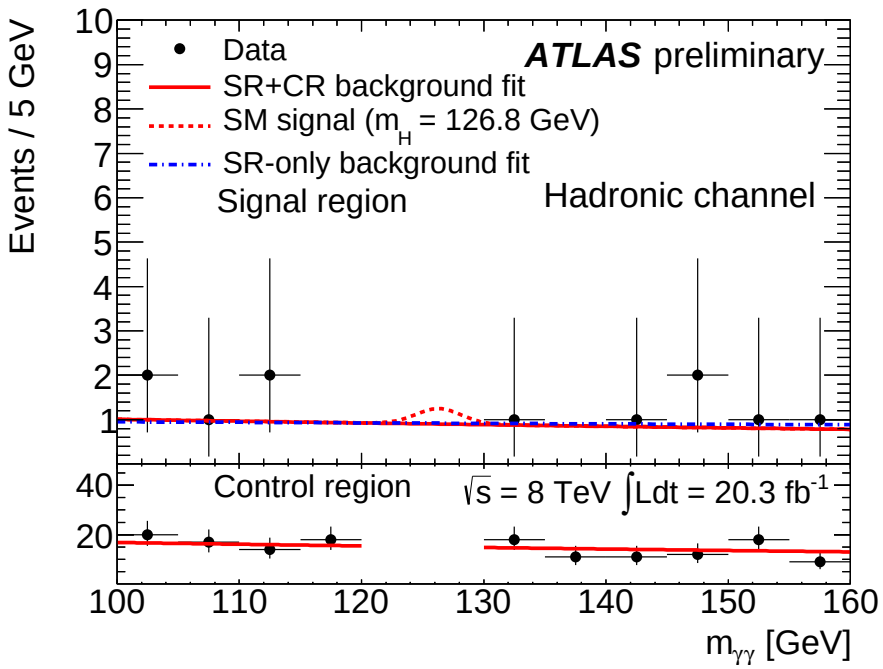
$t\bar{t}H \to t\bar{t} + \gamma\gamma$: signal regions

- Hadronic $t\bar{t}$ channel: ≥ 6 jet ≥ 2 b - $N_{\text{signal}} = 0.36$
- Leptonic $t\bar{t}$ channel: ≥ 1-lepton, ≥ 1 b - $N_{\text{signal}} = 0.55$
- 2 isolated high p_T photons - search for $m_{\gamma\gamma}$ resonance
- Model $m_{\gamma\gamma}$ for background with exponential function
- Simultaneous fit to signal and control regions with relaxed kinematic cuts

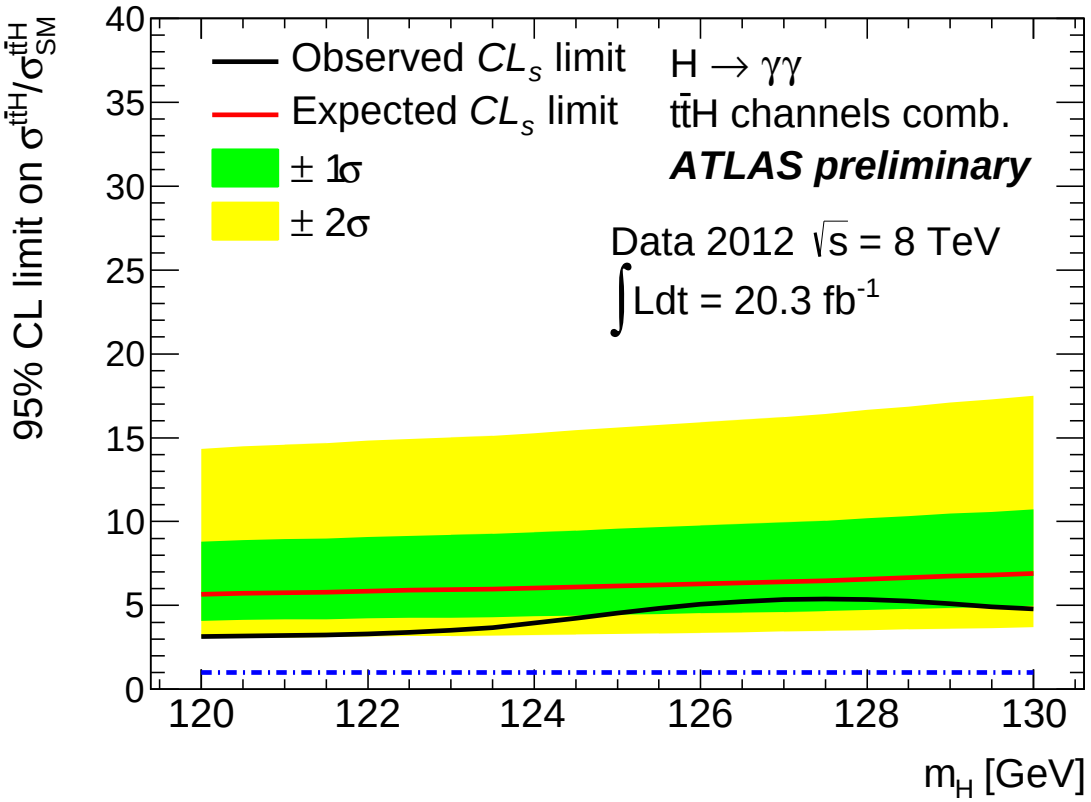
Leptonic



Hadronic



$t\bar{t}H \to t\bar{t} + \gamma\gamma$: results



- Observed 95% CL limit: 5.3×SM (6.4×SM) for $m_H = 126.8$ GeV
- 9-12% uncertainty on $\sigma(t\bar{t}H)$ and 5% uncertainty on $BR(H \to \gamma\gamma)$
- 4-6% uncertainty on photon id and isolation in multi-jet environment
- 5-10% uncertainty on jet energy scale and b-tagging in hadronic channel
- ATLAS-CONF-2013-080

Summary and outlook

$t\bar{t}H \to t\bar{t} + b\bar{b}$

- Observed (expected) 95% CL limit: 4.1× SM (2.6× SM)

$t\bar{t}H \to t\bar{t} + \gamma\gamma$

- Observed (expected) 95% CL limit: 5.3× SM (6.4× SM)

Outlook

- Publications of improved analyses of these final states are forthcoming
- Results of multi-lepton analyses will be also published
- $t\bar{t}H$ cross-section increases by 3.9 at $\sqrt{s} = 13$ TeV compared to 8 TeV
- ATLAS pixel detector upgrade: added Insertable B-Layer
- Expect to reach SM sensitivity in Run 2

BACKUP

$t\bar{t}H \rightarrow t\bar{t} + b\bar{b}$ analysis strategy

1-lepton:

- $t\bar{t}H \rightarrow$ 6 jets 4 b-jets
- 1 electron or muon with $p_T > 25$ GeV
- ≥ 4 jets
- ≥ 2 b-jets

2-lepton:

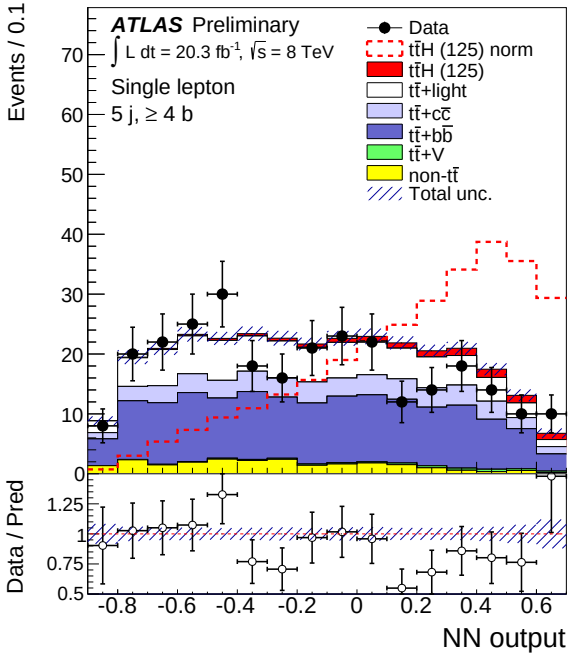
- $t\bar{t}H \rightarrow$ 4 jets 4 b-jets
- 2 electron or muon with $p_T > 25(15)$ GeV
- ≥ 2 jets
- ≥ 2 b-jets
- $e\mu$: $H_T > 130$ GeV
- ll: $m_{ll} > 15 GeV$ and Z veto
- Exactly 2 b ll: $m_{ll} > 60$ GeV

- Jets with $p_T > 25$ GeV in $|\eta| < 2.5$
- 70% b-tagging working point with 1% mis-tag

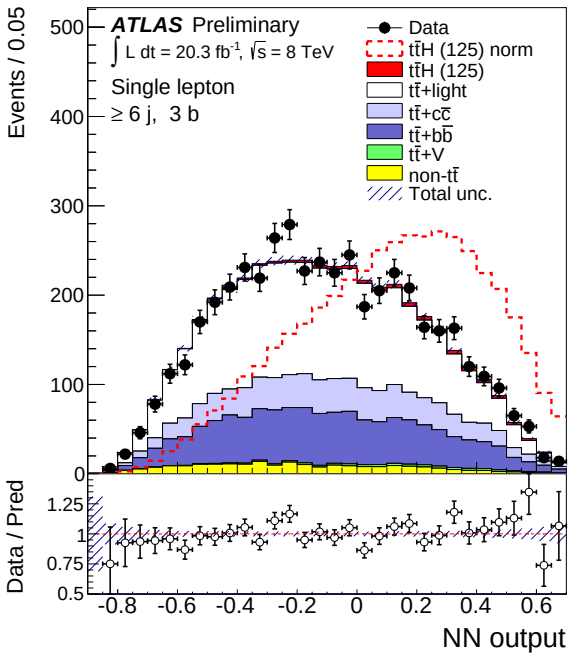
$t\bar{t}H \to t\bar{t} + b\bar{b}$: multi-variate discriminant output

- Neural Network trained in each signal region
- Select 10 highest rank variables with NeuroBayes
- Use all MC events - weight light jets with b-jet mistag rate maps

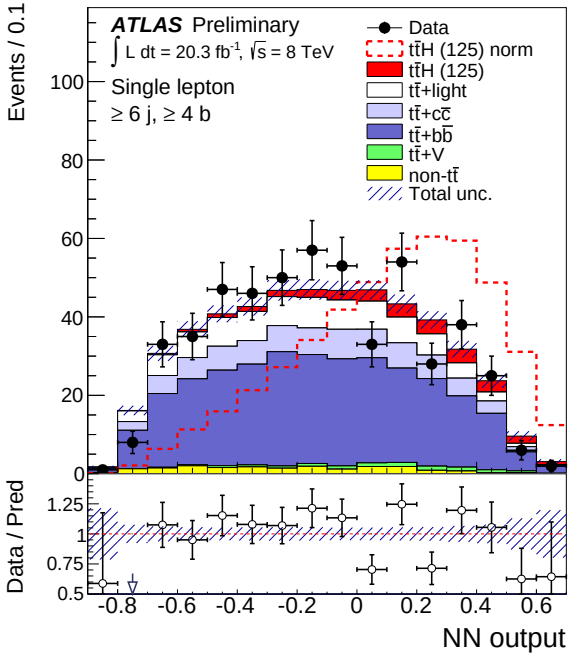
1-lepton 5 jet $\geq$4 b



1-lepton 6 jet 3 b



1-lepton 6 jet $\geq$4 b



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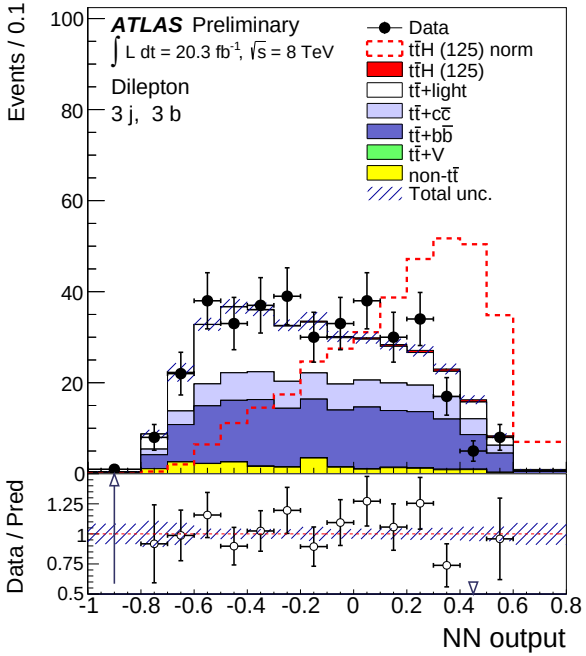
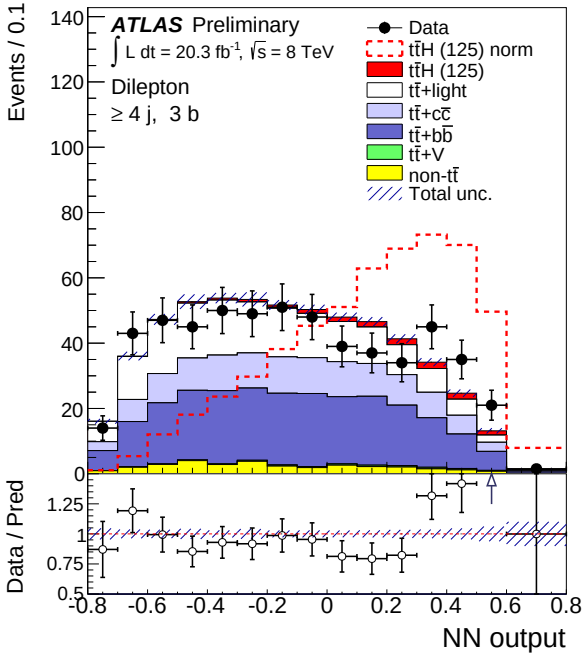


1-lepton 6 jet 3 b



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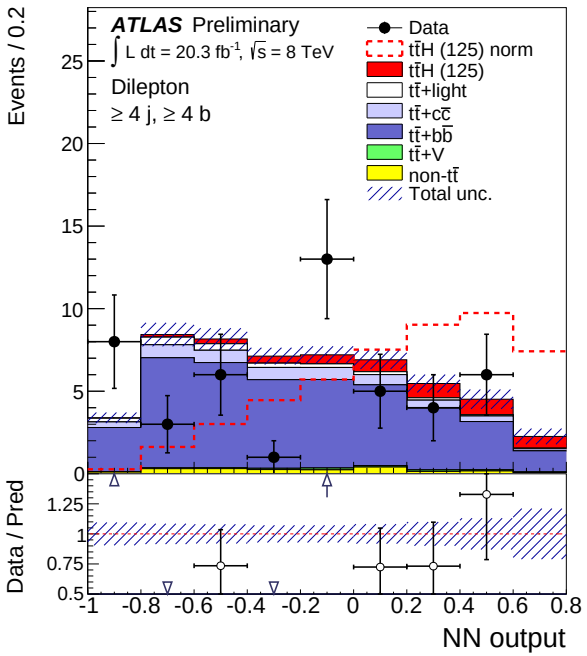


1-lepton variables

Variable	Definition
$\mathrm{Centrality}$	Sum of the p_{T} divided by sum of the E for all jets and the lepton
H1	Second Fox-Wolfram moment computed using all jets and the lepton
$m_{\mathrm{bb}}^{\mathrm{min\ \Delta R}}$	Mass of the combination of two b-tagged jets with the smallest ΔR
N_{40}^{jet}	Number of jets with $p_{\mathrm{T}} \geq 40 GeV$
$\Delta R_{\mathrm{bb}}^{\mathrm{avg}}$	Average ΔR for all b-tagged jet pairs
$m_{\mathrm{jj}}^{\mathrm{max\ p_T}}$	Mass of the combination of any two jets with the largest vector sum p_{T}
$\mathrm{Aplanarity}_{\mathrm{b-jet}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor built with only b-tagged jets
$H_{\mathrm{T}}^{\mathrm{had}}$	Scalar sum of jet p_{T}
$m_{\mathrm{jj}}^{\mathrm{min\ \Delta R}}$	Mass of the combination of any two jets with the smallest ΔR
$\Delta R_{\mathrm{lep-bb}}^{\mathrm{min\ \Delta R}}$	ΔR between the lepton and the combination of two b-tagged jets with the smallest ΔR
$m_{\mathrm{bj}}^{\mathrm{min\ \Delta R}}$	Mass of the combination of a b-tagged jet and any jet with the smallest ΔR
$m_{\mathrm{bj}}^{\mathrm{max\ p_T}}$	Mass of the combination of a b-tagged jet and any jet with the largest vector sum p_{T}
$m_{\mathrm{uu}}^{\mathrm{min\ \Delta R}}$	Mass of the combination of two untagged jets with the smallest ΔR
$p_{\mathrm{T}}^{\mathrm{jet5}}$	Fifth leading jet p_{T}
$\Delta R_{\mathrm{bb}}^{\mathrm{max\ p_T}}$	ΔR between two b-tagged jets with the largest vector sum p_{T}
$m_{\mathrm{bb}}^{\mathrm{max\ m}}$	Mass of the combination of two b-tagged jets with the largest invariant mass
$p_{T,\mathrm{uu}}^{\mathrm{min\ \Delta R}}$	Scalar sum of the p_{T}'s of the pair of untagged jets with the smallest ΔR
m_{jjj}	Mass of the jet triplet with the largest vector sum p_{T}
$\Delta R_{\mathrm{uu}}^{\mathrm{min\ \Delta R}}$	Minimum ΔR between two untagged jets
$m_{\mathrm{bb}}^{\mathrm{max\ p_T}}$	Mass of the combination of two b-tagged jets with the largest vector sum p_{T}

2-lepton variables

Variable	Definition
$m_{b\bar{b}}$	Mass of the two b-tagged jets from the Higgs candidate system
H_{T}	Scalar sum of jet p_{T} and lepton p_{T}s
$p_{\mathrm{T}}^{\mathrm{jet3}}$	Third leading jet p_{T}
$p_{\mathrm{T}}^{\mathrm{jet4}}$	Fourth leading jet p_{T}
$\mathrm{Centrality}$	Sum of the p_{T} divided by sum of the E for all jets and both leptons
$\mathrm{Aplanarity}_{\mathrm{jet}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor built with all jets
H1	Second Fox-Wolfram moment computed using all jets and both leptons
H4	Fifth Fox-Wolfram moment computed using all jets and both leptons
$\Delta R_{\mathrm{hl}}^{\mathrm{min}\ \Delta\mathrm{R}}$	ΔR between the Higgs candidate and the closest lepton
$\Delta R_{\mathrm{hl}}^{\mathrm{max}\ \Delta\mathrm{R}}$	ΔR between the Higgs candidate and the furthest lepton
$\mathrm{N}_{30}^{\mathrm{Higgs}}$	Number of Higgs candidates within 30 GeV of the defined Higgs mass
$m_{\mathrm{jj}}^{\mathrm{closest}}$	Dijet mass between any two jets closest to the defined Higgs mass
$\Delta\eta_{\mathrm{jj}}^{\mathrm{max}\ \Delta\eta}$	Maximum $\Delta\eta$ between any two jets in the event
$m_{\mathrm{jj}}^{\mathrm{min\ m}}$	Minimum dijet mass between any two jets
$m_{\mathrm{jj}}^{\mathrm{max\ p_T}}$	Mass of the combination of any two jets with the largest vector sum p_{T}
$m_{\mathrm{bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of two b-tagged jets with the smallest ΔR
$\Delta R_{\mathrm{bj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Minimum ΔR between a b-tagged jet and any jet
$\Delta R_{\mathrm{lj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Minimum ΔR between any lepton and jet
$\Delta R_{\mathrm{bb}}^{\mathrm{max\ p_T}}$	ΔR between two b-tagged jets with the largest vector sum p_{T}
$\Delta R_{\mathrm{bb}}^{\mathrm{max\ m}}$	ΔR between two b-tagged jets with the largest invariant mass

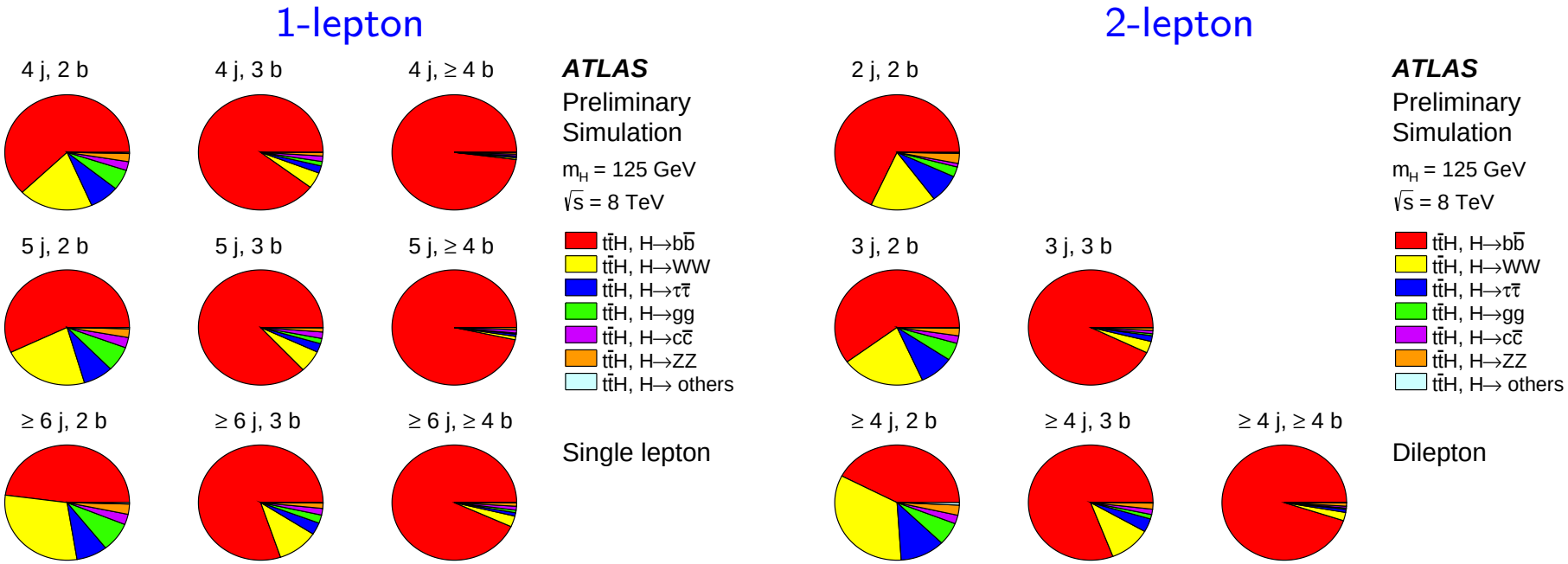
Variable	($\geq$ 6j, $\geq$ 4b)	($\geq$ 6j, 3b)	(5j, $\geq$ 4b)	(5j, 3b)
$\Delta R_{\mathrm{bb}}^{\mathrm{avg}}$	1	5	5	-
$m_{\mathrm{bb}}^{\mathrm{min\ \Delta R}}$	2	9	3	1
Centrality	3	2	1	-
H1	4	3	2	-
$p_{\mathrm{T}}^{\mathrm{jet5}}$	5	8	-	-
$\mathrm{Aplanarity}_{\mathrm{b-jet}}$	6	-	7	-
$m_{\mathrm{uu}}^{\mathrm{min\ \Delta R}}$	7	7	-	2
$\Delta R_{\mathrm{bb}}^{\mathrm{max\ p_T}}$	8	-	-	-
$\Delta R_{\mathrm{lep-bb}}^{\mathrm{min\ \Delta R}}$	9	10	10	-
$m_{\mathrm{bj}}^{\mathrm{max\ p_T}}$	10	6	-	-
N_{40}^{jet}	-	1	4	-
$m_{\mathrm{bj}}^{\mathrm{min\ \Delta R}}$	-	4	-	-
$m_{\mathrm{jj}}^{\mathrm{max\ p_T}}$	-	-	6	-
$H_{\mathrm{T}}^{\mathrm{had}}$	-	-	8	-
$m_{\mathrm{jj}}^{\mathrm{min\ \Delta R}}$	-	-	9	-
$m_{\mathrm{bb}}^{\mathrm{max\ m}}$	-	-	-	3
$p_{T,\mathrm{uu}}^{\mathrm{min\ \Delta R}}$	-	-	-	4
m_{jjj}	-	-	-	5
$\Delta R_{\mathrm{uu}}^{\mathrm{min\ \Delta R}}$	-	-	-	6
$m_{\mathrm{bb}}^{\mathrm{max\ p_T}}$	-	-	-	7

Table: The lists and rankings of the variables considered in each of the regions in the single lepton channel where a NN is used.

Variable	($\geq$ 4j, $\geq$ 4b)	($\geq$ 4j, 3b)	(3j, 3b)
$\Delta\eta_{\mathrm{jj}}^{\mathrm{max}\ \Delta\eta}$	1	1	1
$m_{\mathrm{bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	2	8	-
$m_{b\bar{b}}$	3	-	-
$\Delta R_{\mathrm{hl}}^{\mathrm{min}\ \Delta\mathrm{R}}$	4	5	-
$\mathrm{N}_{30}^{\mathrm{Higgs}}$	5	2	5
$\Delta R_{\mathrm{bb}}^{\mathrm{max}\ \mathrm{p_T}}$	6	4	8
$\mathrm{Aplanarity}_{\mathrm{jet}}$	7	7	-
$m_{\mathrm{jj}}^{\mathrm{min}\ \mathrm{m}}$	8	3	2
$\Delta R_{\mathrm{hl}}^{\mathrm{max}\ \Delta\mathrm{R}}$	9	-	-
$m_{\mathrm{jj}}^{\mathrm{closest}}$	10	-	10
H_{T}	-	6	3
$\Delta R_{\mathrm{bb}}^{\mathrm{max}\ \mathrm{m}}$	-	9	-
$\Delta R_{\mathrm{lj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	-	10	-
Centrality	-	-	7
$m_{\mathrm{jj}}^{\mathrm{max}\ \mathrm{p_T}}$	-	-	9
H4	-	-	4
$p_{\mathrm{T}}^{\mathrm{jet3}}$	-	-	6

Table: The lists and rankings of the variables considered in each of the regions in the dilepton channel where a NN is used.

$t\bar{t}$ + jets signal region composition regions

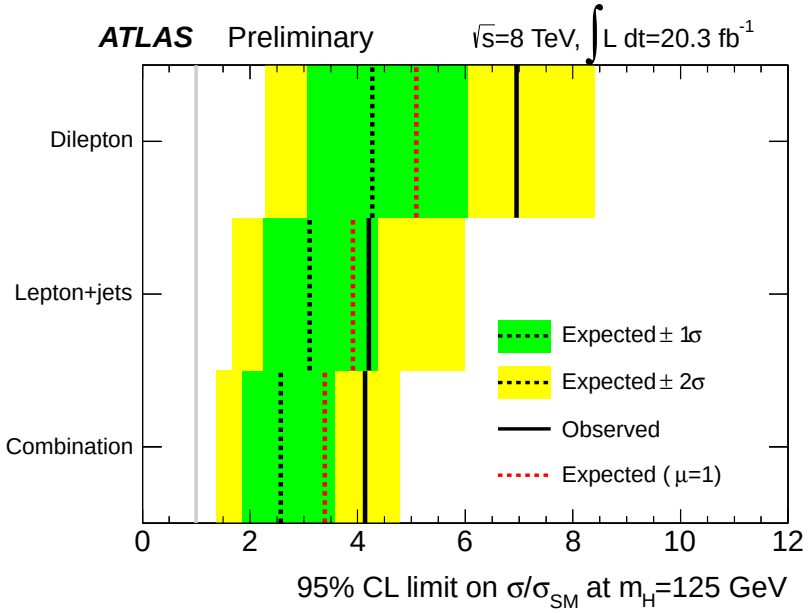


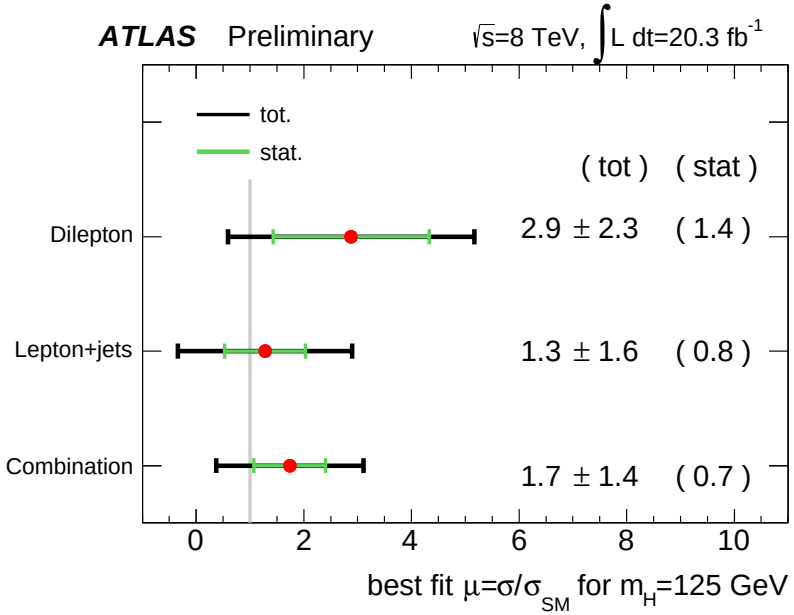
$(\geq 6\mathrm{j}, \geq 4\mathrm{b})$ systematic uncertainties

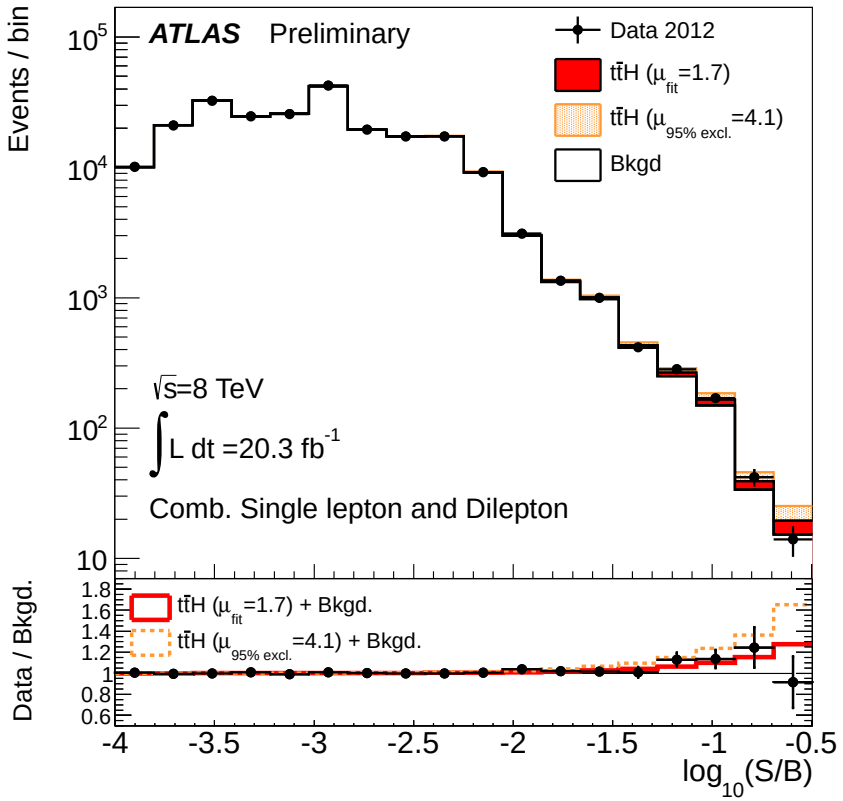
	Pre-fit			
	$t\bar{t}H$ (125)	$t\bar{t}$ + light	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$
Jet energy scale	± 6.5	± 14	± 10	± 8.2
Jet efficiencies	± 1.6	± 5.4	± 2.5	± 2.4
Jet energy resolution	± 0.1	± 8.5	± 4.1	± 4.3
b-tagging efficiency	± 9.0	± 5.8	± 5.1	± 9.2
c-tagging efficiency	± 1.9	± 7.3	± 14	± 2.8
Light jet-tagging efficiency	± 1.0	± 17	± 4.4	± 1.5
$t\bar{t}$ modelling: reweighting	–	± 11	± 13	± 13
$t\bar{t}$ modelling: parton shower	–	± 7.5	± 1.8	± 10
$t\bar{t}$ heavy-flavour: normalisation	–	–	± 50	± 50
Total pre-fit	± 12	± 30	± 57	± 56
Total post-fit	± 7.2	± 14	± 25	± 14

$t\bar{t}$ + jets signal regions

5







$t\bar{t}H \to t\bar{t} + \gamma\gamma$: analysis strategy

- Hadronic $t\bar{t}$ channel: $\geq$ 6 jet $\geq$ 2 b - $N_{signal} = 0.36$
- Leptonic $t\bar{t}$ channel: $\geq$ 1-lepton, $\geq$ 1 b - $N_{signal} = 0.55$
- Aim for high efficiency to maximize signal yields
- 80% b-tagging working point with $\approx$ 4% light quark jet rejection
- 2 isolated high p_T photons - 40 (30) GeV
- Jets with $p_T > 25$ GeV in $|\eta| < 2.5$