Higgs to $b\bar{b}$ and $\tau\tau$ and beyond SM Higgs searches with ATLAS

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on behalf of the ATLAS collaboration

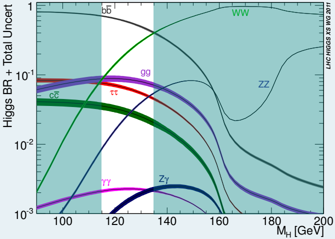
CPPM Marseille

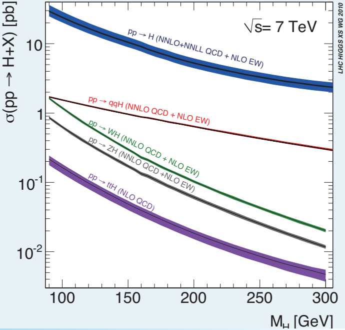
LHC Days

Split, 1 October 2012

July 2012: observation of an SM-like Higgs boson at 126 GeV

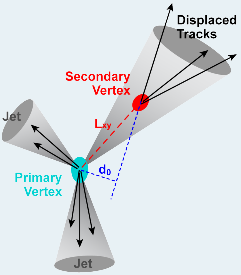
- New particle discovered
- Is it the SM Higgs boson?
- At 126 GeV: good place to be, access to many decays
- Need to test coupling to fermions, in particular:
  - BR($H \to b\bar{b}$) = 56%
  - BR($H \to \tau\tau$) = 6%
- Will help characterise new boson
- Divergences may point to new physics
- New physics could also be revealed by discovery of extended Higgs sector
- This talk:
  1. $H \to b\bar{b}$ in VH and $t\bar{t}H$
  2. $H \to \tau\tau$
  3. BSM Higgs searches





Identifying b jets

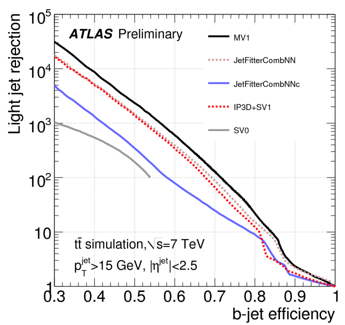
- Long decay length
- Secondary vertices
- Large impact parameter tracks



b-tagging performance

- Several algorithms focusing on 3D impact parameter (IP3D), displaced vertices (SV1) and inclusive vertex finding along *b*-hadron line of flight (JetFitter)
- Combined with neural network (MV1)

- At $\varepsilon_b \sim 70\%$: $\varepsilon_{\text{light}} \sim 0.6\%$ $\varepsilon_c \sim 20\%$

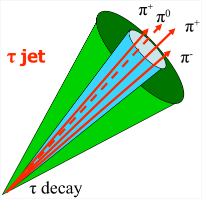


▸ ATLAS-CONF-2012-043

Tau lepton identification

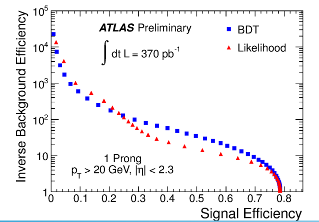
Hadronic tau decays ($\tau_{\rm had}$)

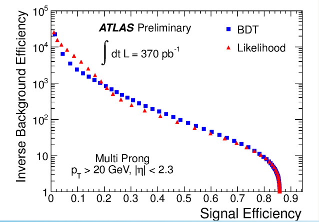
- 35% of taus decay to $\ell(e/\mu) + \nu_\ell \nu_\tau$: $\tau_{\rm lep} = \tau_e/\tau_\mu$, hard to distinguish from prompt ℓ
- Others decay hadronically, typically to ν_τ, 1 or 3 $\pi^\pm$ and possibly some π^0
- Signature: collimated calorimeter shower and small number of closeby tracks



Multivariate identification

- Using boosted decision trees (BDT) to distinguish $\tau_{\rm had}$ from jets and another BDT to reject electrons faking taus





$\varepsilon_\tau \sim 50\%$:
$\varepsilon_{\rm jet} \sim 1\%$

VH($\to b\bar{b}$) analysis

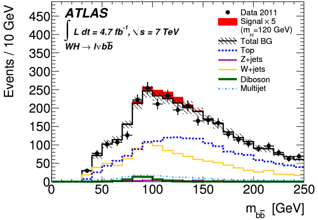
3 channels

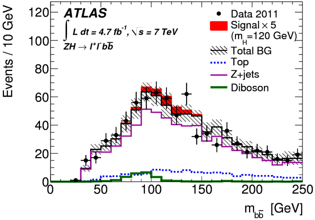
Process	Main backgrounds
$WH \to \ell\nu b\bar{b}$	$t\bar{t}$ & single top, W+jets
$ZH \to \ell\ell b\bar{b}$	Z+jets
$ZH \to \nu\bar{\nu} b\bar{b}$	Z+jets, $t\bar{t}$ & single top, W+jets and diboson

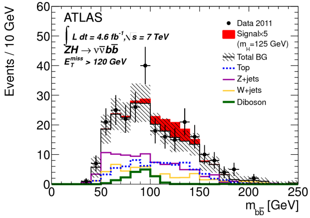
Optimisation

- Each channel subdivided in bins of p_{T}^{V} to exploit varying S/B and bkg composition (11 subchannels)
- Look for an excess in $m_{b\bar{b}}$ distribution

arXiv:1207.0210

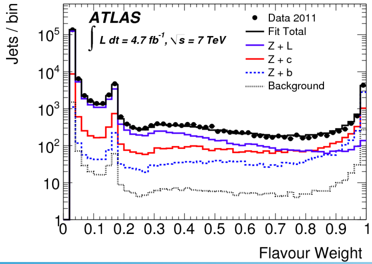


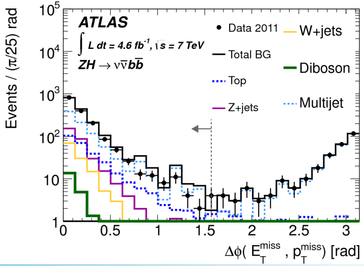




Background modelling for VH($\rightarrow b\bar{b}$)

- $m_{b\bar{b}}$ shapes from Monte Carlo (MC), except multijet
- Scale factors (SF) from simultaneous fit to data outside signal region $80 < m_{b\bar{b}} < 150$ GeV and in top control regions (CR):
  - flavour composition ($V+b$, $V+c$, $V+$light) determined before nominal fit, from fit to b-tagging weight
  - V+jets SF: 0.8–2.4, depending on jet flavour and multiplicity
  - top SF: compatible with 1 within 20%
- Multijet estimated from data, strongly suppressed by selection
- Minor backgrounds normalised to theory expectations





Uncertainties in VH($\to b\bar{b}$) analysis

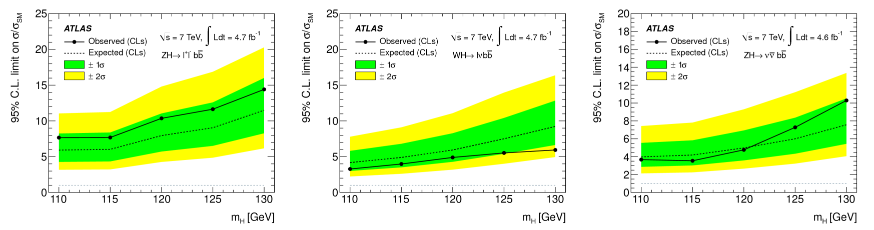
Main background uncertainties

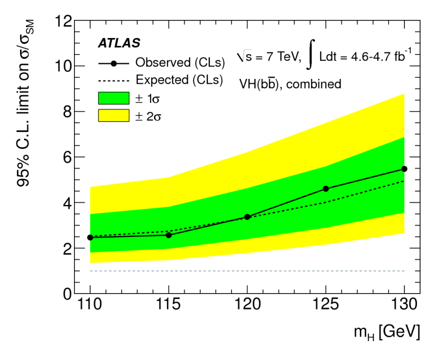
- Theory 1–15% ($m_{b\bar{b}}$ and p_T^V modelling in V+heavy flavour)
- b-tagging 1–7% (distortions of $m_{b\bar{b}}$ and p_T^V)
- Jet energy scale/resolution, E_T^{miss} 1–12% (E_T^{miss} dominant for $ZH \to \nu\bar{\nu}b\bar{b}$)
- Background normalisation 2–5% (limited statistics in global fit)
- Total: up to 20%, highest in best S/B high p_T bins

Main signal uncertainties

- b-tagging 6–14%
- Jet energy scale/resolution, E_T^{miss} 3–7%
- Theory 3–8%:
  - inclusive and differential (jet multiplicity requirement)
  - EW NLO corrections (reduces cross section at high p_T)
- Total: 9–17%, highest in best S/B high p_T bins

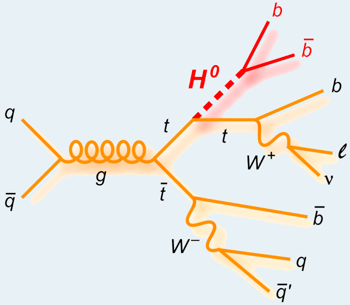
Limits in VH($\rightarrow b\bar{b}$)





- 95% CL upper limits using CLs
- Observed (expected) per channel sensitivity ($\times\sigma_{\mathrm{SM}}$):
  - $ZH \rightarrow \ell\ell b\bar{b}$: 8(6)–14(12)
  - $WH \rightarrow \ell\nu b\bar{b}$: 3(4)–6(9)
  - $ZH \rightarrow \nu\bar{\nu} b\bar{b}$: 4(4)–10(8)
- Combined: 2.5–5.5 times SM expectation, 4.6 at $m_H = 125$ GeV
- Coming: 2012 data, improved $m_{b\bar{b}}$ resolution, MVA

Selection (semileptonic $t\bar{t}$)



- single lepton trigger
- 1 isolated lepton ($p_T^{e/\mu}$>25/20 GeV)
- at least 4 jets
- E_T^{miss}>35 GeV
- e: m_T>30 GeV
- μ: $E_T^{miss}+m_T$>60 GeV

Analysis strategy

- Split in channels according to (b)jet multiplicity:
  - 4 SR: 5 and $\geq$ 6 jets, with 3 or $\geq$ 4 b-jets
  - 5 bkg regions used to constrain systematics: 4 jets with 0, 1&$\geq$ 2 b-jets, 5 and $\geq$ 6 jets with 2 b-jets
  - 4 CR to validate extrapolation results from fit to data

Combinatorics

- Final discriminant: $m_{b\bar{b}}$ for events with $\geq$ 6 jets and $\geq$ 3 b-jets, sum of jet p_T otherwise (H_T^{had})
- Kinematic likelihood fit for $t\bar{t}b\bar{b}$ to get $m_{b\bar{b}}$

ATLAS-CONF-2012-135

Backgrounds to $t\bar{t}H(\to b\bar{b})$

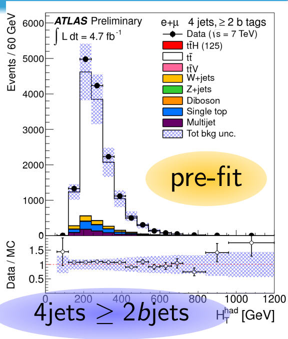
Main contributions

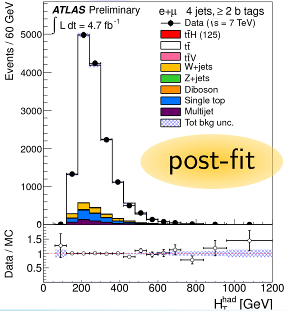
- $t\bar{t}$+jets
- depending on subchannel: single top, multijet, $t\bar{t}V$, W+jets

Data-driven background estimates

- Multijet: matrix method. To minimise statistics issues, use templates from ≥ 2 b-jets in SR
- W+jets: use charge asymmetry
  - get $N_{W^+} - N_{W^-}$ from data and $r_{\mathrm{MC}} = \frac{N_{W^+}}{N_{W^-}}$ from MC
  - $N_W = \left(\frac{r_{\mathrm{MC}}+1}{r_{\mathrm{MC}}-1}\right)(N_{W^+} - N_{W^-})$
  - shape from MC

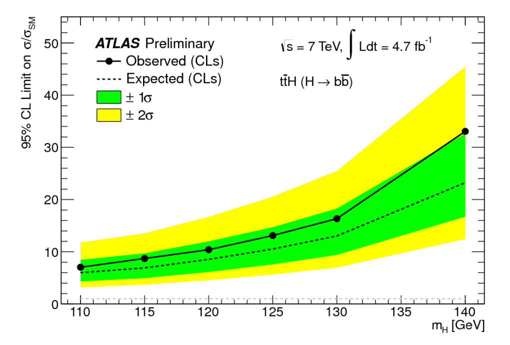
- Significant constraints from profiling (thanks to bkg regions) on ε_{btag}, W+jets, $t\bar{t}$ and $t\bar{t}$+HF

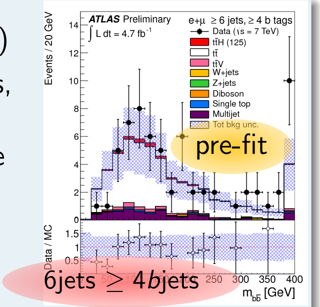


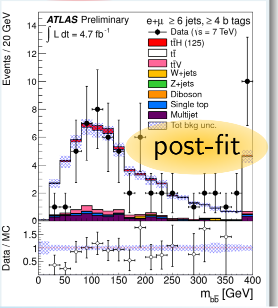


Results for $t\bar{t}H(\to b\bar{b})$

- Fit results validated in CR (not part of the fit)
- Most significant systematics: $t\bar{t}$+HF fractions, light and c-tagging efficiencies, multijet background normalisation and jet energy scale
- At $m_H = 125$ GeV: observed (expected) 95% CL upper limit of 13.1(10.5) times σ_{SM}







Categories and production processes

Split by tau decay ($\tau_{\text{lep}}\tau_{\text{lep}}$, $\tau_{\text{lep}}\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$) and jet topology:

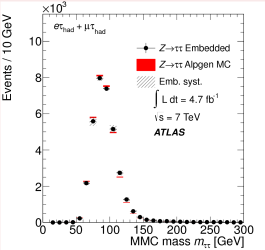
- 0-jet: bulk of gluon fusion $pp \rightarrow H$
- 1-jet: boosted Higgs in $pp \rightarrow H$ with high p_{T} jet
- 2-jet VBF: $pp \rightarrow qqH$ with 2 jets well separated in η
- 2-jet VH: $pp \rightarrow VH, H$, all other H+2-jet events

H $\rightarrow \tau\tau$ mass reconstruction

- *Collinear mass*: $m_{\tau\tau} = \frac{m_{\ell\ell}(m_{hh})}{\sqrt{x_1 \cdot x_2}}$ (x_i=momentum fraction carried by visible decay products)
- *Missing mass calculator* (MMC): likelihood based on compatibility of decay products with tau mass and kinematics to constrain neutrino momenta
- *Effective mass* (m_{eff}): invariant mass of leptons and $E_{\text{T}}^{\text{miss}}$

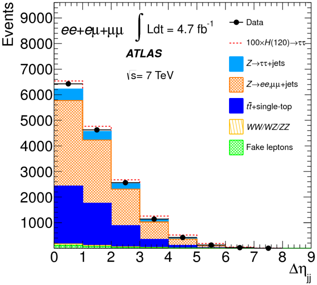
Z $\rightarrow \tau\tau$ modelling

- Main background in all channels
- Embedding: take $Z \rightarrow \mu\mu$ data events and replace μ by simulated tau decays from events with similar kinematics



arXiv:1206.5971

$H \to \tau_{lep}\tau_{lep}$ channel

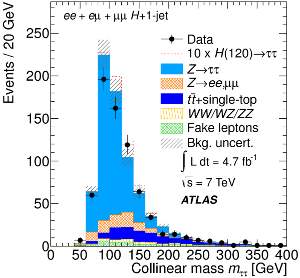


Selection

- 4 categories: H+0jet ($e\mu$ only, 95% $gg \to H$), H+1jet (72% $gg \to H$), H+2jet VH (37% VH), H+2jet VBF (80% VBF)
- 2 isolated opposite charge leptons
- Jet veto or $p_T > 40/25$ GeV; $b$jet veto
- Selection on invariant masses ($m_{\ell\ell}$, $m_{\tau\tau j}$, m_{jj})
- Separate VH ($\Delta\eta_{jj} < 2$) and VBF ($\Delta\eta_{jj} > 3$)

Backgrounds

- Dominant $Z \to \tau\tau$ from embedding
- Top: MC shapes, normalised in CR with b-jets (H+1/2) or large H_T^ℓ
- $Z \to \ell\ell$: MC shapes normalised in CR with low $E_T^{\rm miss}$
- Fake lepton: fit p_T of subleading lepton shape from CR with reversed isolation



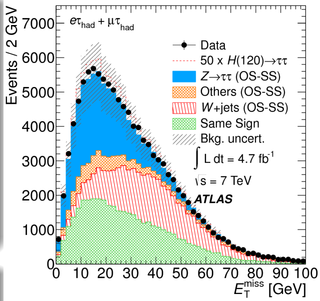
$H \to \tau_{lep}\tau_{had}$ channel

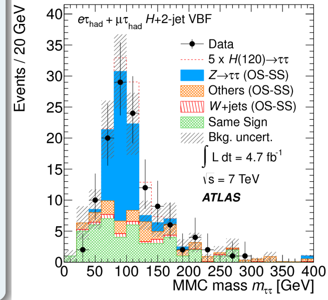
Selection

- 4 categories: H+0jet ($E_T^{miss} < 20$ GeV and $E_T^{miss} > 20$ GeV, $>98\%$ $gg \to H$), H+1jet (76% $gg \to H$), H+2jet VBF (70% VBF)
- 1 isolated lepton; 1 opposite charge tau
- Jet veto or $p_T > 25$ GeV; $E_T^{miss} > 20$ GeV
- VBF: $\Delta\eta_{jj} > 3$ in opposite hemispheres

Backgrounds

- $n_{\mathrm{OS}}^{\mathrm{bkg}} = n_{\mathrm{SS}}^{\mathrm{all}} + n_{\mathrm{OS-SS}}^{W+\mathrm{jets}} + n_{\mathrm{OS-SS}}^{Z\to\tau\tau} + n_{\mathrm{OS-SS}}^{\mathrm{other}}$
- Same sign (SS): as SR but with same charge ℓ/τ instead of opposite
- Multijet: sign-symmetric $\Rightarrow OS - SS = 0$ (verified in low E_T^{miss}/anti-isolated lepton CR)
- Dominant $Z \to \tau\tau$ from embedding
- W+jets: MC, normalised in CR with $m_T > 50$ GeV; others from simulation





H+1jet
ditau trigger (p_T>29/20 GeV)
no lepton
2 opposite charge taus (pt>35/25 GeV)
E_T^{miss}>20 GeV
≥1jet p_T>40 GeV
$\Delta R_{\tau\tau}$<2.2
$m_{\tau\tau j}$>225 GeV
Signal composition ($gg \rightarrow H$:VBF:VH %)
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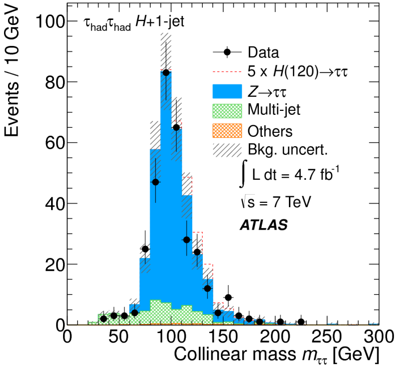
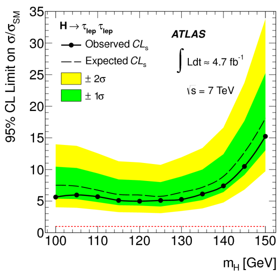
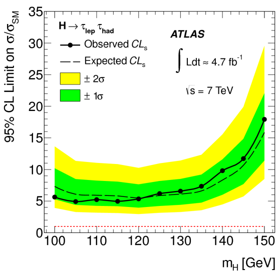


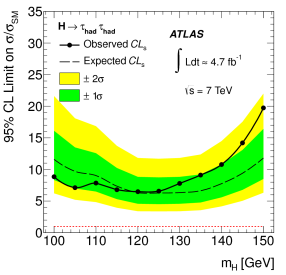
Backgrounds

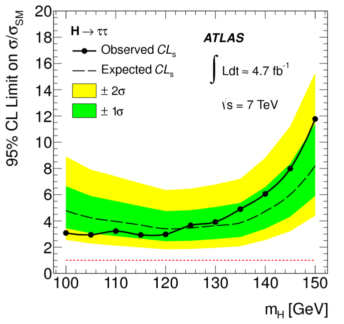
- In CR with $m_{\tau\tau} < 100$ GeV and $\Delta R_{\tau\tau} < 2.8$, fit 2D track multiplicity of tau candidates in cone $\Delta R < 0.6 \Rightarrow Z \rightarrow \tau\tau$ contribution
- Multijet template from SS events, do same fit in signal region for multijet contribution

Limits on $H \to \tau\tau$









- 95% CL upper limits using CLs
- Most sensitive: $\tau_{\rm had}\tau_{\rm had}$, H+2jet VBF in $\tau_{\rm lep}\tau_{\rm had}$ and $\tau_{\rm lep}\tau_{\rm lep}$
- Combined observed (expected) limit: 2.9(3.4)–11.7(8.2) times SM expectation, 3.7 at $m_H = 125$ GeV
- Coming: 2012 data analysis

Beyond the SM Higgs searches

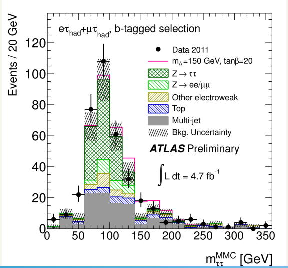
Overview (7 TeV analyses)

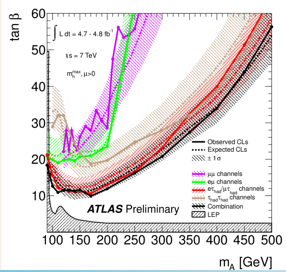
Channel	Lumi	Reference
MSSM $h/A/H \to \tau\tau/\mu\mu$	4.7-4.8 fb^{-1}	ATLAS-CONF-2012-094
$H^{\pm} \to \tau\nu$	4.6 fb^{-1}	JHEP 1206 (2012) 039
$H^{\pm} \to c\bar{s}$	0.035 fb^{-1}	ATLAS-CONF-2011-094
SM with 4$^{\text{th}}$ fermion generation	1.0-2.3 fb^{-1}	ATLAS-CONF-2011-135
Fermiophobic Higgs	4.9 fb^{-1}	arXiv:1205.0701
Light scalar Higgs ($a \to \mu\mu$)	0.039 fb^{-1}	ATLAS-CONF-2011-020
Higgs to light scalar particles	4.9 fb^{-1}	ATLAS-CONF-2012-079
Doubly Charged $H^{\pm\pm} \to ee/\mu\mu$	4.7 fb^{-1}	ATLAS-CONF-2012-069
Higgs to long-lived particles	1.9 fb^{-1}	PRL 108 (2012) 251801
Higgs to displaced muon jets	1.9 fb^{-1}	ATLAS-CONF-2012-089

MSSM h/A/H $\rightarrow \tau\tau / \mu\mu$

- Production via *gg* fusion or in association with *b* quarks (more important with higher $\tan\beta$)
  $\Rightarrow$ search separately for final states with and without *b*-jets
- $h/A/H \rightarrow \tau\tau$: conceptually similar to SM $H \rightarrow \tau\tau$ except for *b*-tagged SR
- $h/A/H \rightarrow \mu\mu$:
  - Dominant backgrounds: Drell-Yan, top (after *b*-tagging)
  - Background model: Z/γ^* interference convoluted with Gaussian resolution
  - Signal model: Breit-Wigner convoluted with Gaussian resolution and Landau function
  - Background in SR from sideband fitting

Results





- No deviation from SM observed
- Limits as low as $\tan\beta = 10$

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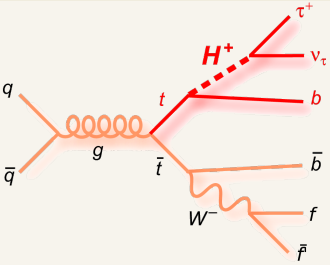
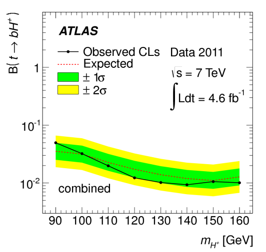
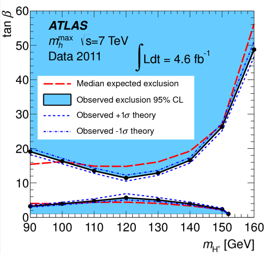
Selection



- 3 channels: $\tau_{\text{lep}}+W(\to\text{jets})$, $\tau_{\text{had}}+W(\to \ell\nu)$ and $\tau_{\text{had}}+W(\to\text{jets})$
- Depending on presence of lepton:
  - Single lepton or tau+$E_{\text{T}}^{\text{miss}}$ trigger
  - Isolated lepton or lepton veto
  - Require jets with $p_{\text{T}} > 20$ GeV jets, with b-tagged jets
  - $E_{\text{T}}^{\text{miss}}$

Results





- No deviation observed
- $H^{\pm}$ allowed phase space heavily constrained

JHEP 1206 (2012) 039

Search for H $\rightarrow aa \rightarrow 4\gamma$

- Some SM extensions (e.g. NMSSM) predict light pseudoscalar Higgs boson a, which can decay to $\gamma\gamma$
- a is very light, $\sim$ 100 MeV $\Rightarrow$ heavily boosted, photons tightly collimated, may appear as one
- Similar selection to SM $H \rightarrow \gamma\gamma$ except
  - removed some shower shape requirements in photon ID
  - no event categorisation
- No excess found, sensitivity decreases with m_a
- Limits for m_a = 100–400 MeV and m_H = 110–150 GeV

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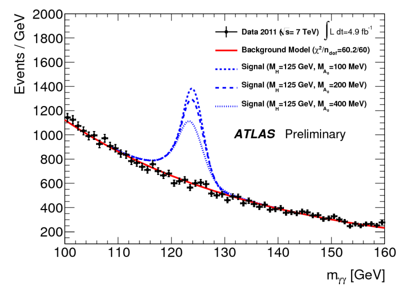
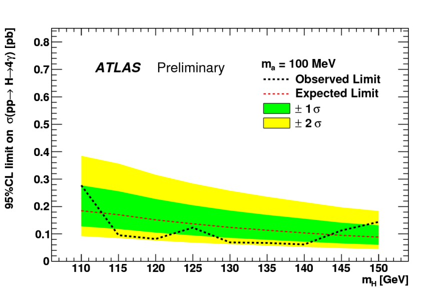
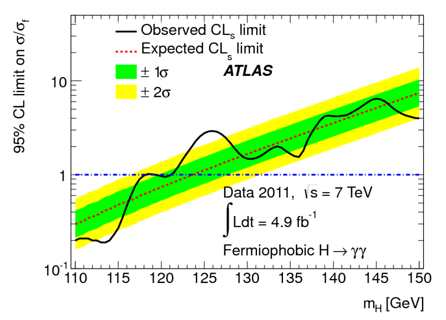




Fermiophobic Higgs search

- Set coupling to fermions to 0
- Production exclusively through VBF, VH processes, decays to $\gamma\gamma, ZZ, WW, Z\gamma$
- Same analysis as SM $H \to \gamma\gamma$: 2 photons, 9 categories based on η_γ, conversions, p_T relative to diphoton thrust axis

- Largest excess at 125.5 GeV, local significance of 2.9 standard deviations (1.6 with look-elsewhere effect)
- Fermiophobic Higgs excluded in [110.0-118.0] GeV and [119.5-121.0] GeV



arXiv:1205.0701

Conclusions

- After observation of a particle at 126 GeV compatible with the SM Higgs boson, crucial to check all decay modes
- In particular coupling to fermions in $H \to b\bar{b}$ and $H \to \tau\tau$ decays
- Modes accessible in gluon fusion, vector boson fusion, vector boson and $t\bar{t}$ associated production
- ATLAS not yet sensitive to several channels
- No deviations from SM observed
- Analysis improvements like multivariate discriminants underway
- Large 2012 dataset analysis ongoing, new results very soon

Backup

$VH(\to b\bar{b})$ selection

$WH \to \ell\nu b\bar{b}$

Single lepton trigger
1 lepton, $p_T > 25$ GeV
$E_T^{miss} > 25$ GeV
Leading $p_T^b > 45$ GeV
2^{nd} $p_T^b > 25$ GeV
$\Delta R(b,\bar{b}) > 0.7$ ($p_T^W < 200$ GeV)
$m_T^W > 40$ GeV, no additional jet

Efficiency $\sim 2.4\%$

$ZH \to \ell\ell b\bar{b}$

Single/dilepton triggers
2 same flavor ℓ, $p_T > 20$ GeV
$E_T^{miss} < 50$ GeV
Leading $p_T^b > 45$ GeV
2^{nd} $p_T^b > 25$ GeV
$\Delta R(b,\bar{b}) > 0.7$ ($p_T^Z < 200$ GeV)
$83 < m_{\ell\ell} < 99$ GeV

Efficiency $\sim 5.0\%$

$ZH \to \nu\bar{\nu} b\bar{b}$

E_T^{miss} trigger
No lepton with $p_T > 10$ GeV
$E_T^{miss} > 120$ GeV
Leading $p_T^b > 45$ GeV
2^{nd} $p_T^b > 25$ GeV
$\Delta R(b,\bar{b}) > 0.7$ ($E_T^{miss} < 200$ GeV)
$p_T^{miss} > 30$ GeV
$\Delta\phi(E_T^{miss}, p_T^{miss}) < \pi/2$

$\Delta\phi_{min}(E_T^{miss}, \text{jet}) > 1.8$
$\Delta R(b,\bar{b}) < 2$
(1.7 for $E_T^{miss} \geq 160$ GeV)
$\Delta\phi(E_T^{miss}, b\bar{b}) > 2.7$
(2.9 for $E_T^{miss} \geq 160$ GeV)
No additional jet

Efficiency $\sim 2.1\%$

($+0.2\%$ from $WH \to \ell\nu b\bar{b}$)

$VH(\to b\bar{b})$ uncertainties

bin	$ZH \to \ell\ell b\bar{b}$ p_T^Z [GeV] 0-50	50-100	100-200	>200	$WH \to \ell\nu b\bar{b}$ p_T^W [GeV] 0-50	50-100	100-200	>200	$ZH \to \nu\bar{\nu} b\bar{b}$ E_T^{miss} [GeV] 120-160	160-200	>200
Components of the relative systematic uncertainties of the background [%]											
b-tag eff	1.4	1.0	0.3	4.8	0.9	1.3	0.9	7.2	4.1	4.2	5.5
BG norm	3.6	3.4	3.6	3.8	2.7	1.8	1.8	4.5	2.7	2.2	3.2
jets/E_T^{miss}	2.1	1.2	2.7	5.1	1.5	1.4	2.1	9.5	7.7	8.2	12.1
leptons	0.2	0.3	1.1	3.4	0.1	0.2	0.2	1.7	0.0	0.0	0.0
luminosity	0.2	0.1	0.2	0.4	0.1	0.1	0.1	0.2	0.2	0.5	0.7
pileup	0.9	1.6	0.5	1.3	0.1	0.2	0.8	0.5	1.6	2.5	3.0
theory	5.2	1.3	4.7	14.9	2.2	0.3	1.6	14.8	2.9	4.0	7.7
total BG	6.9	4.3	6.6	17.3	3.9	2.7	3.4	19.6	9.7	10.6	16.0
Components of the relative systematic uncertainties of the signal [%]											
b-tag eff	6.4	6.4	7.0	13.7	6.4	6.4	7.0	12.1	7.1	8.2	9.2
jets/E_T^{miss}	4.9	3.2	3.5	5.5	5.8	4.6	3.7	3.3	7.3	5.1	6.3
leptons	0.9	1.2	1.7	2.6	3.0	3.0	3.0	3.2	0.0	0.0	0.0
luminosity	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
pileup	0.5	1.1	1.8	2.2	1.2	0.3	0.3	1.6	0.2	0.2	0.0
theory	4.6	3.6	3.3	5.3	4.4	4.7	5.0	8.0	3.3	3.3	5.6
total signal	10.1	9.1	9.6	16.5	11.4	10.8	11.0	16.0	11.8	11.4	13.4

$H \to \tau\tau$ selections

$H \to \tau_{lep}\tau_{lep}$ channel

H+0jet ($e\mu$ only)	H+1jet	H+2jet VH	H+2jet VBF
single and dilepton triggers, 2 isolated opposite charge leptons			
$30 < m_{e\mu} < 100$ GeV, $30 < m_{ee/\mu\mu} < 75$ GeV			
–	$E_T^{miss} > 20(40)$ GeV for $e\mu(ee,\mu\mu)$		
no jet with $p_T > 40$ GeV	jet $p_T > 40$ GeV	jet $p_T > 40(25)$ GeV	
	no $b$jet with $p_T > 25$ GeV		
$\Delta\Phi_{\ell\ell} > 2.5$	$0.5 < \Delta\Phi_{\ell\ell} < 2.5$		
$H_T^{\ell} = \sum p_T^{\ell} + E_T^{miss} < 120$ GeV	$m_{\tau\tau j} > 225$ GeV	$50 < m_{jj} < 120$ GeV $\Delta\eta_{jj} < 2$	$m_{jj} > 350$ GeV $\Delta\eta_{jj} > 3$
Signal composition ($gg \to H$:VBF:VH %)			
95:3:2	72:21:7	56:7:37	19:80:1

$H \to \tau_{lep}\tau_{had}$ channel

H+0jet		H+1jet	H+2jet VBF ($e \oplus \mu$ combined)
single lepton trigger, 1 isolated lepton ($p_T^{e/\mu} > 25/20$ GeV), 1 opposite charge tau			
$m_T < 30$ GeV			
$E_T^{miss} < 20$ GeV	$E_T^{miss} > 20$ GeV		
no jet with $p_T > 25$ GeV		≥ 1jet $p_T > 25$ GeV (fail VBF)	≥ 2jet $p_T > 25$ GeV $\Delta\eta_{jj} > 3$, $\eta_j^1 \cdot \eta_j^2 < 0$, $m_{jj} > 300$ GeV
Signal composition ($gg \to H$:VBF:VH %)			
99:0.5:0.5	98:1:1	76:14:10	29:70:1

MSSM charged Higgs $H^\pm \to \tau\nu$ in $t\bar{t}$ decays

$\tau_{\rm lep}$+W(→jets)

- single lepton trigger
- 1 isolated lepton
- at least 4 $p_T > 20$ GeV jets
- exactly 2 b-jets
- $E_T^{\rm miss} > 40$ GeV
- $m_T < 60$ GeV
- $\cos\theta^*_\ell = \frac{2m^2_{b\ell}}{m^2_{\rm top} - m^2_W} - 1 < -0.6$

$\tau_{\rm had}$+W(→jets)

- tau+$E_T^{\rm miss}$ trigger
- exactly 1 tau
- no other lepton
- at least 4 $p_T > 20$ GeV jets
- at least 1 b-jet
- $E_T^{\rm miss} > 65$ GeV
- $120 < m_{jjb} < 240$ GeV

$\tau_{\rm had}$+W($\to \ell\nu$)

- single lepton trigger
- 1 isolated lepton
- 1 opposite charge tau
- at least 2 $p_T > 20$ GeV jets
- at least 1 b-jet
- vertex $\sum p_T > 100$ GeV