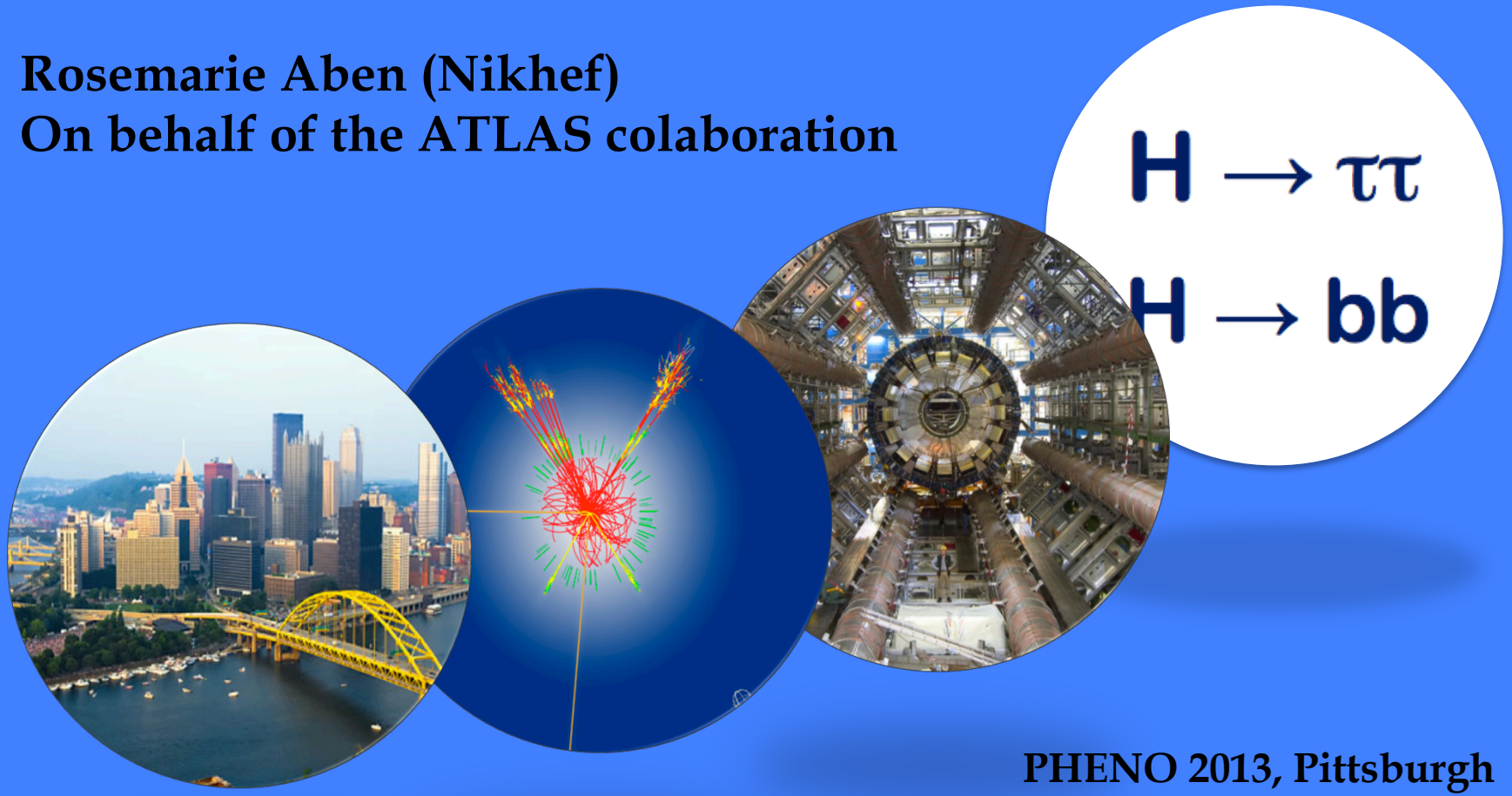
Search for a Higgs boson in fermion final states using the ATLAS detector

Rosemarie Aben (Nikhef)
On behalf of the ATLAS colaboration



PHENO 2013, Pittsburgh

Why looking at Higgs boson decay into fermions?

Test theory: do we observe what is predicted by the S.M. with Higgs mechanism.

Test of specific Higgs couplings:

- Direct coupling fermions and Higgs
- Coupling leptons and Higgs

Higgs coupling to mass:

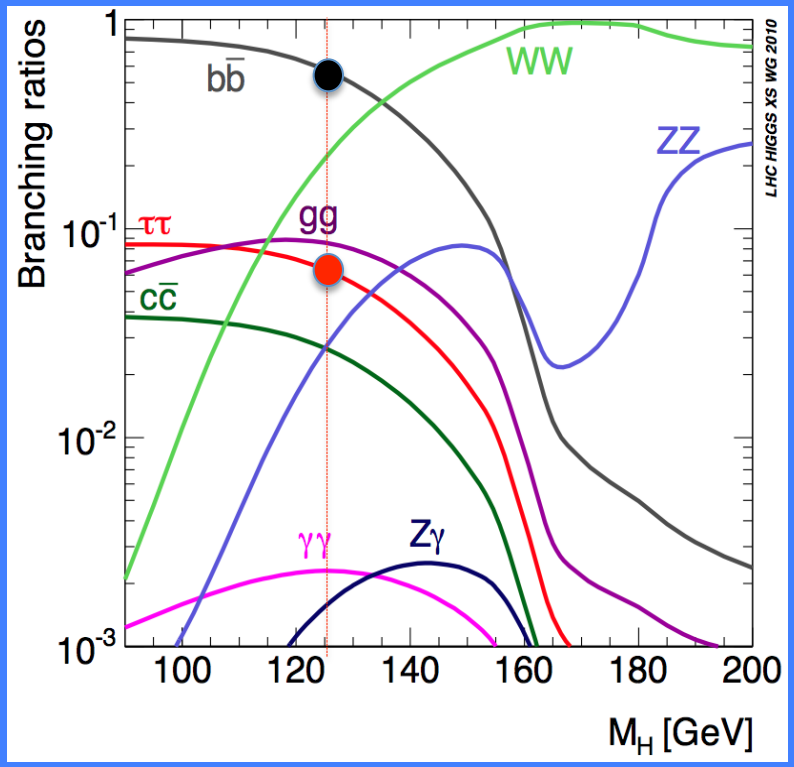
- Coupling to M_W , M_Z: ~ 80-90 GeV
- Coupling to M_t: ~ 170 GeV
- Coupling to M_τ , M_b: ~ 2-4 GeV

Branching ratios are large for M_H=125GeV:

- BR (H→bb) = 57.7%
- BR (H→ττ)= 6.3%

Probing Higgs production modes:

- ggF, VBF, VH, ttH



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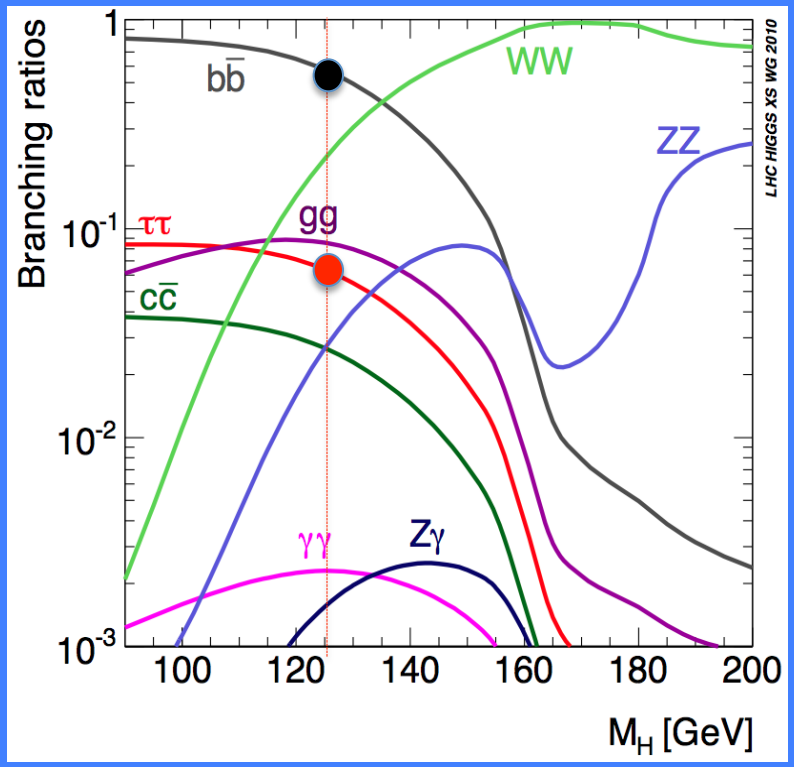


This talk:

Channels: H → ττ, VH → bb and ttH → bb.

ATLAS searches for SM Higgs 100 < M_H/GeV < 150.

Data: 4.7 fb^{-1} of $\sqrt{s}$ = 7 TeV, up to 13 fb^{-1} of $\sqrt{s}$ = 8 TeV.

Challenges: the background

High rates of other S.M. processes make extraction of a Higgs signal difficult.

Main background for H→bb:

High p_T b-jet production ~10^6 larger

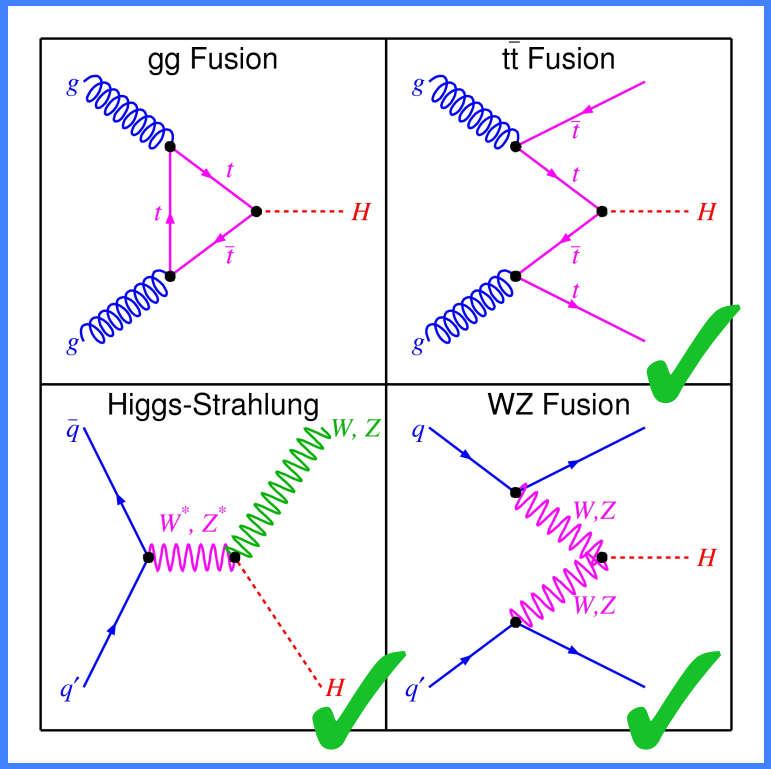
Main background for H→ττ:

Z→ττ production ~10^5 larger

Handles against the backgrounds:

- Features of decay products: E_T^{miss}, p_T, #jets, b-tags, # leptons, invariant mass.
- Higgs production signatures.

Make event selections using these features.



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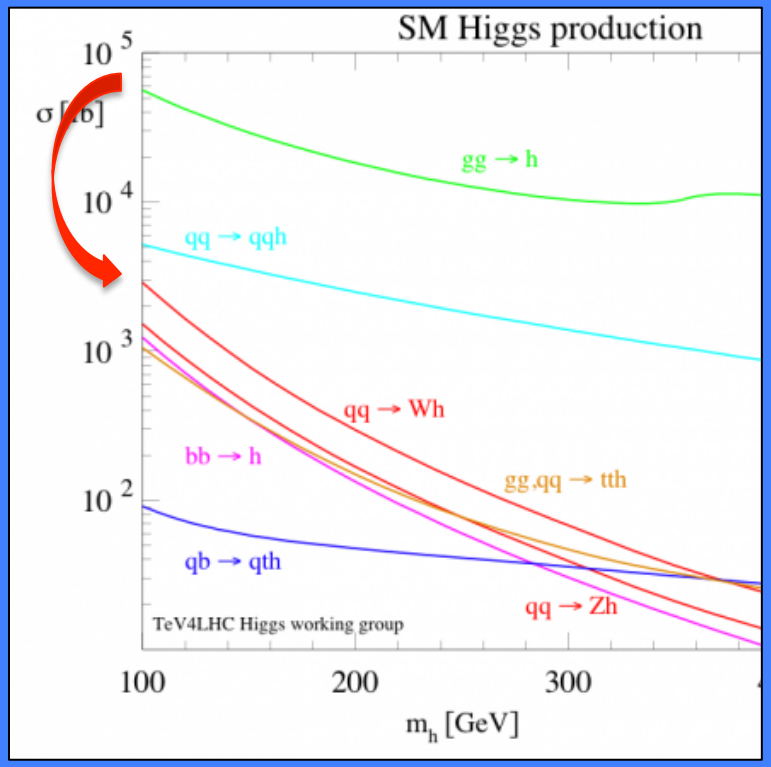

Handles against the backgrounds:

- Features of decay products: E_T^{miss}, p_T, #jets, b-tags, # leptons, invariant mass.
- Higgs production signatures.

Make event selections using these features.

Result: few Higgs signal events, with better signal to background ratio.

$H \rightarrow \tau^+\tau^-$

Data: 4.7 fb^{-1} of $\sqrt{s}$ = 7 TeV and 13 fb^{-1} of $\sqrt{s}$ = 8 TeV

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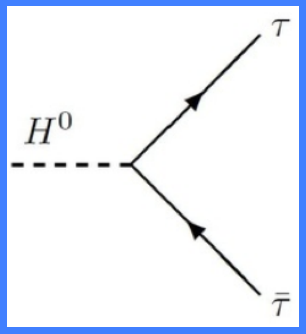
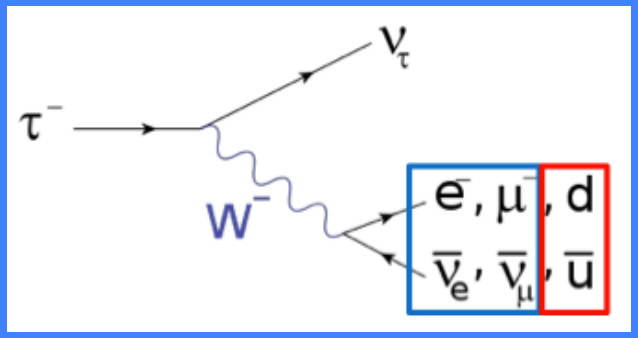
H→ττ Analysis strategy



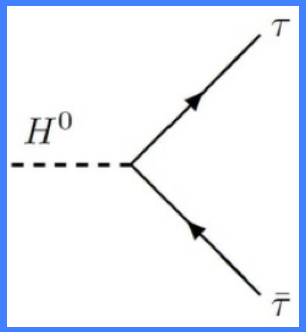


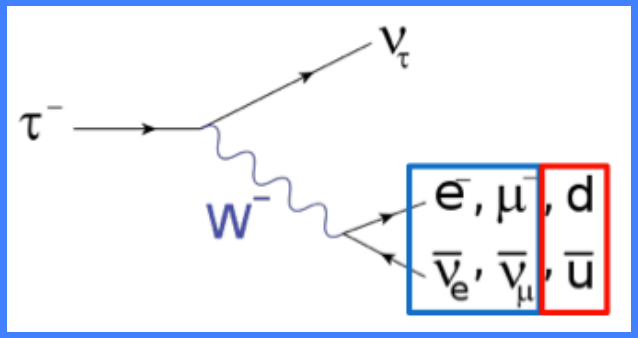
Six final states:

- $H \rightarrow \tau_{lep}\tau_{lep} \rightarrow ee, \mu\mu, e\mu$ ~10%
- $H \rightarrow \tau_{lep}\tau_{had} \rightarrow e\ had, \mu\ had$ ~45%
- $H \rightarrow \tau_{had}\tau_{had} \rightarrow had\ had$ ~45%

Preselection: $E_T^{miss} > 20$ GeV + 2 tau candidates (hadronic and/or leptonic)
Analysis divided in different categories depending on final state, #jets and kinematics.

H→ττ Analysis strategy





Six final states:

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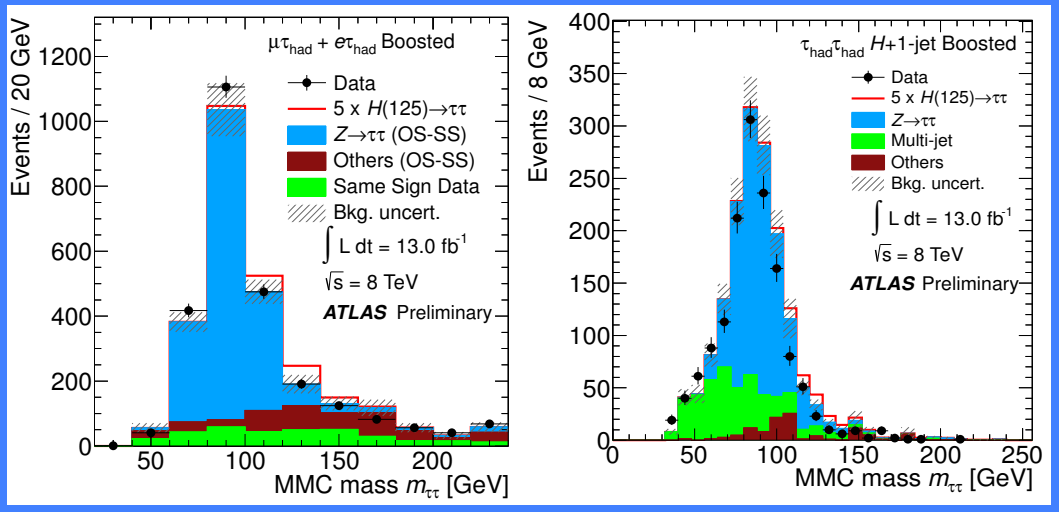
Preselection: E_T^{miss} > 20 GeV + 2 tau candidates (hadronic and/or leptonic)
Analysis divided in different categories depending on final state, #jets and kinematics.

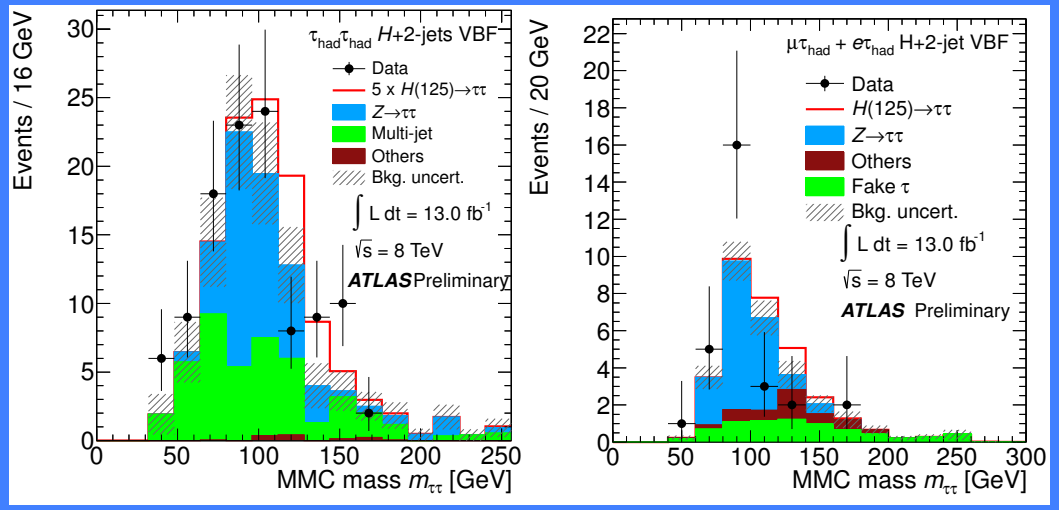
Priority → high/low sens.	2-jet VBF 2 jets with Δηjj>3	Boosted high-pT taus	2-jet VH Δ ηjj<2	1-jet ≥ 1jet	0-jet
$H\to\tau_{lep}\tau_{lep}$ Nlep==2	$S/\sqrt{B}$ 0.57	0.45	0.14	0.28	0.23 only for 7 TeV
$H\to\tau_{lep}\tau_{had}$ Nlep==1	0.65	0.60	n.a.	0.77	0.57
$H\to\tau_{had}\tau_{had}$ Nlep==0	0.48	0.33	n.a.	n.a.	n.a.

Final discriminant $M_{\tau\tau}$ Reconstructed with Missing Mass Calculator (MMC), it uses momenta, E_T^{miss} and the angle between visible and missing momenta.
ref: Elagin et al., arXiv:1012.4686

Results: $M_{\tau\tau}$ distributions

Results for 8 TeV data for the VBF and boosted categories ($\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$).





N.B. $\tau_{lep}\tau_{lep}$ distributions are in the back-up

Boosted category (top):

Sensitive to ggF → high stats.

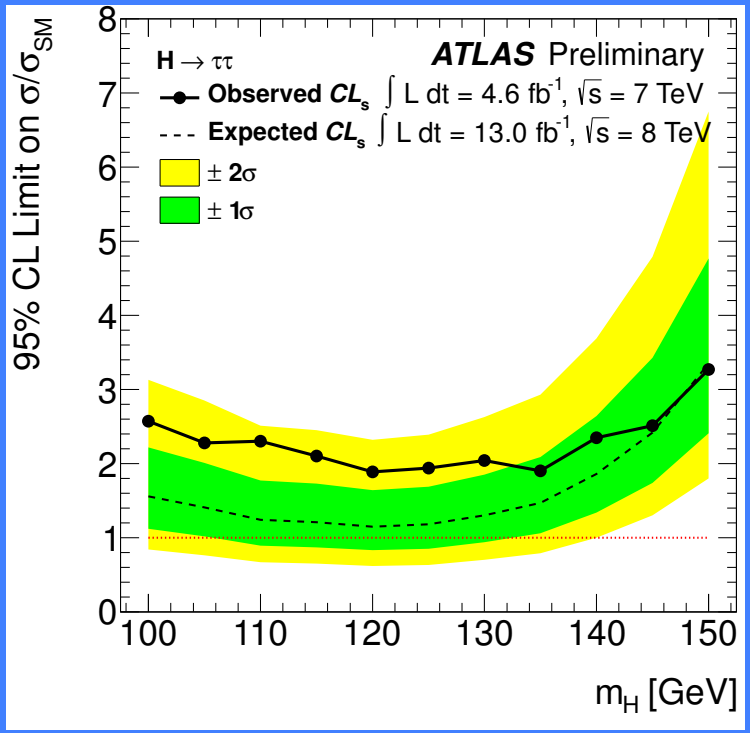
VBF category (bottom):

Limited statistics, but better S/B.

Largest background: Z→ττ, estimated from data using Z→μμ events and replacing μ− with τ-signature taken from simulation.

Main systematics: τ-energy scale and theoretical uncertainties.

Results: H→ττ limits



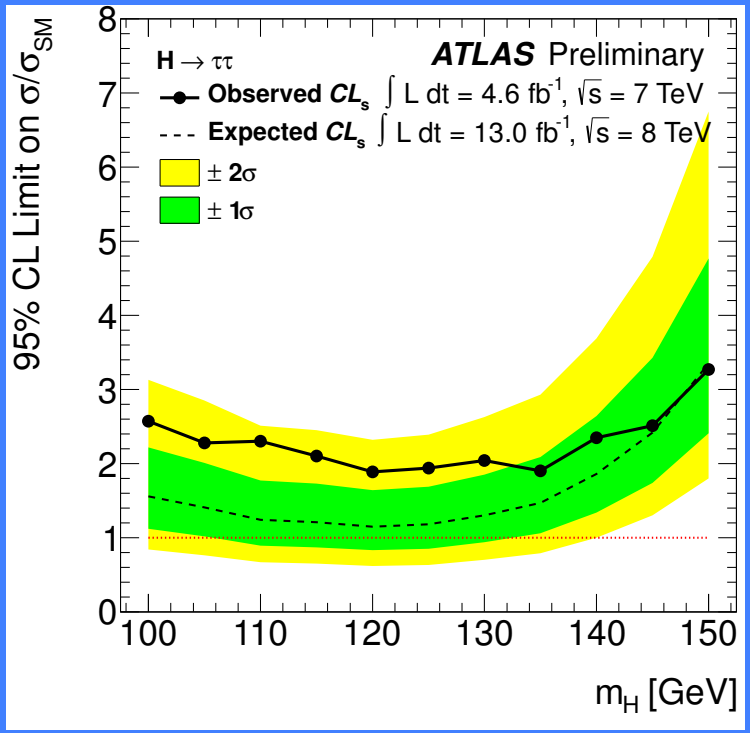
95% CL upper limits on normalised cross section (σxBR/σ_{SM}xBR$_{SM}$):

- Observed: 1.9
- Expected: 1.2

Signal strength: 0.7 ± 0.7

No significant excess of data above predicted backgrounds. This is expected. More data are needed.

Results: H→ττ limits



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Signal strength: 0.7 ± 0.7

No significant excess of data above predicted backgrounds. This is expected. More data are needed.

Prospects:

- Update to full dataset: 8fb^{-1} to be added.
- Use a multivariate analysis (BDT).
- Improve modeling of Z→ττ background.

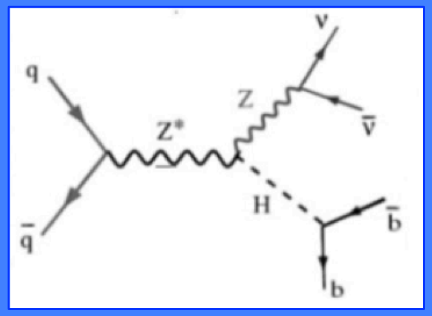
$VH \rightarrow b\bar{b}$

Data: 4.7 fb^{-1} of $\sqrt{s}$ = 7 TeV and 13 fb^{-1} of $\sqrt{s}$ = 8 TeV

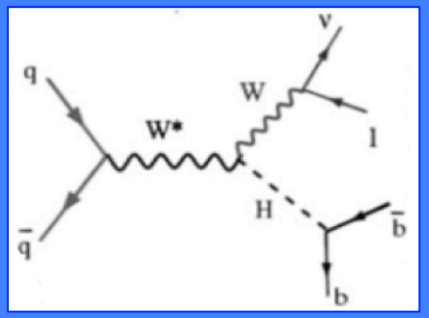
ATLAS-CONF-2012-161

VH→bb Analysis strategy

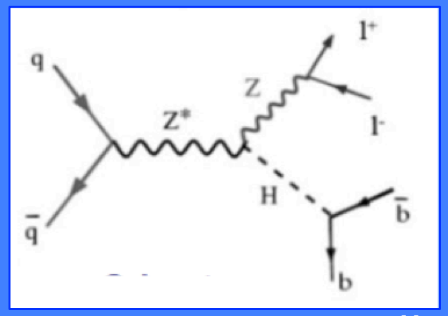
Analysis divided in three channels, according to number of leptons.



0 lepton: ZH→ bbνν



1 lepton: WH→ bblν



2 leptons: WH→ bbll

~20% migration due to undetected lepton

Preselection:

- 1 or 2 or 3 leptons
- 2 or 3 jets, 2 b-tags
- Selection on E_T^{miss}

Strategy

Exploit increasing S/B for increasing vector boson transverse momentum:

divide analysis into p_T^V (E_T^{miss}/ $p_T^{l\nu}$ / p_T^{ll}) bins.

In total 16 signal regions, depending on #leptons, #jets, and #bins in p_T^V.

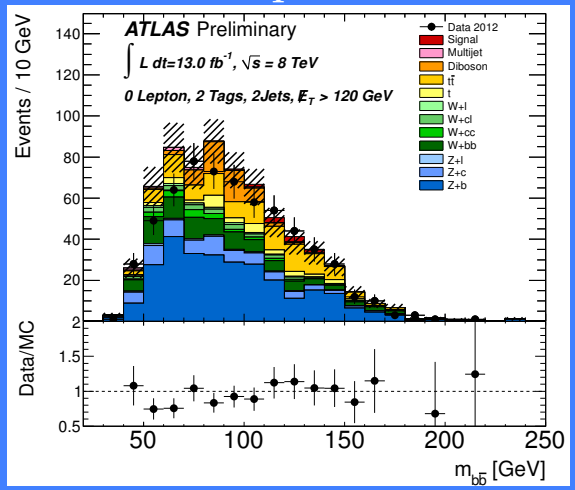
Analysis defined without looking at 2 b-tag signal region, 80 GeV < m_{bb} < 150 GeV.

Final discriminant M_{bb}: reconstructed from the two b-tagged jets.

VH→bb backgrounds

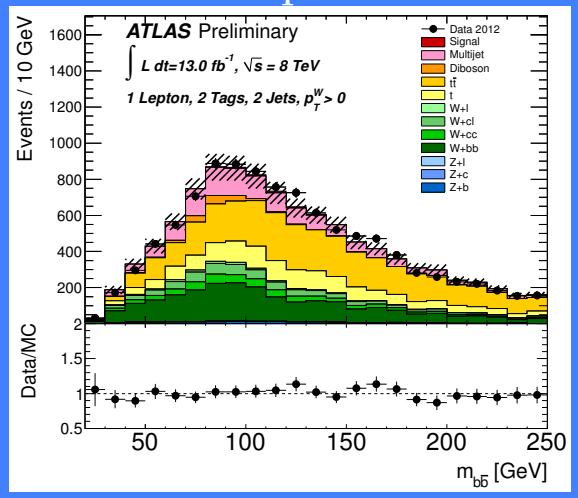
Composition of the background depends on the number of leptons in signal.

0 lepton



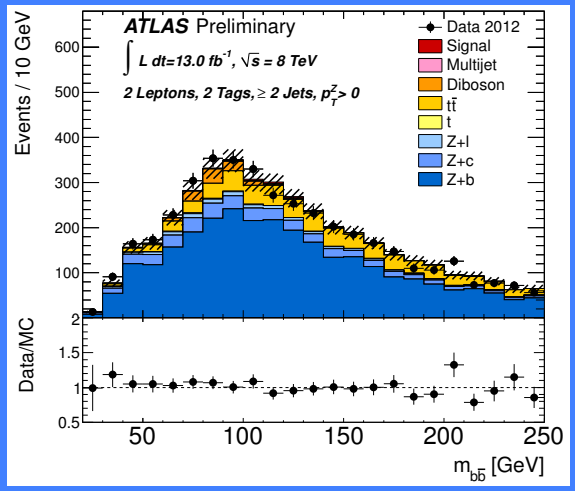
Z+jets W+jets Top

1 lepton



W+jets Top

2 leptons



Z+jets

Background modeling

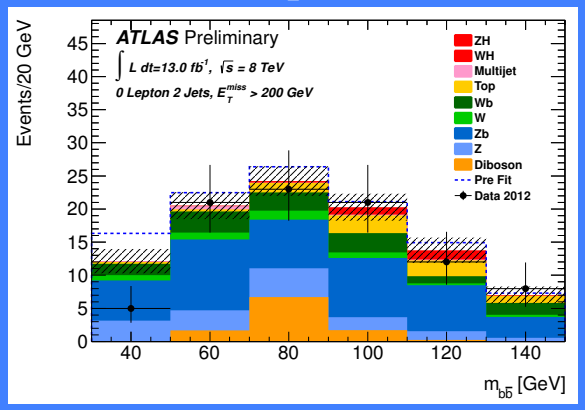
- Background shapes from simulations with normalisation from data.
- Multi-jet background determined with data-driven technique.
- WZ/ZZ shapes and normalisation from simulations.

Main systematics: b-tagging, jets/E_T^{miss}, MC statistics.

Results: M_{bb} distributions and limits

Highest p_T^V bins are most sensitive to Higgs signal. Results for p_T^V > 200 GeV.

0 lepton



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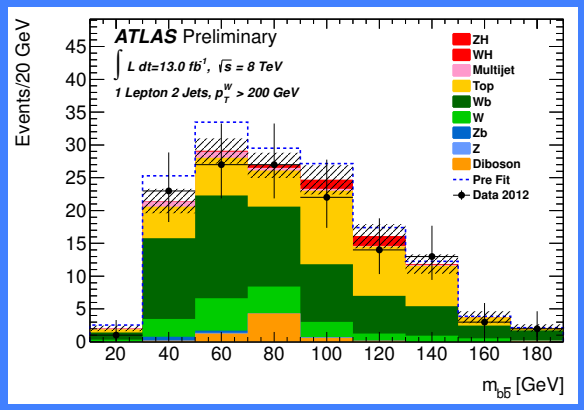
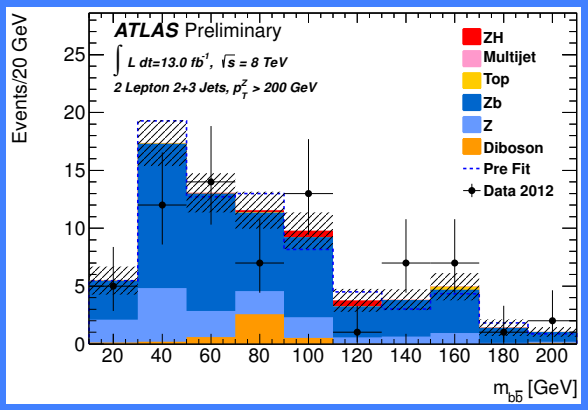


2 leptons



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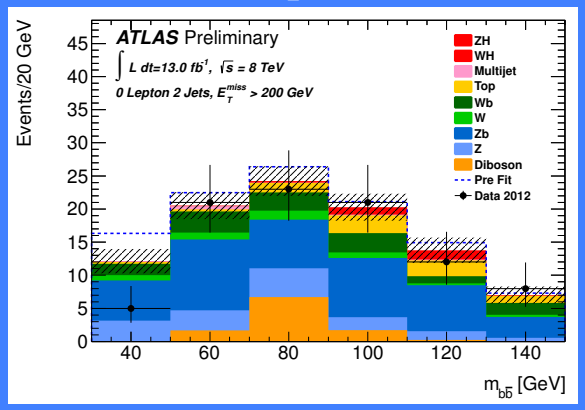

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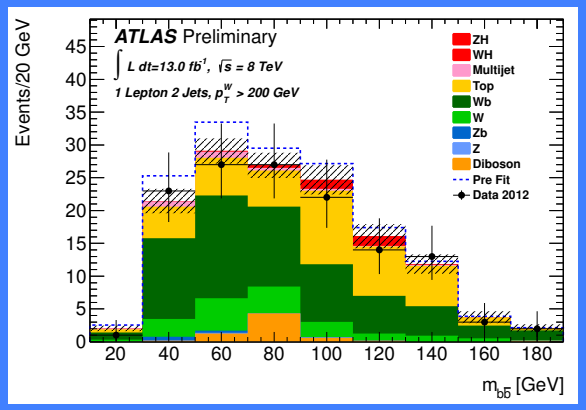
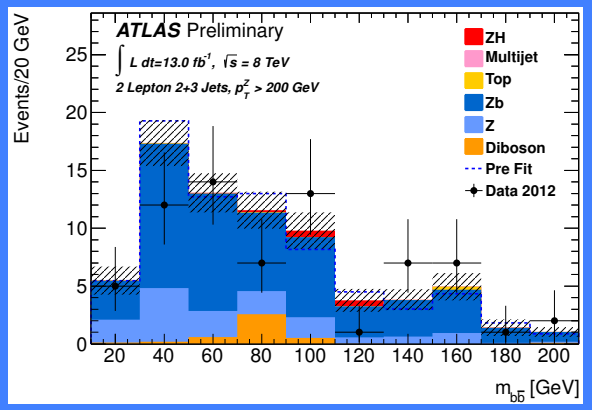
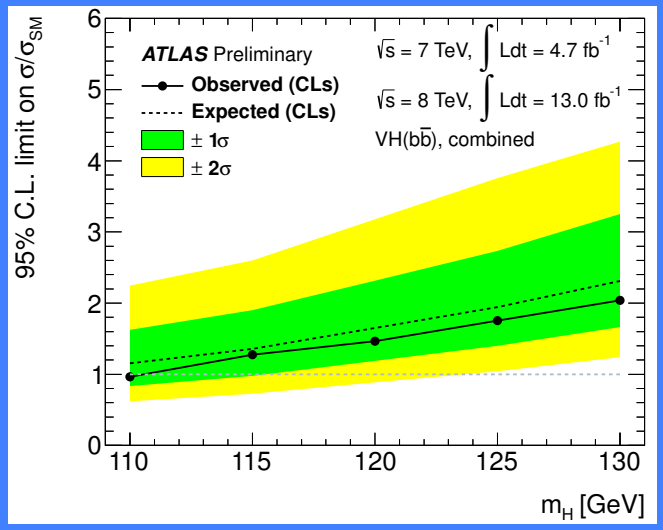


2 leptons





95% CL limits on cross section ($\sigma \times BR / \sigma_{SM} \times BR_{SM}$):

- Observed: 1.8
- Expected: 1.9

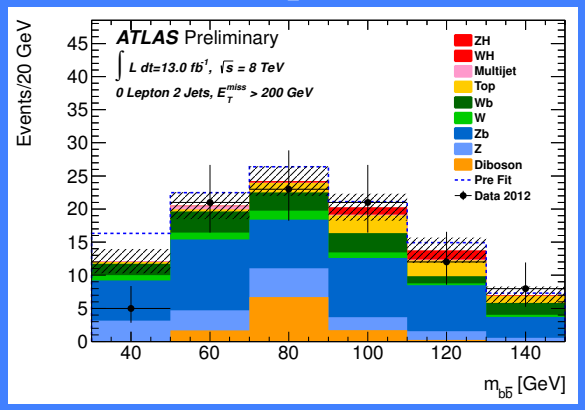
Signal strength: -0.4 ± 0.7 (stat.) ± 0.8 (syst.)

No excess of data above predicted backgrounds.

Results: M_{bb} distributions and limits

Highest p_T^V bins are most sensitive to Higgs signal. Results for p_T^V > 200 GeV.

0 lepton



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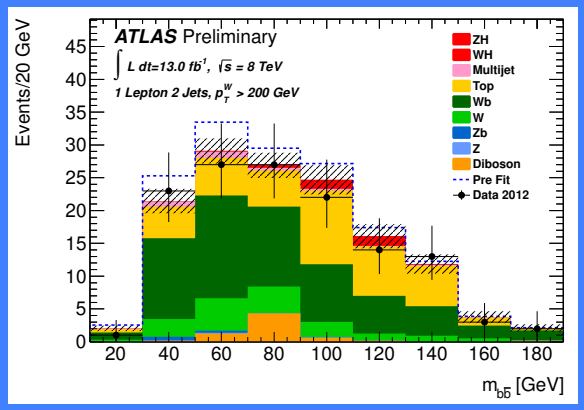
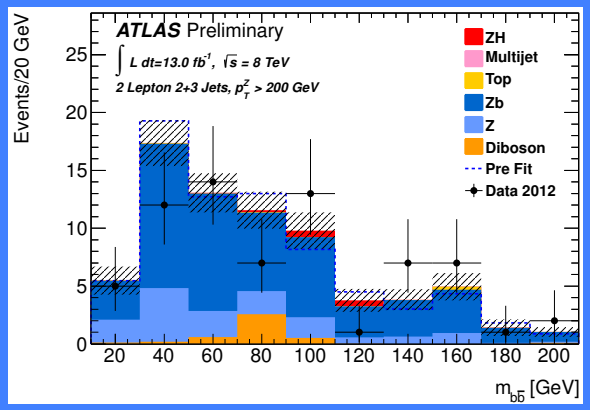
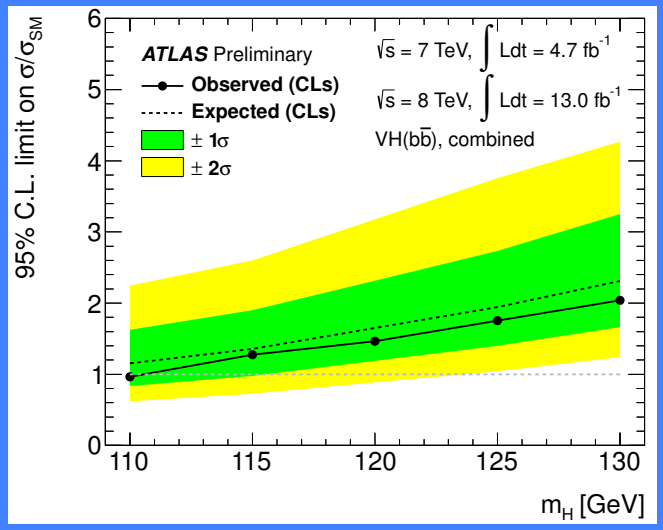


2 leptons





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No excess of data above predicted backgrounds.

Prospects: update to full dataset, introduce MVA analysis, further improve profiling of systematics.

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

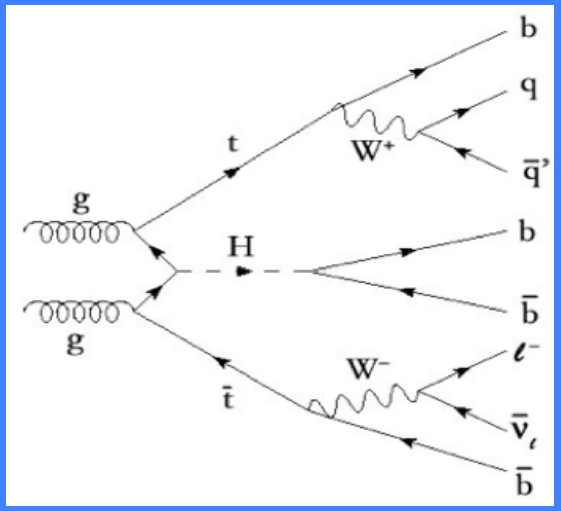
Data: 4.7 fb^{-1} of $\sqrt{s}$ = 7 TeV

ATLAS-CONF-2012-135

ttH→bb Analysis strategy

Use only events with 1 leptonically and 1 hadronically decaying $W^{\pm}$:

- ttH→W^+b W^-b bb→lνb jjb bb



Signature

- High jet multiplicity: 4 b-jets + 2 jets.
- 1 high-p_T isolated μ (p_T>20 GeV) or e (p_T>25 GeV).
- High E_T^{miss} (> 20 GeV for μ, > 30 GeV for e).

ttH→bb Analysis strategy

Use only events with 1 leptonically and 1 hadronically decaying $W^{\pm}$:

- $ttH \rightarrow W^{+}b\ W^{-}b\ bb \rightarrow l\nu b\ jjb\ bb$

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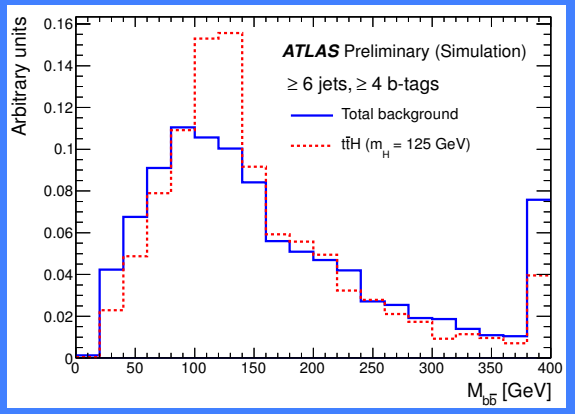


m_{bb} distribution for 6 jets, 4 b-tags: Comparing the S and B shape.

Strategy

Define signal and background enriched categories based on #jet and #b-tags.

- Signal enriched region: ≥ 3 b-tags, ≥ 6 jets.
  - Discriminating variable m_{bb} . Constructed such that lνb => m_t and jjb => m_t .
  - From possible b-jet permutations the one with highest likelihood is taken.
- Background enriched categories: < 3 b-tags or < 6 jets.
  - Included to improve sensitivities and constrain background.
  - Discriminating variable H_T^{had} : scalar sum of jet p_T .

ttH→bb fit distributions and limits

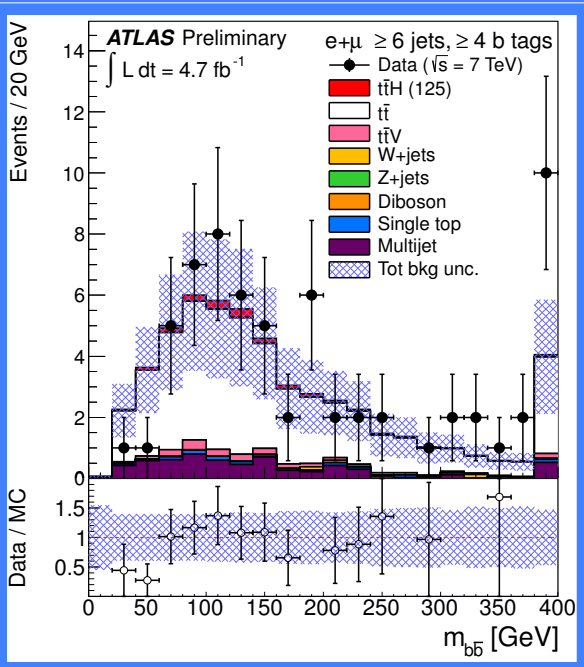
Main background

ttbar production

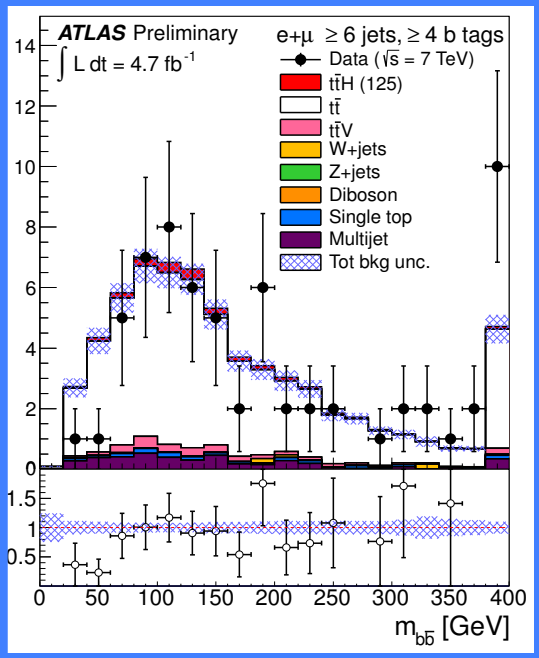
Main systematics

b/c-tagging, ttbar modeling

After selections a fit to the data is performed, constraining the background (systematics).



Pre-fit



Post-fit

ttH→bb fit distributions and limits

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ttbar production

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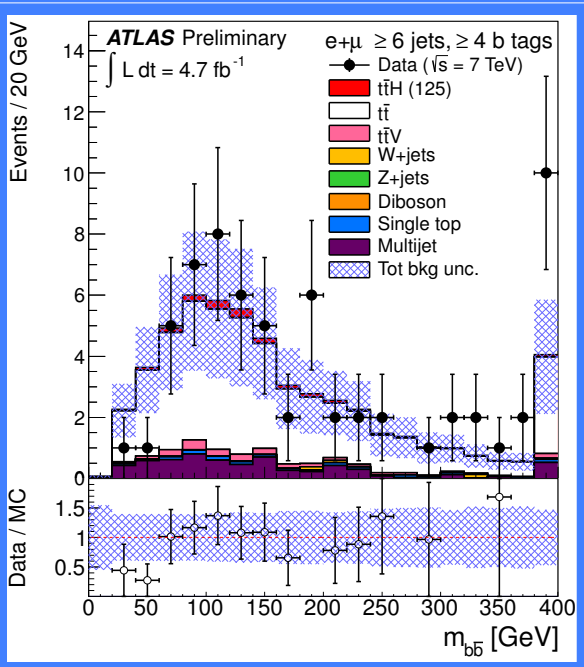
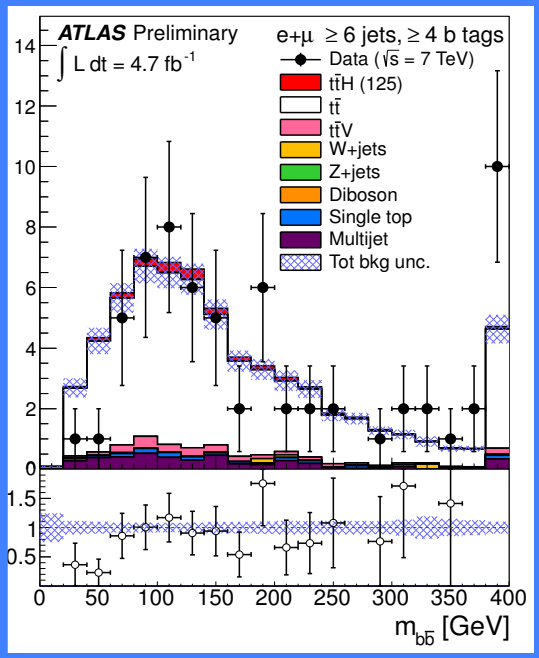
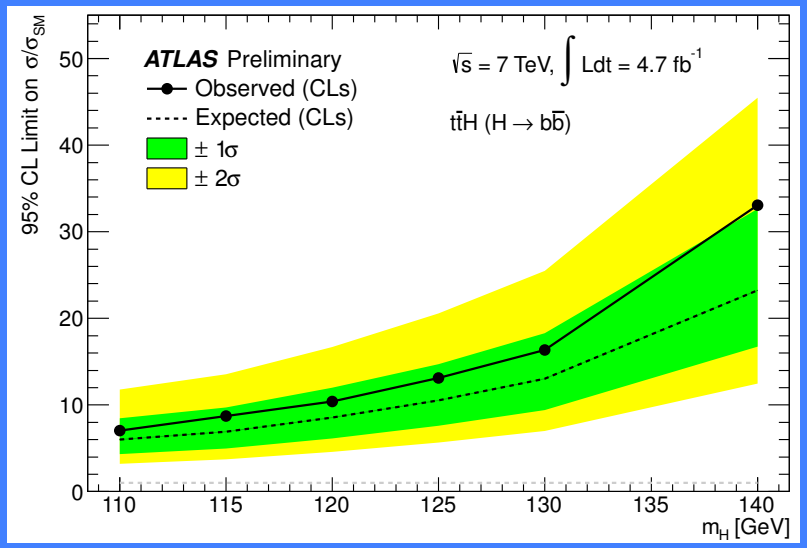


Pre-fit



Post-fit



95% CL limits on cross section ($\sigma \times BR / \sigma_{SM} \times BR_{SM}$):

- Observed: 13.1
- Expected: 10.5

No significant excess of data above predicted backgrounds.

ttH→bb fit distributions and limits

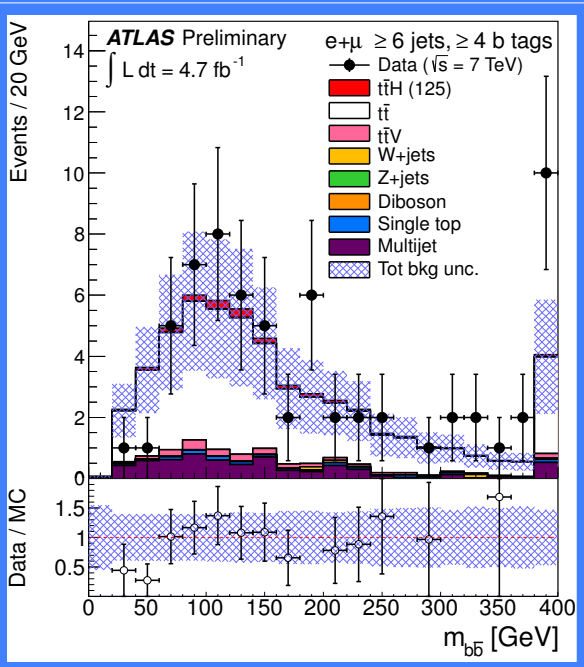
Main background

ttbar production

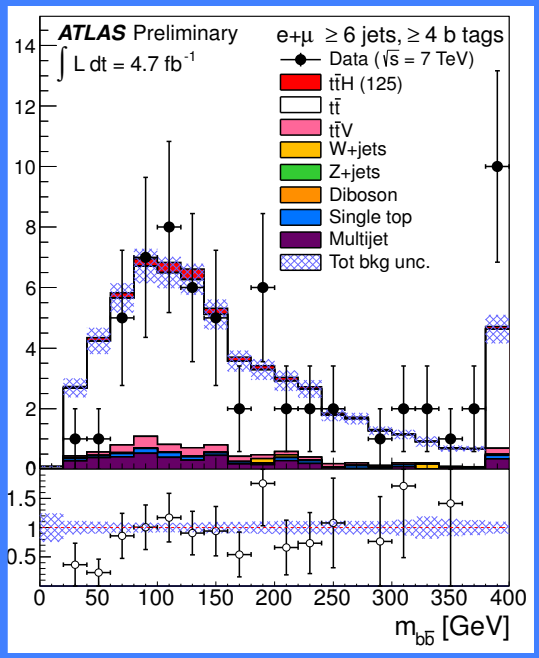
Main systematics

b/c-tagging, ttbar modeling

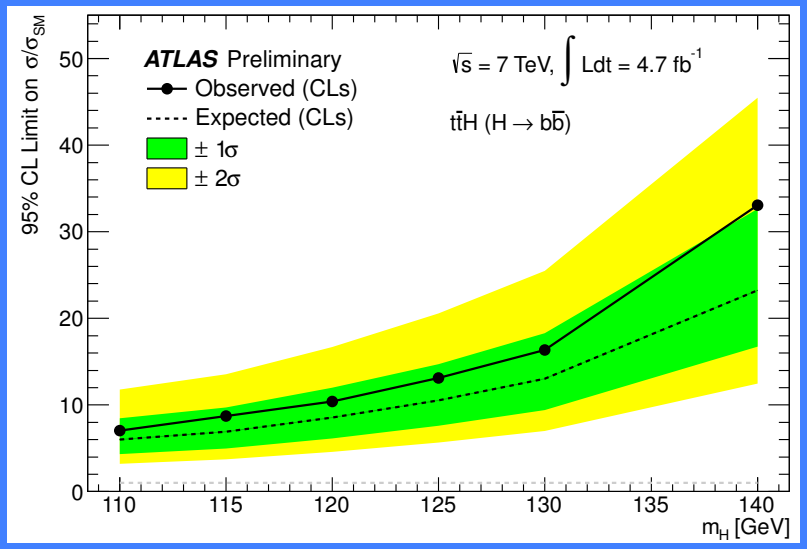
After selections a fit to the data is performed, constraining the background (systematics).



Pre-fit



Post-fit



Prospects

- Include 2012 dataset.
- Include dilepton channel (2x W→lν).
- Optimize tt+jets modeling.

Conclusions on fermion final states in Higgs searches

- The Higgs to fermions decay modes are important to study in order to constrain the true nature of the Higgs boson.

- Large backgrounds and complex final states make the fermion modes analyses very challenging.

- For the $H \rightarrow \tau\tau$ a slight excess in data is measured around $M_H = 125$ GeV, however more data are needed to conclude on this excess.

- No observation of a SM Higgs boson decaying into bbar in the range $110 < M_H/\text{GeV} < 140$ is measured. This is as expected, given the reached sensitivity.

- Results for the analyses with the full ATLAS dataset and optimized techniques are in the pipeline.

Back-up

Back-up for H→ττ

The event selections for $H \to \tau_{lep}\tau_{lep}$ for the different categories

2-jet VBF	Boosted	2-jet VH	1-jet
Pre-selection: exactly two leptons with opposite charges			
30 GeV $< m_{\ell\ell} <$ 75 GeV (30 GeV $< m_{\ell\ell} <$ 100 GeV) for same-flavor (different-flavor) leptons, and $p_{T,\ell 1} + p_{T,\ell 2} > 35$ GeV			
At least one jet with $p_T > 40$ GeV ($\lvert JVF_{\text{jet}}\rvert > 0.5$ if $\lvert\eta_{\text{jet}}\rvert < 2.4$)			
$E_{\text{T}}^{\text{miss}} > 40$ GeV ($E_{\text{T}}^{\text{miss}} > 20$ GeV) for same-flavor (different-flavor) leptons			
$H_{\text{T}}^{\text{miss}} > 40$ GeV for same-flavor leptons			
$0.1 < x_{1,2} < 1$			
$0.5 < \Delta\phi_{\ell\ell} < 2.5$			
$p_{T,j2} > 25$ GeV (JVF)	excluding 2-jet VBF	$p_{T,j2} > 25$ GeV (JVF)	excluding 2-jet VBF, Boosted and 2-jet VH
$\Delta\eta_{jj} > 3.0$	$p_{T,\tau\tau} > 100$ GeV	excluding Boosted	$m_{\tau\tau j} > 225$ GeV
$m_{jj} > 400$ GeV	b-tagged jet veto	$\Delta\eta_{jj} < 2.0$	b-tagged jet veto
b-tagged jet veto	–	30 GeV $< m_{jj} <$ 160 GeV	–
Lepton centrality and CJV		b-tagged jet veto	
0-jet (7 TeV only)			
Pre-selection: exactly two leptons with opposite charges			
Different-flavor leptons with 30 GeV $< m_{\ell\ell} <$ 100 GeV and $p_{T,\ell 1} + p_{T,\ell 2} > 35$ GeV			
$\Delta\phi_{\ell\ell} > 2.5$			
b-tagged jet veto			

The JVF cut is for 7 TeVdata, the lepton centrality is not applied for 7 TeV analysis, and the 0-jet category is not used for 8 TeV data analysis.

Back-up for H→ττ

The event selections for $H \to \tau_{lep}\tau_{had}$ for the different categories

7 TeV		8 TeV	
VBF Category	Boosted Category	VBF Category	Boosted Category
▹ $p_T^{\tau_{had\text{-}vis}}$ >30 GeV	–	▹ $p_T^{\tau_{had\text{-}vis}}$ >30 GeV	▹ $p_T^{\tau_{had\text{-}vis}}$ >30 GeV
▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV
▹ ≥ 2 jets	▹ $p_T^H > 100$ GeV	▹ ≥ 2 jets	▹ $p_T^H > 100$ GeV
▹ $p_T^{j1}, p_T^{j2} > 40$ GeV	▹ $0 < x_1 < 1$	▹ $p_T^{j1} > 40, p_T^{j2} > 30$ GeV	▹ $0 < x_1 < 1$
▹ $\Delta\eta_{jj} > 3.0$	▹ $0.2 < x_2 < 1.2$	▹ $\Delta\eta_{jj} > 3.0$	▹ $0.2 < x_2 < 1.2$
▹ $m_{jj} > 500$ GeV	▹ Fails VBF	▹ $m_{jj} > 500$ GeV	▹ Fails VBF
▹ centrality req.	–	▹ centrality req.	–
▹ $\eta_{j1} \times \eta_{j2} < 0$	–	▹ $\eta_{j1} \times \eta_{j2} < 0$	–
▹ $p_T^{Total} < 40$ GeV	–	▹ $p_T^{Total} < 30$ GeV	–
–	–	▹ $p_T^{\ell} >26$ GeV	–
• m_T <50 GeV	• m_T <50 GeV	• m_T <50 GeV	• m_T <50 GeV
• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$
• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 1.6$	• $\sum \Delta\phi < 2.8$	–
–	–	• b-tagged jet veto	• b-tagged jet veto
1 Jet Category	0 Jet Category	1 Jet Category	0 Jet Category
▹ ≥ 1 jet, p_T >25 GeV	▹ 0 jets p_T >25 GeV	▹ ≥ 1 jet, p_T >30 GeV	▹ 0 jets p_T >30 GeV
▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV
▹ Fails VBF, Boosted	▹ Fails Boosted	▹ Fails VBF, Boosted	▹ Fails Boosted
• m_T <50 GeV	• m_T <30 GeV	• m_T <50 GeV	• m_T <30 GeV
• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$	• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$
• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$
–	• $p_T^{\ell} - p_T^{\tau} < 0$	–	• $p_T^{\ell} - p_T^{\tau} < 0$

Requirements marked with a triangle (◃) are categorization requirements, meaning that if an event fails that requirement it is still considered for the remaining categories. Requirements marked with a bullet (•) are only applied to events passing all categorization requirements in a category; events failing such requirements are discarded.

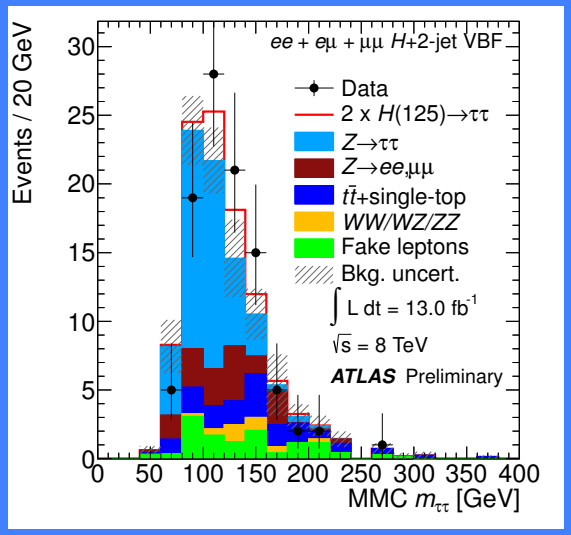
Back-up for H→ττ

The event selections for $H\to\tau_{had}\tau_{had}$ for the different categories

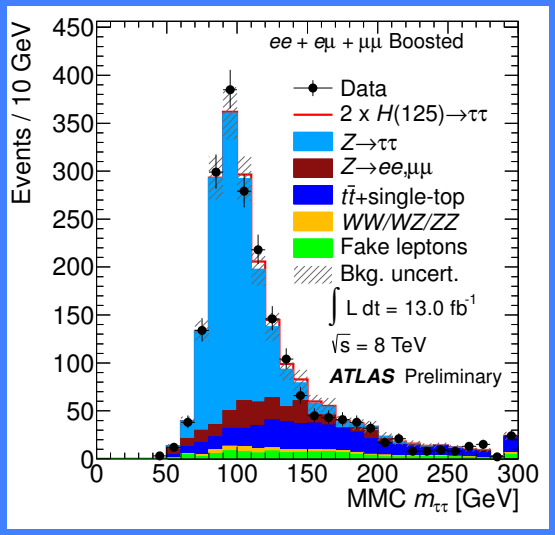
Cut	Description
Preselection	No muons or electrons in the event
	Exactly 2 medium τ_{had} candidates matched with the trigger objects
	At least 1 of the τ_{had} candidates identified as tight
	Both τ_{had} candidates are from the same primary vertex
	Leading $\tau_{\text{had-vis}}$ $p_T > 40$ GeV and sub-leading $\tau_{\text{had-vis}}$ $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$
	τ_{had} candidates have opposite charge and 1- or 3-tracks
	$0.8 < \Delta R(\tau_1, \tau_2) < 2.8$
	$\Delta\eta(\tau, \tau) < 1.5$
	if $E_{\mathrm{T}}^{\mathrm{miss}}$ vector is not pointing in between the two taus, $\min\left\{\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_1), \Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_2)\right\} < 0.2\pi$
VBF	At least two tagging jets, j_1, j_2, leading tagging jet with $p_{\mathrm{T}} > 50$ GeV
	$\eta_{j1} \times \eta_{j2} < 0$, $\Delta\eta_{jj} > 2.6$ and invariant mass $m_{jj} > 350$ GeV
	$\min(\eta_{j1}, \eta_{j2}) < \eta_{\tau 1}, \eta_{\tau 2} < \max(\eta_{j1}, \eta_{j2})$
	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV
Boosted	Fails VBF
	At least one tagging jet with $p_{\mathrm{T}} > 70(50)$ GeV in the 8(7) TeV dataset
	$\Delta R(\tau_1, \tau_2) < 1.9$
	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV
	if $E_{\mathrm{T}}^{\mathrm{miss}}$ vector is not pointing in between the two taus, $\min\left\{\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_1), \Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_2)\right\} < 0.1\pi$.

Back-up for H→ττ

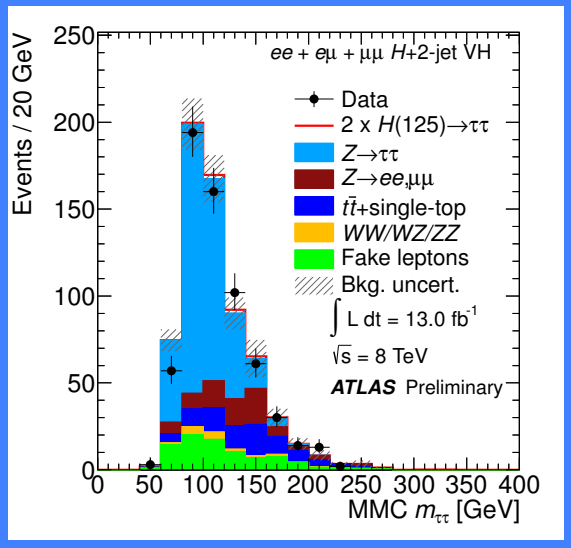
Distributions of $M_{\tau\tau}$ for $H \to \tau_{lep}\tau_{lep}$ for the 8 TeV dataset ($13fb^{-1}$) in the 4 categories.



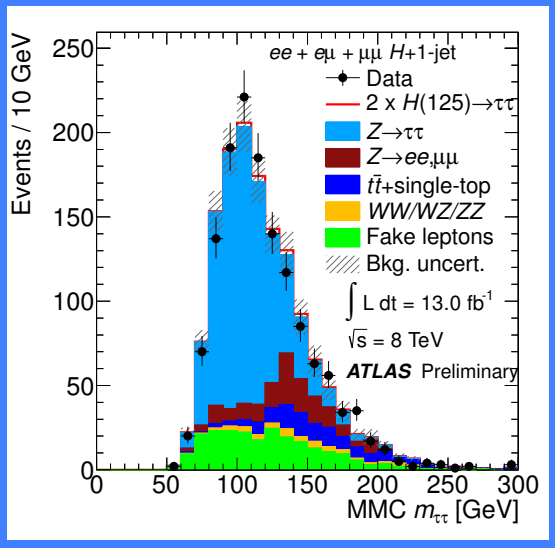
(a) H+2-jet VBF



(b) H+1-jet Boosted



(c) H+2-jet VH



(d) H+1-jet

Back-up for H→ττ

Event yields for $H \to \tau_{lep}\tau_{lep}$ for 7 TeV (top) and 8 TeV (bottom) datasets.

The errors on the background yields are first stats. then syst.

			$ee + \mu\mu + e\mu$		
	VBF category	Boosted category	VH category	1-jet category	0-jet category
$gg \to H$ (125 GeV)	0.20 ± 0.04 ± 0.07	3.5 ± 0.2 ± 0.4	0.4 ± 0.1 ± 0.1	2.0 ± 0.1 ± 0.8	25±1±4
VBF H (125 GeV)	1.05 ± 0.03 ± 0.10	0.90 ± 0.03 ± 0.05	0.05 ± 0.01 ± 0.01	0.56 ± 0.02 ± 0.01	0.97±0.03±0.06
VH (125 GeV)	0.0	0.71 ± 0.03 ± 0.09	0.20 ± 0.01 ± 0.02	0.14 ± 0.01 ± 0.02	0.63±0.02±0.04
$Z/\gamma^* \to \tau\tau$ embedded	20 ± 2 ± 2	(0.41 ± 0.01 ± 0.02)×10^3	113 ± 5 ± 8	272 ± 8 ± 41	(10.71±0.05±0.07)×10^3
$Z/\gamma^* \to \ell\ell$	1.5 ± 0.6 ± 0.6	77 ± 7 ± 6	27 ± 4 ± 9	45 ± 5 ± 24	(0.17±0.01±0.01)×10^3
Top	4.8 ± 0.5 ± 0.6	132 ± 3 ± 6	27 ± 1 ± 6	31 ± 2 ± 10	284±4±15
Diboson	0.8 ± 0.1 ± 0.2	17.4 ± 0.7 ± 0.6	4.3 ± 0.4 ± 1.0	12 ± 1 ± 3	347±3±20
Backgrounds with fake leptons	2.7 ± 0.3 ± 0.9	22 ± 3 ± 4	19 ± 3 ± 6	24 ± 3 ± 10	(1.56±0.02±0.40)×10^3
Total background	29 ± 3 ± 2	(0.66 ± 0.01 ± 0.02)×10^3	190± 7 ± 15	(0.38±0.01 ± 0.05)×10^3	(13.07±0.06±0.41)×10^3
Observed data	28	673	176	371	13214

		$ee + \mu\mu + e\mu$		
	VBF category	Boosted category	VH category	1-jet category
$gg \to H$ (125 GeV)	1.3 ± 0.2 ± 0.4	12.4 ± 0.6 ± 2.9	2.5 ± 0.3 ± 0.6	7.0 ± 0.5 ± 1.6
VBF H (125 GeV)	3.63 ± 0.10 ± 0.02	3.36 ± 0.09 ± 0.30	0.21 ± 0.03 ± 0.02	1.82 ± 0.07 ± 0.18
VH (125 GeV)	0.01 ± 0.01 ± 0.01	2.20 ± 0.05 ± 0.22	0.64 ± 0.03 ± 0.09	0.44 ± 0.02 ± 0.05
$Z/\gamma^* \to \tau\tau$ embedded	47 ± 2 ± 1	(1.24 ± 0.01 ± 0.08)×10^3	393 ± 7 ± 26	(0.86 ± 0.01 ± 0.06)×10^3
$Z/\gamma^* \to \ell\ell$	14 ± 3 ± 2	(0.21 ± 0.02 ± 0.04)×10^3	(0.08 ± 0.01 ± 0.02)×10^3	(0.16 ± 0.01 ± 0.03)×10^3
Top	15 ± 2 ± 3	(0.39 ± 0.01 ± 0.07)×10^3	87 ± 4 ± 23	117 ± 5 ± 18
Diboson	3.6 ± 0.8 ± 0.6	55 ± 3 ± 10	15 ± 1 ± 4	40 ± 3 ± 7
Backgrounds with fake leptons	12 ± 2 ± 3	102 ± 7 ± 23	86 ± 4 ± 16	230 ± 8 ± 52
Total background	91 ± 5 ± 5	(2.01 ± 0.03 ± 0.12)×10^3	(0.66 ± 0.02 ± 0.05)×10^3	(1.40 ± 0.02 ± 0.08)×10^3
Observed data	98	2014	636	1405

Back-up for H→ττ

Event yields for $H \to \tau_{lep}\tau_{had}$ for 7 TeV (top) and 8 TeV (bottom) datasets for VBF and boosted categories.

Process	Events	
	Boosted	VBF
$gg \to H$ (125 GeV)	4.1 ± 0.1 ± 1.0	0.17 ± 0.03 ± 0.06
VBF H (125 GeV)	1.52 ± 0.03 ± 0.13	0.87 ± 0.02 ± 0.15
VH (125 GeV)	0.86 ± 0.04 ± 0.08	<0.001
$Z/\gamma^* \to \tau\tau$ †	(0.70 ± 0.02 ± 0.10)×10^3	6.5 ± 0.6 ± 1.5
Diboson †	8.4 ± 0.7 ± 0.8	0.12 ± 0.06 ± 0.03
$Z/\gamma^* \to \ell\ell$ †	3.7 ± 1.3 ± 1.0	0.8 ± 0.3 ± 1.0
Top †	52 ± 2 ± 9	1.2 ± 0.3 ± 0.1
W boson + jets (OS-SS)	41 ± 7 ± 8	–
Same sign data	90 ± 10 ± 5	–
Fake-$\tau_{\text{had-vis}}$ backgrounds	–	0.8 ± 0.2 ± 0.4
Total background	(0.90 ± 0.02 ± 0.10)×10^3	9.5 ± 0.8 ± 1.9
Observed data	834	10

Process	Events	
	Boosted	VBF
$gg \to H$ (125 GeV)	20.3 ± 0.7 ± 5.1	0.5 ± 0.1 ± 0.3
VBF H (125 GeV)	5.3 ± 0.2 ± 0.3	2.5 ± 0.2 ± 0.4
VH (125 GeV)	2.7 ± 0.2 ± 0.2	<0.001
$Z/\gamma^* \to \tau\tau$ †	(1.78 ± 0.03 ± 0.11)×10^3	17 ± 2 ± 6
Diboson †	12.2 ± 0.9 ± 1.0	0.6 ± 0.3 ± 0.4
$Z/\gamma^* \to \ell\ell$ †	18 ± 9 ± 4	1.7 ± 0.5 ± 1.2
Top †	111 ± 8 ± 33	2.0 ± 0.7 ± 1.0
W boson + jets (OS-SS)	(0.27 ± 0.06 ± 0.04)×10^3	–
Same sign data	(0.34 ± 0.02 ± 0.01)×10^3	–
Fake-$\tau_{\text{had-vis}}$ backgrounds	–	7.6 ± 0.7 ± 3.8
Total background	(2.53 ± 0.07 ± 0.13)×10^3	29 ± 2 ± 7
Observed data	2602	29

Back-up for H→ττ

Event yields for $H \to \tau_{had}\tau_{had}$ for 7 TeV (top) and 8 TeV (bottom) datasets for VBF and boosted categories.

$H \to \tau_{had}\tau_{had}$	7 TeV analysis (4.6 fb^{-1})		8 TeV analysis (13.0 fb^{-1})	
	VBF category	Boosted category	VBF category	Boosted category
$gg \to H$ (125 GeV)	0.36 ± 0.06 ± 0.12	2.4 ± 0.2 ± 0.7	1.0 ± 0.1 ± 0.3	8.2 ± 0.4 ± 1.8
VBF H (125 GeV)	1.12 ± 0.04 ± 0.18	0.68 ± 0.03 ± 0.07	3.01 ± 0.09 ± 0.48	1.98 ± 0.07 ± 0.30
VH (125 GeV)	<0.02	0.61 ± 0.05 ± 0.06	<0.05	1.4 ± 0.2 ± 0.2
$Z/\gamma^* \to \tau\tau$ embedded	20 ± 2 ± 3	392 ± 9 ± 12	50 ± 4 ± 6	1080 ± 20 ± 110
W/Z boson+jets	1.5 ± 0.7 ± 0.4	5 ± 1 ± 1	0.4 ± 0.4	90 ± 20 ± 30
Top	1.0 ± 0.2 ± 0.2	3.0 ± 0.3 ± 0.5	1.4 ± 1.0	21 ± 3 ± 5
Diboson	0.10 ± 0.07 ± 0.02	4.4 ± 0.6 ± 0.7	<0.01	<0.5
Multijet	10.2 ± 0.9 ± 5.0	156 ± 6 ± 30	44 ± 5 ± 7	420 ± 20 ± 60
Total background	32.5 ± 2.2 ± 5.9	561 ± 11 ± 32	96 ± 6 ± 9	1607 ± 37 ± 130
Observed data	38	535	110	1435

Back-up for VH→bb

The event selections for H→bb for the three channels, as well as the division in P_T^V bins.

Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets	2 b-tags $p_T^1 > 45$ GeV $p_T^2 > 20$ GeV + ≤ 1 extra jets	2 b-tags $p_T^1 > 45$ GeV $p_T^2 > 20$ GeV + 0 extra jets	2 b-tags $p_T^1 > 45$ GeV $p_T^2 > 20$ GeV -
Missing E_T	$E_T^{miss} > 120$ GeV $p_T^{miss} > 30$ GeV $\Delta\phi(E_T^{miss}, p_T^{miss}) < \pi/2$ Min$[\Delta\phi(E_T^{miss}, \text{jet})] > 1.5$ $\Delta\phi(E_T^{miss}, b\bar{b}) > 2.8$	-	$E_T^{miss} < 60$ GeV
Vector Boson	-	$m_T^W < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

0-lepton channel					
E_T^{miss} (GeV)	120-160		160-200		>200
$\Delta R(b,\bar{b})$	0.7-1.9		0.7-1.7		<1.5
1-lepton channel					
p_T^W (GeV)	0-50	50-100	100-150	150-200	>200
$\Delta R(b,\bar{b})$	>0.7			0.7-1.6	<1.4
E_T^{miss} (GeV)	> 25				> 50
m_T^W(GeV)	> 40			-	
2-lepton channel					
p_T^Z(GeV)	0-50	50-100	100-150	150-200	>200
$\Delta R(b,\bar{b})$	>0.7			0.7-1.8	<1.6

Back-up for VH→bb

Event yields after the profile likelihood fit for the 8TeV dataset (13 fb^{-1}).

	0-lepton, 2 jet			0-lepton, 3 jet			1-lepton					2-lepton				
Bin	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]						p_{T}^{W} [GeV]					p_{T}^{Z} [GeV]				
	120-160	160-200	>200	120-160	160-200	>200	0-50	50-100	100-150	150-200	> 200	0-50	50-100	100-150	150-200	>200
ZH	2.9	2.1	2.6	0.8	0.8	1.1	0.3	0.4	0.1	0.0	0.0	4.7	6.8	4.0	1.5	1.4
WH	0.8	0.4	0.4	0.2	0.2	0.2	10.6	12.9	7.5	3.6	3.6	0.0	0.0	0.0	0.0	0.0
Top	89	25	8	92	25	10	1440	2276	1120	147	43	230	310	84	3	0
$W+c$,light	30	10	5	9	3	2	580	585	209	36	17	0	0	0	0	0
$W+b$	35	13	13	8	3	2	770	778	288	77	64	0	0	0	0	0
$Z+c$,light	35	14	14	8	5	8	17	17	4	1	0	201	230	91	12	15
$Z+b$	144	51	43	41	22	16	50	63	13	5	1	1010	1180	469	75	51
Diboson	23	11	10	4	4	3	53	59	23	13	7	37	39	16	6	4
Multijet	3	1	1	1	1	0	890	522	68	14	3	12	3	0	0	0
Total Bkg.	361	127	98	164	63	42	3810	4310	1730	297	138	1500	1770	665	97	72
	± 29	± 11	± 12	± 13	± 8	± 5	± 150	± 86	± 90	± 27	± 14	± 90	± 110	± 47	± 12	± 12
Data	342	131	90	175	65	32	3821	4301	1697	297	132	1485	1773	657	100	69

Back-up for ttH→bb

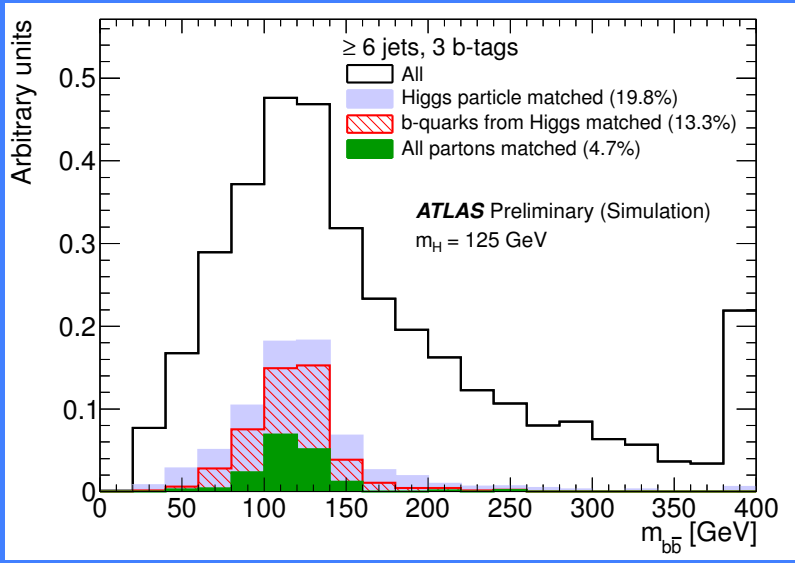
Post-fit event yields for the 7 TeV dataset.

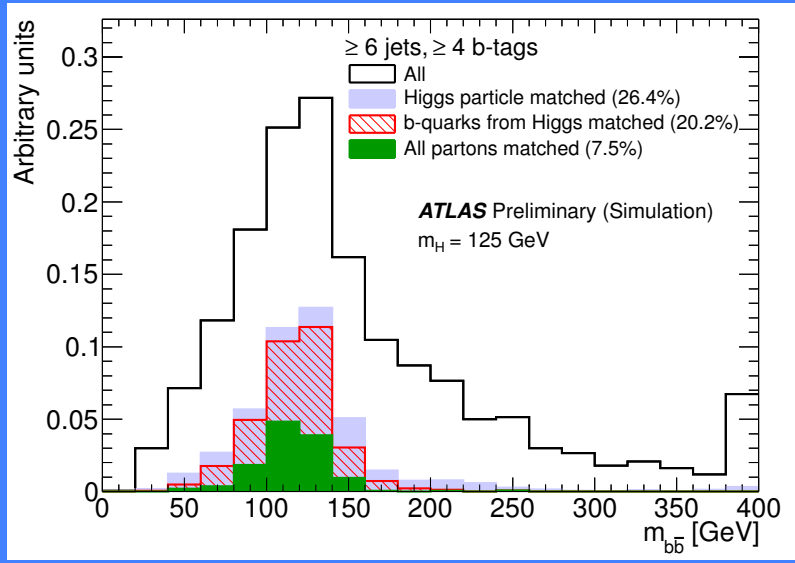
	4 jets, 0 b tags	4 jets, 1 b tags	4 jets, ≥ 2 b tags	5 jets, 2 b tags	5 jets, 3 b tags
$t\bar{t}H(125)$	0.20 ± 0.03	1.1 ± 0.1	3.0 ± 0.2	2.7 ± 0.2	2.3 ± 0.1
$t\bar{t}$+ jets	3440 ± 230	12600 ± 400	13040 ± 160	5900 ± 100	837 ± 24
W+jets	28350 ± 1000	5100 ± 470	655 ± 100	210 ± 50	16 ± 4
Z+jets	3700 ± 600	480 ± 70	33 ± 6	16 ± 4	1.1 ± 0.3
Single top	500 ± 30	1380 ± 70	820 ± 40	266 ± 15	31 ± 2
Diboson	411 ± 50	85 ± 10	15 ± 2	3.1 ± 0.4	0.26 ± 0.05
$t\bar{t}V$	12 ± 3	35 ± 9	30 ± 8	32 ± 9	6 ± 2
Multijet	3800 ± 700	1560 ± 280	460 ± 90	210 ± 50	23 ± 10
Total bkg.	40200 ± 280	21240 ± 200	15040 ± 150	6640 ± 80	915 ± 24
Data	40209	21248	15066	6653	878

	5 jets, ≥ 4 b tags	≥ 6 jets, 2 b tags	≥ 6 jets, 3 b tags	≥ 6 jets, ≥ 4 b tags
$t\bar{t}H(125)$	0.74 ± 0.04	3.4 ± 0.2	4.0 ± 0.2	2.2 ± 0.1
$t\bar{t}$+ jets	38 ± 3	3030 ± 90	560 ± 20	54 ± 5
W+jets	1.1 ± 0.4	74 ± 20	8 ± 3	0.7 ± 0.3
Z+jets	0.03 ± 0.01	6 ± 2	0.4 ± 0.2	0.01 ± 0.01
Single top	1.6 ± 0.2	92 ± 7	15 ± 1	1.5 ± 0.2
Diboson	0.01 ± 0.01	0.7 ± 0.1	0.09 ± 0.03	0.01 ± 0.01
$t\bar{t}V$	0.8 ± 0.2	45 ± 10	13 ± 4	2.7 ± 0.7
Multijet	3 ± 2	114 ± 30	34 ± 10	4 ± 3
Total bkg.	45 ± 3	3360 ± 80	634 ± 19	62 ± 5
Data	41	3340	676	65

Back-up for ttH→bb

Result for the reconstruction of M_{bb} in two signal enriched regions.





Overlaid are the distributions for the subset of events where the reconstructed Higgs boson matches (in η and ϕ) the generator-level Higgs boson particle (labeled as "Higgs particle matched"), the subset of events where the two b jets used for mbb match the b quarks from the Higgs boson decay (labeled as "b quarks from Higgs matched"), and the subset of events where all jets considered in the kinematic fit match the partons from the decays of the top quarks and Higgs boson (labeled as "all partons matched").
In all instances angular matching is performed by requiring $\Delta R < 0.4$.