

$t\bar{t}H$ searches at ATLAS



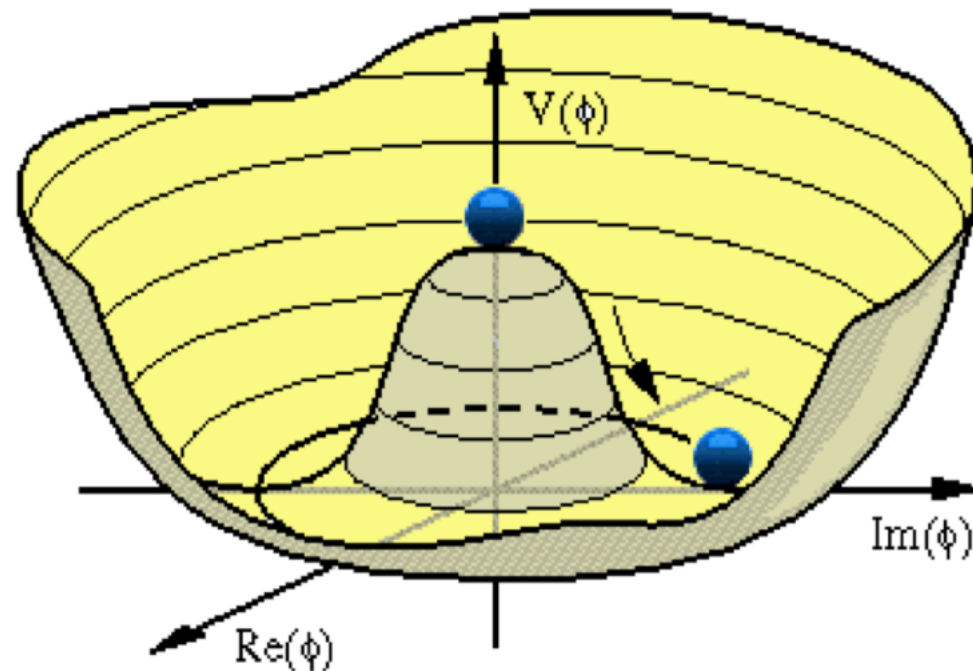
top
quark



Higgs
boson

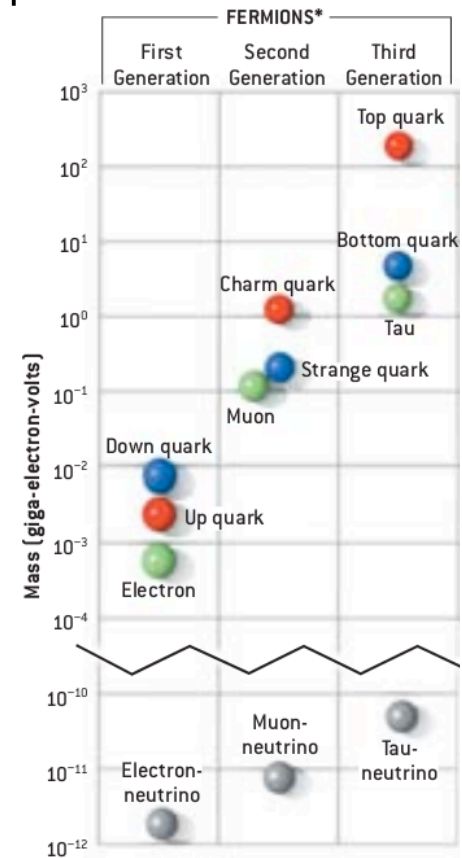
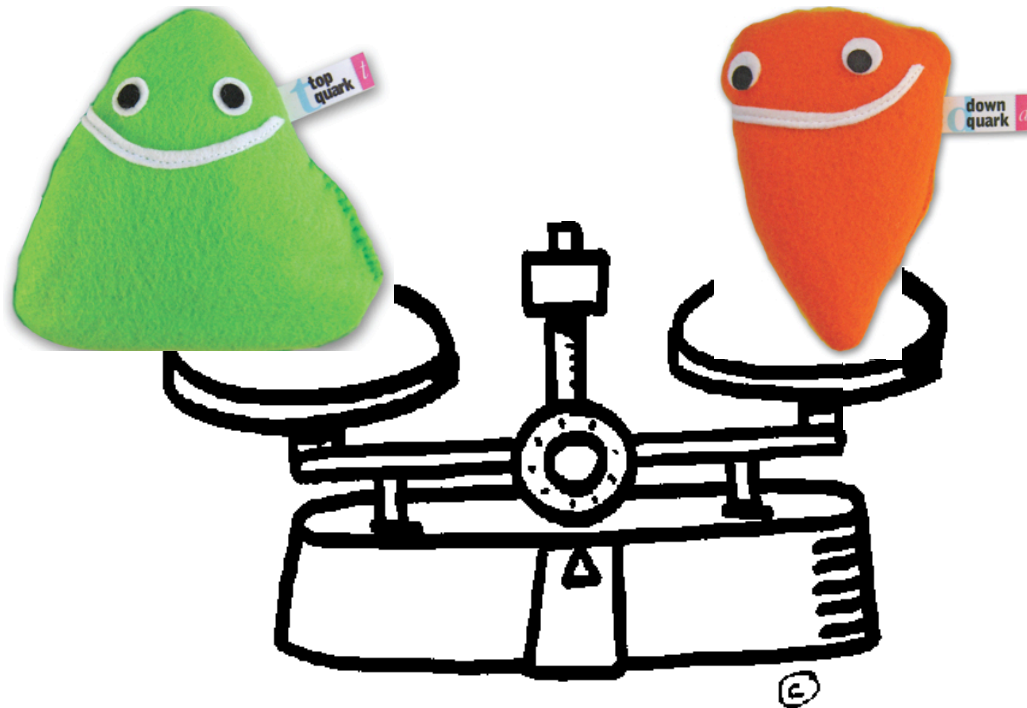
We knew something was responsible for electroweak symmetry breaking

Higgs mechanism gives mass not just to W and Z bosons but also to all the fermions ...



Yukawa couplings

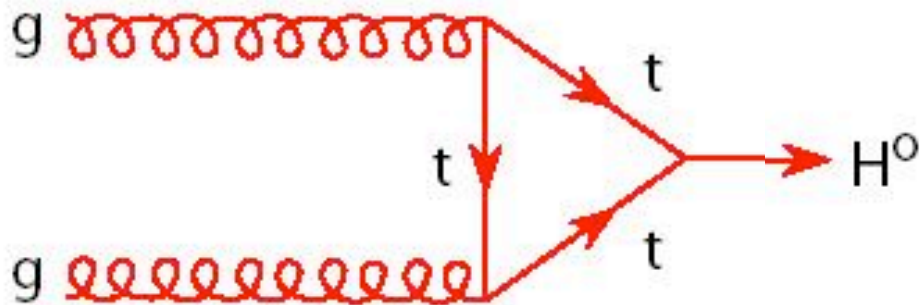
- Mass of fermions proportional to their coupling to the Higgs field
- Top quark Yukawa coupling > 0.9 (close to unity!)
- Does this point to a special role for the top quark in electroweak symmetry breaking?



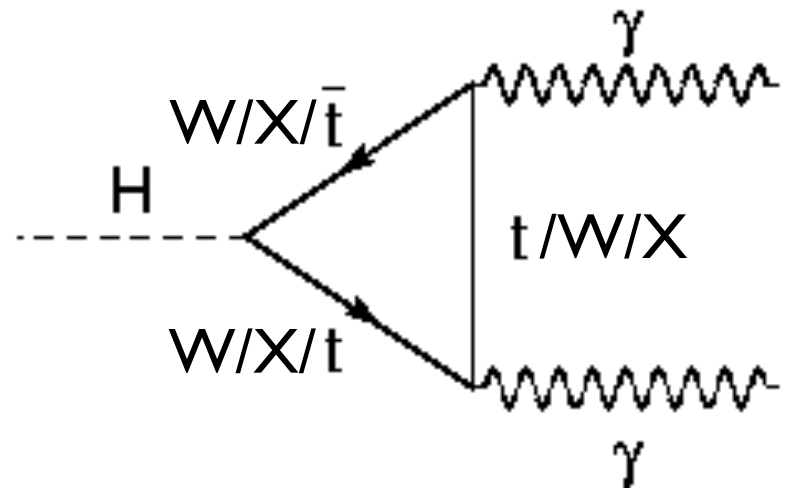
Indirect evidence for top-Higgs coupling

Already strong, indirect evidence of top quark-Higgs boson coupling

Gluon-gluon fusion (dominant Higgs boson production mechanism at LHC)



Induces decay to massless photons. Destructive interference with W boson

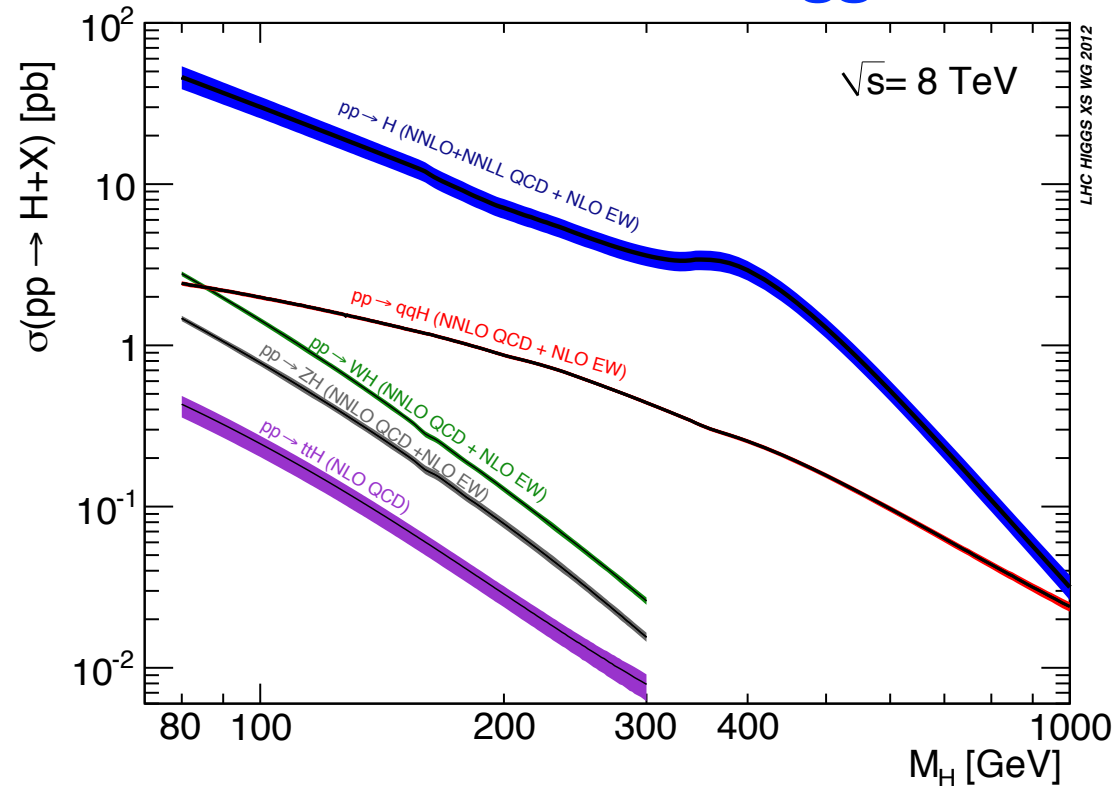
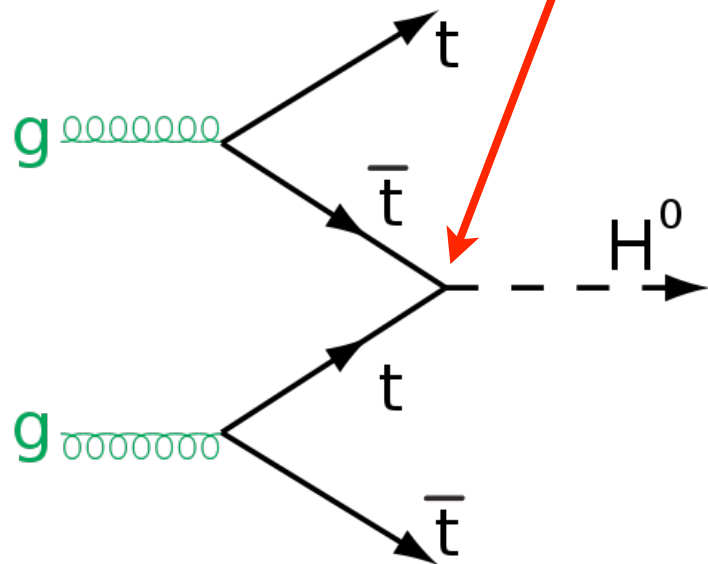


Cross sections for $t\bar{t}H$ production at 8 (14) TeV

- ggFusion: 19 pb (50 @ 14 TeV)
- VBFusion: 1.6 pb (4.2 @ 14 TeV)
- WH associated: 0.70 pb (1.5 @ 14 TeV)
- ZH associated: 0.42 pb (0.88 @ 14 TeV)
- **$t\bar{t}H$: 0.13 pb (0.61 @ 14 TeV)**

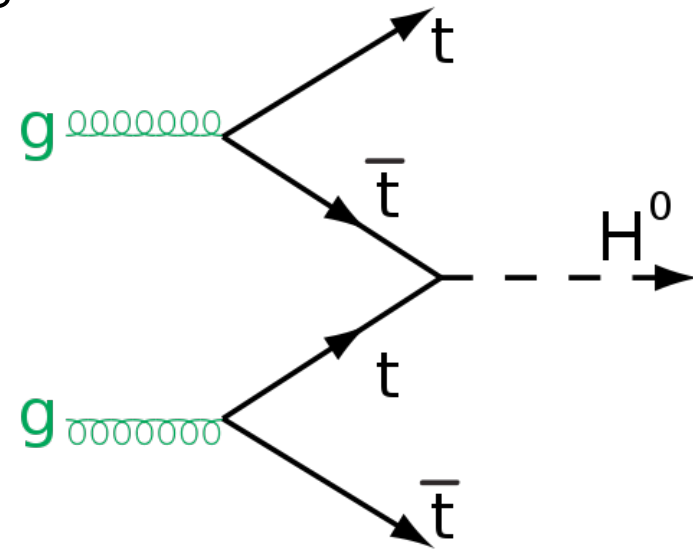
LHC Higgs WG

Direct observation
of $t\bar{t}H$ vertex

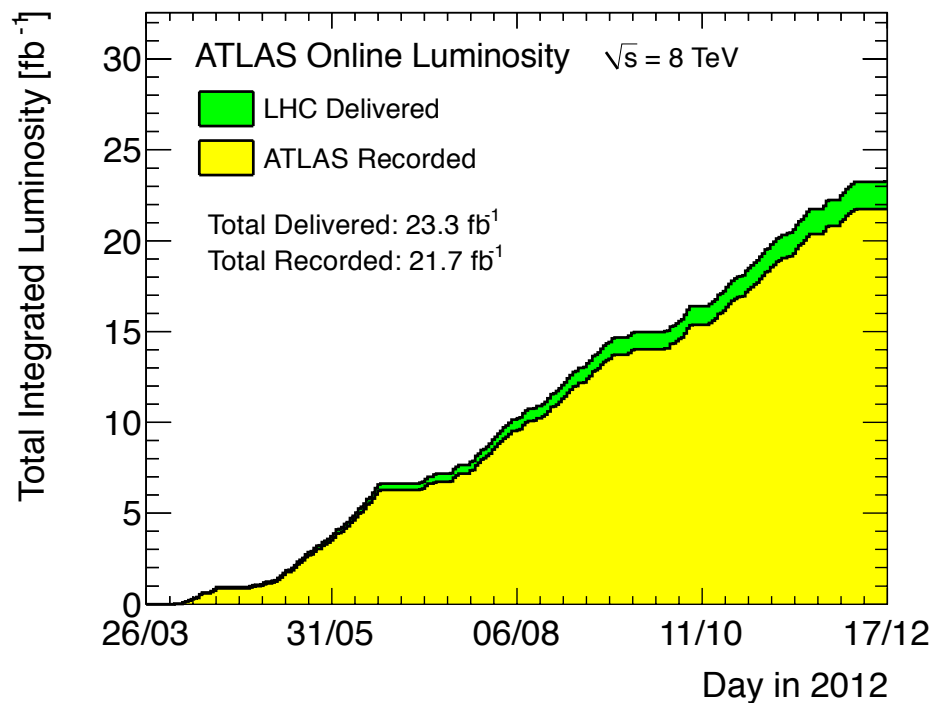


Direct searches for top-Higgs coupling are not easy ...

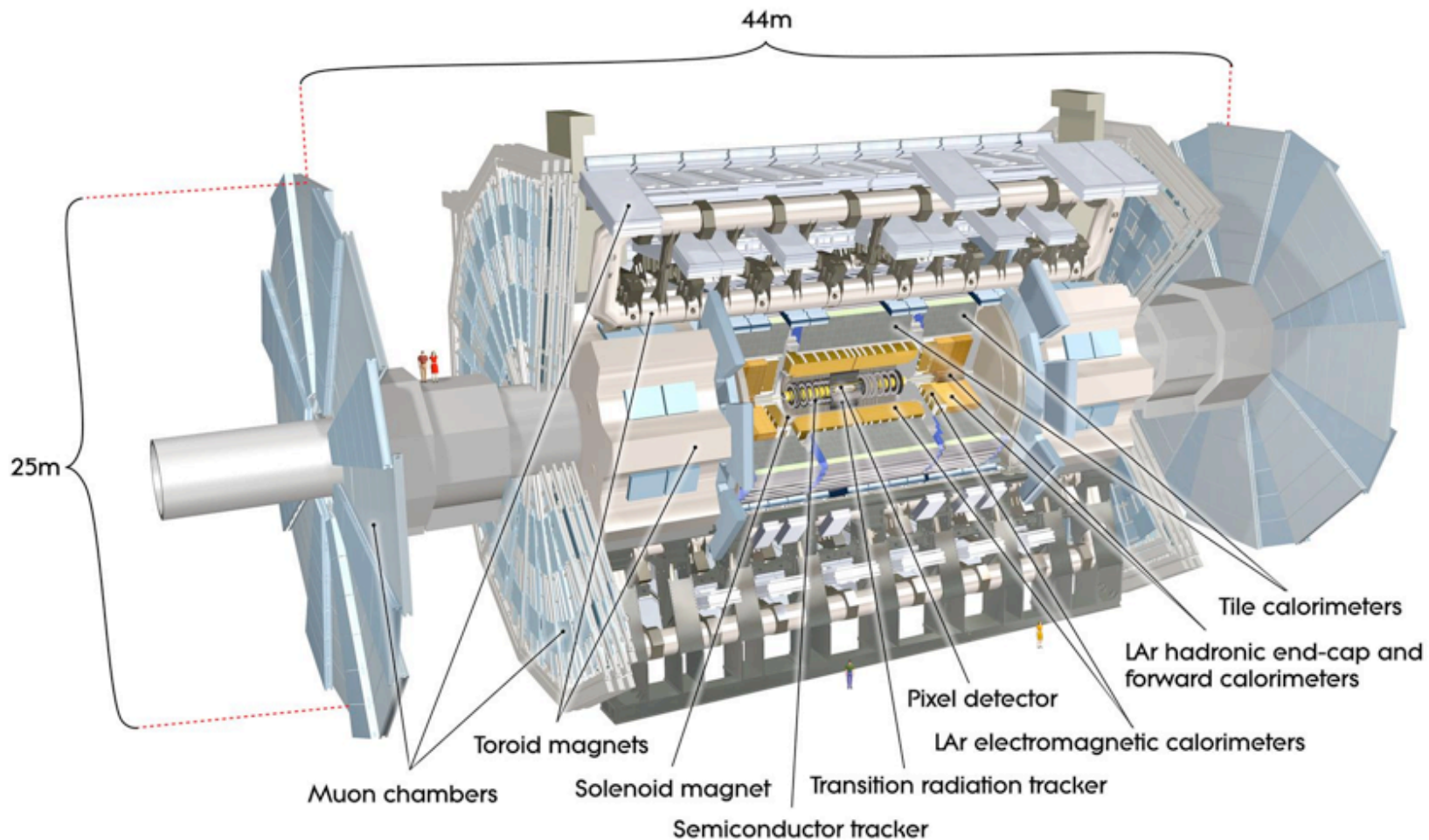
- We know that the production cross sections are small
 - Relative to other Higgs boson production processes, let alone $t\bar{t}$ production, EW processes and QCD
- Busy final state
 - Minimum of 8 final state objects in the event
- So what's the plan of attack?



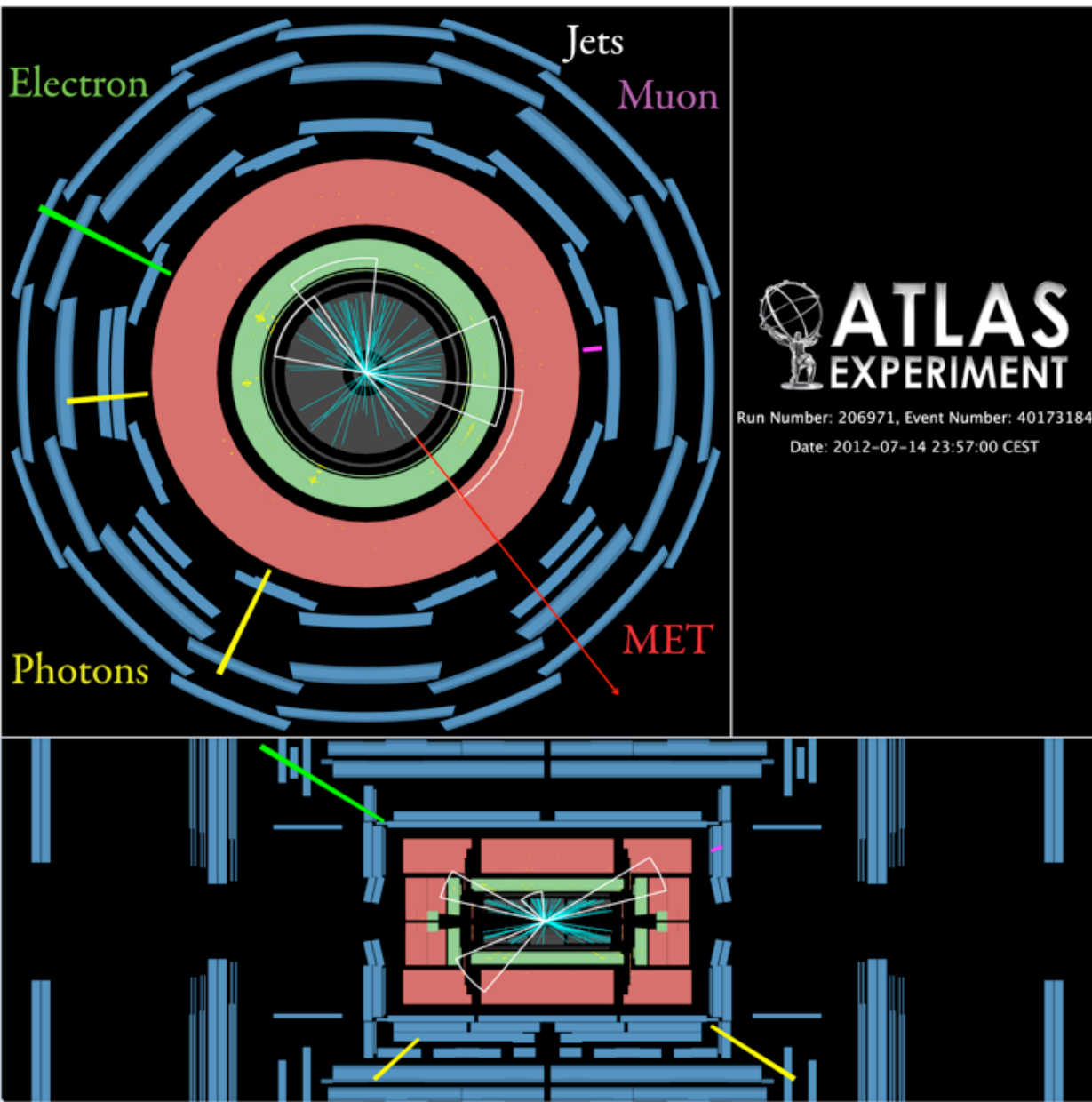
As much data as we can get our hands on (including 7 TeV data, when handy)



Well understood detector



Excellent detector



Single
candidate $t\bar{t}H$
event from
earlier ATLAS
analysis

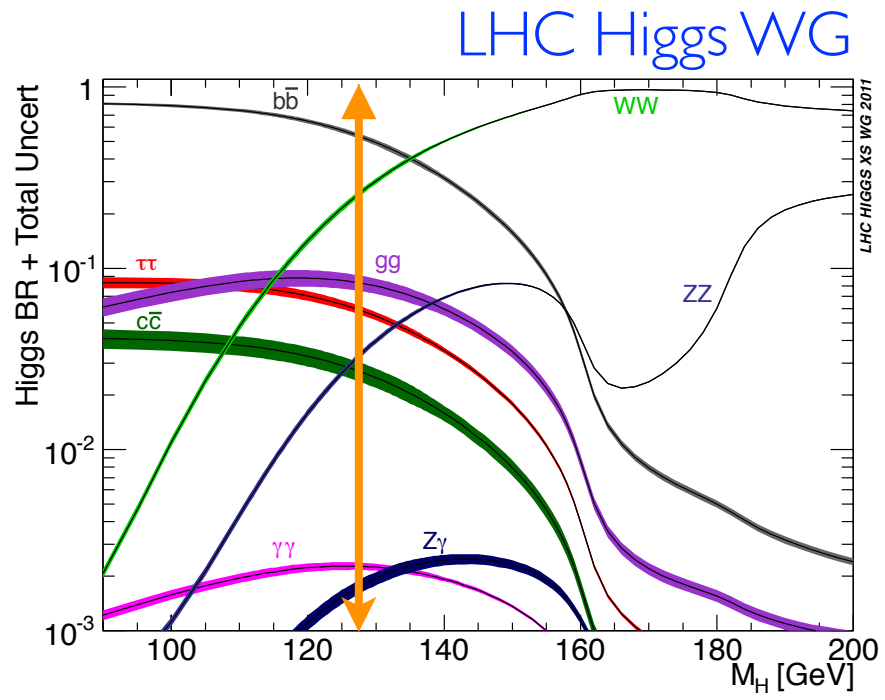
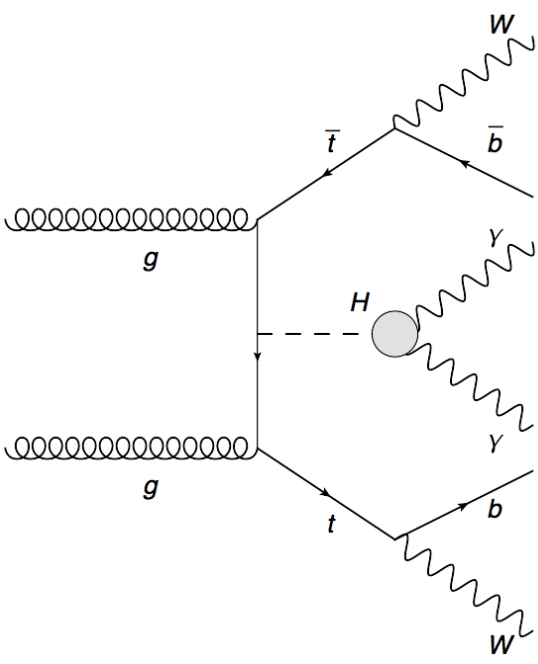
Lots of hard work and ingenuity



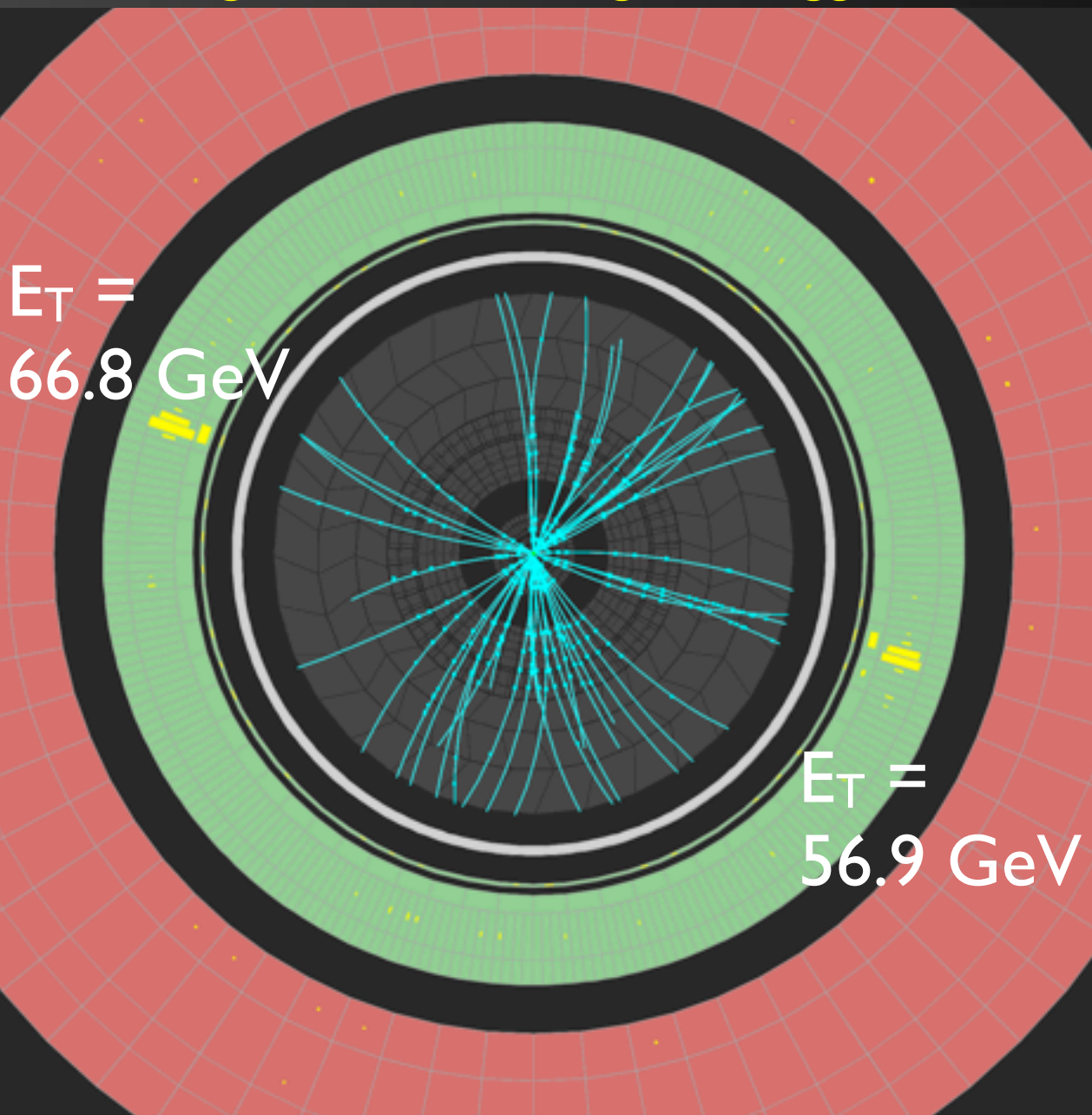
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$t\bar{t}H, H \rightarrow \gamma\gamma$

- Diphoton branching ratio @ 125 GeV = 2.28e-3
- Small number of expected signal events
- Narrow reconstructed Higgs mass resolution ~ 1.5 GeV
- Fit the sidebands to estimate backgrounds
- Use 105-160 GeV diphoton mass window



How to go about looking for Higgs bosons?

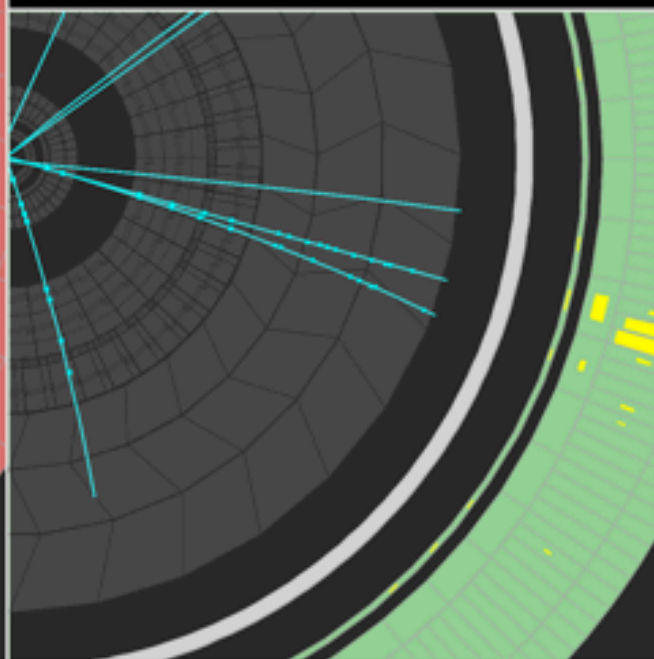


ATLAS EXPERIMENT

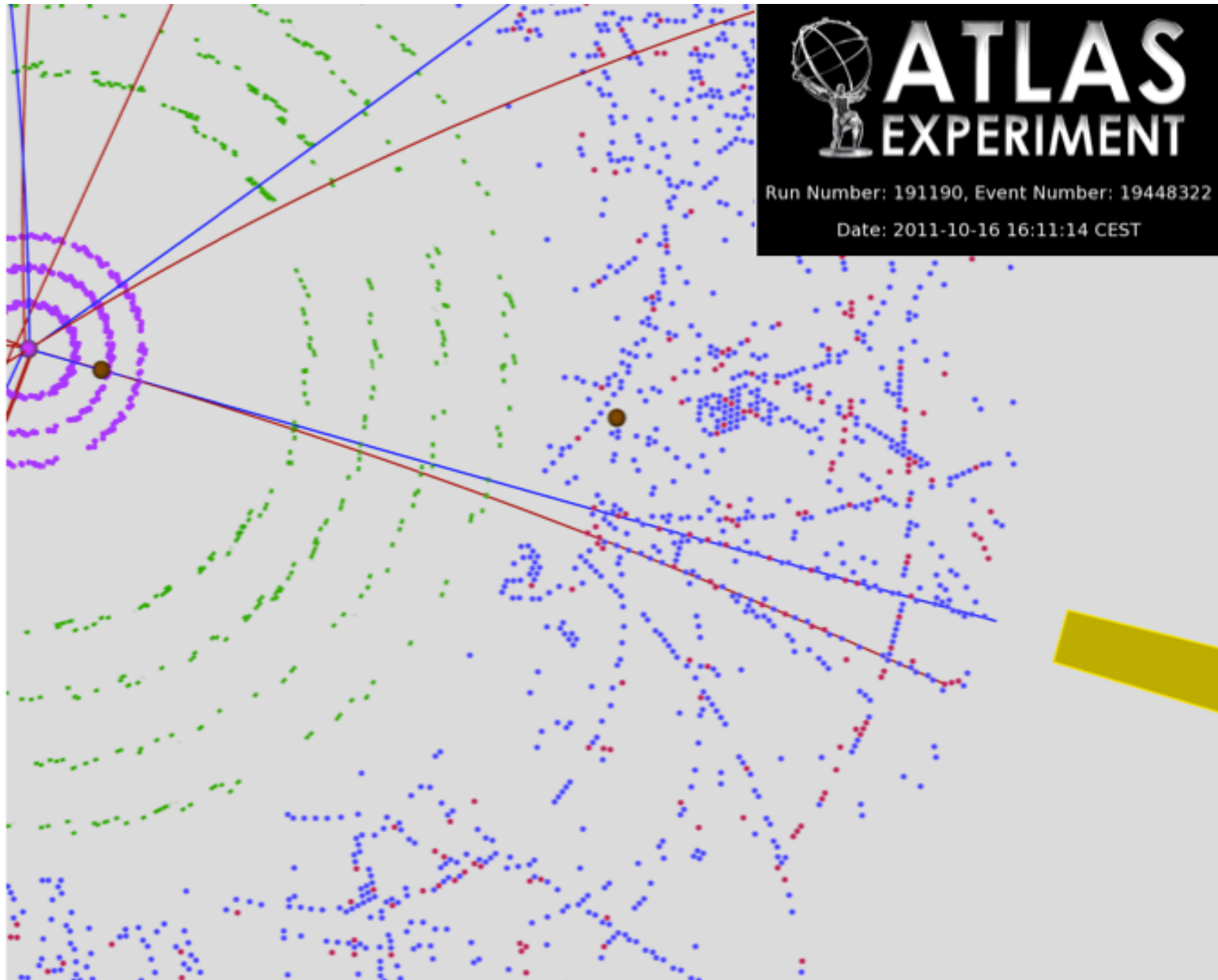
Run Number: 191190, Event Number: 19448322

Date: 2011-10-16 16:11:14 CEST

$m_{\gamma\gamma} = 125.8 \text{ GeV}$



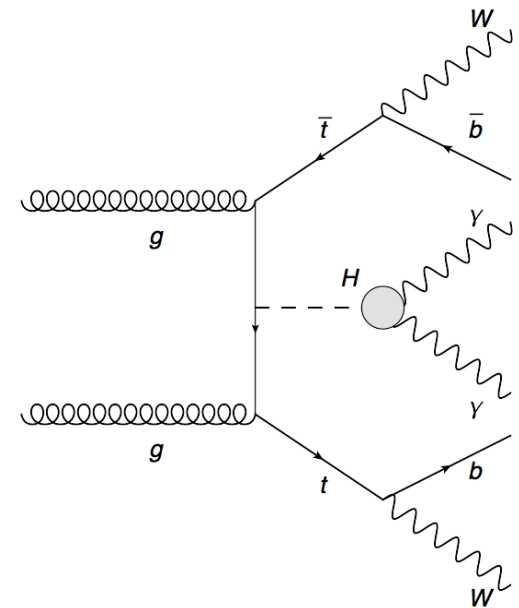
Zooming in on a converted photon



	8 TeV (20.3 fb⁻¹)	7 TeV (4.5 fb⁻¹)
Photon E _T	35/25 GeV trigger, 0.35/0.25 m _{γγ} offline	20 GeV trigger, 0.35/0.25 m _{γγ} offline
Photon track iso	< 2.6 GeV in a cone of ΔR < 0.2	< 2.2 GeV in a cone of ΔR < 0.2
Photon calo iso	< 6 GeV in a cone of ΔR < 0.4	< 5.5 GeV in a cone of ΔR < 0.4
Electron E _T	> 15 GeV	
Electron track iso	< 20% of electron E _T in a cone of ΔR < 0.4	
Electron calo iso	< 15% of electron E _T in a cone of ΔR < 0.2	
Muon p _T	> 10 GeV	
Muon track iso	< 20% of muon p _T in a cone of ΔR < 0.4	
Muon calo iso	< 15% of muon p _T in a cone of ΔR < 0.2	
Jet p _T	> 25 (or 30) GeV, anti-k _T jets R=0.4	
Jet b-tagging	80% efficiency/4% mistag, 70% efficiency/ 1% mistag, 60% efficiency/0.1% mistag	85% efficiency/10% mistag

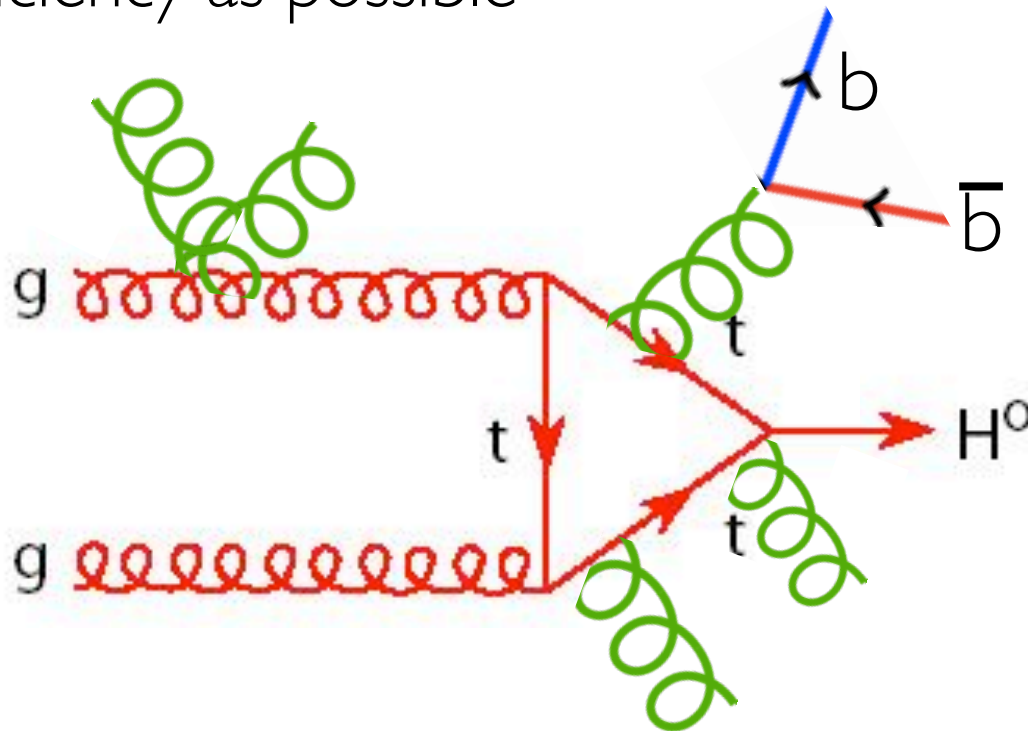
$t\bar{t}H, H \rightarrow \gamma\gamma$ leptonic selection

- Aim to capture both single and dilepton $t\bar{t}$ decays
- Two tight photons + ≥ 1 lepton with ≥ 1 loose btag \rightarrow small backgrounds
- Events with e-photon mass between 84-94 GeV are rejected to remove Z 's with electrons faking photons
- Use loosest working point for b-tagging
 - For events with only one b-tag, require $MET > 20$ GeV
 - Two-tag event background dominated by $t\bar{t}$; no MET cut



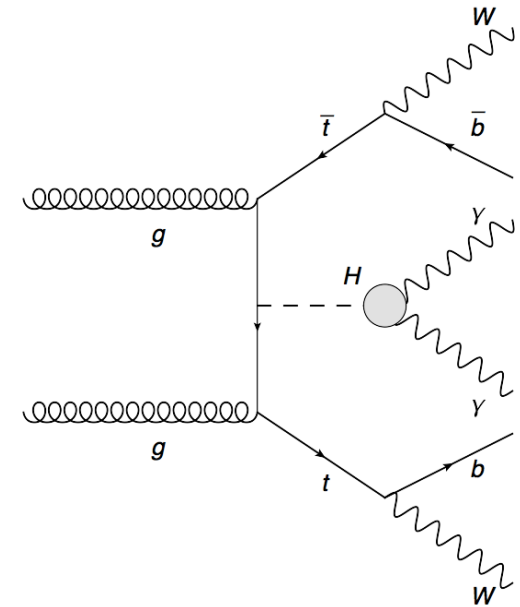
$t\bar{t}H, H \rightarrow \gamma\gamma$ hadronic selection

- Aim to capture all-hadronic $t\bar{t}$ events while rejecting $t\bar{t}$ background + QCD background
- Worry is gluon-gluon fusion background!
 - How to model Higgs + lots of extra jets + lots of b-tags?
 - A priori aim for no more than 10% ggF with as high a selection efficiency as possible



$t\bar{t}H, H \rightarrow \gamma\gamma$ hadronic selection

- Require always zero charged leptons
- Then require at least six jets with $p_T > 25$ GeV, ≥ 2 b-tags (80% working point)
- OR require at least five jets with $p_T > 30$ GeV, ≥ 2 b-tags (70% working point)
- OR require at least six jets with $p_T > 30$ GeV, = 1 b-tag (60% working point)
- For 7 TeV data, require six jets with $p_T > 25$ GeV, ≥ 2 b-tags (loosest working point)



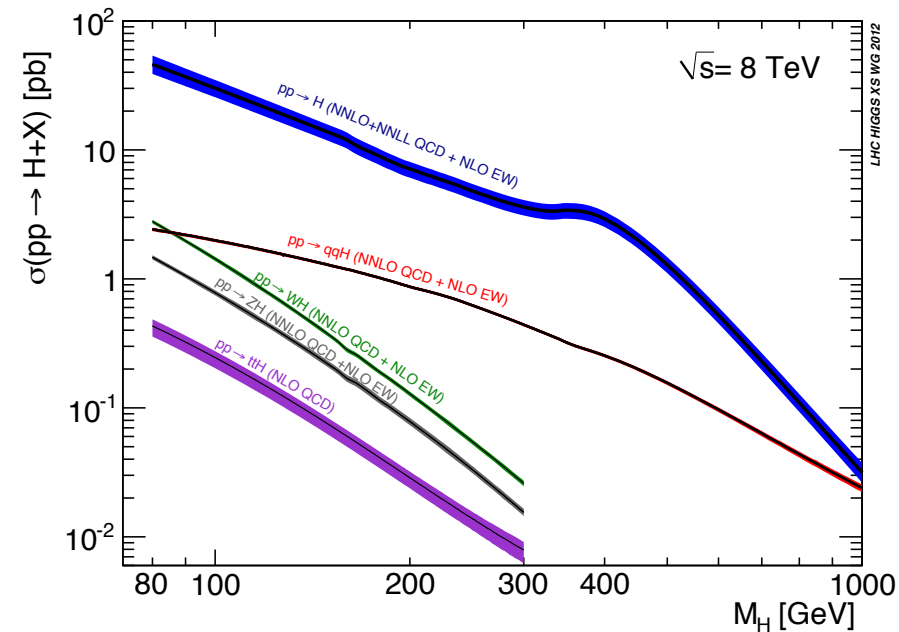
Percent contributions

Category	N_H	ggF	VBF	WH	ZH	$t\bar{t}H$	$tHqb$	WtH
7 TeV leptonic selection	0.10	0.6	0.1	14.9	4.0	72.6	5.3	2.5
7 TeV hadronic selection	0.07	10.5	1.3	1.3	1.4	80.9	2.6	1.9
8 TeV leptonic selection	0.58	1.0	0.2	8.1	2.3	80.3	5.6	2.6
8 TeV hadronic selection	0.49	7.3	1.0	0.7	1.3	84.2	3.4	2.1

Overall, selection efficiency for **all** ttH events is 14.8%
(14.6%) for 8 TeV (7 TeV)

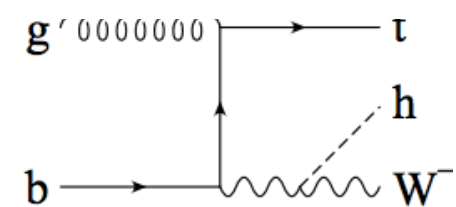
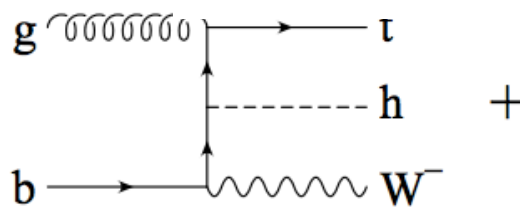
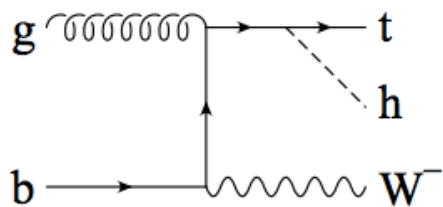
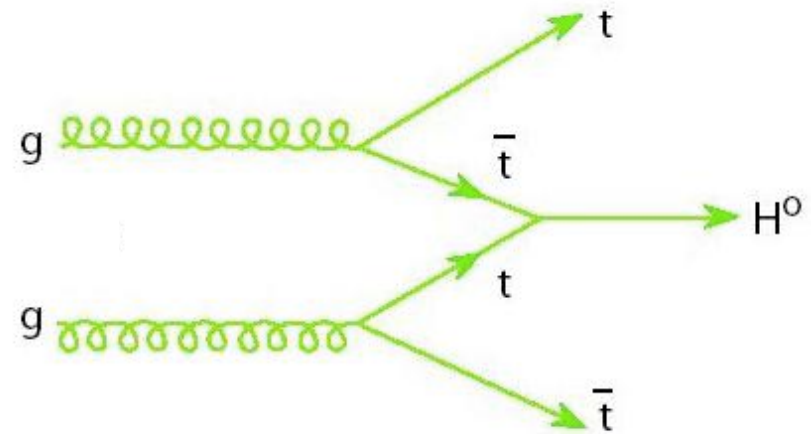
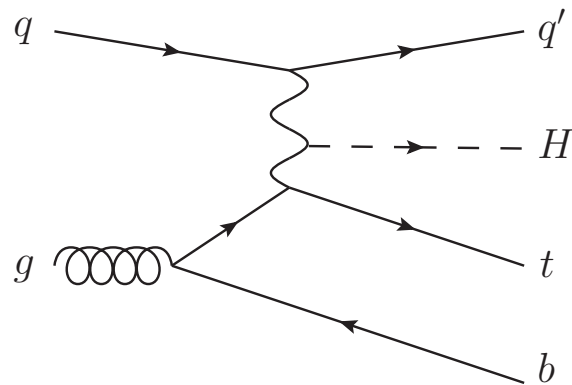
Higgs background estimation

- W/Z + Higgs simulated using Pythia 8
 - WH xsec at NLO with EW corrections
 - ZH xsec at NNLO with EW corrections
- gg and VV fusion with Powheg-Box
 - ggF xsec at NNLO+leading-log resummation and EW corrections
 - VV fusion at NLO+EW and approximate NNLO corrections



Higgs signal simulation

- ttH signal estimated at NLO using Powheg + Pythia8
- tHqb production simulated with Madgraph+Pythia
 - aMC@NLO used to estimate xsection
- WtH production simulated with aMC@NLO (also for xsections)



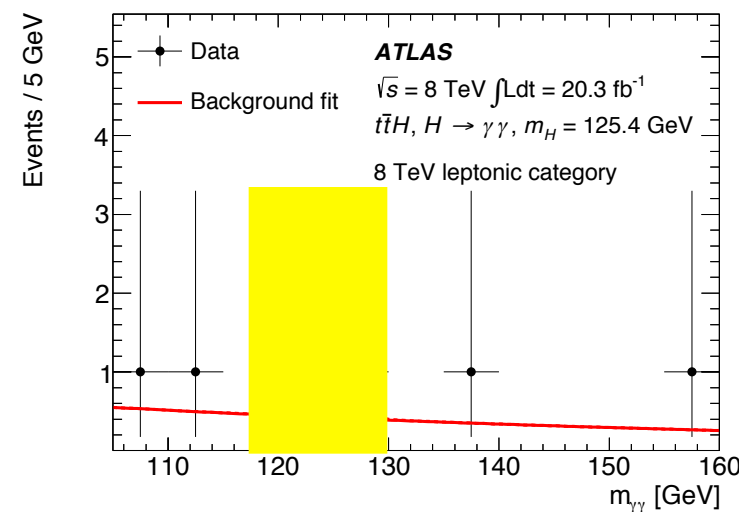
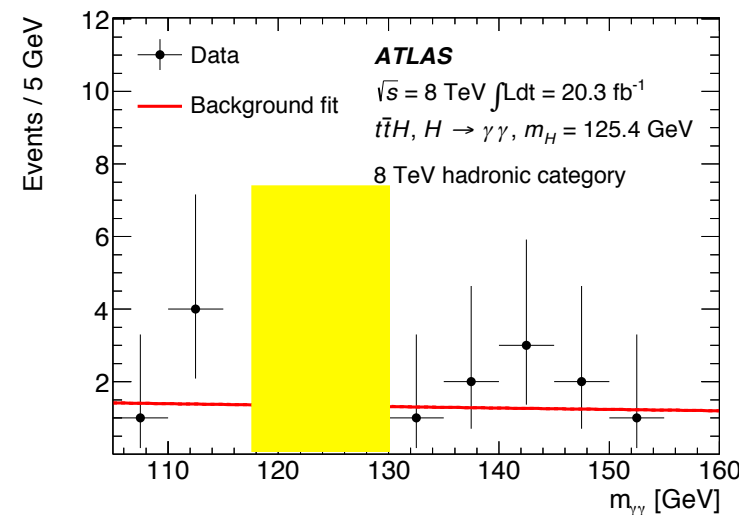
Higgs signal parameterization

- Diphoton mass for Higgs processes modeled with Crystal Ball + Gaussian
 - Width of our signal bump = 1.3-1.5 GeV
 - Derived from simulation, and interpolated to any m_H
 - Higgs mass of 125.4 GeV is used, with cross sections that vary with mass, as appropriate
 - Acceptance effects in the region of interest are negligible



Background estimation

- Exponential function to model background
 - Simple function, few parameters
 - Normalization taken directly from diphoton mass sidebands
- Choice of fit function (and systematic uncertainty due to the choice) estimated from control regions with photon ID and/or isolation inverted
 - Replace leptons with jets
 - For leptonic channel, $Z \rightarrow ee$ contribution added in
- 7 and 8 TeV shapes are constrained to same value



$t\bar{t}H, H \rightarrow \gamma\gamma$ systematic uncertainties

Quite extensive list of uncertainties - all are small compared to statistical uncertainties on the backgrounds

8 TeV

	$t\bar{t}H$ [%]		$tHqb$ [%]		WtH [%]		ggF [%]	WH [%]
	had.	lep.	had.	lep.	had.	lep.	had.	lep.
Luminosity	± 2.8							
Photons	± 5.6	± 5.5	± 5.6	± 5.5	± 5.6	± 5.5	± 5.6	± 5.5
Leptons	< 0.1	± 0.7	< 0.1	± 0.6	< 0.1	± 0.6	< 0.1	± 0.7
Jets and E_T^{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 ($\sigma \times \text{BR}$)	$+10, -13$		$+7, -6$		$+14, -12$		$+11, -11$	$+5.5, -5.4$
MC Modeling	± 11	± 3.3	± 12	± 4.4	± 12	± 4.6	± 130	± 100

Photon uncertainties

	$t\bar{t}H$ [%]		$tHqb$ [%]		WtH [%]		ggF [%]	WH [%]
	had.	lep.	had.	lep.	had.	lep.	had.	lep.
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Larger photon uncertainty than standard diphoton analyses because of jetty environment (ID and isolation vs njet studied with $Z \rightarrow ee$ events)

Jet uncertainties

	$t\bar{t}H$ [%]		$tHqb$ [%]		WtH [%]		ggF [%]	WH [%]
	had.	lep.	had.	lep.	had.	lep.	had.	lep.
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MC Modeling	± 11	± 3.3	± 12	± 4.4	± 12	± 4.6	± 130	± 100

Require many more jets for hadronic selection, so jet-related uncertainties larger

Uncertainties on background shape/modeling

	$t\bar{t}H$ [%]		$tHqb$ [%]		WtH [%]		ggF [%]	WH [%]	
	had.	lep.	had.	lep.	had.	lep.	had.	lep.	
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MC Modeling	± 11	± 3.3	± 12	± 4.4	± 12	± 4.6	± 130	± 100	

Using control regions, fit S+B and find maximum apparent (fake) signal in 116-135 GeV range

Theory uncertainties

	$t\bar{t}H$ [%]		$tHqb$ [%]		WtH [%]		ggF [%]	WH [%]
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Changes in cross section and branching ratio due to PDF and scale uncertainties

Theory uncertainties

	$t\bar{t}H$ [%]		$tHqb$ [%]		WtH [%]		ggF [%]	WH [%]
	had.	lep.	had.	lep.	had.	lep.	had.	lep.
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Uncertainty on acceptance when conservatively turn off multiple parton interactions in simulation, and vary renormalization and factorization scales

Additional uncertainties on Higgs + heavy flavor

	$t\bar{t}H$ [%]		$tHqb$ [%]		WtH [%]		ggF [%]	WH [%]
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MC Modeling	± 11	± 3.3	± 12	± 4.4	± 12	± 4.6	± 130	± 100

100% uncertainty extra assigned to ggF and WH
plus extra jets with heavy flavor

Additional uncertainties on Higgs + heavy flavor

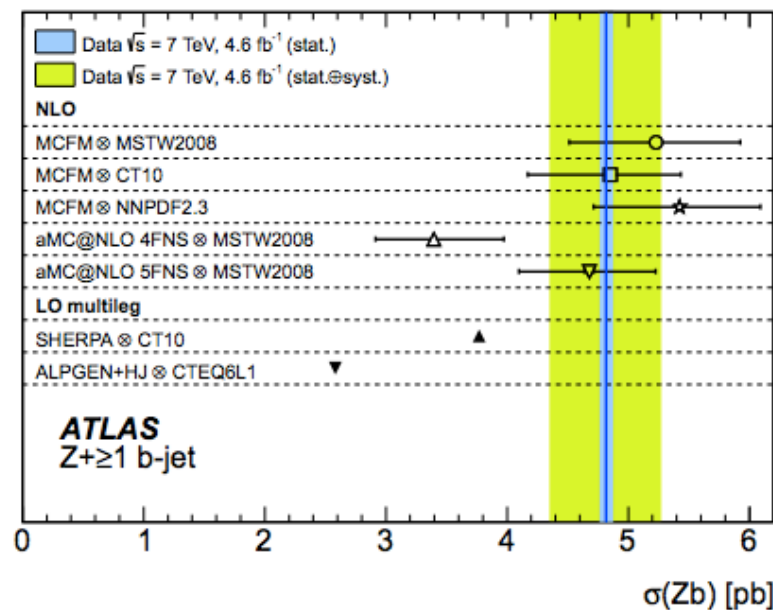
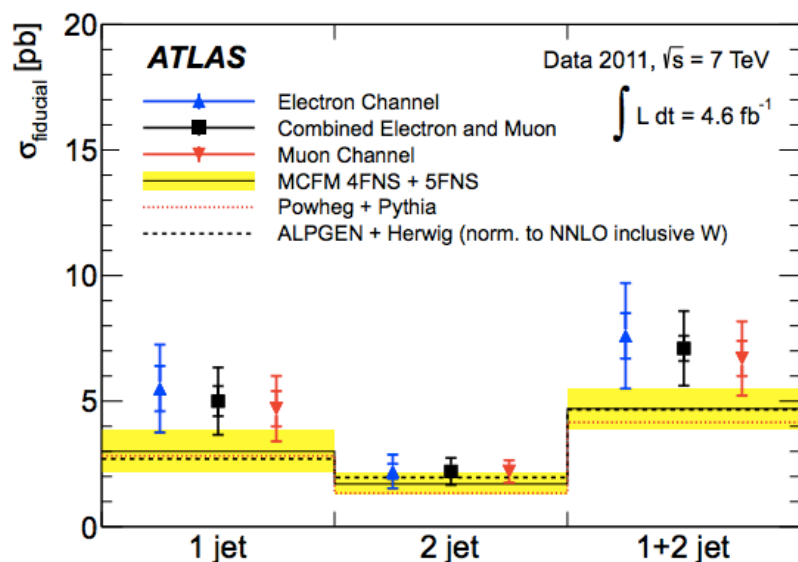
100% uncertainty on heavy flavor contribution in ggF, VBF and WH processes motivated by V+HF (and ttbar studies, too)

W+b jet

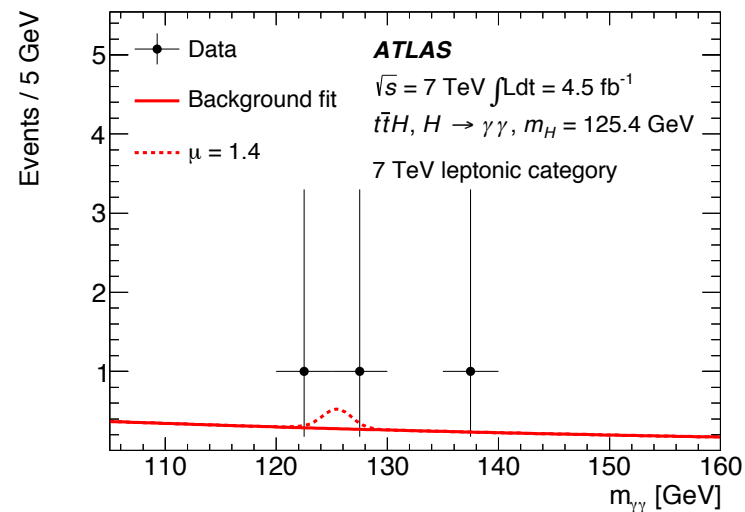
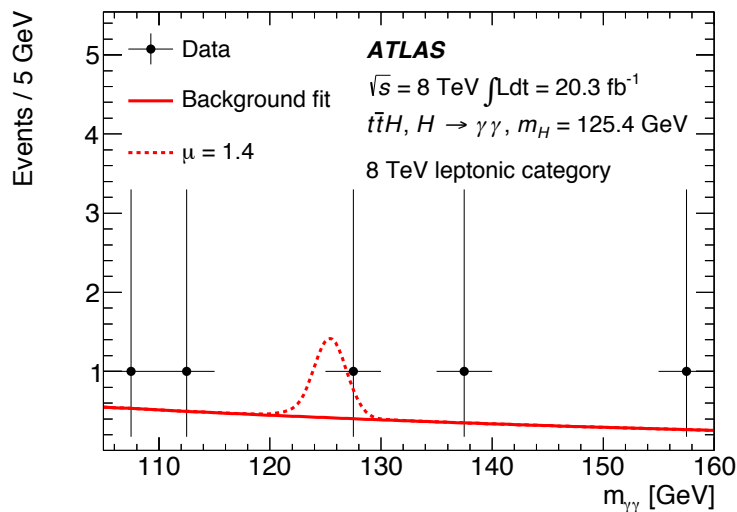
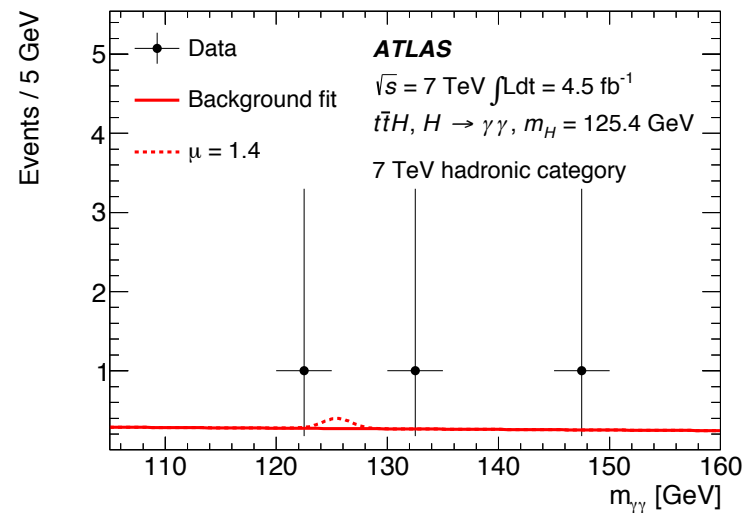
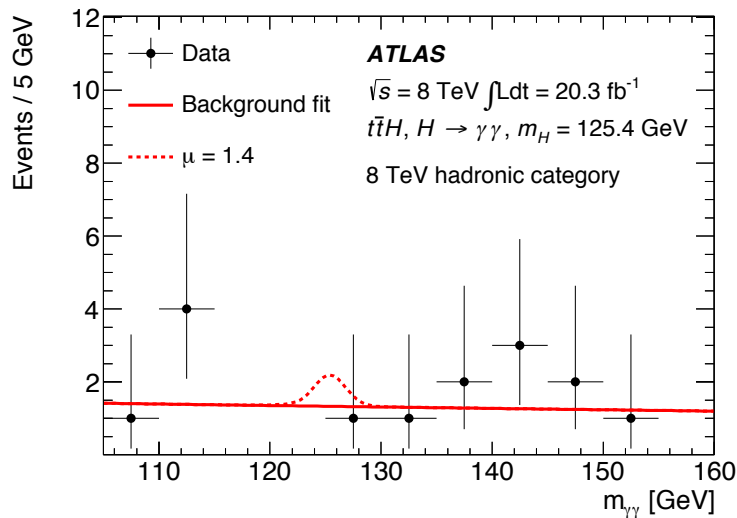
arXiv: 1302.2929

Z+b jet

ATL-COM-PHYS-2014-037



ATLAS $t\bar{t}H, H \rightarrow \gamma\gamma$ signal region

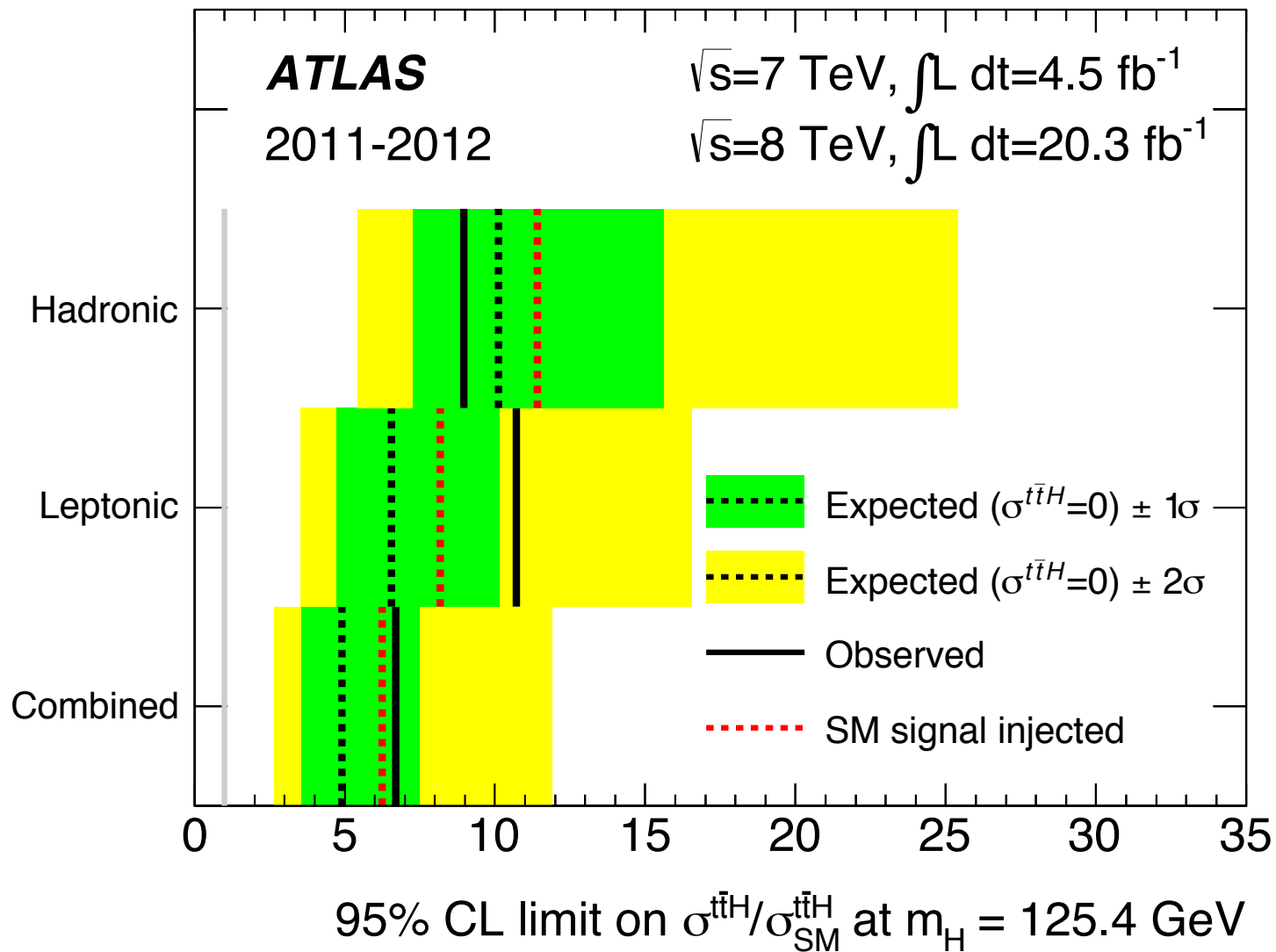


Category	N_H	ggF	VBF	WH	ZH	$t\bar{t}H$	$tHqb$	WtH	N_B
7 TeV leptonic selection	0.10	0.6	0.1	14.9	4.0	72.6	5.3	2.5	$0.5^{+0.5}_{-0.3}$
7 TeV hadronic selection	0.07	10.5	1.3	1.3	1.4	80.9	2.6	1.9	$0.5^{+0.3}_{-0.3}$
8 TeV leptonic selection	0.58	1.0	0.2	8.1	2.3	80.3	5.6	2.6	$0.9^{+0.6}_{-0.4}$
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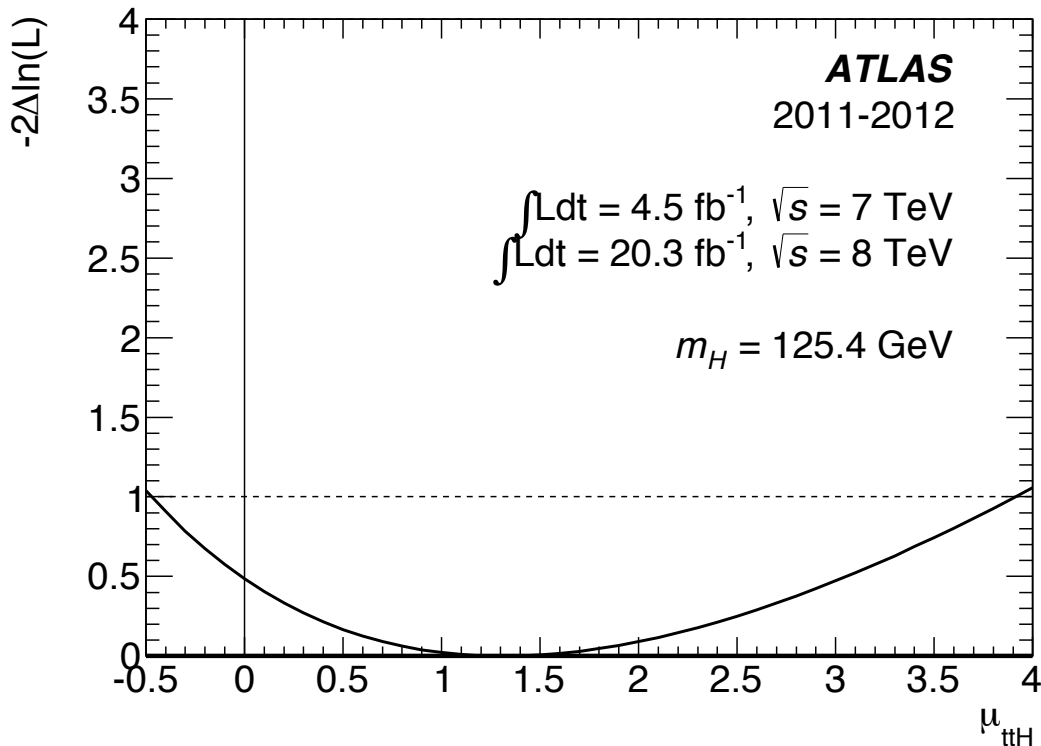
Limits on ttH production (other processes fixed to SM expectation)

	Observed limit	Expected limit	+2 σ	+1 σ	-1 σ	-2 σ
Combined (with systematics)	6.7	4.9	11.9	7.5	3.5	2.6
Combined (statistics only)	6.3	4.7	10.5	7.0	3.4	2.5
Leptonic (with systematics)	10.7	6.6	16.5	10.1	4.7	3.5
Leptonic (statistics only)	10.2	6.4	15.1	9.6	4.6	3.4
Hadronic (with systematics)	9.0	10.1	25.4	15.6	7.3	5.4
Hadronic (statistics only)	8.5	9.5	21.4	14.1	6.8	5.1

$t\bar{t}H, H \rightarrow \gamma\gamma$ results



$t\bar{t}H, H \rightarrow \gamma\gamma$ likelihood scans

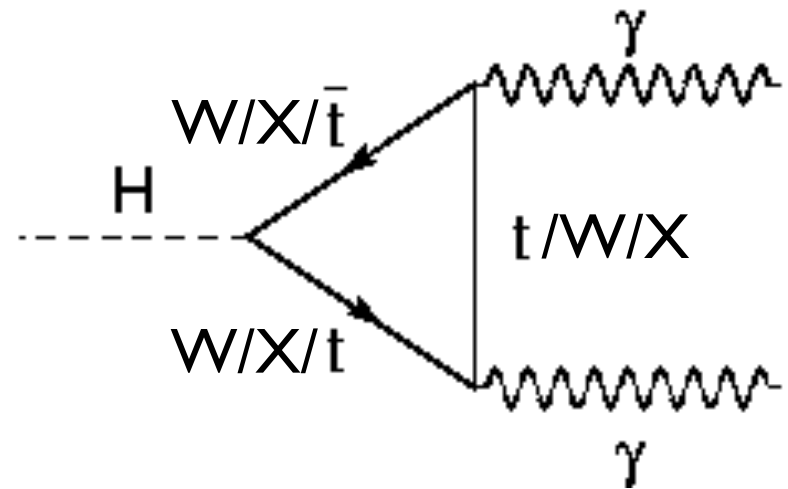
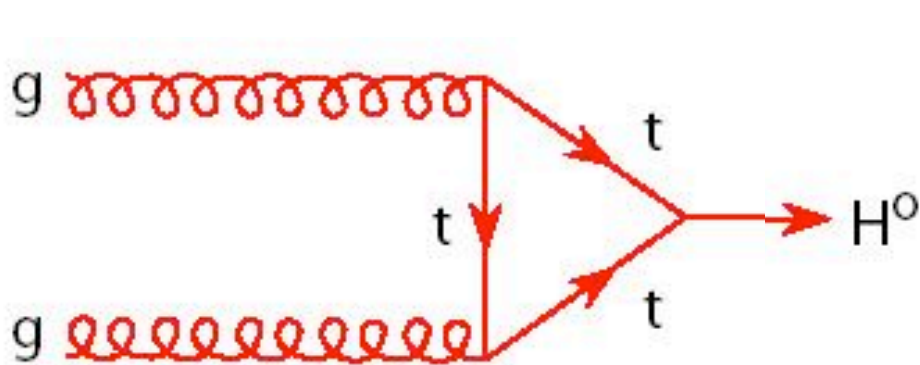


$$\mu_{t\bar{t}H} = 1.3^{+2.5}_{-1.7}(\text{stat})^{0.8}_{-0.4}(\text{syst})$$

$$\mu = 1.4^{+2.1}_{-1.4}(\text{stat})^{0.6}_{-0.3}(\text{syst})$$

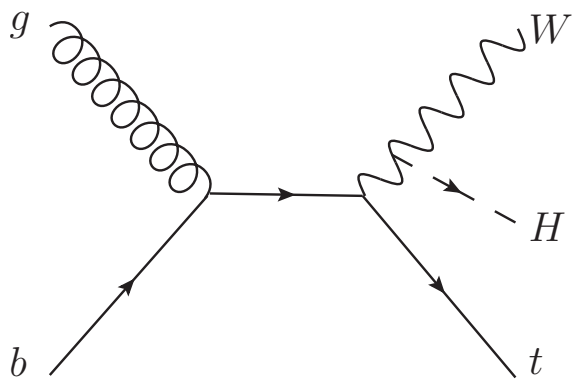
Top quark Yukawa coupling?

- How to probe the top quark Yukawa coupling (Y_t)?
 - Gluon fusion Higgs boson production sensitive to magnitude of $Y_t = \mathbf{K}_t Y_t(\text{SM})$
 - Interference between top quark and W boson in diphoton Higgs decay sensitive to sign and magnitude of \mathbf{K}_t (assuming no other physics?!)

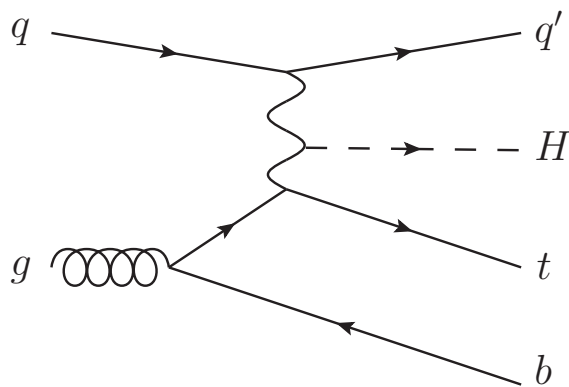
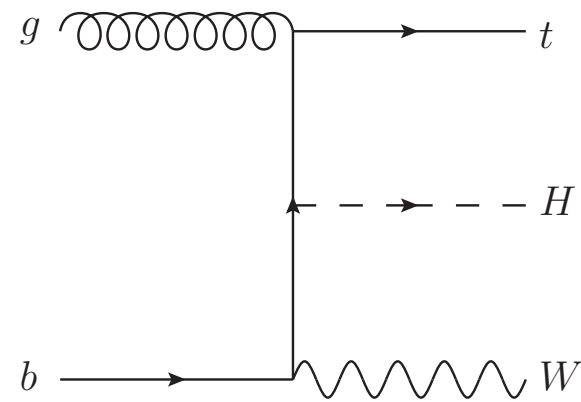


Single top quark + Higgs production

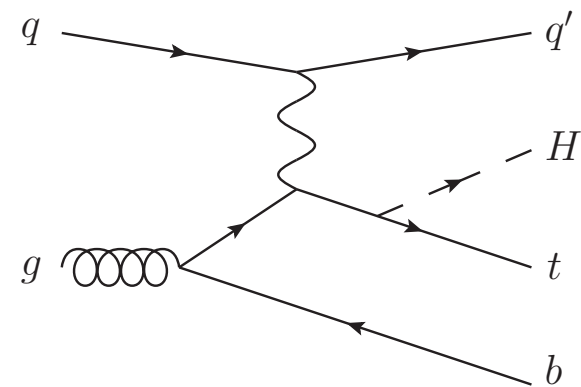
- How to probe the top quark Yukawa coupling?
- Single top quark production directly sensitive to sign and magnitude of top quark Yukawa coupling

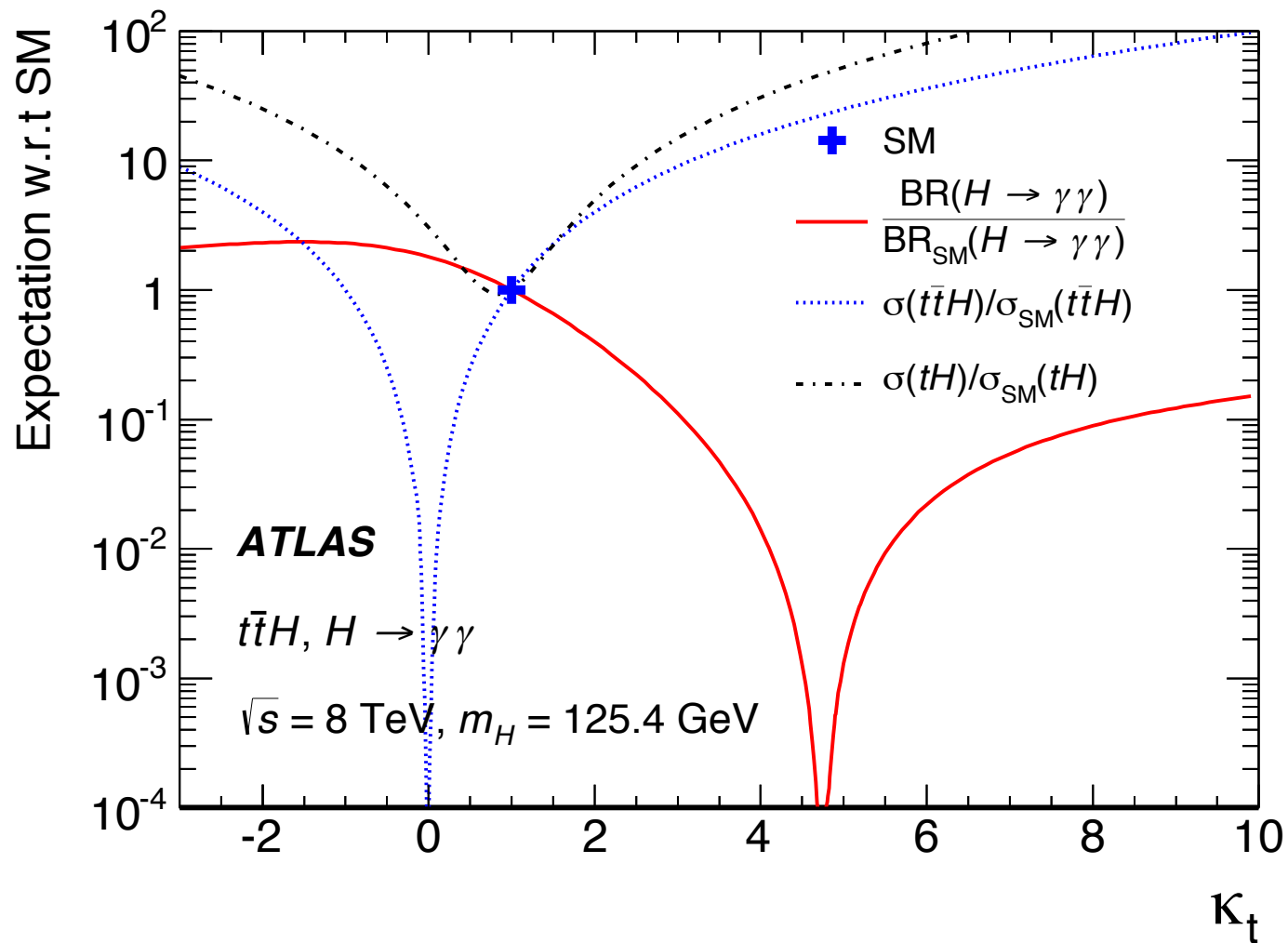


VS

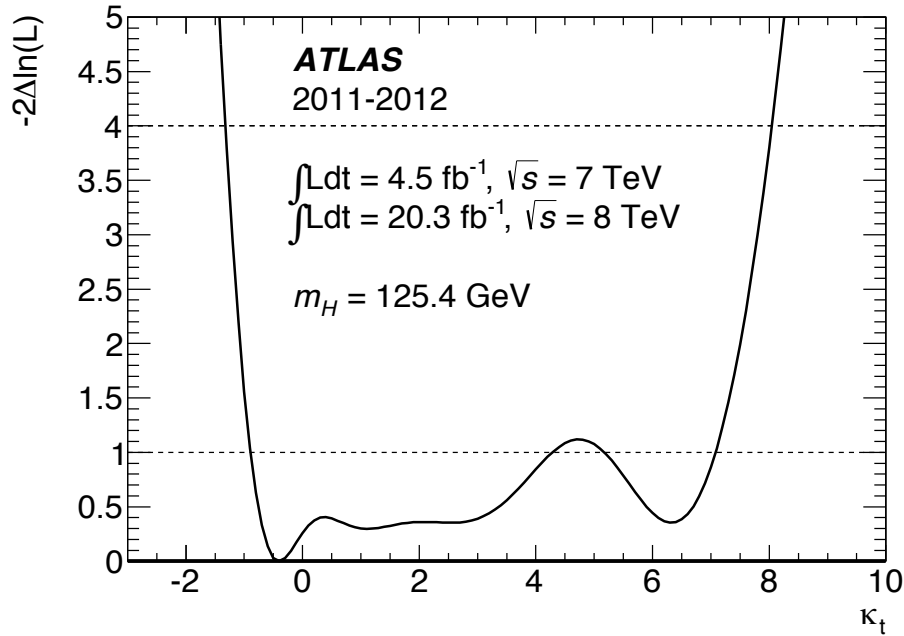


VS



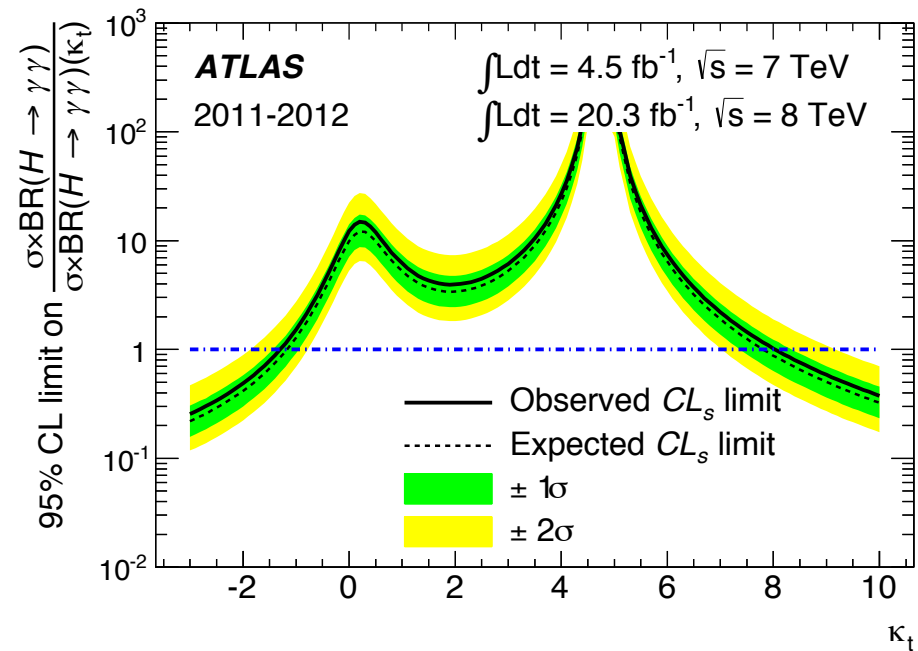
Scanning across K_t 

Set limits on κ_t



Expected 95% CL
limits: $-1.2 < \kappa_t < 7.8$

Set 95% CL
limits: $-1.3 < \kappa_t < 8.0$

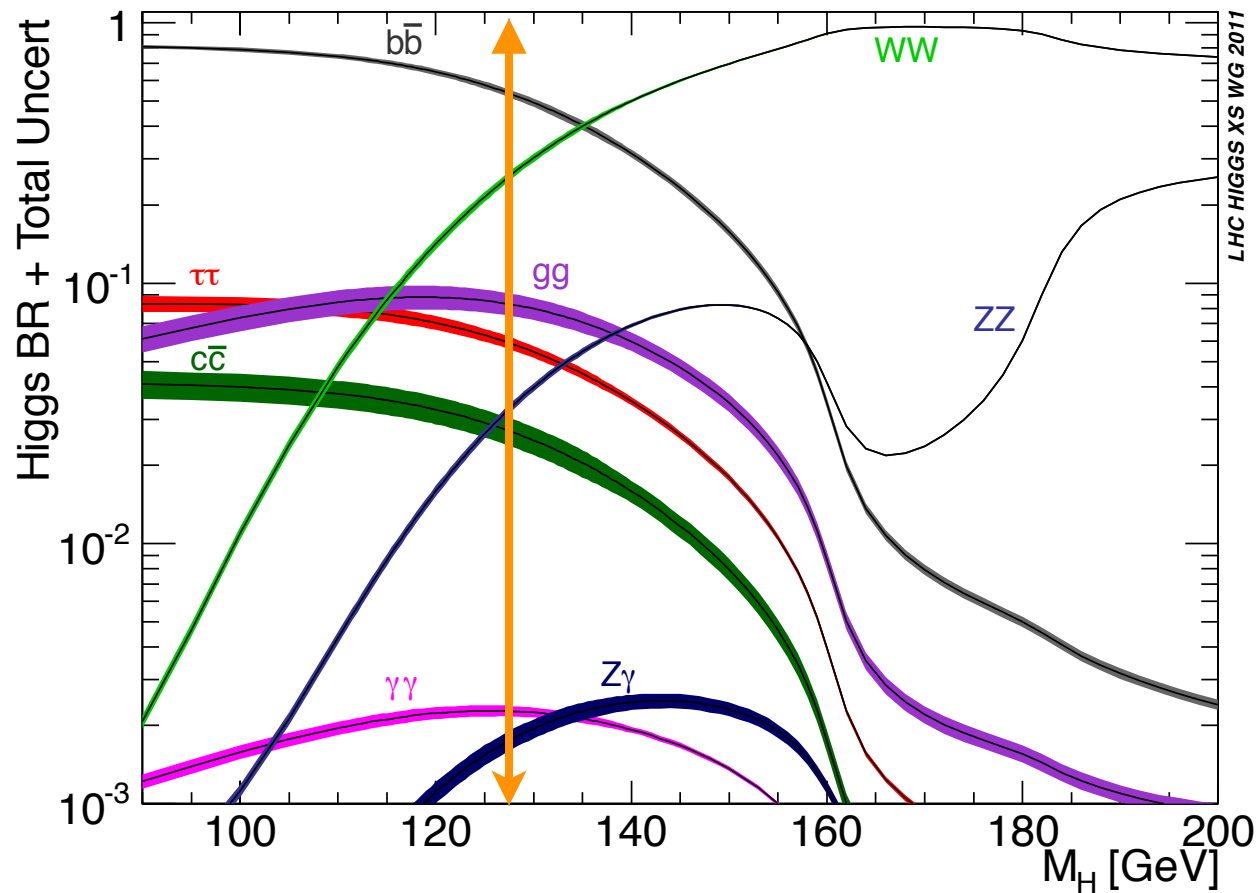




ATLAS

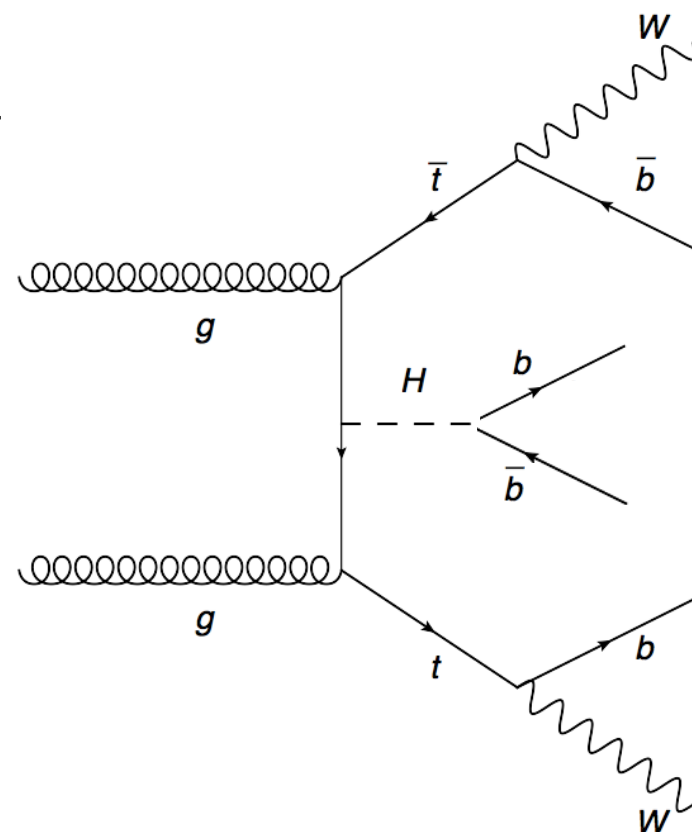
Another approach

Aim for largest signal sample: 57.7% of Higgs decays to $b\bar{b}$



$t\bar{t}H, H \rightarrow b\bar{b}$

- Highest statistics, but challenging
 - We know that $t\bar{t}$ reconstruction is difficult to begin with, and now we added two additional heavy flavor jets
 - Lots of jets, combinatorics, no narrow signal resonance
- Produced 1500 $t\bar{t}H, H \rightarrow b\bar{b}$ events at each LHC experiment in 2012
 - vs 100,000 $t\bar{t}b\bar{b}$ events (with large uncertainty)
 - vs 5 million $t\bar{t}$ events
 - Multivariate techniques helpful



$t\bar{t}H$, $H \rightarrow b\bar{b}$ object selection

	8 TeV (20.3 fb ⁻¹) Lepton+Jets	8 TeV (20.3 fb ⁻¹) Dilepton
Triggers	24/60 GeV single electron and 24/36 GeV single muon	
Jets	25 GeV anti-k _T jets R=0.4, 70% efficiency b-tagging (1% mistag rate)	
Electron E _T	25 GeV	25/15 GeV
Electron track iso	90% efficient cut in a cone of $\Delta R < 0.2$ (varies with E _T and η)	Isolation/p _T in a cone of $\Delta R < 0.3$ less than 0.12
Electron calo iso	90% efficient cut in a cone of $\Delta R < 0.3$ (varies with E _T and η)	
Muon p _T	25 GeV	25/15 GeV
Muon track iso	Isolation/p _T in a cone of $\Delta R = 10 \text{ GeV}/p_T$ less than 0.05	

$t\bar{t}H, H \rightarrow bb$ dilepton event selection

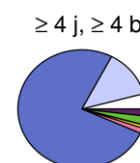
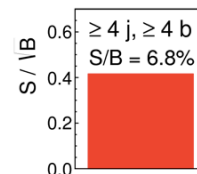
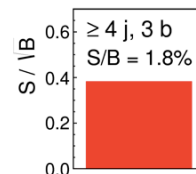
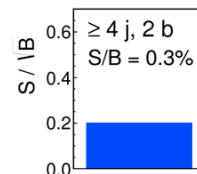
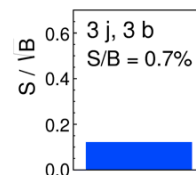
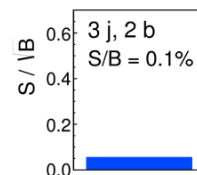
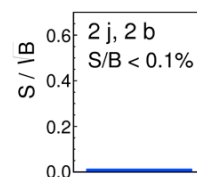
- Dilepton: Exactly two oppositely-signed electrons + muons, and at least 2 jets + at least 2 b-tags
- Lepton must match trigger object and have $p_T > 25$ GeV
- $ee/\mu\mu$: $m_{ll} > 60(15)$ GeV for events with 2(>2) b-tags, also not within 8 GeV of Z mass
- $e\mu$: Sum p_T of leptons + jets > 130 GeV

ATLAS Preliminary Simulation

$\sqrt{s} = 8$ TeV, $\int L dt = 20.3 \text{ fb}^{-1}$

Dilepton

$m_H = 125$ GeV



ATLAS
Preliminary
Simulation

$m_H = 125$ GeV

$\sqrt{s} = 8$ TeV

$t\bar{t}$ +light
 $t\bar{t}$ + $c\bar{c}$
 $t\bar{t}$ + $b\bar{b}$
 $t\bar{t}$ +V
 Z+jets
 Diboson
 Single top
 Multijet

Dilepton

ttH, H → bb lepton+jets event selection

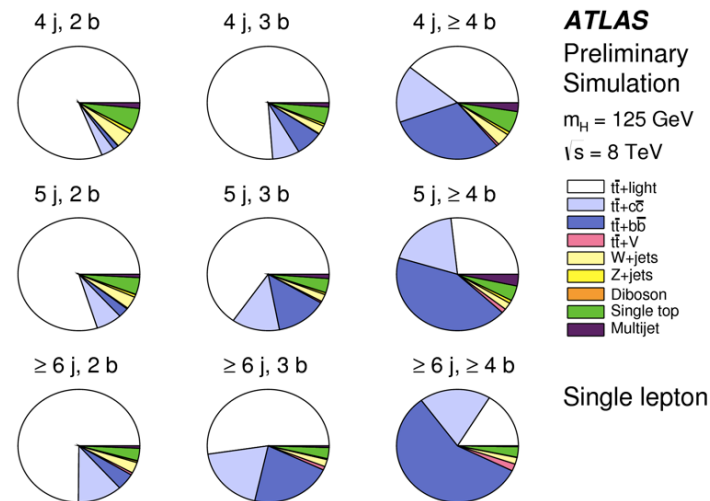
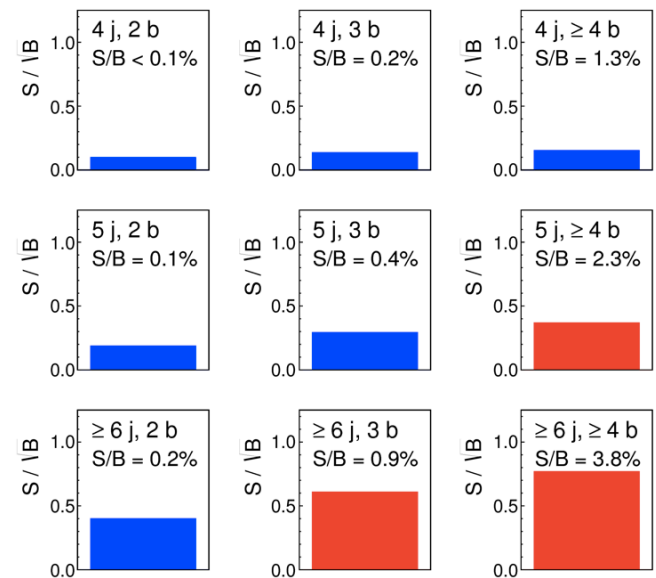
- Lepton+Jets: Exactly one charged lepton at least 4 jets with at least 2 b-tags
- Lepton must match trigger object
- Event must have failed dilepton selection
- As in dilepton selection, divide events based on the number of b-tags

ATLAS Preliminary Simulation

$\sqrt{s} = 8 \text{ TeV}$, $\int \mathcal{L} dt = 20.3 \text{ fb}^{-1}$

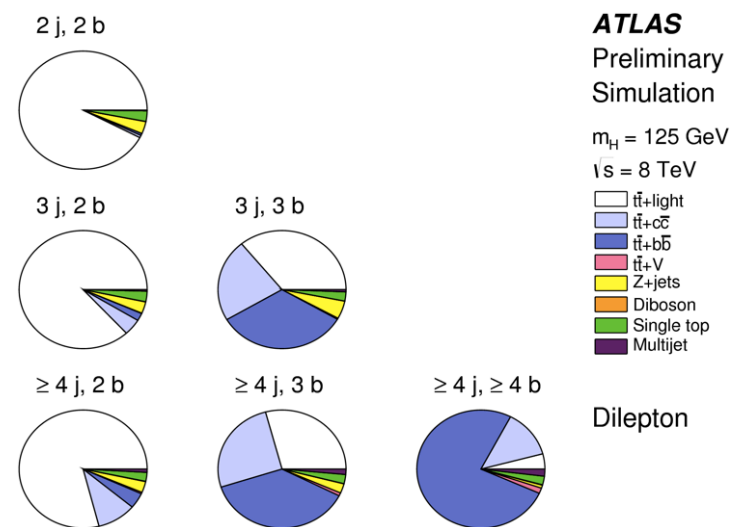
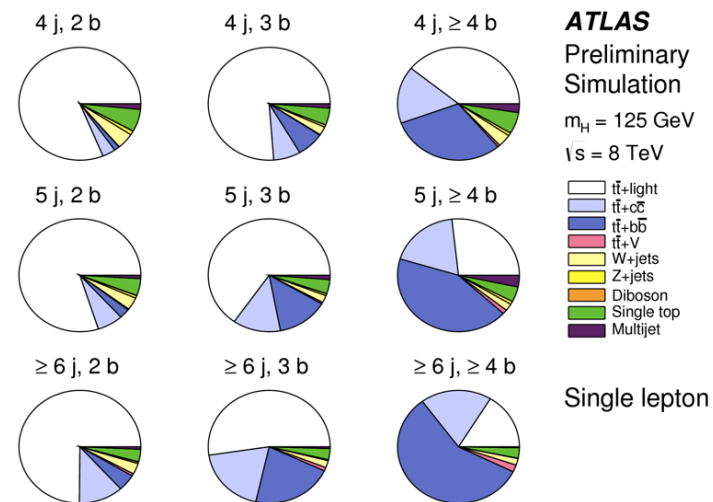
Single lepton

$m_H = 125 \text{ GeV}$



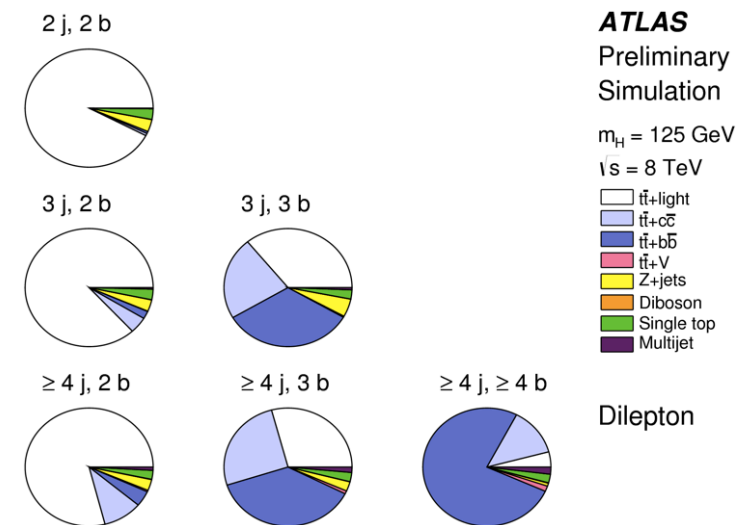
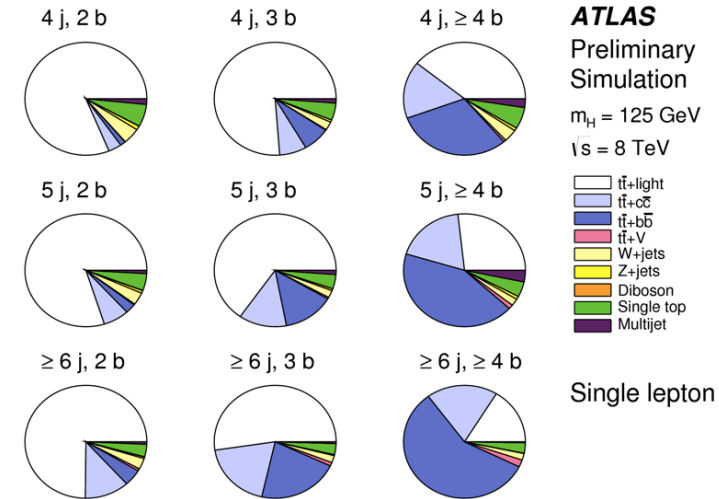
Backgrounds

- Dominated by $t\bar{t}$, with contributions from $t\bar{t}+qq/cc/bb$ depending on n_{jet} and n_{tag} bin
- Classification based on matching particle jets to quarks in fiducial region
- $t\bar{t}bb$: At least one matched b
- $t\bar{t}cc$: No matched b, at least one matched c
- $t\bar{t}qq$: Otherwise
- Smaller contributions from V +jets, single top, diboson, $t\bar{t}V$, multijet processes



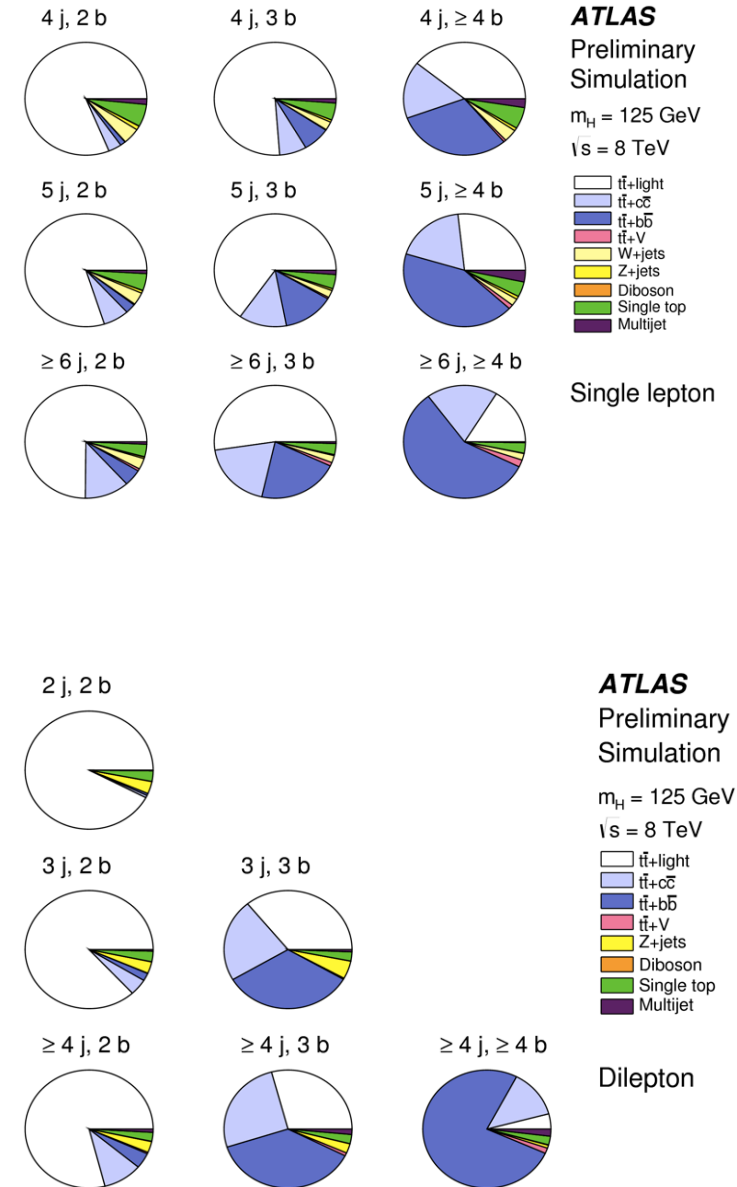
The smaller backgrounds

- W/Z + jets modeled with Alpgen samples + MLM matching scheme up to 5 additional partons, including $bb/cc/c$ and heavy flavor overlap removal
- Reweighted to match Z +jets p_T spectra in data
- HF content reweighted to match rates of $Z+0$ vs $Z+1$ b-tag data
- Use inclusive NNLO cross section



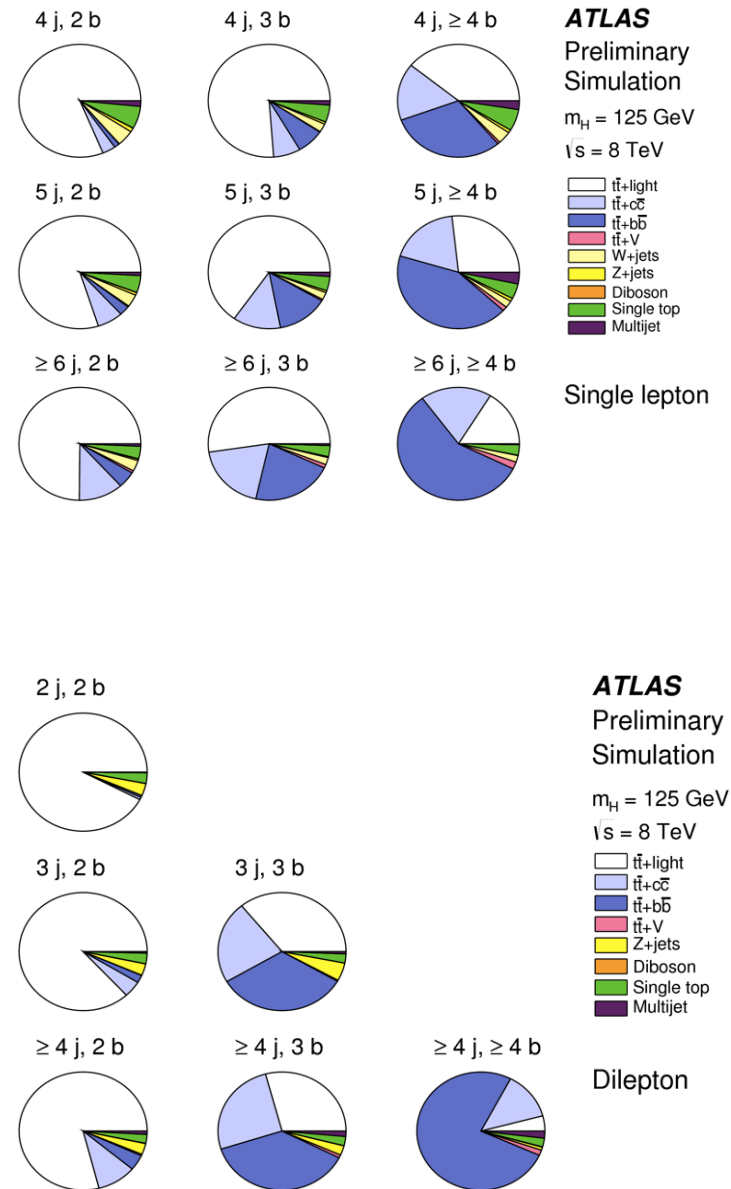
The smaller backgrounds

- Diboson modeled with Alpgen up to 3 additional partons, normalized to NLO xsections
- Single top s-channel and Wt use Powheg interfaced to Pythia normalized to NNLO
- t channel: Acer + Pythia normalized to NNLO
- $t\bar{t}V$ generated with Madgraph + Pythia, normalized to NLO

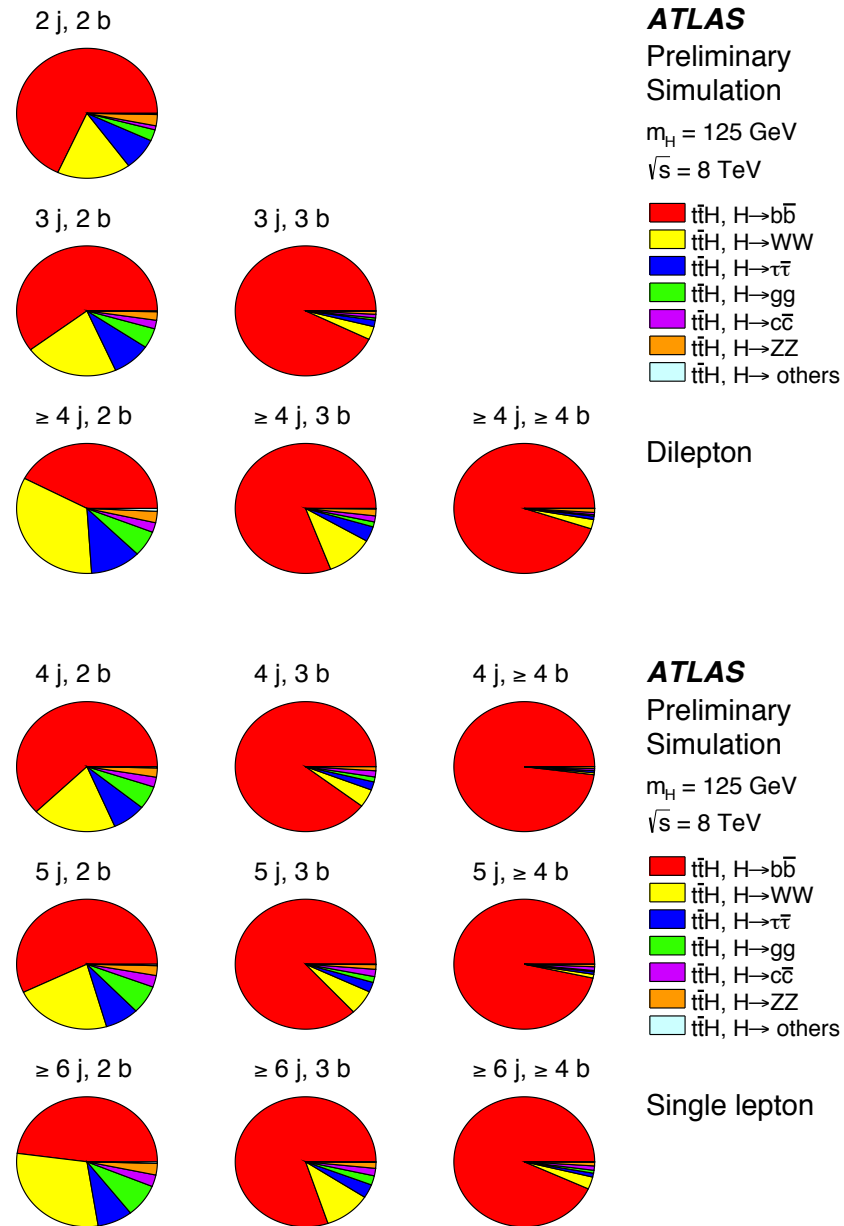


Multijet processes

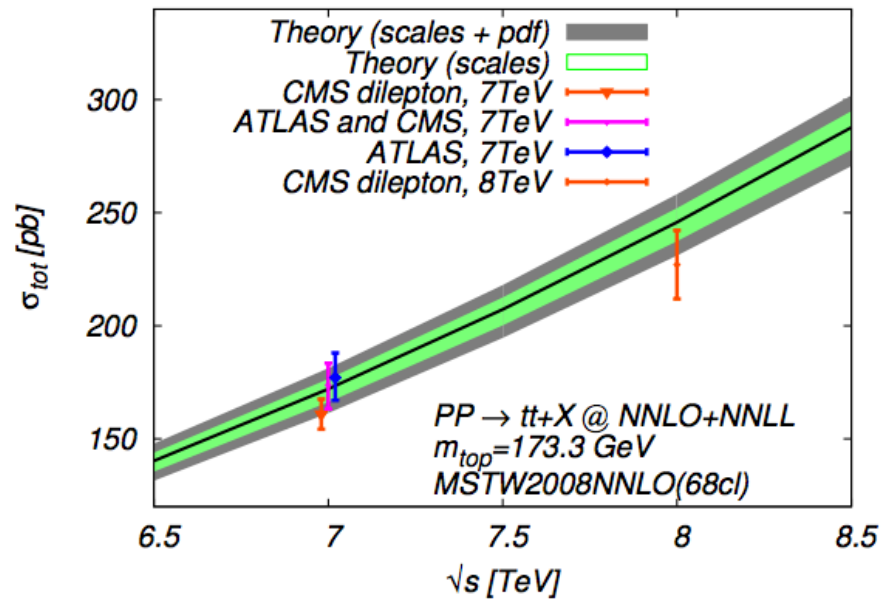
- Lepton+Jets uses a data-driven matrix method, though fake leptons are anyway a small contribution
- Dilepton uses simulation to model fake leptons, with comparisons to same-sign data for uncertainty
- Very small contribution to the sample



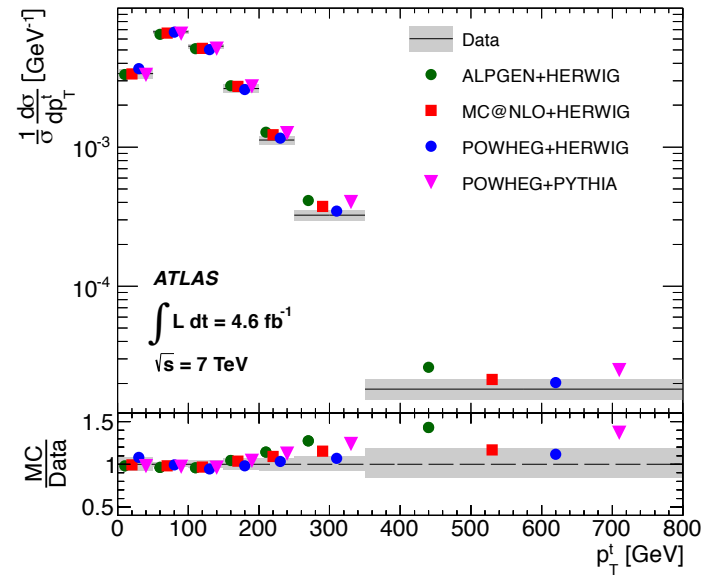
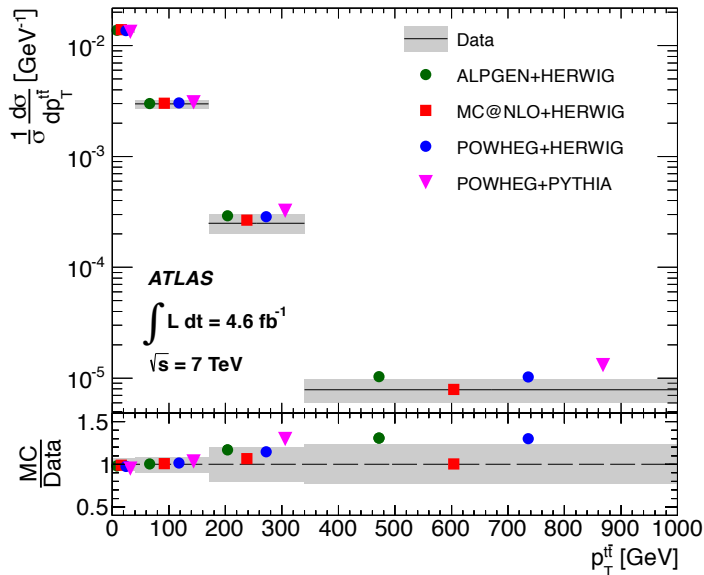
- Use the same $t\bar{t}H$ modeling as the diphoton analysis, using NLO matrix elements from the HELAC-OneLoop package, interfaced to Powheg + Pythia
- Include small (but non-zero) contributions from $t\bar{t}H$ production with non- $b\bar{b}$ decays



- Generated using Powheg, interfaced to Pythia.
Normalized to NNLO xsection, including resummation of NNLL soft gluon terms
- Theoretical uncertainty down to 6% (!), including PDF, scale and top quark mass uncertainties, using Top+++



- Impressively, the HF content and kinematics of Powheg + Pythia match the HF content from Madgraph + Pythia
- Simulation reweighted to 7 TeV differential xsec measurement of top quark p_T (changes jet p_T) and ttbar p_T (changes njet)
- After which, tt+HF from Powheg matches NLO predictions (Sherpa+OpenLoops)

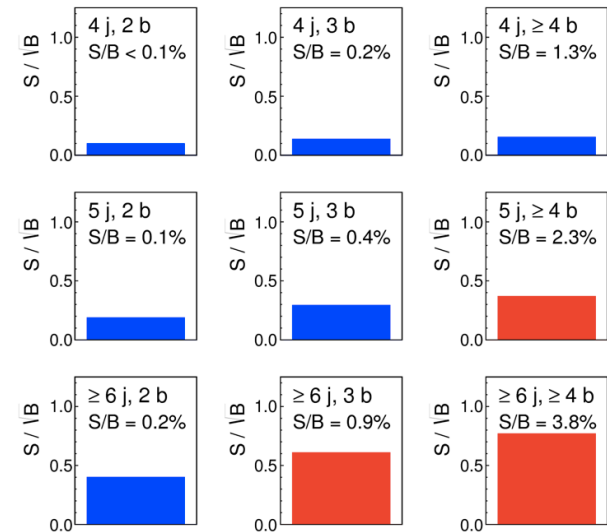


ttH, $H \rightarrow bb$ plan of attack

- In **signal-depleted regions**, use H_T to understand nuisance parameters and systematic uncertainties
- In **signal-enriched regions**, use a 3-layer, 10-variable neural network trained separately in each region to discriminate signal and background
 - L+J: $(5j, \geq 4b)$, $(\geq 6j, 3b)$, $(\geq 6j, \geq 4b)$, plus additional $(5j, 3b)$ NN to separate $tt+LF$ from $tt+HF$ backgrounds
 - DIL: $(3j, 3b)$, $(\geq 4j, 3b)$, $(\geq 4j, \geq 4b)$
 - Check modeling of variable in ntag and njet bins

ATLAS Preliminary Simulation

$\sqrt{s} = 8 \text{ TeV}$, $\int L dt = 20.3 \text{ fb}^{-1}$

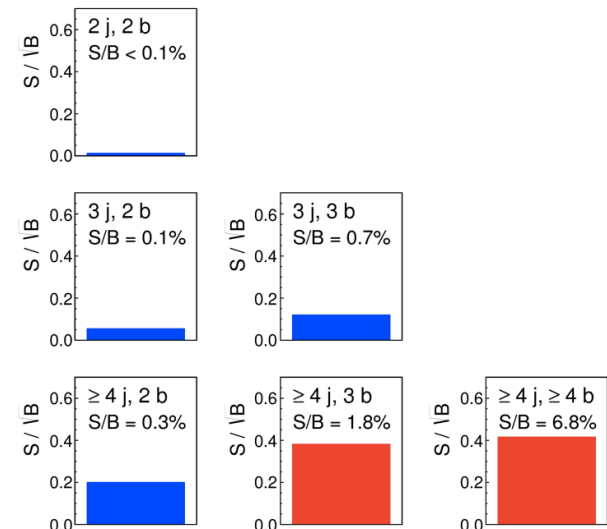


Single lepton

$m_H = 125 \text{ GeV}$

ATLAS Preliminary Simulation

$\sqrt{s} = 8 \text{ TeV}$, $\int L dt = 20.3 \text{ fb}^{-1}$



Dilepton

$m_H = 125 \text{ GeV}$

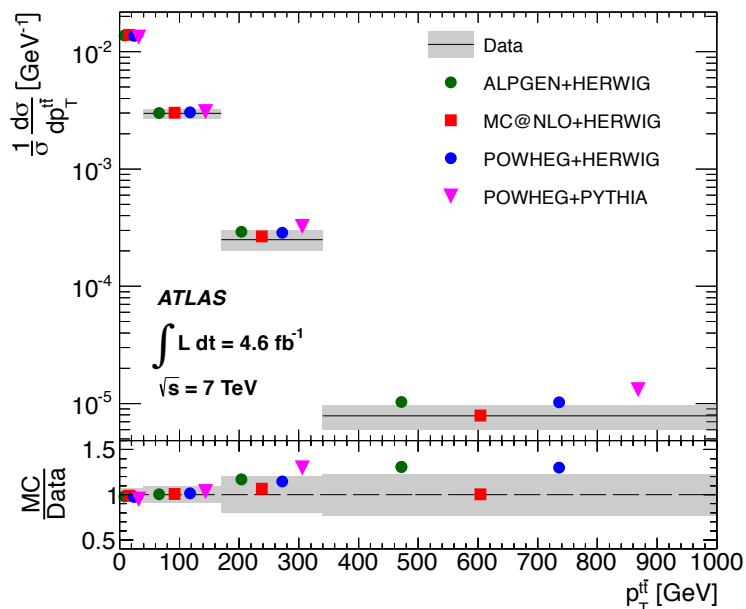
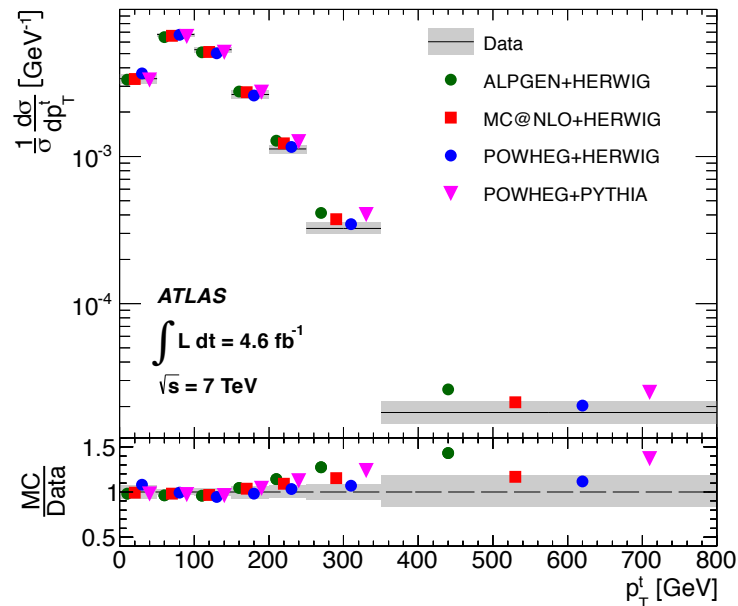
Systematic uncertainties

Systematic uncertainty	Type	Components
Luminosity	N	1
Physics Objects		
Electron	SN	5
Muon	SN	6
Jet energy scale	SN	22
Jet vertex fraction	SN	1
Jet energy resolution	SN	1
Jet reconstruction	SN	1
<i>b</i> -tagging efficiency	SN	6
<i>c</i> -tagging efficiency	SN	6
Light jet-tagging efficiency	SN	12
Background Model		
<i>t</i> \bar{t} cross section	N	1
<i>t</i> \bar{t} modelling: p_T reweighting	SN	9
<i>t</i> \bar{t} modelling: parton shower	SN	2
<i>t</i> \bar{t} +heavy-flavour: normalisation	N	2
<i>t</i> \bar{t} +heavy-flavour: HF reweighting	SN	2
<i>t</i> \bar{t} +heavy-flavour: generator	SN	5
<i>W</i> +jets normalisation	N	3
<i>W</i> p_T reweighting	SN	1
<i>Z</i> +jets normalisation	N	2
<i>Z</i> p_T reweighting	SN	1
Multijet normalisation	N	3
Multijet shape dilepton	S	1
Single top cross section	N	1
Dibosons cross section	N	1
<i>t</i> \bar{t} <i>V</i> cross section	N	1
Signal Model		
<i>t</i> \bar{t} <i>H</i> modelling	SN	2

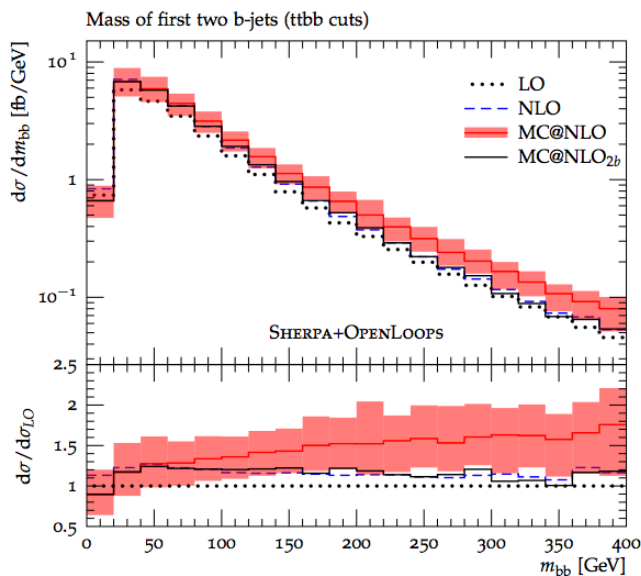
Long and rather nasty list of nuisance parameters/systematic uncertainties considered, but want to point out just a few ...

Systematic uncertainties on ttbar modeling

- Uncertainties on parton shower (Pythia vs Herwig)
 - Separate for tt+LF and tt+HF (uncorrelated)
- Uncertainties from differential xsection measurement at 7 TeV assumed uncorrelated with any uncertainties at 8 TeV
 - Include jet uncertainties, tagging uncertainties, choice of generator reweighted to, uncertainties on modeling of radiation in ttbar events

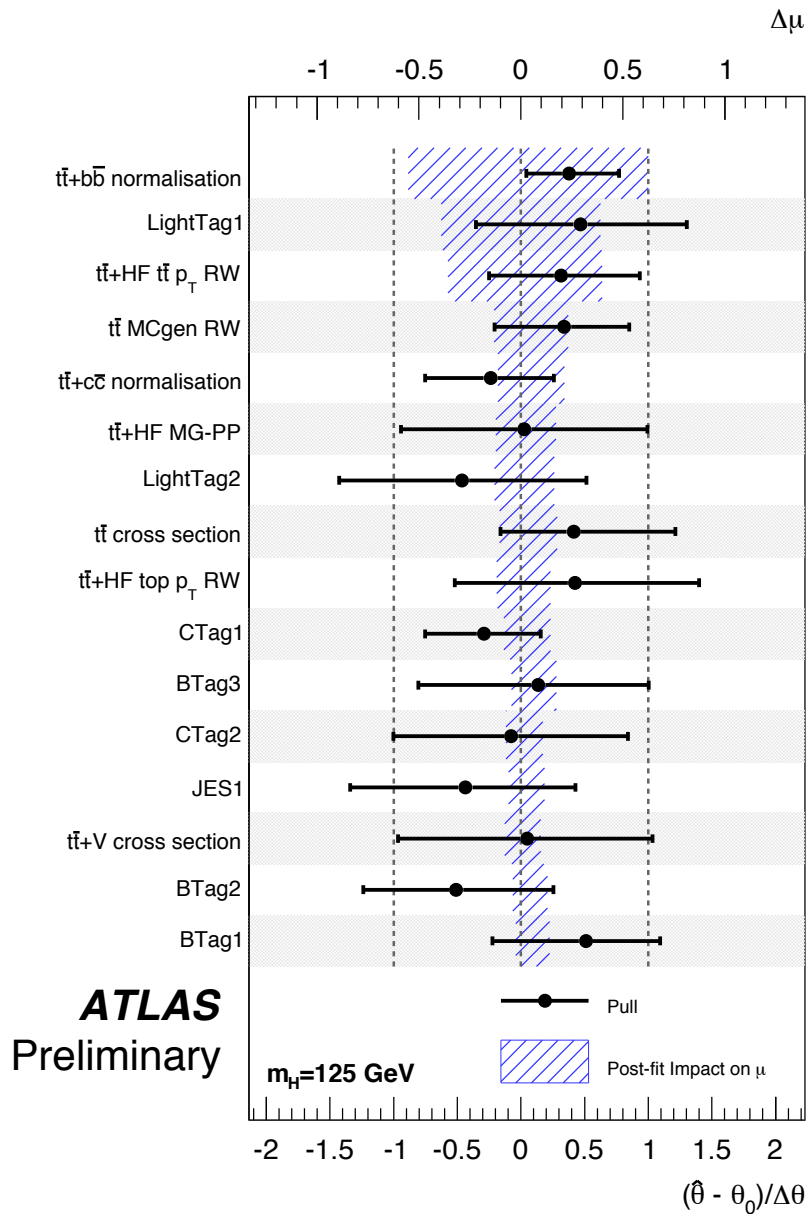


Systematic uncertainties on $t\bar{t}+HF$



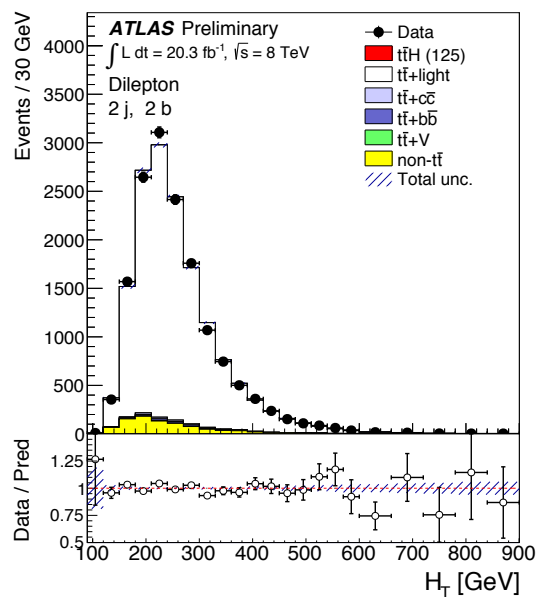
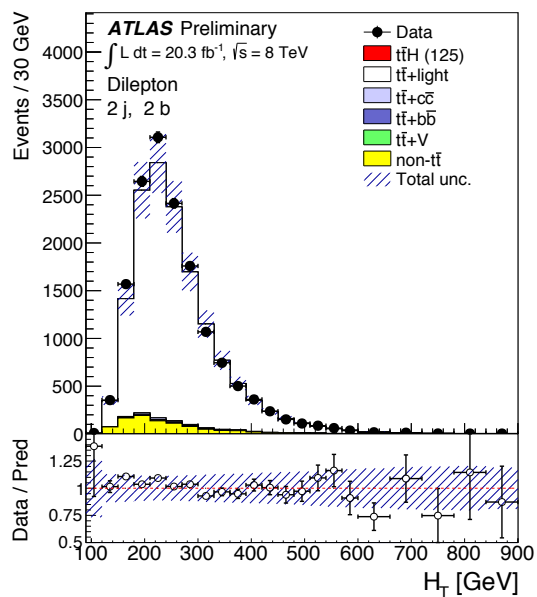
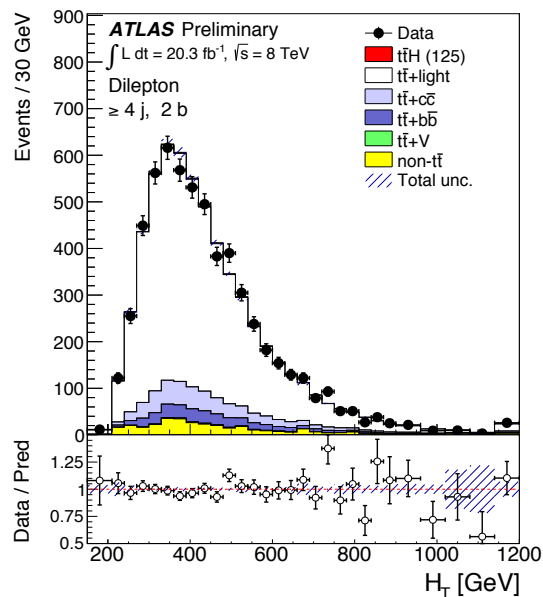
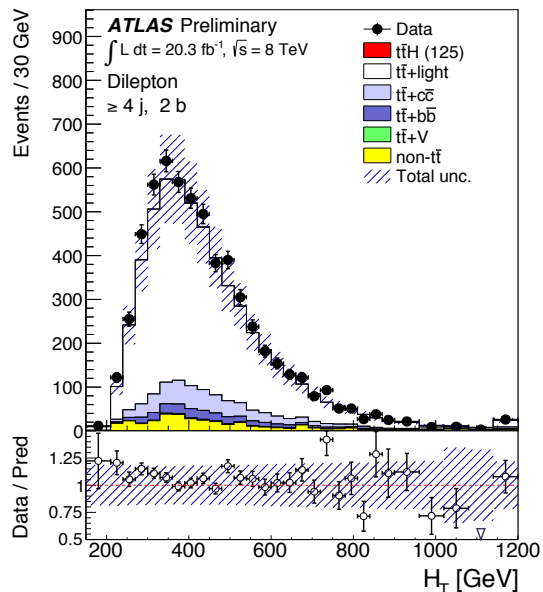
- Two nuisance parameters for applying top p_T and $t\bar{t}$ p_T reweighting specifically to $t\bar{t}+HF$ events (on vs off for each)
- 50% overall prior on $t\bar{t}+HF$
 - Constrained by data to 15% for $ttbb$, 29% for $ttcc$
- Nuisance parameters to completely match Powheg+Pythia to Madgraph+Pythia
 - Also factorization and renormalization scale in Madgraph, matching thresholds and quark mass uncertainties

A few other important uncertainties



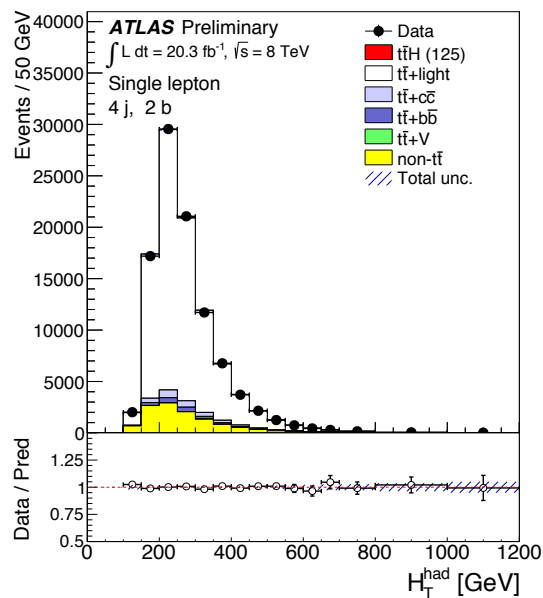
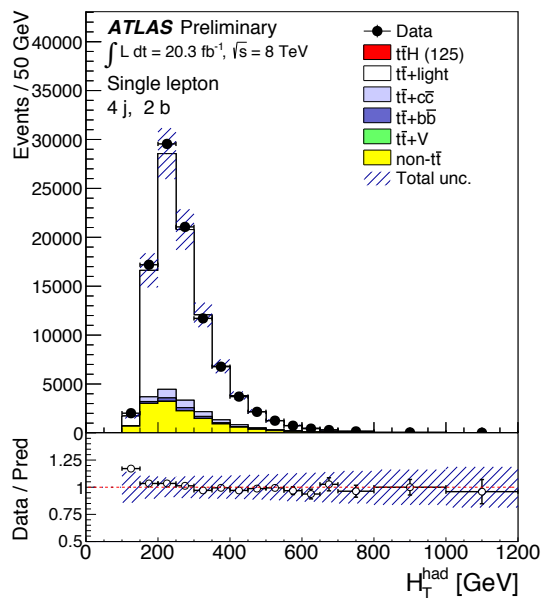
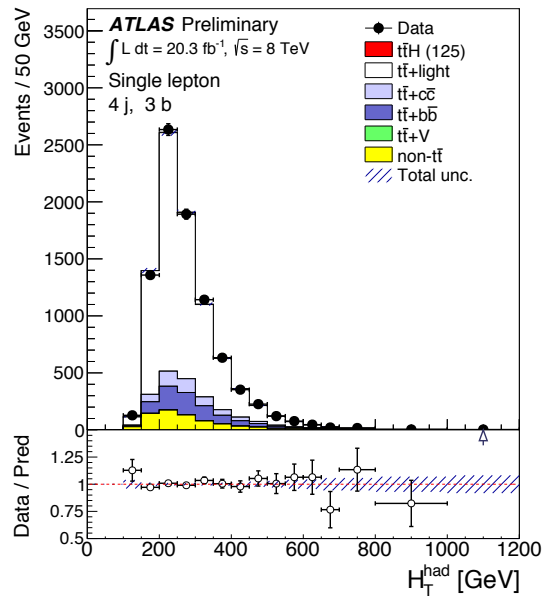
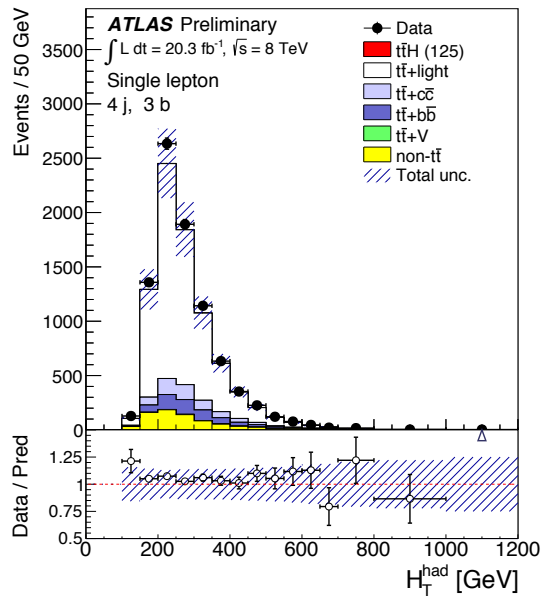
- Jet energy scale and can be important, as expected
- B-tag (and c-tag) scale factors can also be important
 - Mistag scale factors important for lepton +jets analysis
- $t\bar{t}+V$ cross section uncertainties non-trivial (30% input to the fit)
 - Can be the same final state as $t\bar{t}H$

H_T in signal-depleted regions (dilepton)



Profiling
 nuisance
 parameters
 gives significant
 improvement
 in data-
 simulation
 agreement, and
 large reduction
 in errors

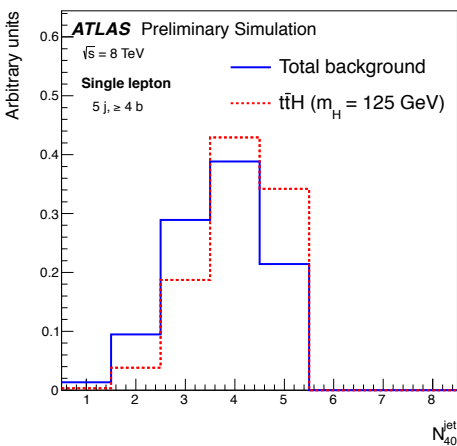
H_T in signal-depleted regions (single lepton)



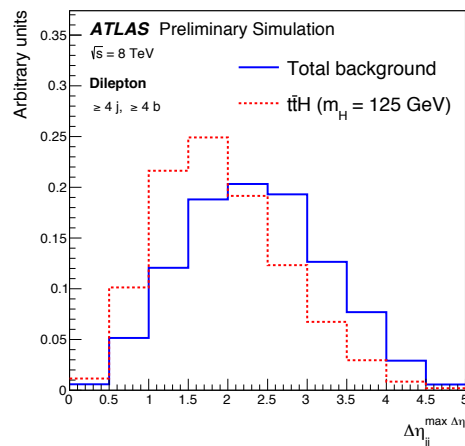
Profiling
 nuisance
 parameters
 gives significant
 improvement
 in data-
 simulation
 agreement, and
 large reduction
 in errors

A word or two on neural networks

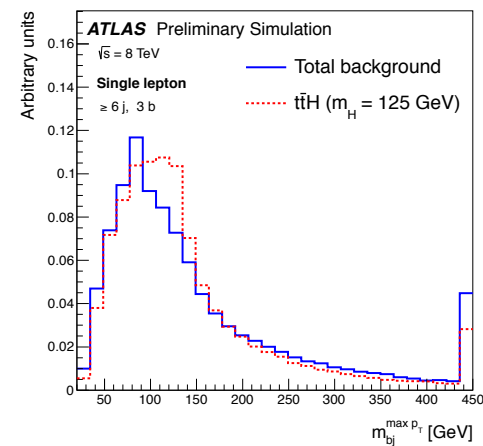
- No direct attempt to reconstruct the m_{bb} system due to difficulty in dealing with large combinatorics for single lepton events and an underconstrained system for dilepton events
- Instead, use kinematic variables that either distinguish $t\bar{t}$ from $t\bar{t}H$, or indirectly attempt to find m_{bb}



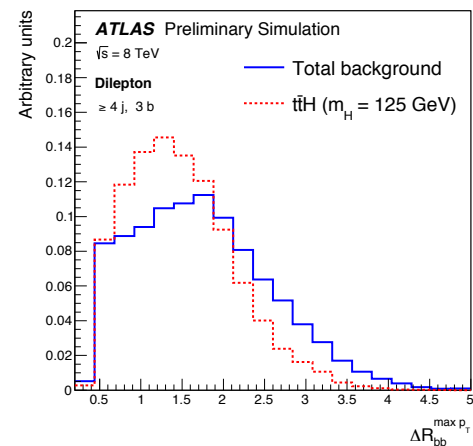
of jets with
 $p_T > 40$ GeV



Max $\Delta\eta$
 between 2 jets

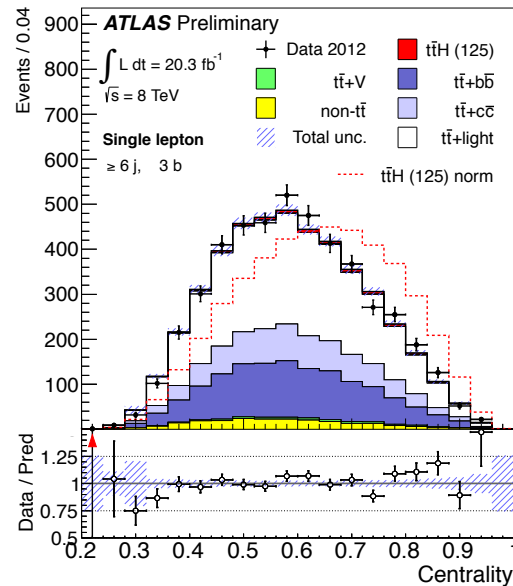
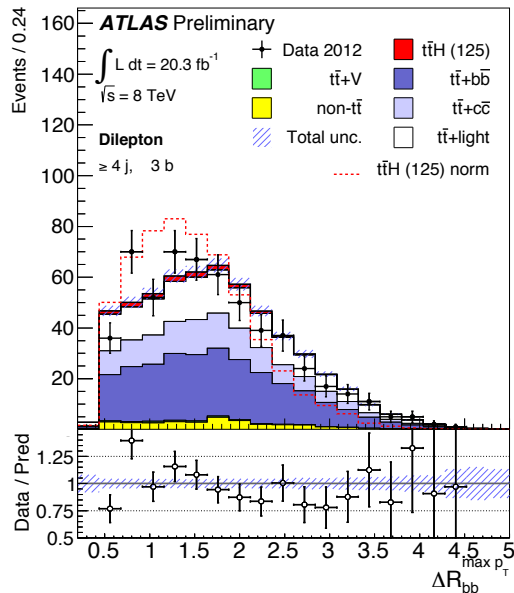
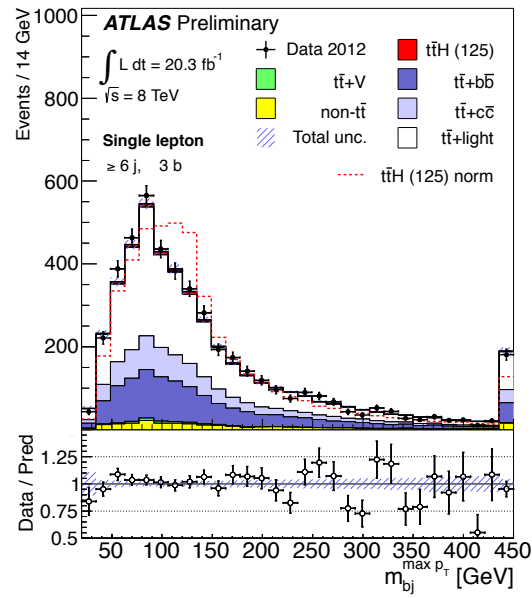
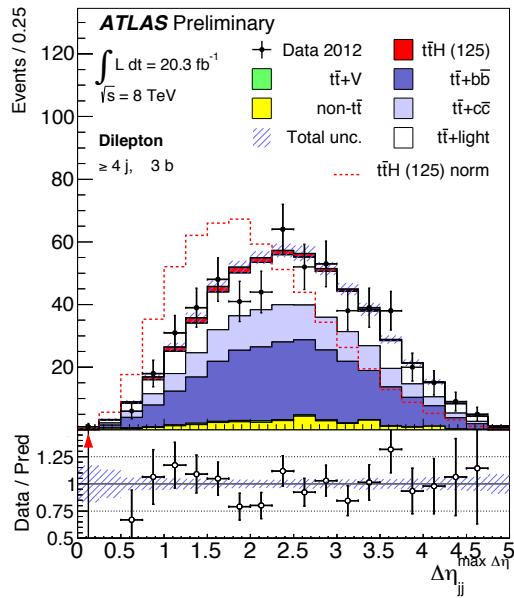


Mass of b_j pair
 w/max Σp_T



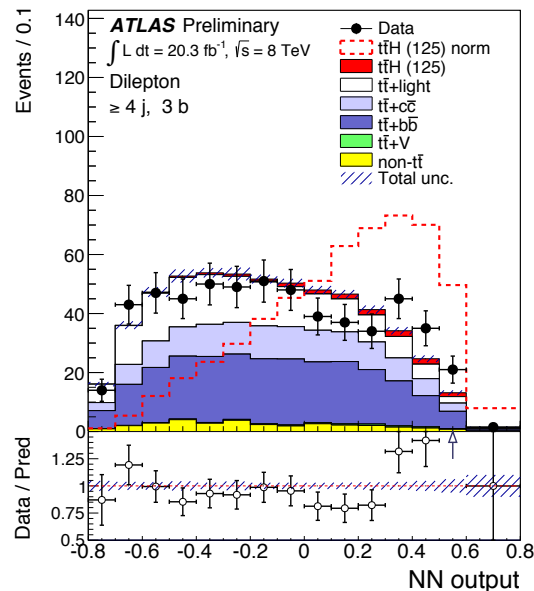
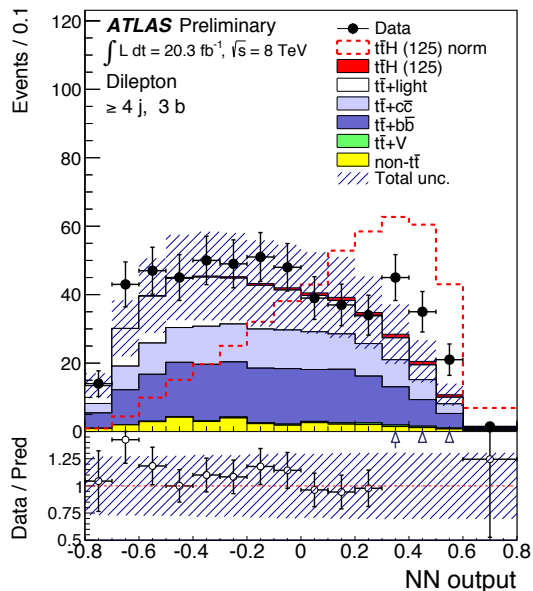
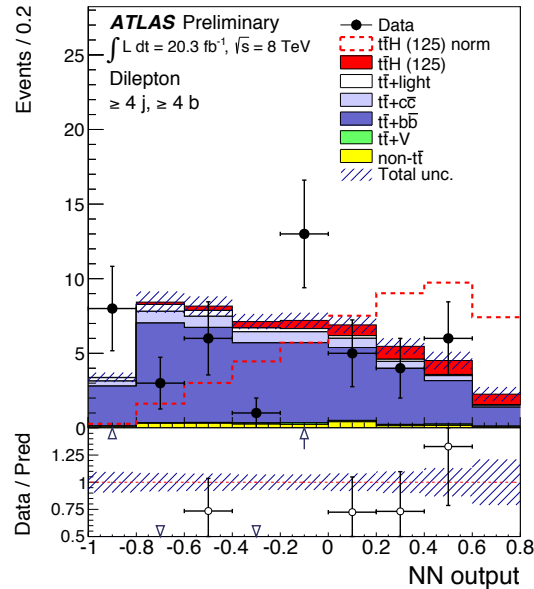
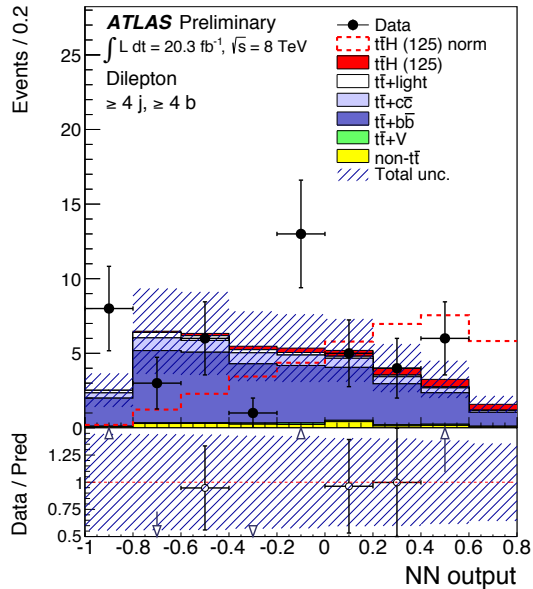
ΔR between
 pairs of tagged
 jets w/max Σp_T

Modeling of NN variables



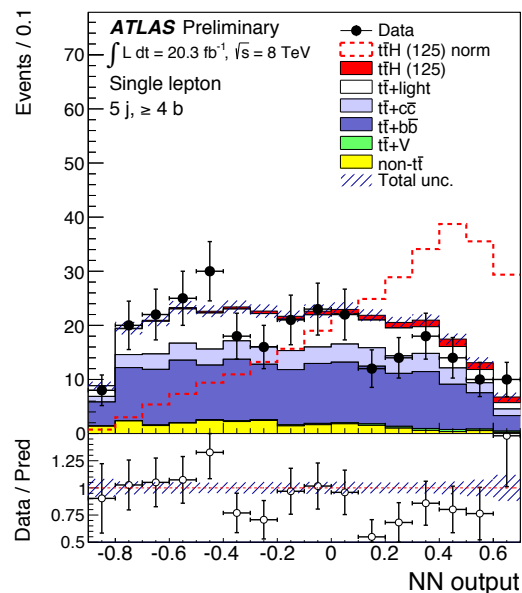
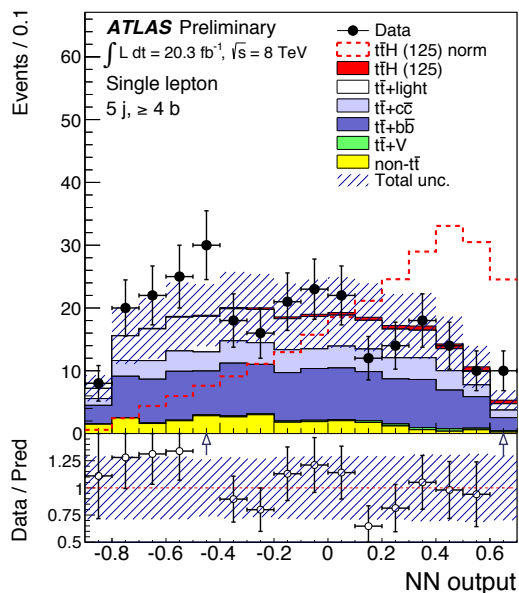
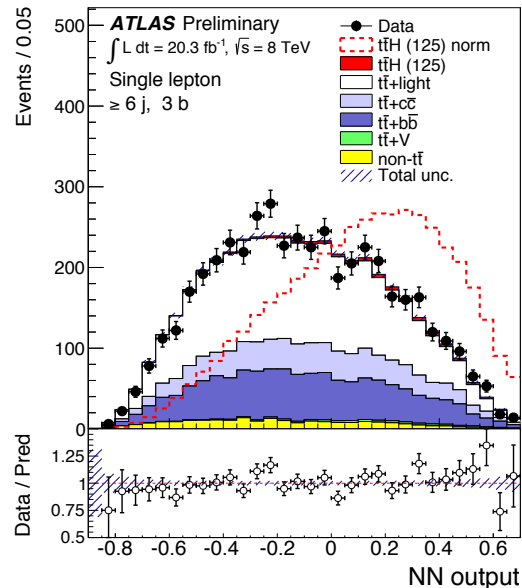
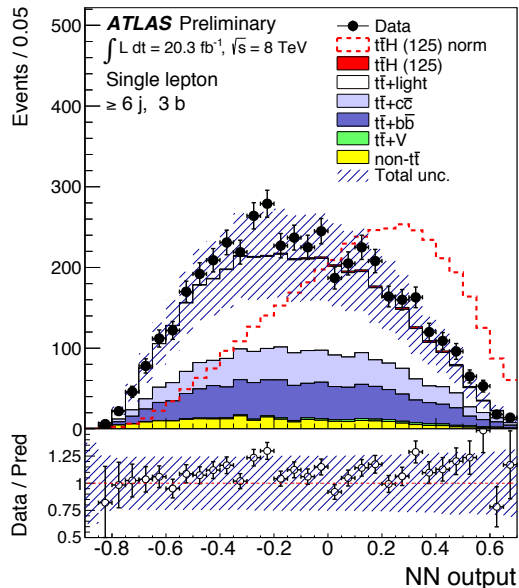
Also checked in higher-statistics regions with fewer jets and fewer b-tags (using b-tag promotion where appropriate)

NN output (dilepton)



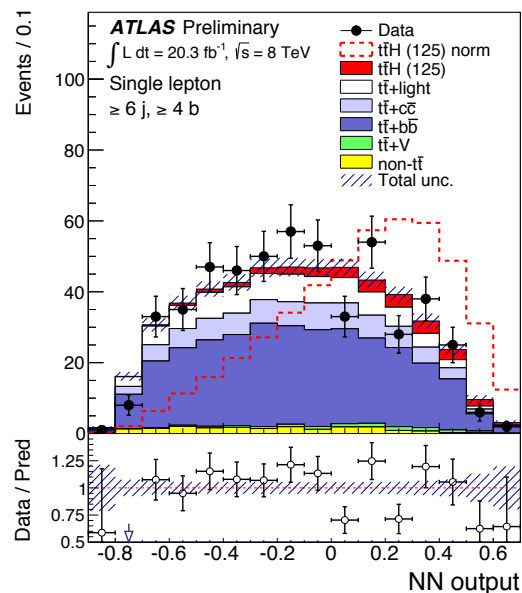
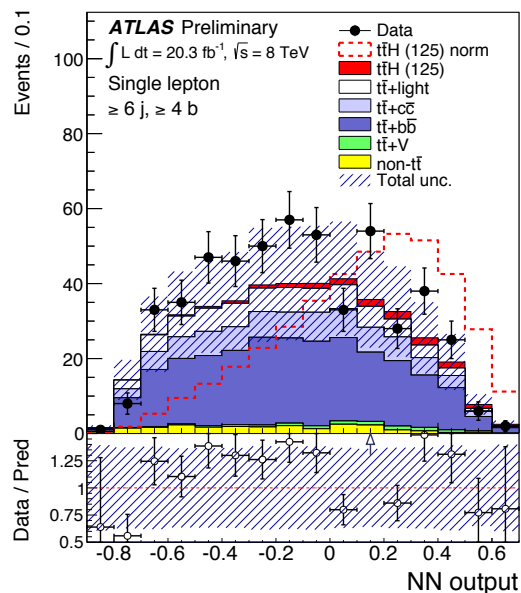
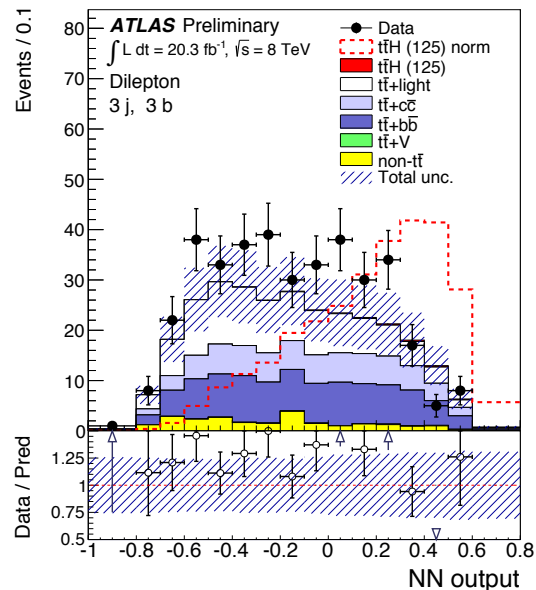
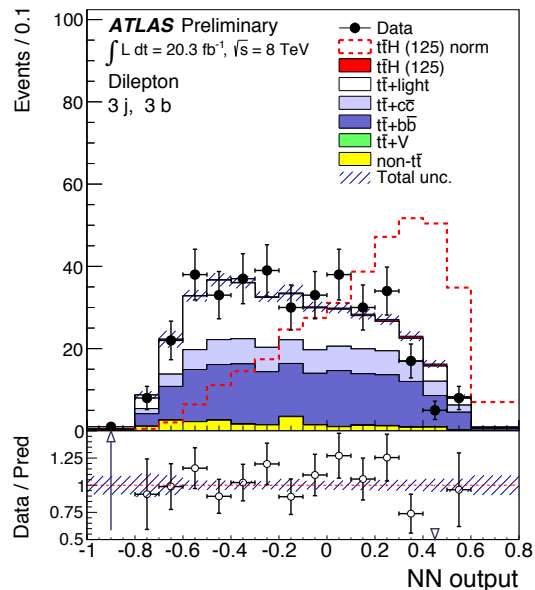
As before,
 significant
 improvement
 and benefit
 from profiling

NN output (single lepton)



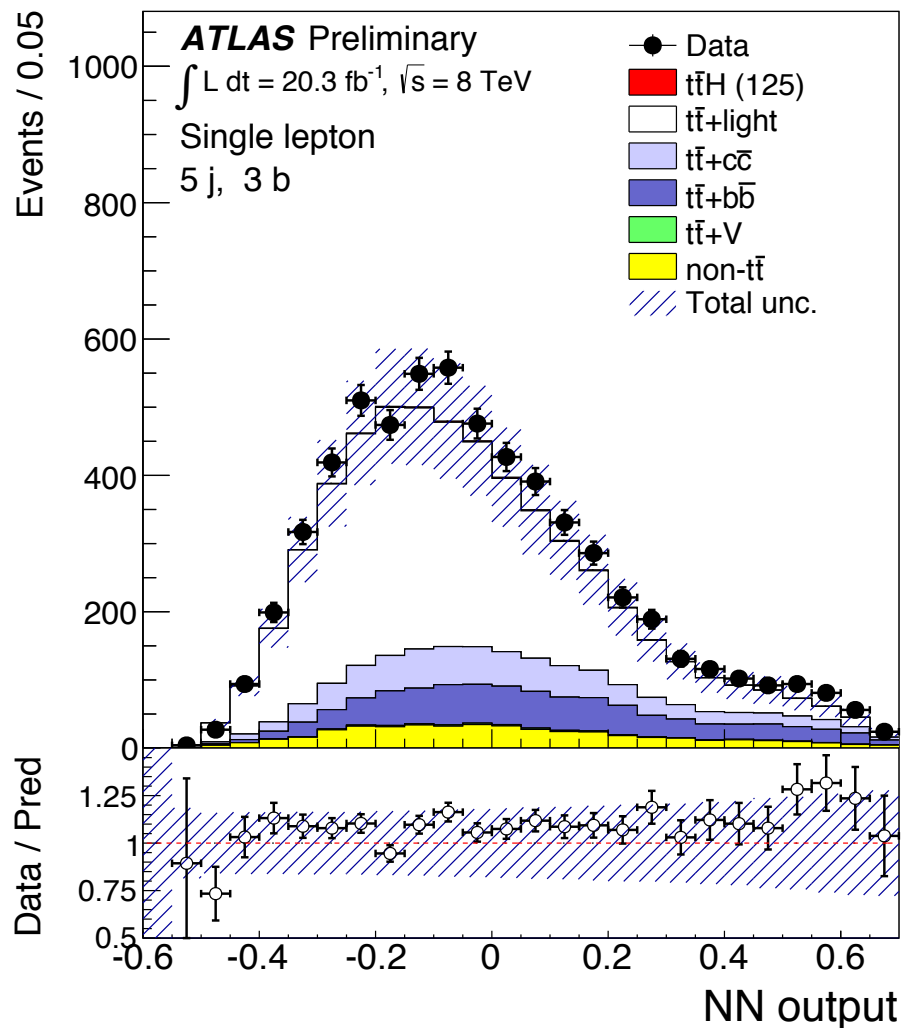
As before,
 significant
 improvement
 and benefit
 from profiling

NN output (single and dilepton)



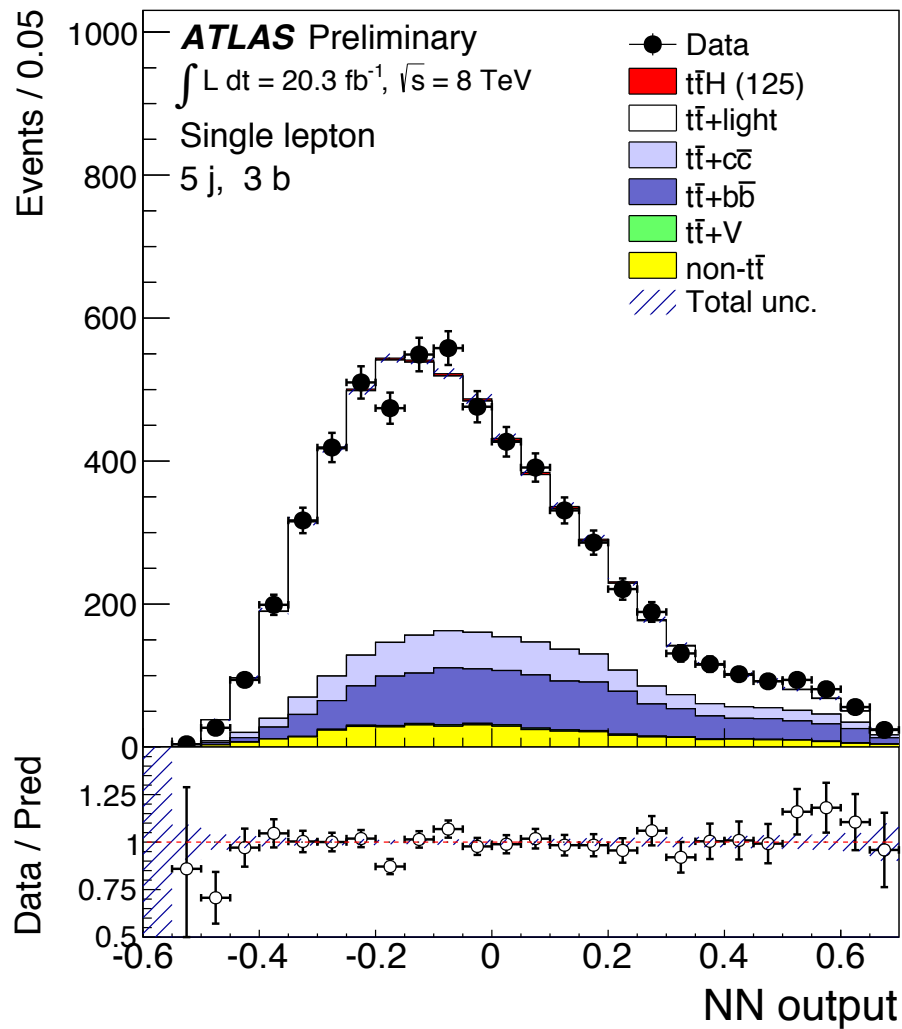
As before,
 significant
 improvement
 and benefit
 from profiling

NN output (single lepton, HF vs LF NN)

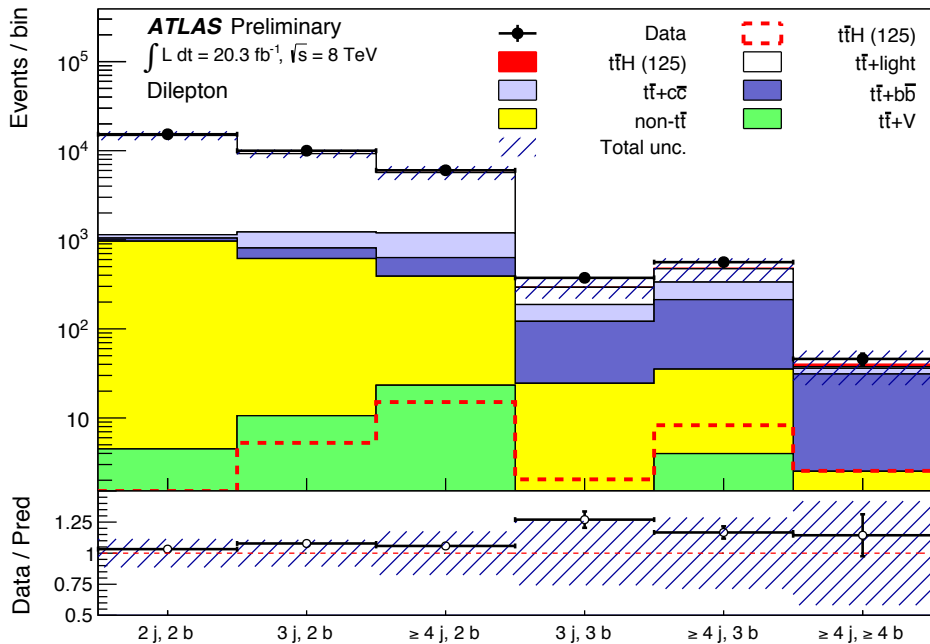


5 jet / 3 tag
 region trained
 to separate
 $t\bar{t}LF$ vs $t\bar{t}HF$
 (dominant
 variable is mass
 of untagged jet
 pair)

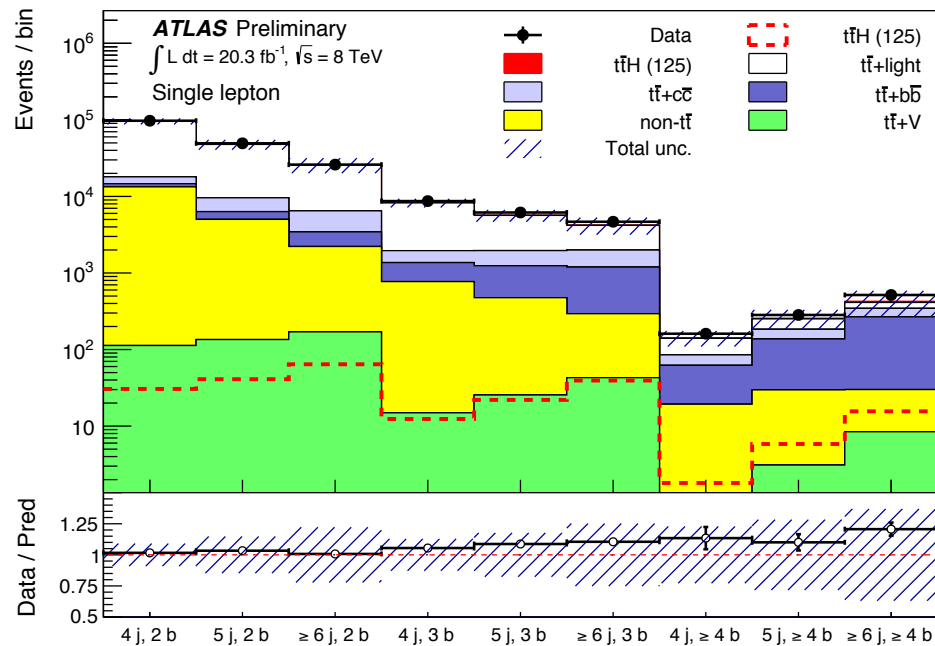
NN output (single lepton, HF vs LF NN)



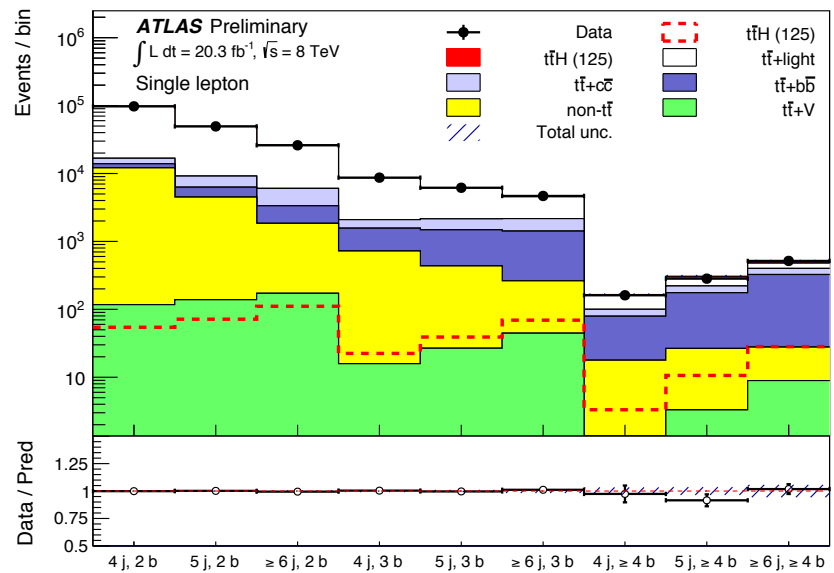
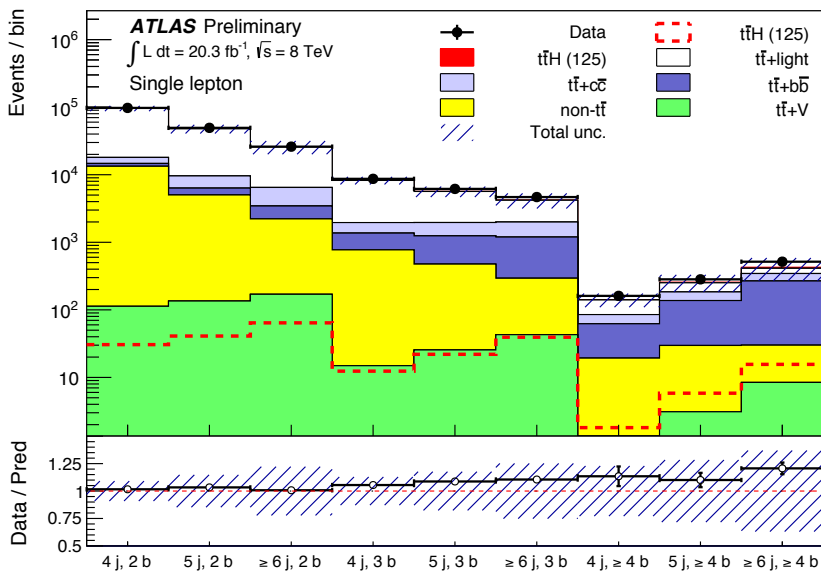
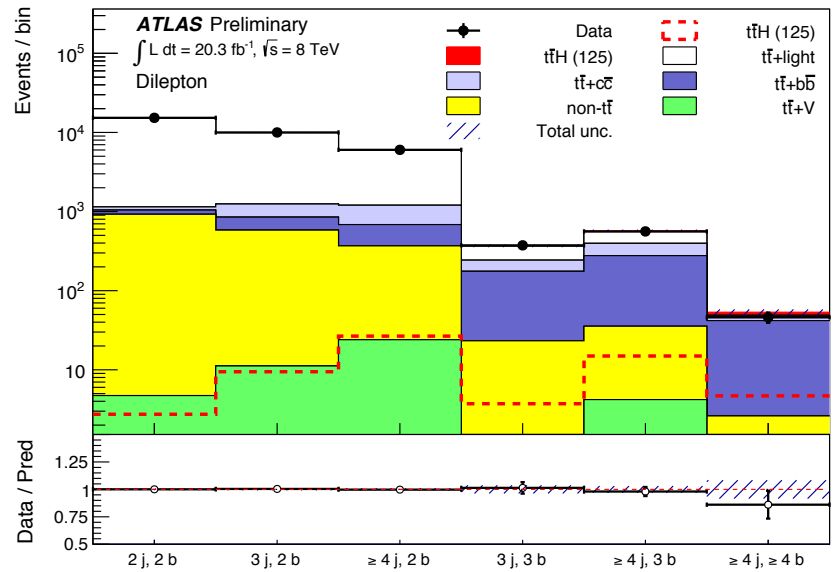
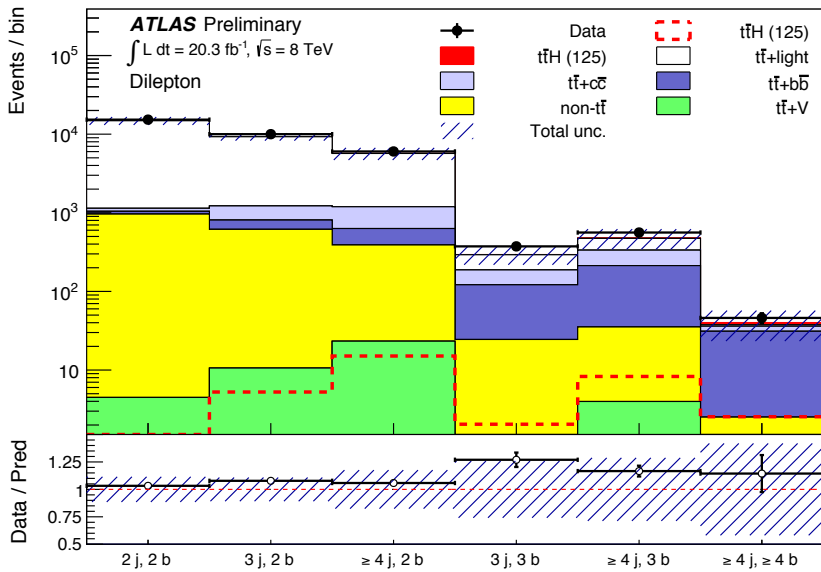
5 jet / 3 tag
 NN also
 benefits from
 profiling
 (common
 theme!)



Good data-MC agreement, but also very large uncertainties, and some trends in HF-enriched regions

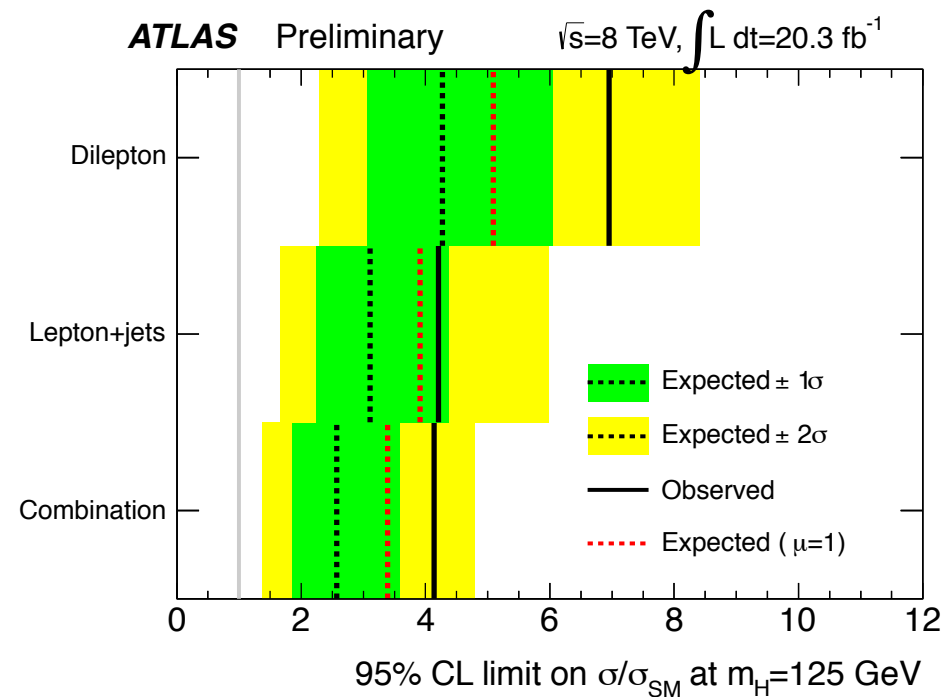
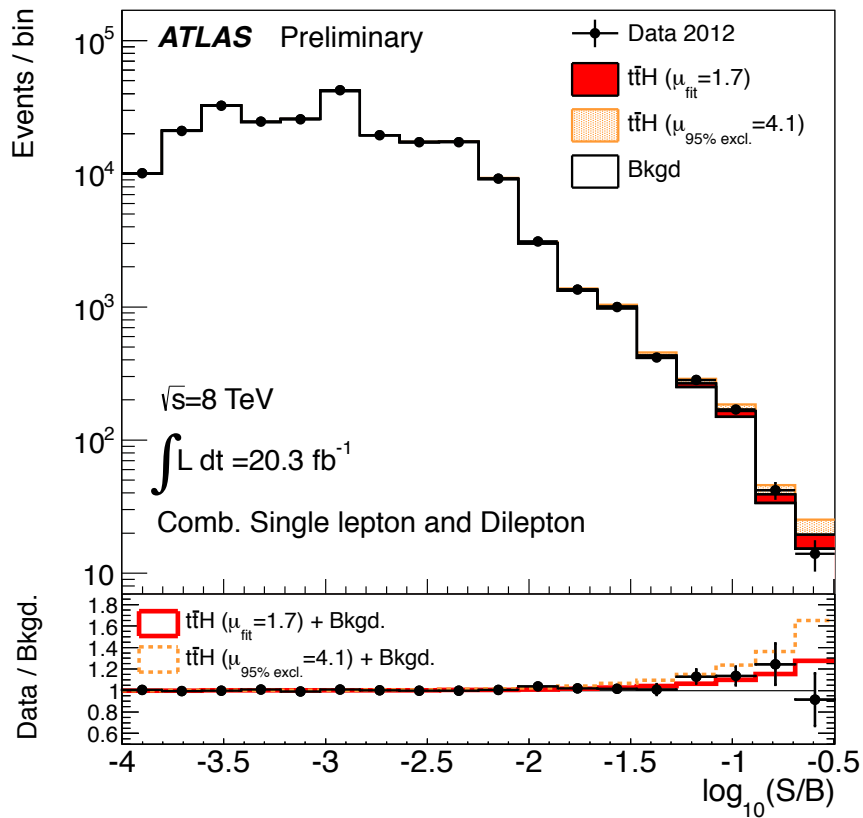


Yields pre-fit vs post-fit

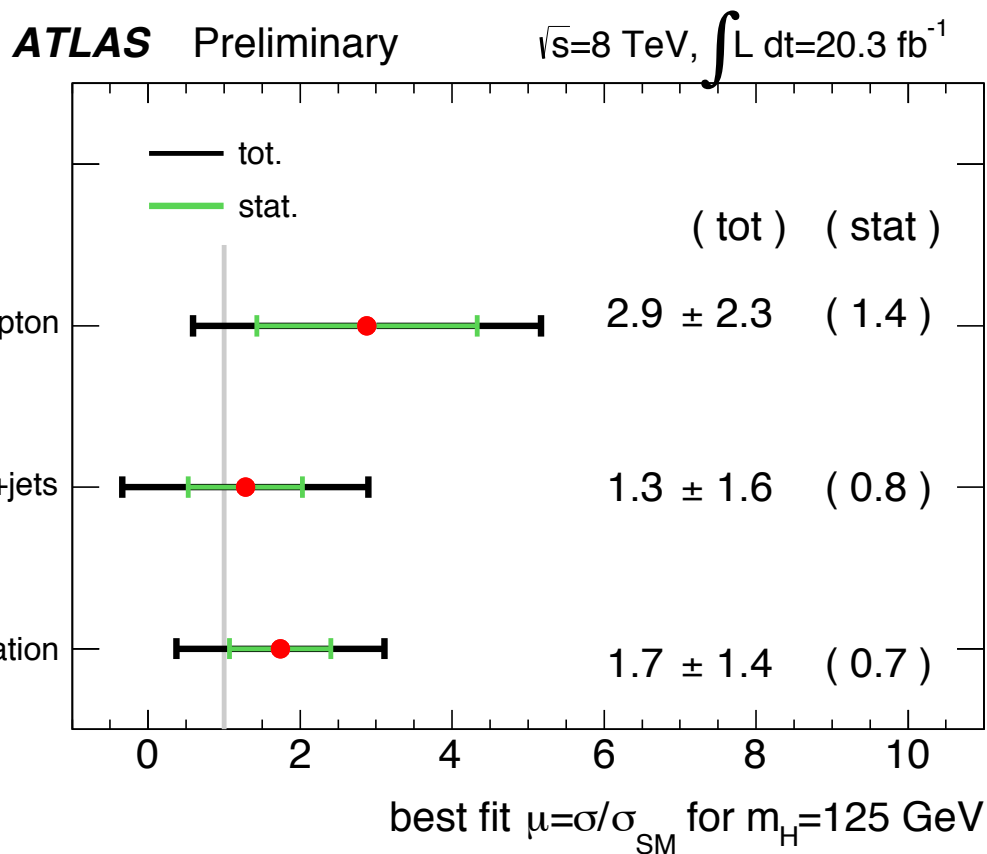


Results

95% CL upper limit on σ/σ_{SM}	observed	-2σ	-1σ	median	$+1\sigma$	$+2\sigma$	median ($\mu = 1$)
Single Lepton	4.2	1.7	2.2	3.1	4.4	6.0	3.9
Dilepton	7.0	2.3	3.1	4.3	6.1	8.4	5.1
Combination	4.1	1.4	1.9	2.6	3.6	5.0	3.4



Fitted signal strength

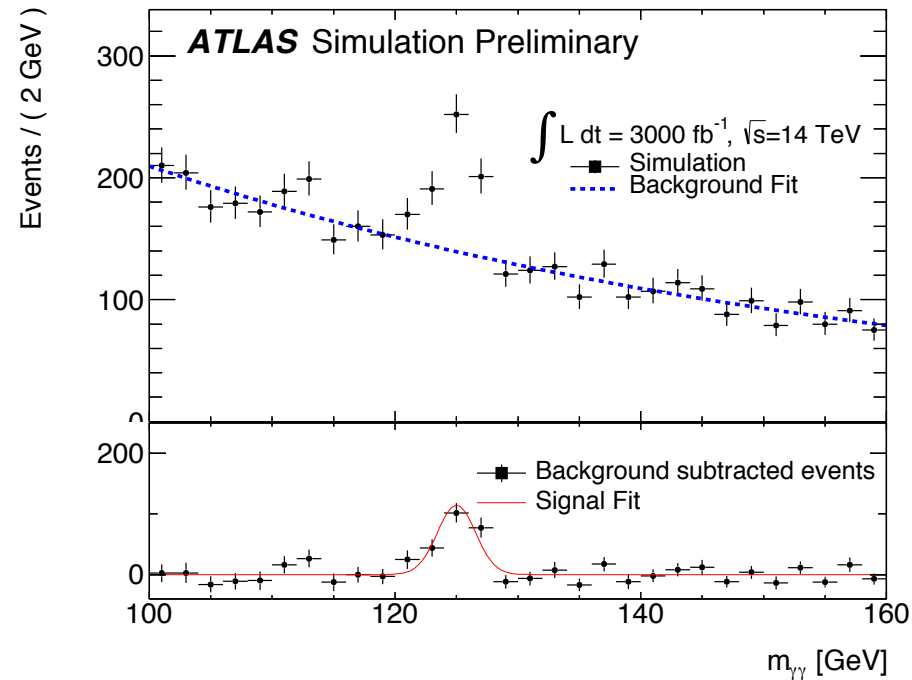


We're doing quite well (and have improvements close to ready for the public), but still have values consistent with 0 (and 1 and 2... and 3)

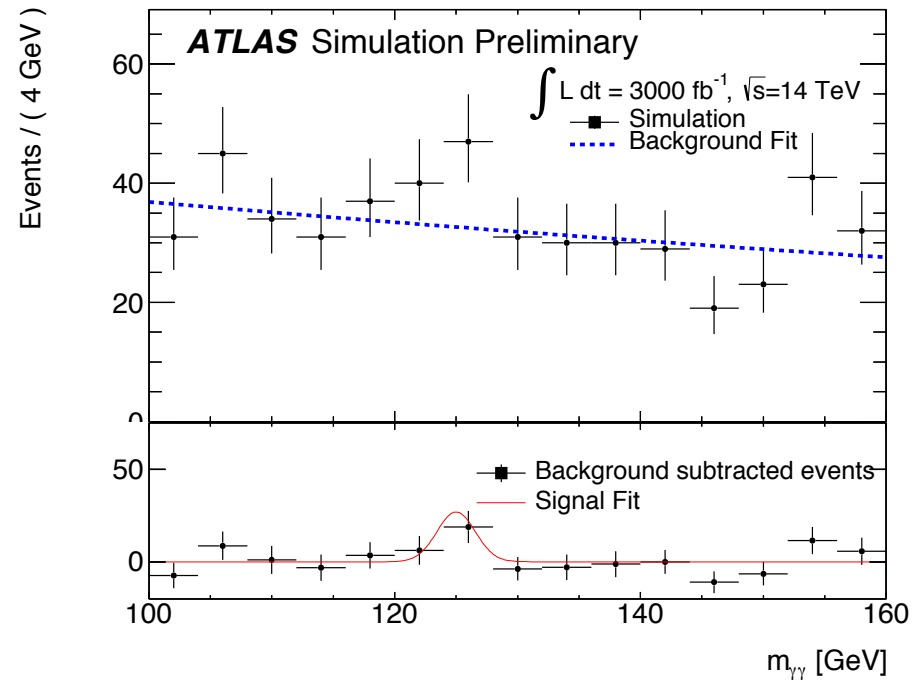
The short-term future

- Expect an updated $ttH(bb)$ paper with improvements to modeling and also statistical power
- In addition, a combination of the latest diphoton and bb results is coming in the very near future
 - Not only will it give a better result than either single analysis, but will also prepare us for...
- Multilepton analyses (ttH production, $H \rightarrow WW/ZZ/\tau\tau$ with leptonic final states)
 - Very challenging analyses, expect to give as good or better limits than $bb\bar{b}$

8.2 σ from diphoton channel with 3 ab⁻¹



ttH(diphoton)
single lepton selection



ttH(diphoton)
dilepton selection

Conclusions

- Lots of great progress in ttH searches in the past year, with a lot more to come in the near future
- New analyses and improved analyses almost ready
 - Work toward combinations of latest results within ATLAS has begun
- Hope that ATLAS+CMS can start to think about serious combinations as well in the near future



	4 jets, 2 b -tags	4 jets, 3 b -tags	4 jets, ≥ 4 b -tags	5 jets, 2 b -tags	5 jets, 3 b -tags	≥ 6 jets, 2 b -tags
$t\bar{t}H$ (125)	$31 \pm 3 \pm 3$	$12 \pm 1 \pm 1$	$1.8 \pm 0.2 \pm 0.2$	$41 \pm 2 \pm 4$	$22 \pm 2 \pm 2$	$64 \pm 5 \pm 7$
$t\bar{t}$ + light	78000 ± 8000	6300 ± 800	55 ± 12	38000 ± 6000	3700 ± 700	19000 ± 5000
$t\bar{t} + c\bar{c}$	3300 ± 1700	590 ± 310	23 ± 12	3300 ± 1700	700 ± 400	3000 ± 1600
$t\bar{t} + b\bar{b}$	1300 ± 700	600 ± 310	43 ± 23	1300 ± 700	800 ± 400	1200 ± 700
$t\bar{t} + V$	113 ± 35	15 ± 5	0.90 ± 0.29	140 ± 40	25 ± 8	170 ± 50
non- $t\bar{t}$	13200 ± 2300	760 ± 110	18.4 ± 3.1	4900 ± 1000	450 ± 80	2000 ± 500
Total	96000 ± 9000	8200 ± 1100	142 ± 32	48000 ± 7000	5700 ± 1000	26000 ± 6000
Data	97450	8692	161	49402	6168	26033

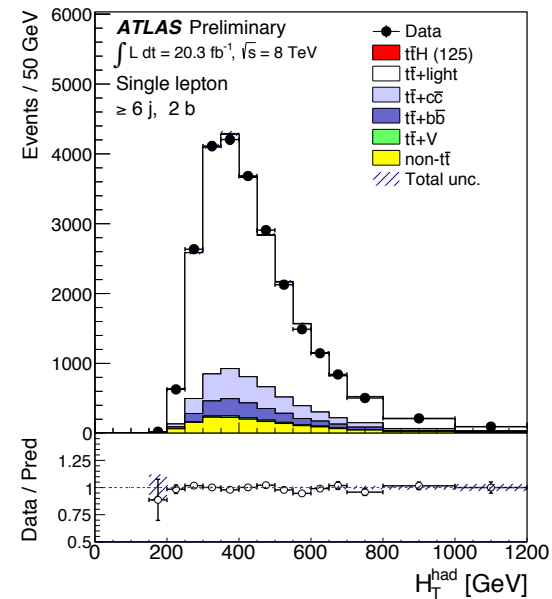
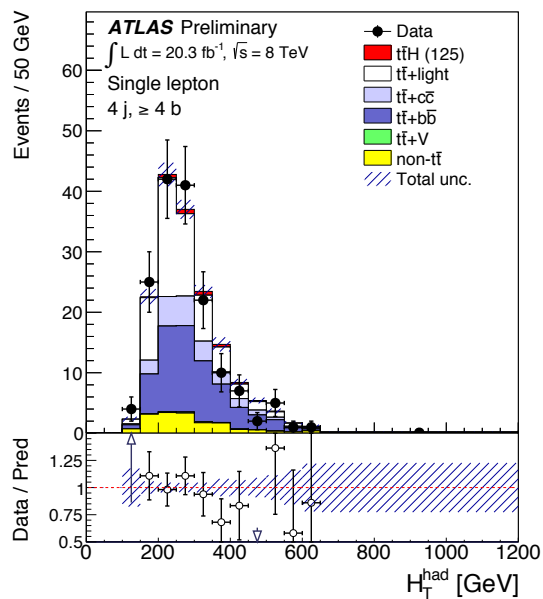
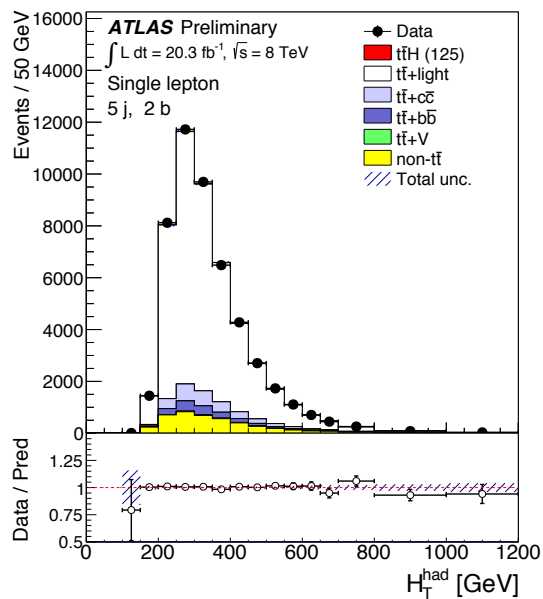
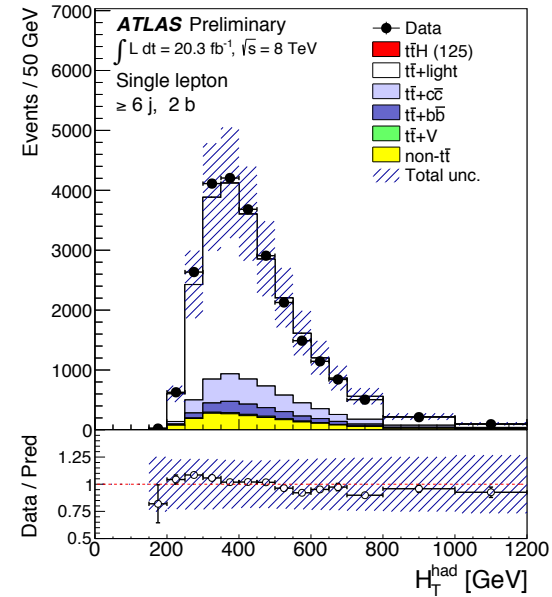
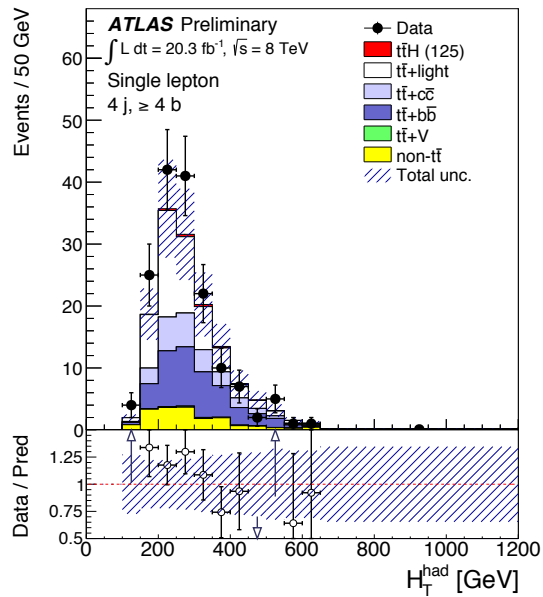
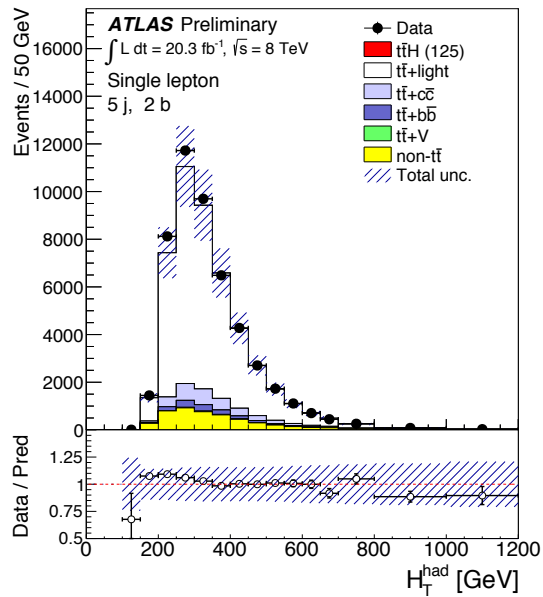
Table 1: Pre-fit event yields for signal, backgrounds and data in each of the signal-depleted regions in the single lepton channel. For signal, the first component of uncertainty is a contribution from acceptance and efficiency effects and the second is a contribution from the inclusive NLO cross section uncertainty taken from Ref. [28]. The quoted uncertainties on the backgrounds are the sum in quadrature of all individual systematic uncertainties on the yields.

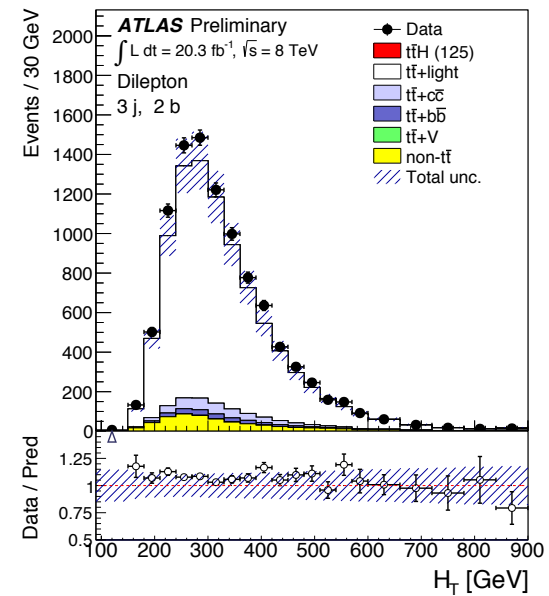
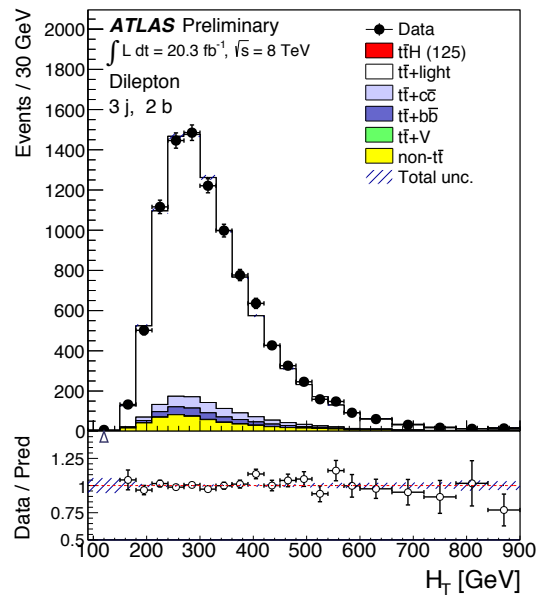
	5 jets, ≥ 4 b -tags	≥ 6 jets, 3 b -tags	≥ 6 jets, ≥ 4 b -tags
$t\bar{t}H$ (125)	$5.8 \pm 0.7 \pm 0.6$	$39 \pm 3 \pm 4$	$16 \pm 2 \pm 2$
$t\bar{t}$ + light	67 ± 16	2200 ± 600	67 ± 20
$t\bar{t} + c\bar{c}$	47 ± 25	800 ± 400	80 ± 40
$t\bar{t} + b\bar{b}$	110 ± 60	900 ± 500	240 ± 130
$t\bar{t} + V$	3.1 ± 1.0	43 ± 14	8.4 ± 2.8
non- $t\bar{t}$	26 ± 5	250 ± 50	22 ± 5
Total	260 ± 70	4200 ± 1100	430 ± 160
Data	283	4671	516

Table 2: Pre-fit event yields for signal, backgrounds and data in each of the signal-rich regions in the single lepton channel. For signal, the first component of uncertainty is a contribution from acceptance and efficiency effects and the second is a contribution from the inclusive NLO cross section uncertainty taken from Ref. [28]. The quoted uncertainties on the backgrounds are the sum in quadrature of all individual systematic uncertainties on the yields.

	2 jets, 2 b -tags	3 jets, 2 b -tags	3 jets, 3 b -tags	≥ 4 jets, 2 b -tags	≥ 4 jets, 3 b -tags	≥ 4 jets, ≥ 4 b -tags
$t\bar{t}H$ (125)	$1.5 \pm 0.2 \pm 0.2$	$5.3 \pm 0.4 \pm 0.6$	$2.0 \pm 0.2 \pm 0.2$	$15.1 \pm 0.8 \pm 1.6$	$8.3 \pm 0.6 \pm 0.9$	$2.5 \pm 0.3 \pm 0.3$
$t\bar{t}$ + light	13700 ± 1700	8000 ± 900	105 ± 20	4500 ± 800	138 ± 34	1.6 ± 0.7
$t\bar{t} + c\bar{c}$	100 ± 50	410 ± 210	70 ± 40	560 ± 300	120 ± 70	5.0 ± 2.8
$t\bar{t} + b\bar{b}$	80 ± 40	190 ± 100	100 ± 60	240 ± 130	180 ± 100	29 ± 16
$t\bar{t} + V$	4.5 ± 1.4	10.6 ± 3.3	0.9 ± 0.3	23 ± 7	4.0 ± 1.3	0.56 ± 0.18
non- $t\bar{t}$	960 ± 140	610 ± 80	24 ± 4	370 ± 60	31 ± 5	2.0 ± 0.4
Total	14800 ± 1700	9300 ± 1000	290 ± 80	5700 ± 1000	480 ± 140	40 ± 17
Data	15296	9997	374	6026	561	46

Table 3: Pre-fit event yields for signal, backgrounds and data in each of the analysis regions in the dilepton channel. For signal, the first component of uncertainty is a contribution from acceptance and efficiency effects and the second is a contribution from the inclusive NLO cross section uncertainty taken from Ref. [28]. The quoted uncertainties on the backgrounds are the sum in quadrature of all individual systematic uncertainties on the yields.





Variable	Definition
m_{bb}	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_T^{jet3}	Third leading jet p_T
p_T^{jet4}	Fourth leading jet p_T
Centrality	Sum of the p_T divided by sum of the E for all jets and both leptons
Aplanarity _{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
$\Delta R_{hl}^{\text{min } \Delta R}$	ΔR between the Higgs candidate and the closest lepton
$\Delta R_{hl}^{\text{max } \Delta R}$	ΔR between the Higgs candidate and the furthest lepton
N_{30}^{Higgs}	Number of Higgs candidates within 30 GeV of the defined Higgs mass
m_{ij}^{closest}	Dijet mass between any two jets closest to the defined Higgs mass
$\Delta\eta_{ij}^{\text{max } \Delta\eta}$	Maximum $\Delta\eta$ between any two jets in the event
$m_{ij}^{\text{min } m}$	Minimum dijet mass between any two jets
$m_{ij}^{\text{max } p_T}$	Mass of the combination of any two jets with the largest vector sum p_T
$m_{bb}^{\text{min } \Delta R}$	Mass of the combination of two b -tagged jets with the smallest ΔR
$\Delta R_{bj}^{\text{min } \Delta R}$	Minimum ΔR between a b -tagged jet and any jet
$\Delta R_{lj}^{\text{min } \Delta R}$	Minimum ΔR between any lepton and jet
$\Delta R_{bb}^{\text{max } p_T}$	ΔR between two b -tagged jets with the largest vector sum p_T
$\Delta R_{bb}^{\text{max } m}$	ΔR between two b -tagged jets with the largest invariant mass

Table 5: List of variables used in the NN in the dilepton channel in at least one region. From the list, 10 variables are chosen in each region

Variable	Definition
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
$m_{bb}^{\min \Delta R}$	Mass of the combination of two b -tagged jets with the smallest ΔR
N_{40}^{jet}	Number of jets with $p_T \geq 40$ GeV
$\Delta R_{bb}^{\text{avg}}$	Average ΔR for all b -tagged jet pairs
$m_{ij}^{\max p_T}$	Mass of the combination of any two jets with the largest vector sum p_T
Aplanarity _{b-jet}	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor built with only b -tagged jets
H_T^{had}	Scalar sum of jet p_T
$m_{ij}^{\min \Delta R}$	Mass of the combination of any two jets with the smallest ΔR
$\Delta R_{\text{lep-bb}}^{\min \Delta R}$	ΔR between the lepton and the combination of two b -tagged jets with the smallest ΔR
$m_{bj}^{\min \Delta R}$	Mass of the combination of a b -tagged jet and any jet with the smallest ΔR
$m_{bj}^{\max p_T}$	Mass of the combination of a b -tagged jet and any jet with the largest vector sum p_T
$m_{uu}^{\min \Delta R}$	Mass of the combination of two untagged jets with the smallest ΔR
p_T^{jet5}	Fifth leading jet p_T
$\Delta R_{bb}^{\max p_T}$	ΔR between two b -tagged jets with the largest vector sum p_T
$m_{bb}^{\max m}$	Mass of the combination of two b -tagged jets with the largest invariant mass
$p_{T,uu}^{\min \Delta R}$	Scalar sum of the p_T 's of the pair of untagged jets with the smallest ΔR
m_{ijj}	Mass of the jet triplet with the largest vector sum p_T
$\Delta R_{uu}^{\min \Delta R}$	Minimum ΔR between two untagged jets
$m_{bb}^{\max p_T}$	Mass of the combination of two b -tagged jets with the largest vector sum p_T

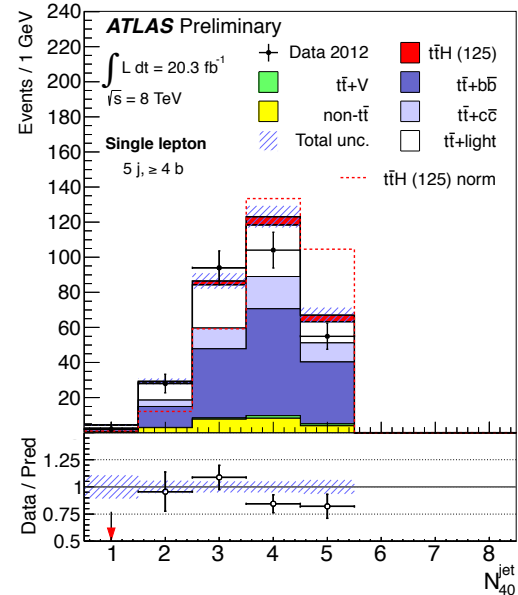
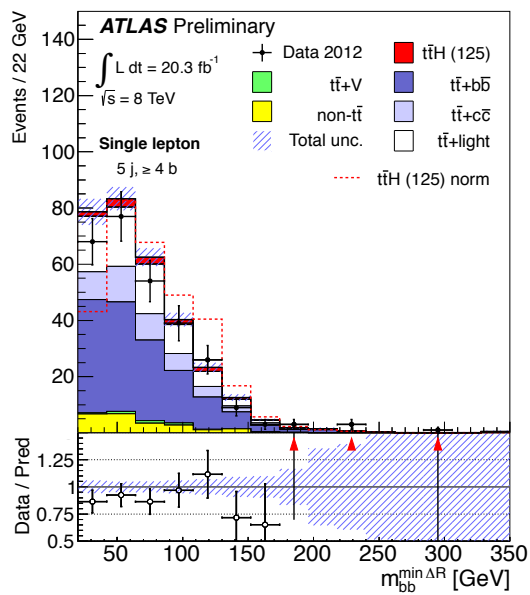
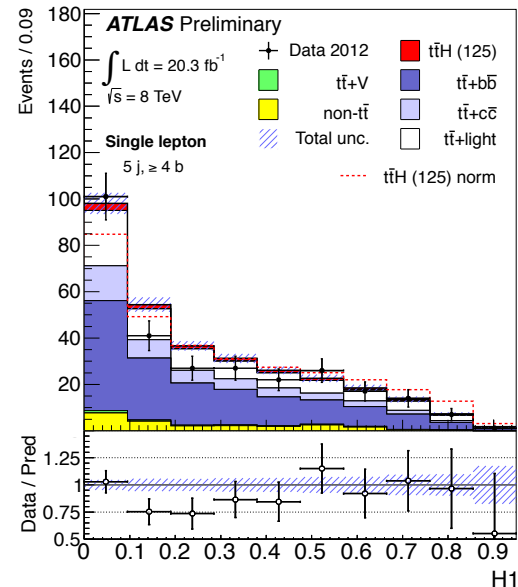
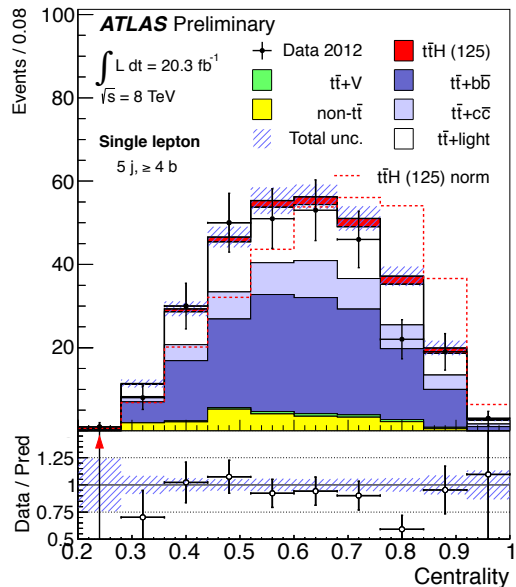
Table 4: List of variables used in the NN in the single lepton channel in at least one region. From the list, 10 variables are chosen in each region.

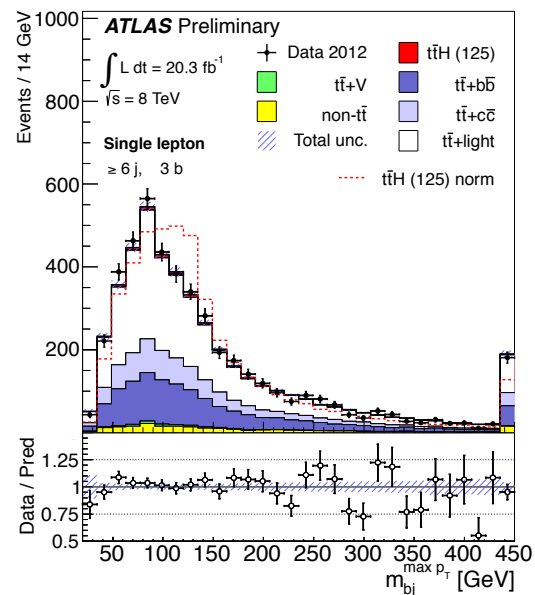
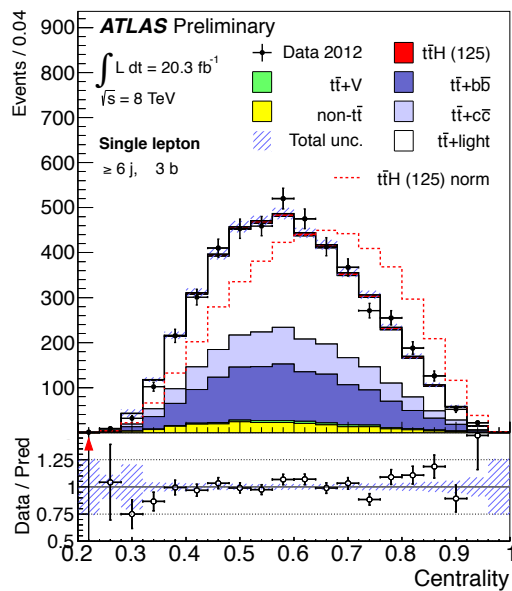
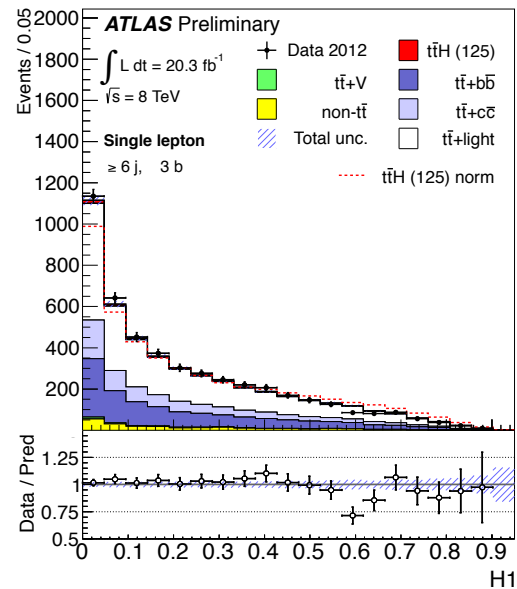
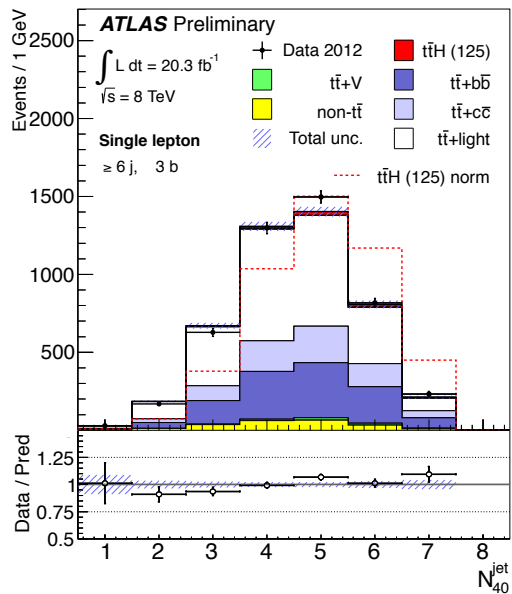
Variable	($\geq 4j, \geq 4b$)	($\geq 4j, 3b$)	($3j, 3b$)
$\Delta\eta_{jj}^{\max \Delta\eta}$	1	1	1
$m_{bb}^{\min \Delta R}$	2	8	-
$m_{b\bar{b}}$	3	-	-
$\Delta R_{hl}^{\min \Delta R}$	4	5	-
N_{30}^{Higgs}	5	2	5
$\Delta R_{bb}^{\max p_T}$	6	4	8
Aplanarity _{jet}	7	7	-
$m_{jj}^{\min m}$	8	3	2
$\Delta R_{hl}^{\max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

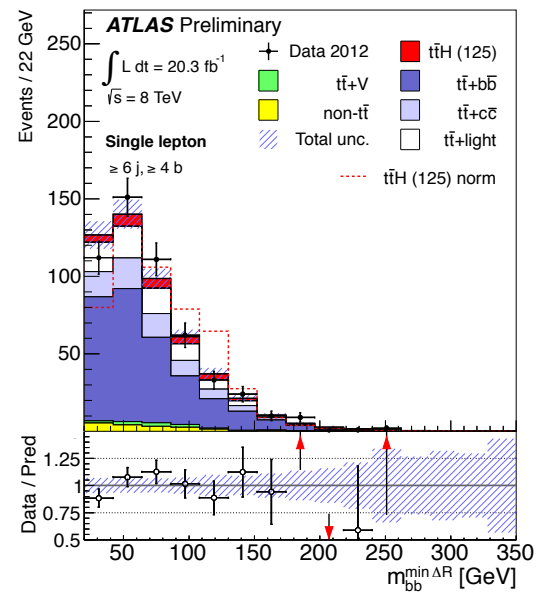
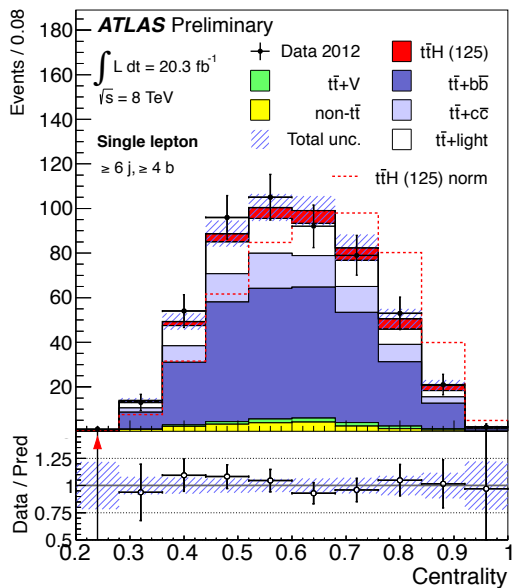
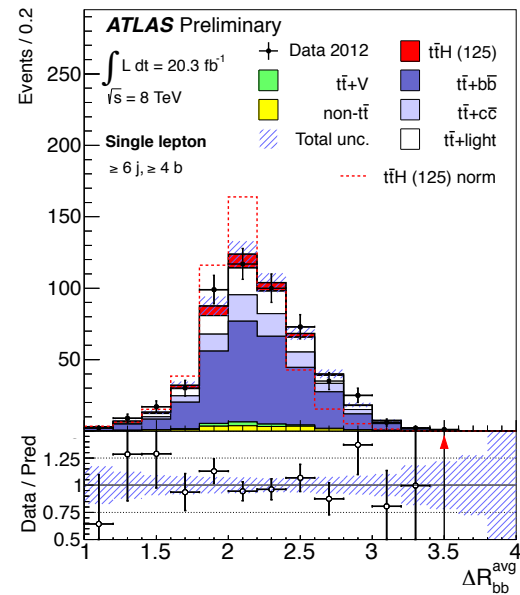
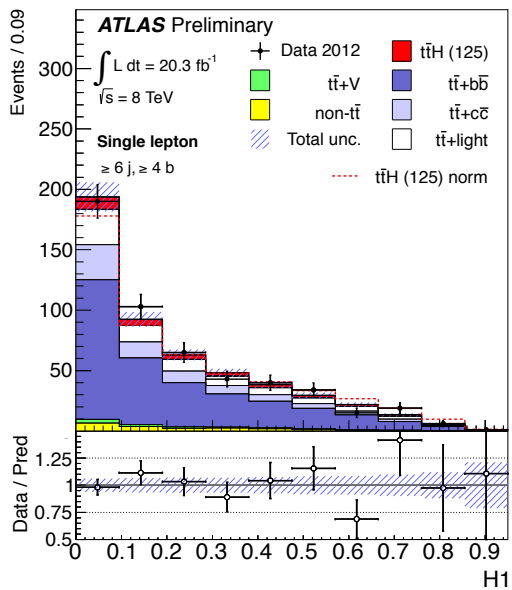
Table 7: The lists and rankings of the variables considered in each of the regions in the dilepton channel where a NN is used.

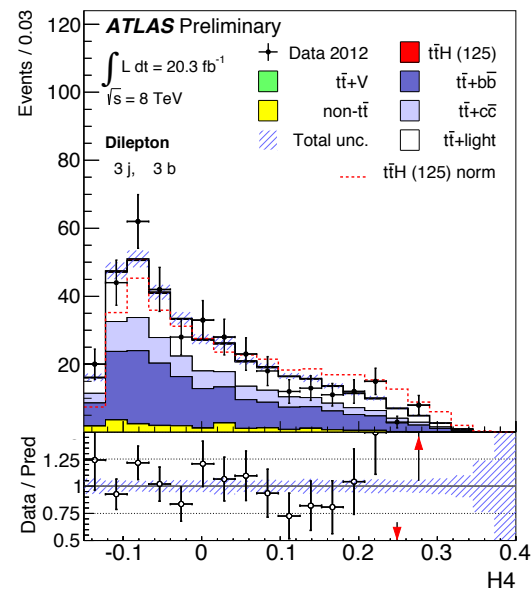
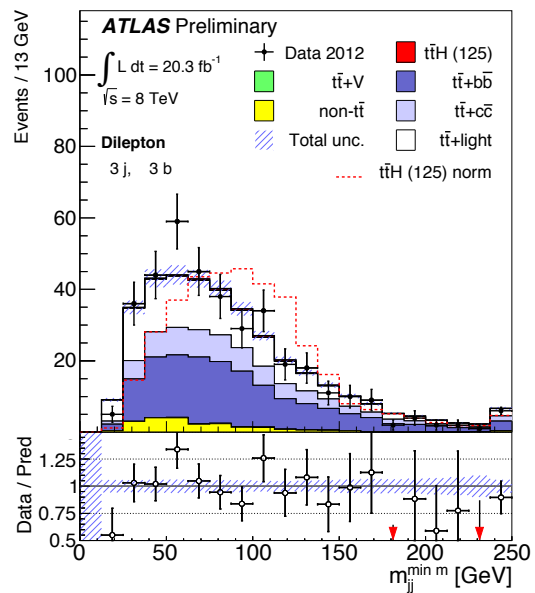
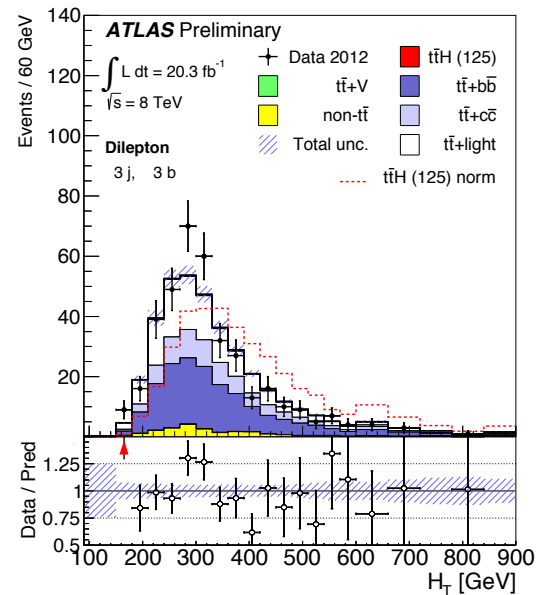
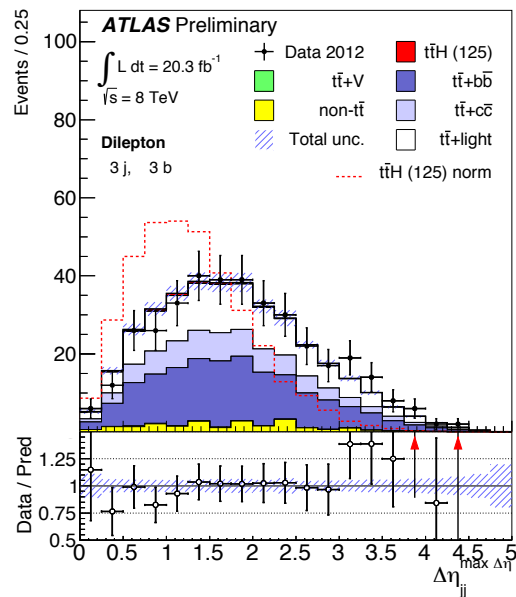
Variable	($\geq 6j, \geq 4b$)	($\geq 6j, 3b$)	($5j, \geq 4b$)	($5j, 3b$)
ΔR_{bb}^{avg}	1	5	5	-
$m_{bb}^{min \Delta R}$	2	9	3	1
Centrality	3	2	1	-
H1	4	3	2	-
p_T^{jet5}	5	8	-	-
Aplanarity _{b-jet}	6	-	7	-
$m_{uu}^{min \Delta R}$	7	7	-	2
$\Delta R_{bb}^{max p_T}$	8	-	-	-
$\Delta R_{lep-bb}^{min \Delta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

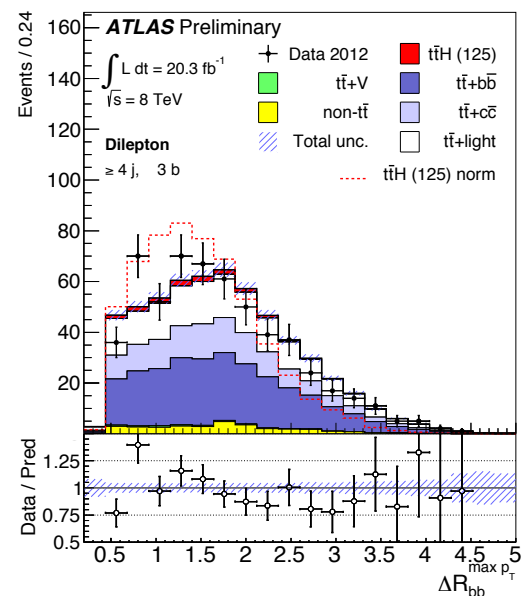
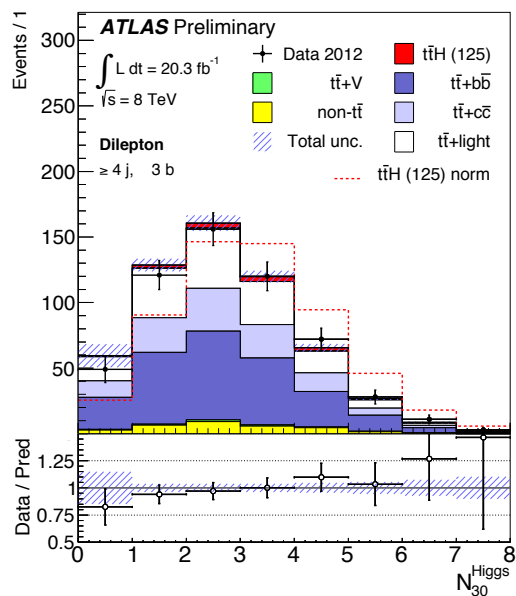
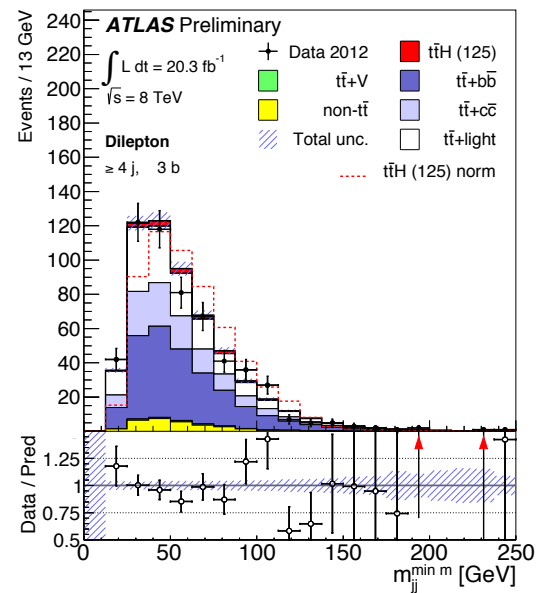
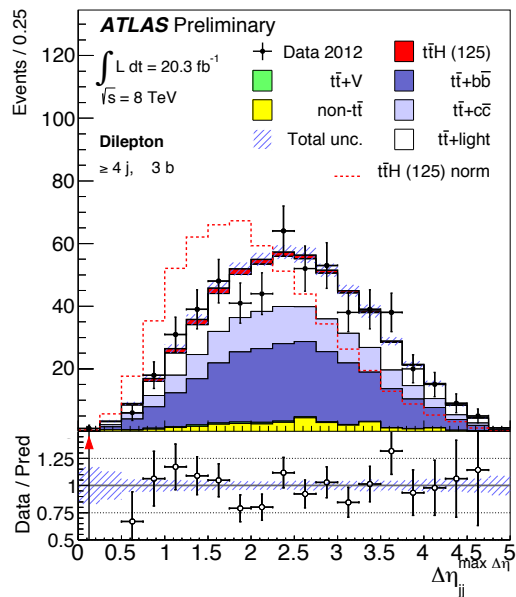
Table 6: The lists and rankings of the variables considered in each of the regions in the single lepton channel where a NN is used.

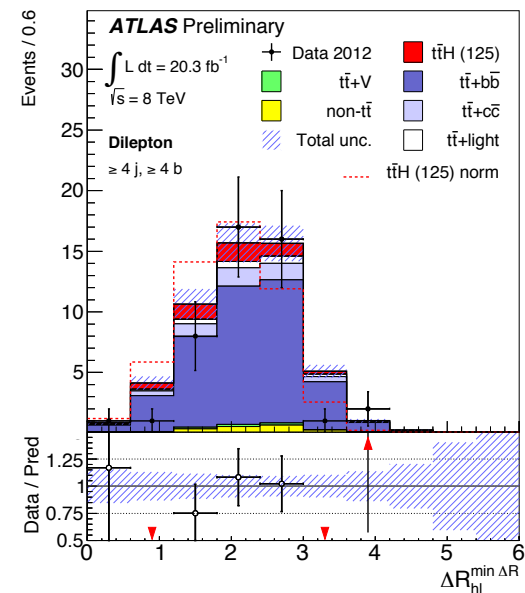
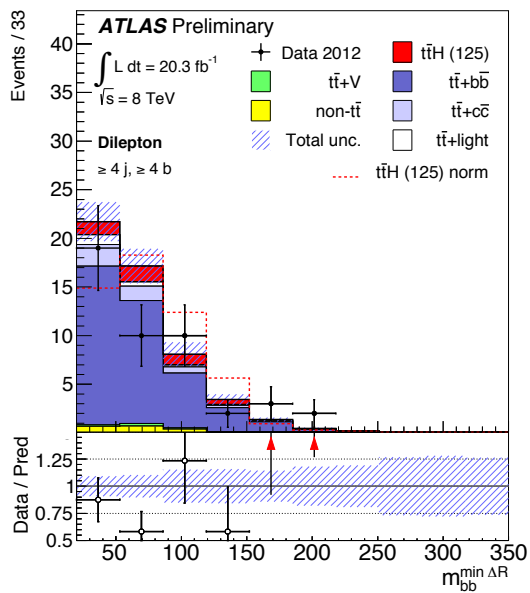
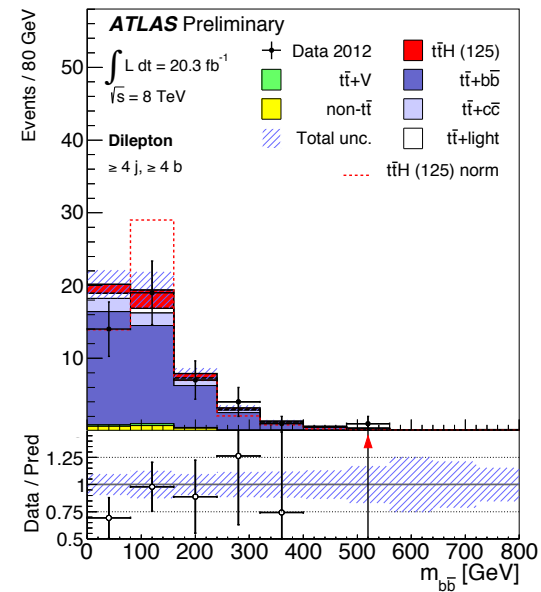
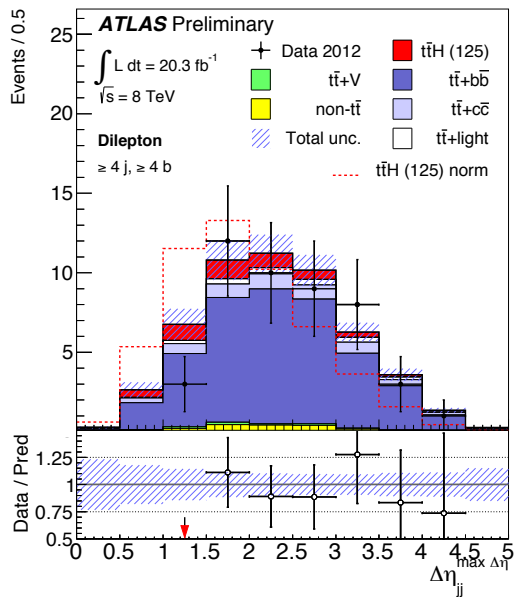


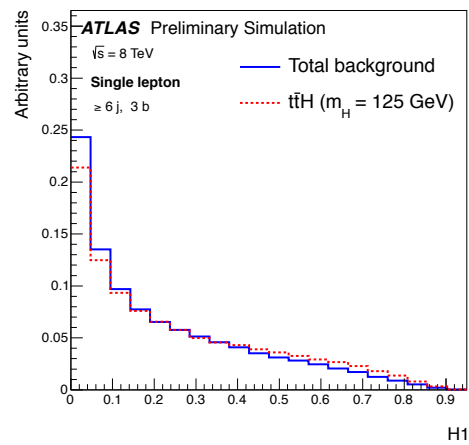
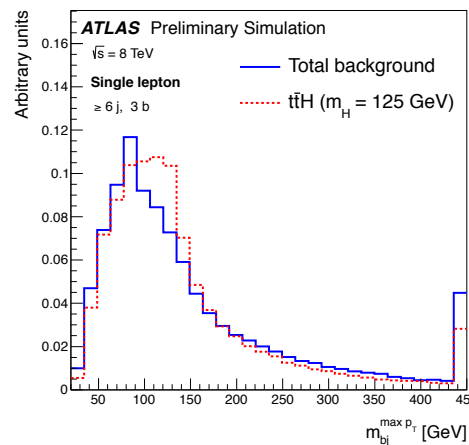
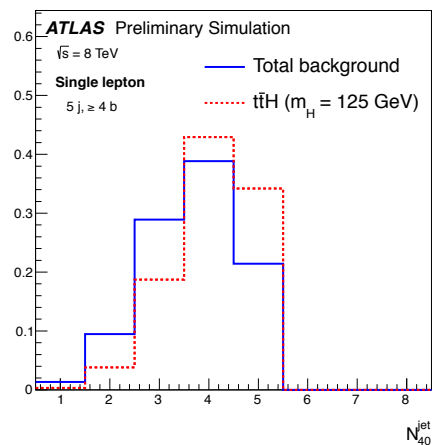
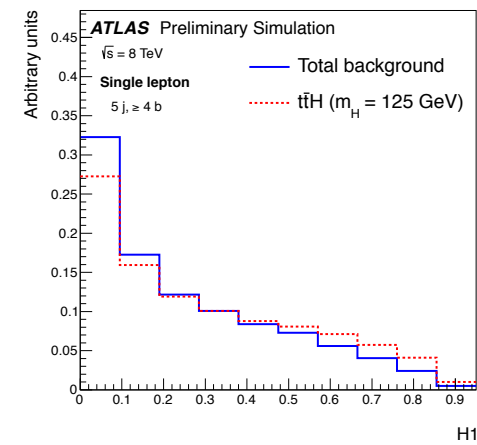
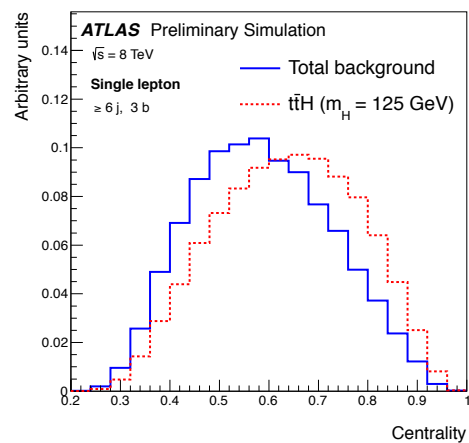
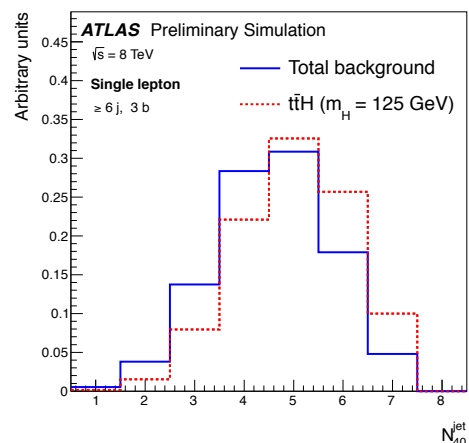
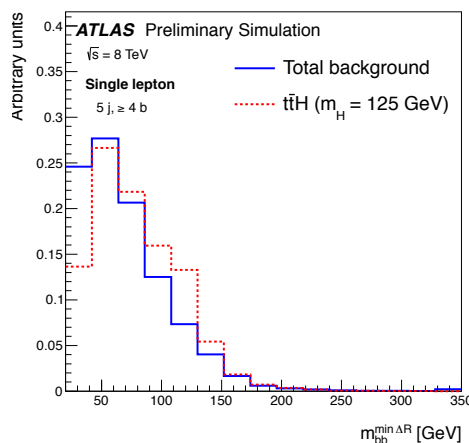
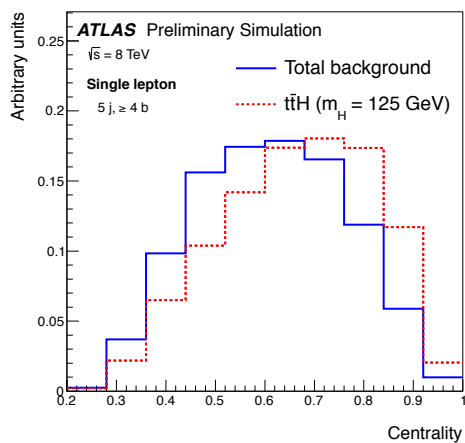


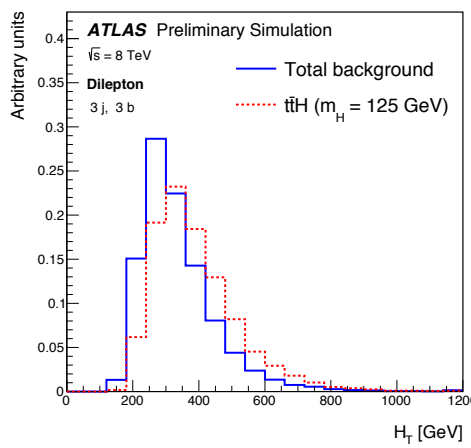
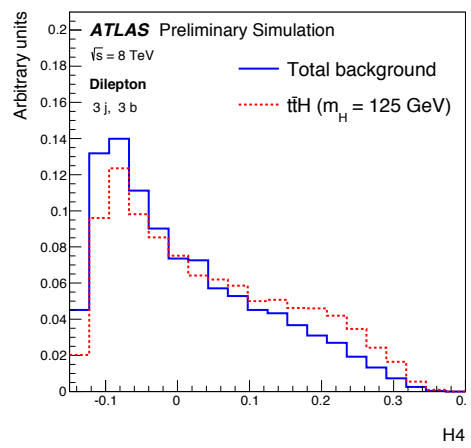
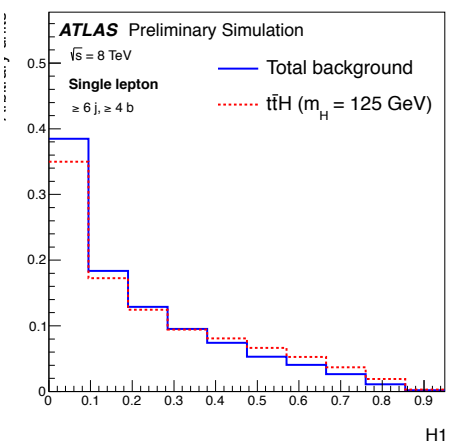
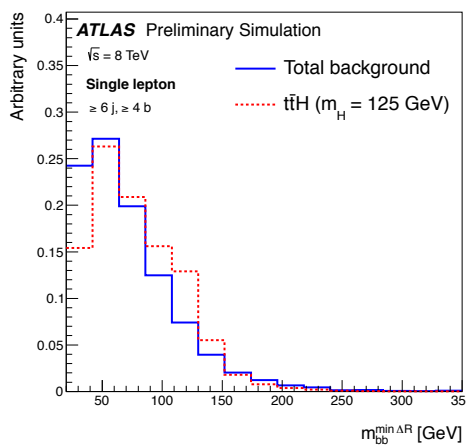
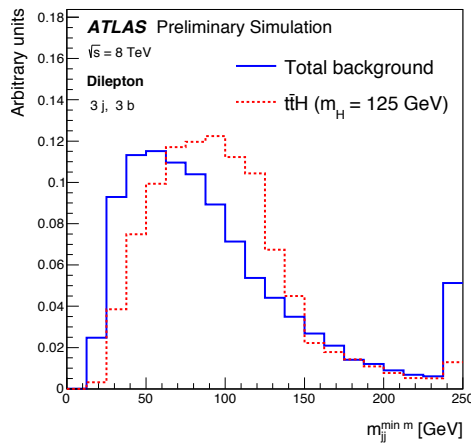
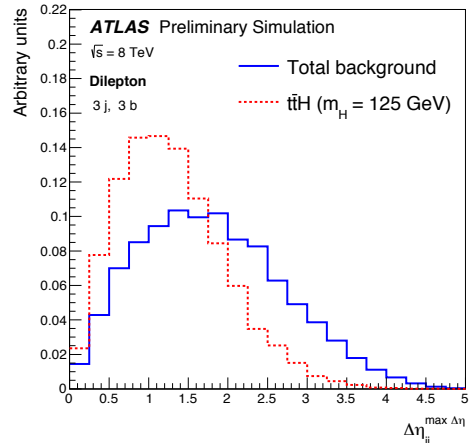
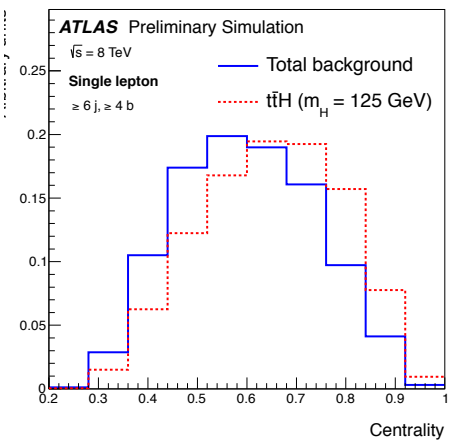
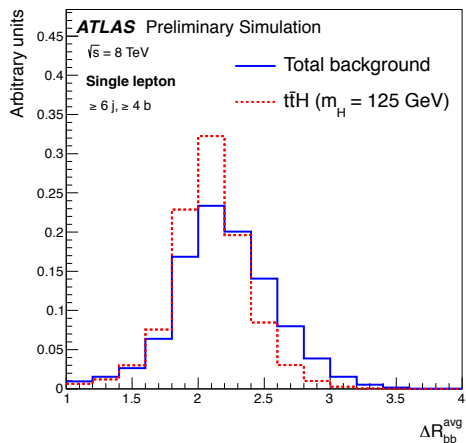


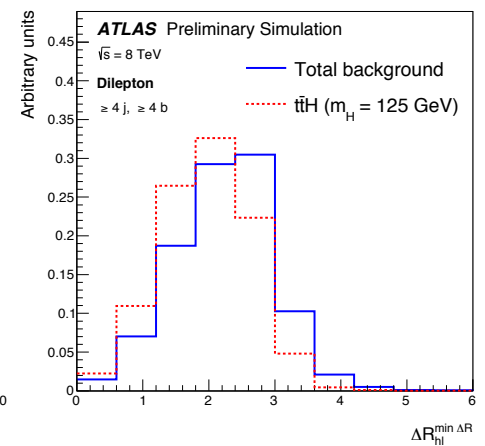
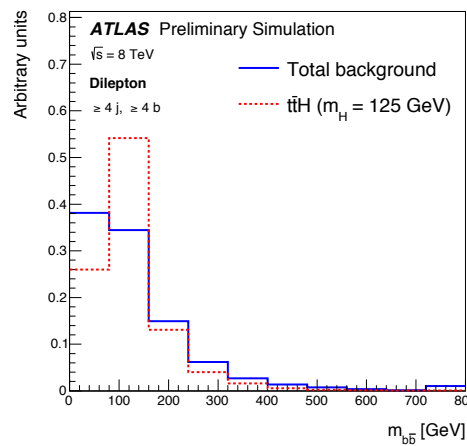
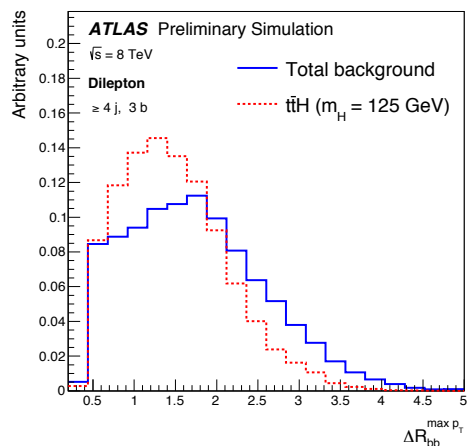
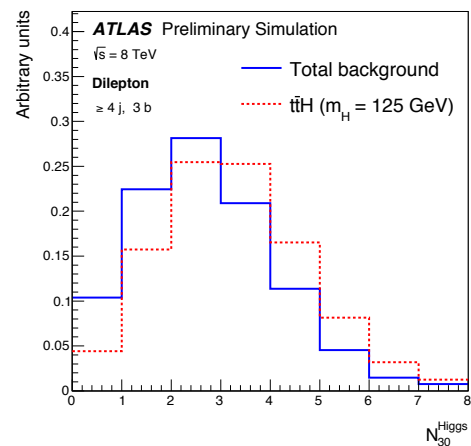
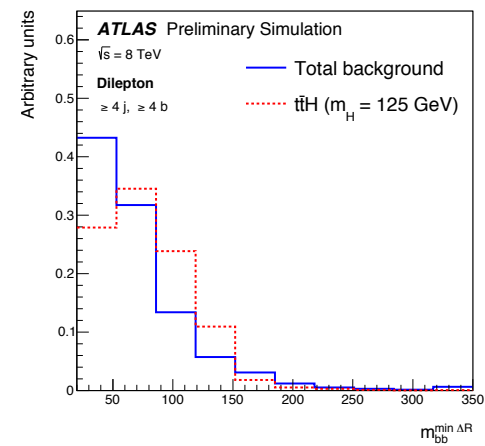
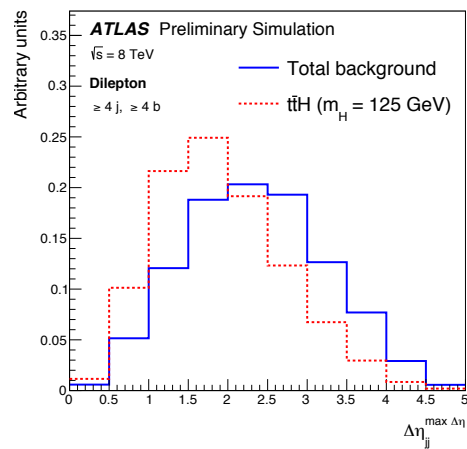
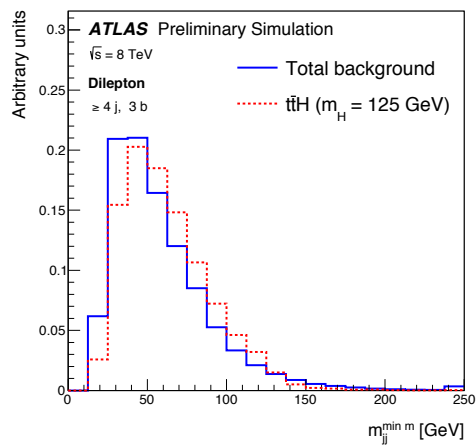
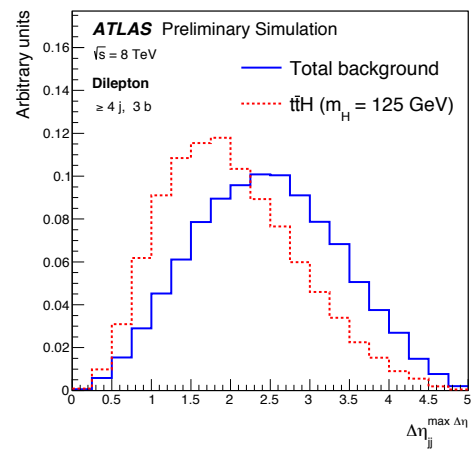












$t\bar{t}H(bb)$ systematic uncertainties

 $\geq 6j, \geq 4b$

	Pre-fit				Post-fit			
	$t\bar{t}H$ (125)	$t\bar{t} + \text{light}$	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$	$t\bar{t}H$ (125)	$t\bar{t} + \text{light}$	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$
Luminosity	± 2.8	± 2.8	± 2.8	± 2.8	± 2.6	± 2.6	± 2.6	± 2.6
Lepton efficiencies	± 1.4	± 1.4	± 1.4	± 1.5	± 1.3	± 1.3	± 1.3	± 1.3
Jet energy scale	± 6.5	± 14	± 10	± 8.2	± 2.6	± 5.9	± 4.2	± 3.5
Jet efficiencies	± 1.6	± 5.4	± 2.5	± 2.4	± 0.7	± 2.3	± 1.1	± 1.1
Jet energy resolution	± 0.1	± 8.5	± 4.1	± 4.3	± 0.1	± 5.6	± 3.7	± 3.9
b -tagging efficiency	± 9.0	± 5.8	± 5.1	± 9.2	± 6.4	± 4.2	± 3.7	± 6.5
c -tagging efficiency	± 1.9	± 7.3	± 14	± 2.8	± 0.8	± 4.0	± 7.8	± 1.6
Light jet-tagging efficiency	± 1.0	± 17	± 4.4	± 1.5	± 0.8	± 14	± 3.7	± 1.2
$t\bar{t}$ modelling: reweighting	–	± 11	± 13	± 13	–	± 5.3	± 6.0	± 6.4
$t\bar{t}$ modelling: parton shower	–	± 7.5	± 1.8	± 10	–	± 2.3	± 0.7	± 4.0
$t\bar{t}$ heavy-flavour: normalisation	–	–	± 50	± 50	–	–	± 29	± 15
$t\bar{t}$ heavy-flavour: reweighting	–	–	± 11	± 12	–	–	± 6.3	± 6.8
$t\bar{t}$ heavy-flavour: generator	–	–	± 2.2	± 2.9	–	–	± 2.2	± 2.8
Theoretical cross sections	–	± 6.2	± 6.3	± 6.3	–	± 4.3	± 4.3	± 4.3
$t\bar{t}H$ modelling	± 1.9	–	–	–	± 1.9	–	–	–
Total	± 12	± 30	± 57	± 56	± 7.2	± 14	± 25	± 14

Table 14: Normalisation uncertainties (expressed in %) on signal and main background processes for the systematic uncertainties considered, before and after the fit to data in ($\geq 6j, \geq 4b$) region of the single lepton channel. The total uncertainty can be different from the sum in quadrature of individual sources due to the anti-correlations between them.

 $\geq 4j, \geq 4b$

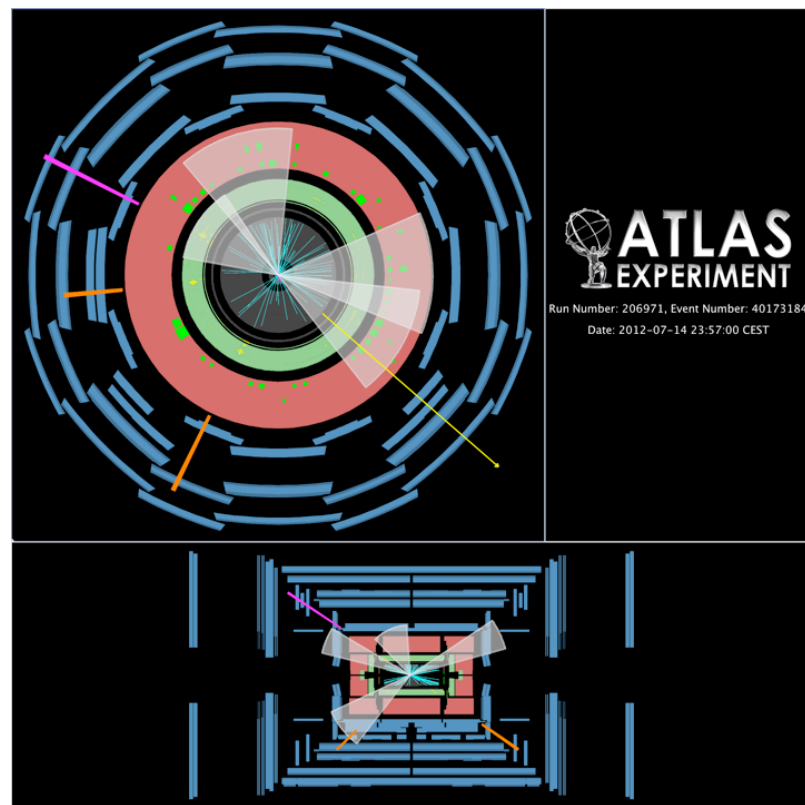
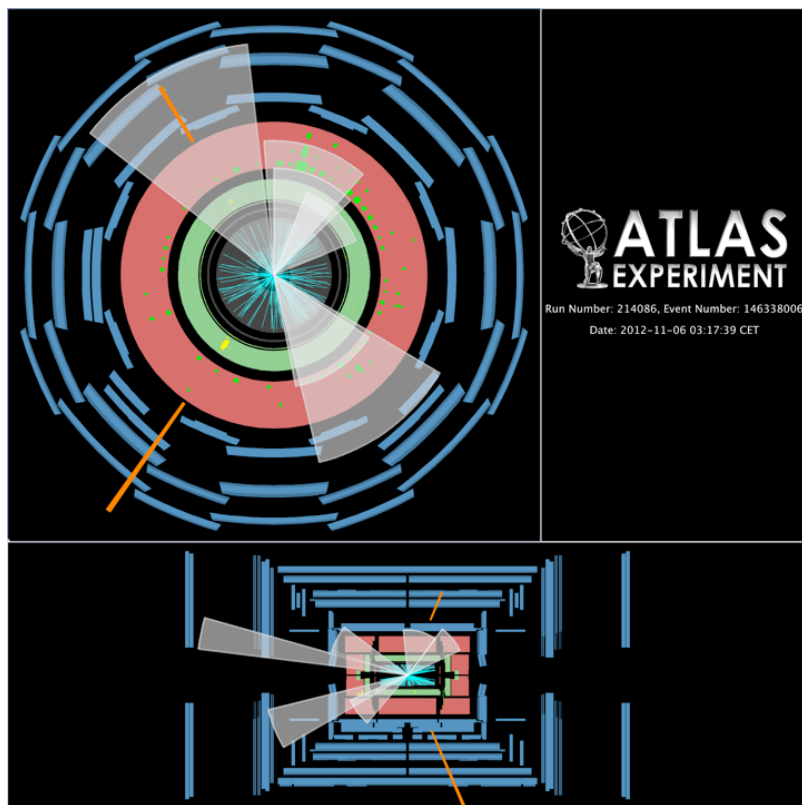
	Pre-fit				Post-fit			
	$t\bar{t}H$ (125)	$t\bar{t} + \text{light}$	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$	$t\bar{t}H$ (125)	$t\bar{t} + \text{light}$	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$
Luminosity	± 2.8	± 2.8	± 2.8	± 2.8	± 2.6	± 2.6	± 2.6	± 2.6
Lepton efficiencies	± 2.6	± 2.5	± 2.6	± 2.5	± 2.0	± 2.0	± 2.0	± 2.0
Jet energy scale	± 4.4	± 19	± 8.5	± 6.8	± 2.1	± 7.8	± 3.4	± 3.2
Jet efficiencies	± 0.3	± 5.3	± 1.6	± 0.9	± 0.1	± 2.3	± 0.7	± 0.4
Jet energy resolution	± 0.1	± 13	± 4.2	± 4.2	± 0.1	± 7.9	± 3.8	± 3.9
b -tagging efficiency	± 10	± 7.9	± 5.4	± 11	± 7.2	± 5.3	± 3.8	± 7.3
c -tagging efficiency	± 0.6	± 1.8	± 14	± 0.7	± 0.3	± 1.0	± 6.9	± 0.3
Light jet-tagging efficiency	± 0.7	± 23	± 5.7	± 1.4	± 0.6	± 18	± 4.7	± 1.2
$t\bar{t}$ modelling: reweighting	–	± 11	± 13	± 13	–	± 5.2	± 6.1	± 6.2
$t\bar{t}$ modelling: parton shower	–	± 23	± 0.3	± 1.1	–	± 6.8	± 0.1	± 0.4
$t\bar{t}$ heavy-flavour: normalisation	–	–	± 50	± 50	–	–	± 29	± 15
$t\bar{t}$ heavy-flavour: reweighting	–	–	± 11	± 11	–	–	± 6.0	± 6.4
$t\bar{t}$ heavy-flavour: generator	–	–	± 3.3	± 3.4	–	–	± 3.2	± 3.3
Theoretical cross sections	–	± 6.3	± 6.3	± 6.3	–	± 4.3	± 4.3	± 4.3
$t\bar{t}H$ modelling	± 0.8	–	–	–	± 0.8	–	–	–
Total	± 12	± 43	± 56	± 55	± 7.4	± 21	± 25	± 14

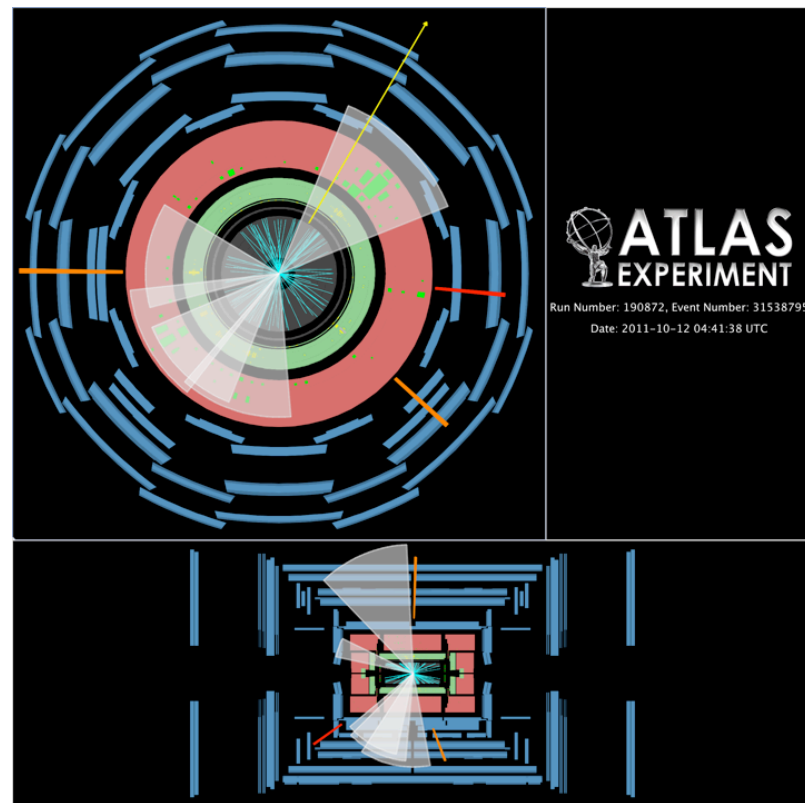
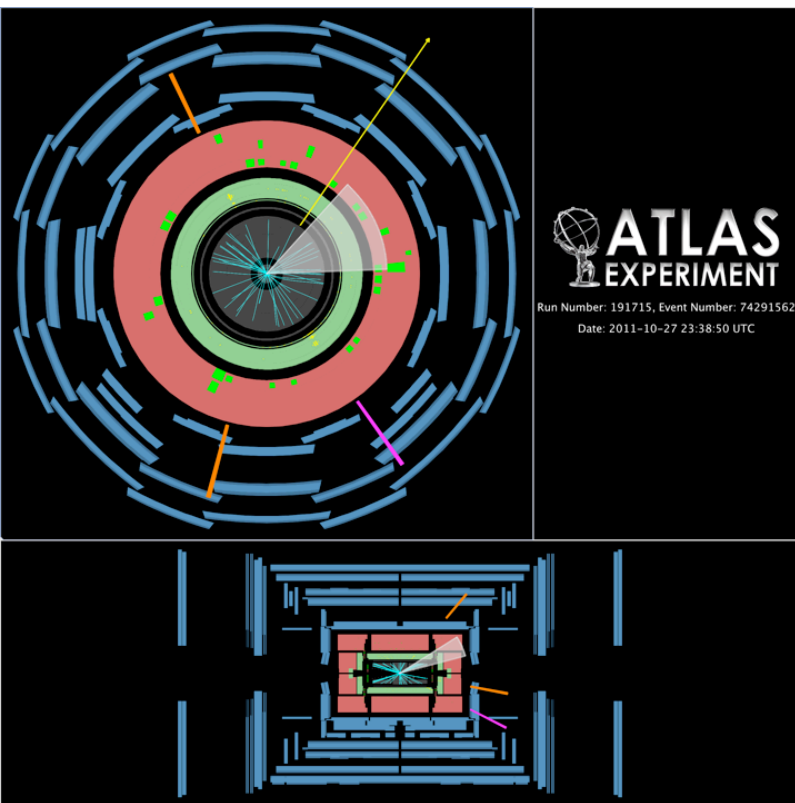
Table 15: Normalisation uncertainties (expressed in %) on signal and main background processes for the systematic uncertainties considered, before and after the fit to data in ($\geq 4j, \geq 4b$) region of the dilepton channel. The total uncertainty can be different from the sum in quadrature of individual sources due to the anti-correlations between them.

A.2 Naming convention

Naming convention for the nuisance parameters corresponding to various systematic uncertainties in Figure 18:

- BTag1, BTag2, BTag3: 3 components of b -tagging uncertainty, beginning with the largest normalisation effect
- CTag1, CTag2: 2 components of c -tagging uncertainties, beginning with the largest normalisation effect
- LightTag1, LightTag2: 2 components of light tag uncertainty, beginning with the largest normalisation effect
- JES1: one of 22 components of jet energy scale uncertainty
- $t\bar{t}$ MCgen RW: choice of the MC generator for $t\bar{t}$ in the differential cross section measurement
- $t\bar{t}$ +HF top p_T RW and $t\bar{t}$ +HF $t\bar{t}$ p_T RW: uncertainties corresponding to switching top p_T and $t\bar{t}$ p_T reweighting off, respectively, for $t\bar{t}$ +HF
- $t\bar{t}$ +HF MG-PP: generator choice for $t\bar{t}$ +HF (Powheg vs Madgraph)
- $t\bar{t}$ cross section: $t\bar{t}$ inclusive cross section
- $t\bar{t}+b\bar{b}$ normalisation: $t\bar{t}+b\bar{b}$ normalisation uncertainty for events with at least one b -jet
- $t\bar{t}+c\bar{c}$ normalisation: $t\bar{t}+c\bar{c}$ normalisation uncertainty for events with at least one c -jet
- $t\bar{t}+V$ cross section: cross section for $t\bar{t} + V, (V = Z, W)$ production





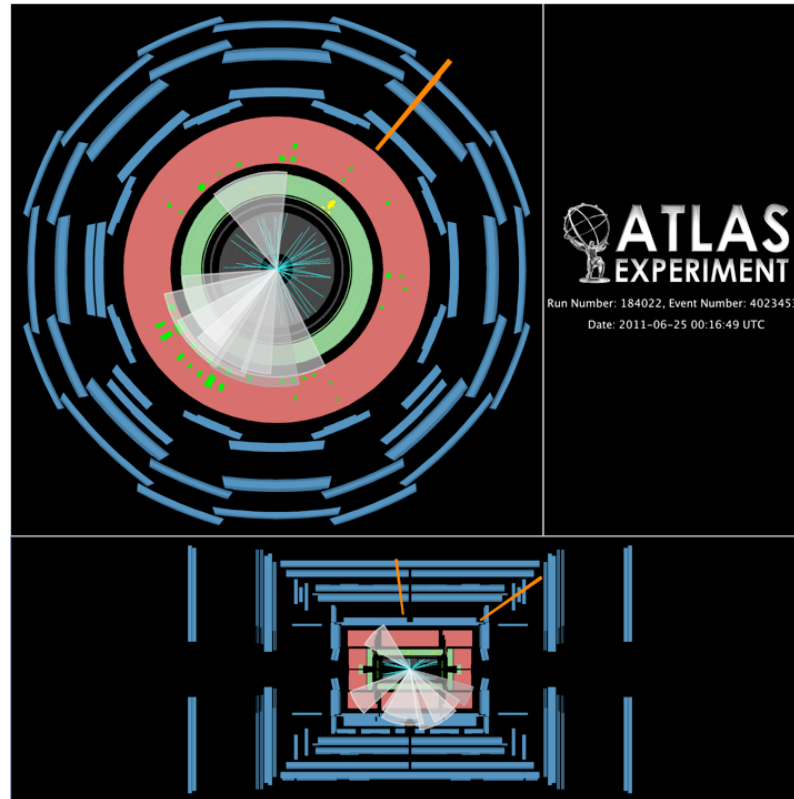
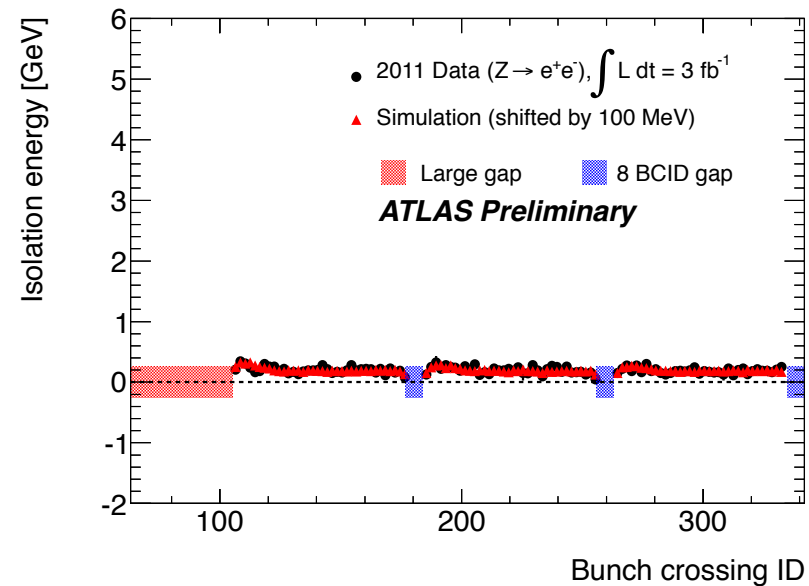
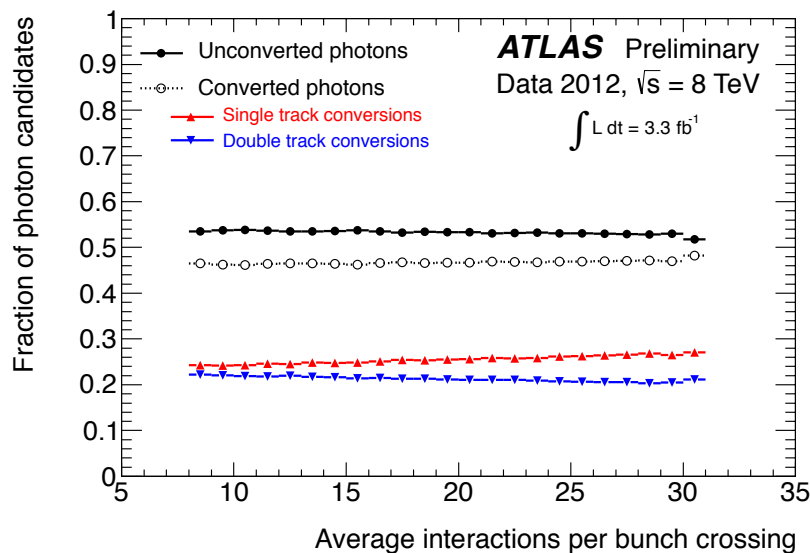


Table 1: Production cross sections for the various Higgs boson processes at 7 TeV and 8 TeV before taking into account the $\text{BR}(H \rightarrow \gamma\gamma)$ at $m_H = 125$ GeV. Also quoted are the theoretical uncertainties from variations of the renormalization and factorization scales and uncertainties on the parton distribution functions [62, 63].

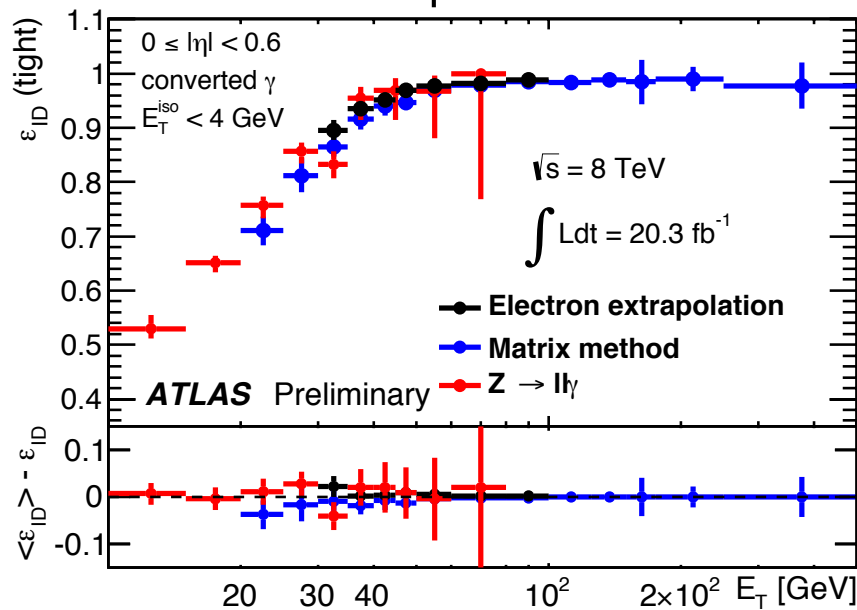
Process	σ [pb] at 7 TeV	σ [pb] at 8 TeV
$t\bar{t}H$	$0.086^{+0.008}_{-0.011}$	$0.129^{+0.012}_{-0.016}$
$tHqb, \kappa_t = +1$	$0.0111^{+0.0009}_{-0.0008}$	$0.0172^{+0.0012}_{-0.0011}$
$tHqb, \kappa_t = 0$	$0.040^{+0.003}_{-0.003}$	$0.059^{+0.004}_{-0.004}$
$tHqb, \kappa_t = -1$	$0.129^{+0.010}_{-0.009}$	$0.197^{+0.014}_{-0.013}$
$WtH, \kappa_t = +1$	$0.0029^{+0.0007}_{-0.0006}$	$0.0047^{+0.0010}_{-0.0009}$
$WtH, \kappa_t = 0$	$0.0043^{+0.0011}_{-0.0008}$	$0.0073^{+0.0017}_{-0.0013}$
$WtH, \kappa_t = -1$	$0.016^{+0.004}_{-0.003}$	$0.027^{+0.006}_{-0.005}$
ggF	15.1 ± 1.6	19.3 ± 2.0
VBF	1.22 ± 0.03	1.58 ± 0.04
WH	0.579 ± 0.016	0.705 ± 0.018
ZH	0.335 ± 0.013	0.415 ± 0.017

- Use “tight” photon ID. Can have unconverted, 1-track converted or 2-track converted photons, all isolated
- Σp_T (tracks with $p_T > 1$ GeV) in cone $dR < 0.2$ from photon < 2.6 GeV
- ΣE_T (calorimeter) in cone $dR < 0.4$ from photon < 6 GeV, corrected for γ energy leakage and pileup

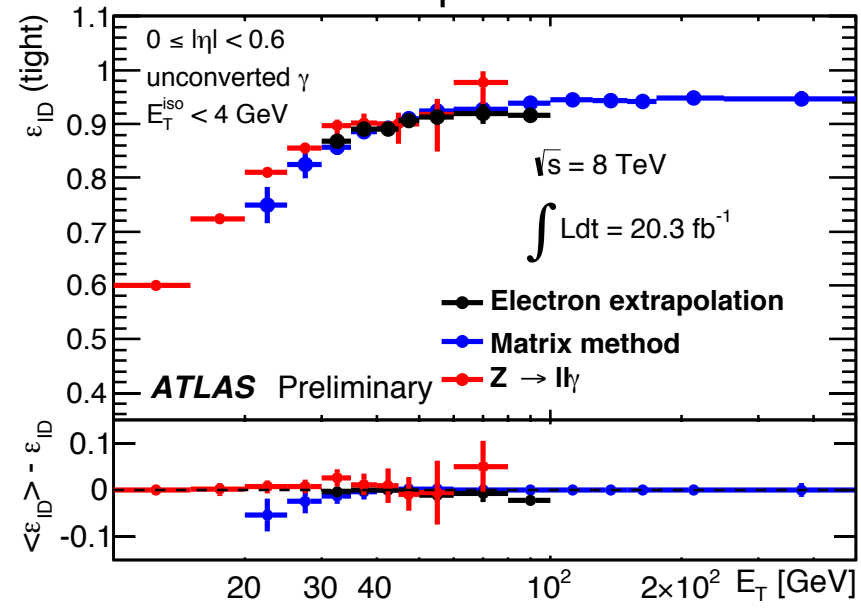


Efficiency extrapolated from $Z \rightarrow ee$ and measured in $Z \rightarrow ll\gamma$ + matrix method using track isolation sidebands

Converted central photons

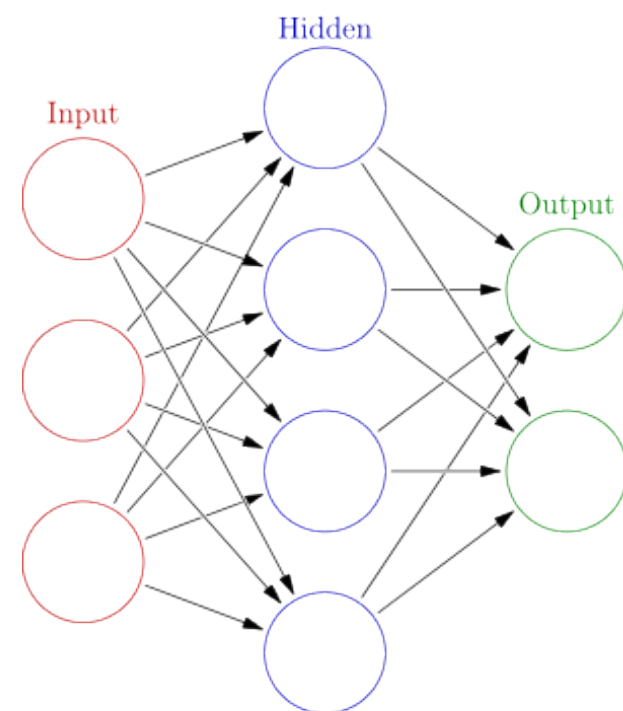


Unconverted central photons



Another word or two (or three) on neural networks

- All variables checked in lower n_{jet}/n_{tag} regions first, including correlations between variables
- Then all variables placed in neural network and tight anti-signal cut made to ensure no signal present before evaluating the signal region
- Fits done first with anti-NN data to check for reasonable pulls of nuisance parameters during profiling
- Then and only then do we unblind the data ...



Efficiency for tHqb (Wth) processes varies with \mathbf{K}_t but for SM version is 6.2% (11.9%) at 8 TeV, and 6.2% (12.9%) at 7 TeV