ATLAS searches for the Higgs Boson

CAP Congress 2014

Doug Schouten
on behalf of the ATLAS Collaboration

17-06-2014

Introduction

- diverse phenomology in SM Higgs sector $\Rightarrow$ *many probes for BSM physics*
- measurements of rare production and decay modes starting to be realized, will be very important in LHC Run II

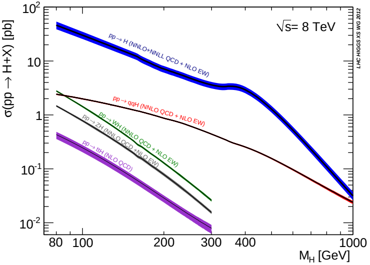


Figure: cross-section for gg-fusion, VBF, associated (WH, ZH) and ttH production (left, largest to smallest) and branching ratios for largest Higgs decay modes (right).

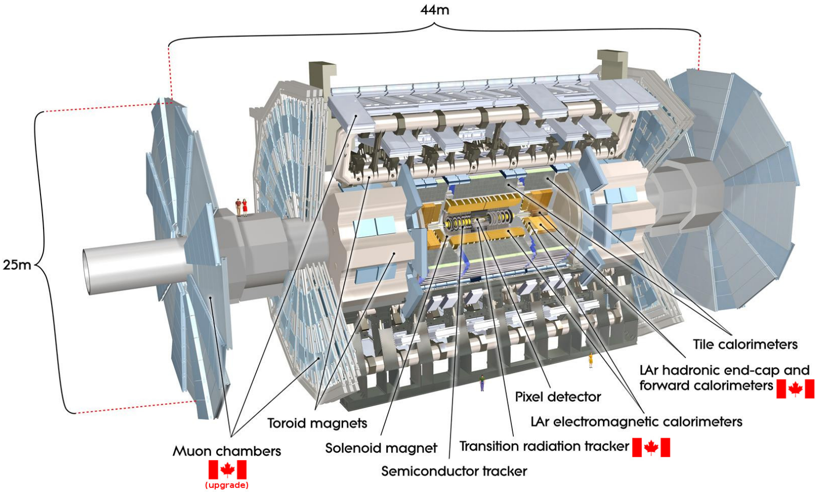
Outline

- this presentation will focus on **new ATLAS results** since [1] (i.e., those published after CAP 2013)
  - updates and new results are denoted with NEW
- impressive collection of measurements have been completed & updated:
  1. "bread and butter" di-boson channels: $\gamma\gamma$, $ZZ \to 4\ell$, $H \to WW^{(*)} \to \ell\nu\ell\nu$
  2. fermionic decay: $H \to \tau\tau$
  3. $ttH(\to \gamma\gamma, bb)$
  4. associated production $WH(\to bb, WW^{(*)})$
  5. rare decay modes: $\mu\mu$ and $Z\gamma$
- could spend $\frac{1}{2}$ hour on each of these individually ... ☹

Further references:

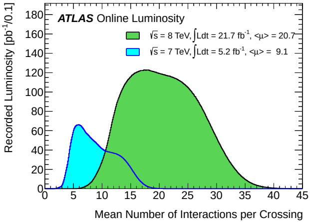
- *Higgs boson production and couplings in diboson final states*: arXiv:1307.1427
- Compendium of *ATLAS Higgs Public Results*: link

Detector Overview



Event Reconstruction

- collected 4.7 fb^{-1} in 2011 @ 7 TeV center-of-mass, 20.7 fb^{-1} in 2012 @ 8 TeV
- sophisticated methods to measure final states in collision events within a very noisy environment



Leptons

- muons from matched tracks in muon spectrometer (MS) to inner tracker (use only MS in $2.5 < |\eta| < 2.7$)
  - calorimeter-tagged and standalone used in $ZZ \to 4\ell$
- electrons reconstructed from tracks matched to clusters
  - select based on cluster shapes in electromagnetic (EM) calorimeter, hadronic leakage
- 1 & 3-prong hadronic τ decays identified with BDT @ 55% efficiency, rejection of jets is O(10^2)

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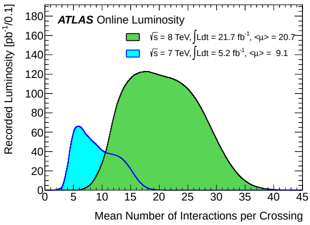

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- built from noise-suppressed clusters with $R = 0.4$ anti-k_T algorithm
- $p_T > 25$ (30) GeV in central (forward) region, track/vertex matching suppresses pileup jets
- correct for pileup using N_{PV} and event energy density ρ, jet area A
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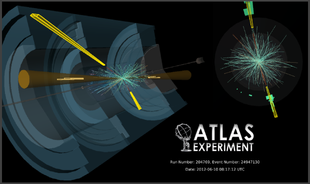
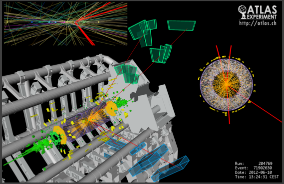
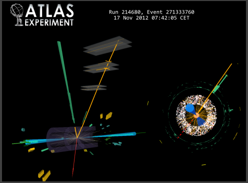
$E_{\mathrm{T}}^{\mathrm{miss}}$

- vectoral sum of reconstructed leptons, photons, jets
  - include calorimeter cells in clusters not included in reconstruced objects
- also calculate $\mathbf{p}_T^{miss}$ using tracks

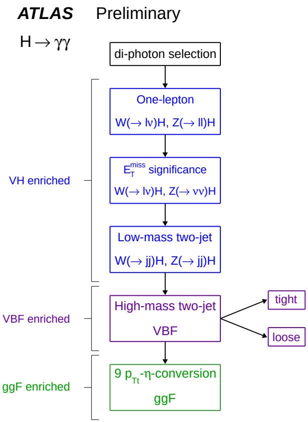
Di-boson Channels: $\gamma\gamma$, $ZZ \to 4\ell$, $WW^{(*)} \to \ell\nu\ell\nu$







Sample Selection



di-photon selection

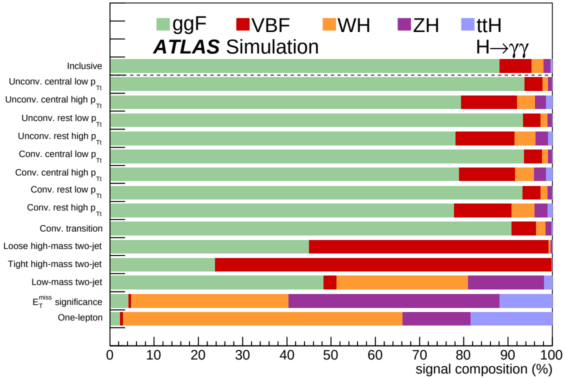
- diphoton trigger $E_T > 20/20$ (35/25) GeV for leading/sub-leading photon in 7 TeV (8 TeV)
- offline $E_T > 40/30$ GeV, (excl. $1.4 \leq \eta \leq 1.6$)
- select events with $100 < m_{\gamma\gamma} < 160$

	central ($\lvert\eta\rvert < 0.75$)		transition ($1.3 < \lvert\eta\rvert < 1.75$)	other ($0.75 < \lvert\eta\rvert < 1.3, 1.75 < \lvert\eta\rvert < 2.37$)	
≥ 1 conversions	$p_{T,t} < 60$	$p_{T,t} > 60$	all $p_{T,t}$	$p_{T,t} < 60$	$p_{T,t} > 60$
unconverted	$p_{T,t} < 60$	$p_{T,t} > 60$	$p_{T,t} < 60$		$p_{T,t} > 60$

Sample Selection

ATLAS Preliminary

Expected signal composition in $H \to \gamma\gamma$ categories



di-photon

- diphoto… leading…
- offline …
- select e…

tight

loose

				…η| < 2.37)
≥ 1 con…				> 60
unconverted	$p_{T,t} < 60$	$p_{T,t} > 60$	$p_{T,t} < 60$	$p_{T,t} > 60$

Signal Yield

- background from fits in $m_{\gamma\gamma}$ sidebands
- dominant uncertainty on signal yield reduced by factor of four, to $\sim 2\%$ NEW

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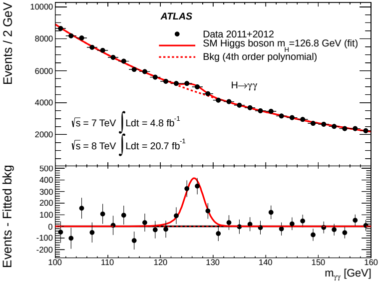
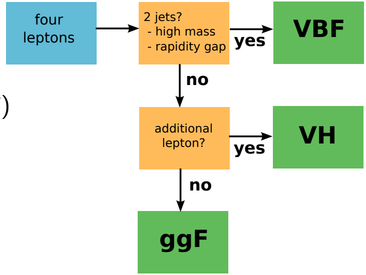
Category	N_D	N_B	N_S	ggF	VBF	WH	ZH	$t\bar{t}H$
Untagged	13931	13202	350	320	19	7.0	4.2	1.0
Loose high-mass two-jet	41	28	5.0	2.3	2.7	< 0.1	< 0.1	< 0.1
Tight high-mass two-jet	23	13	7.7	1.8	5.9	< 0.1	< 0.1	< 0.1
Low-mass two-jet	19	21	3.1	1.5	< 0.1	0.92	0.54	< 0.1
E_T^{miss} significance	8	4	1.2	< 0.1	< 0.1	0.43	0.57	0.14
Lepton	20	12	2.7	< 0.1	< 0.1	1.7	0.41	0.50
All categories (inclusive)	14025	13280	370	330	27	10	5.8	1.7



- combined observed $Z_0 = 7.4\sigma$, compared to 4.3σ expected
  - *discovery-level signal in just this channel*

Sample Selection

- largely unchanged w.r.t. discovery analysis, see Ref [1]
- select four leptons ($p_T > 20/15/10/6-7$)
- quadruplets satisfy $50 < m_{12} < 106$ GeV, $m_{\text{min}} < m_{34} < 115$ GeV[a]
  - m_{12} is mass closest to m_Z, m_{34} is the other pair mass
- selection efficiency ranges between 19% ($4e$) and 39% (4μ)
- split into analysis categories NEW



[a] Note: m_{min} ranges from 12 to 50 depending on $m_{4\ell}$, select one with minimal $|m_{34} - m_Z|$

Background & Signal Yield

- use NLO simulation for irreducible background ZZ
- $\ell\ell + \mu\mu$: non-isolated muon sample for $Z + bb$ and $t\bar{t}$ backgrounds[a]
- relax electron cuts to determine $\ell\ell + ee$ fakes background

[a] *fit* m_{12} *distribution*

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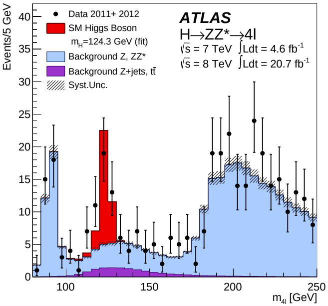
- relax electron cuts to determine $\ell\ell + ee$ fakes background
- largest uncertainties on fitted signal arise from electron efficiencies and $Z + bb$ background estimate
- maximal deviation is $Z_0 = 6.6\sigma$ (4.4σ expected) at $m_H = 124.3$ GeV
  - *also clear signal in just this channel*

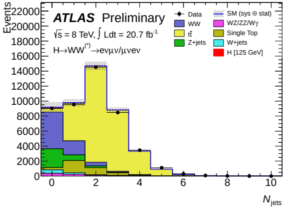


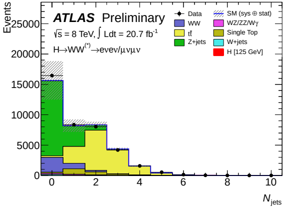
	Signal	ZZ^*	$Z + \text{jets},\ t\bar{t}$	Observed
4μ	6.3±0.8	2.8±0.1	0.55±0.15	13
$2e2\mu/2\mu2e$	7.0±0.6	3.5±0.1	2.11±0.37	13
$4e$	2.6±0.4	1.2±0.1	1.11±0.28	6

[a] *fit m_{12} distribution*

Sample Selection

- select two leptons with $p_T > 25/15$ GeV
- complicated channel in terms of background composition, and has poor mass resolution





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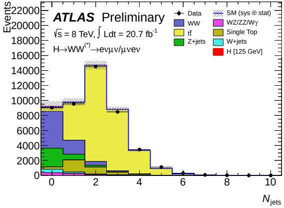
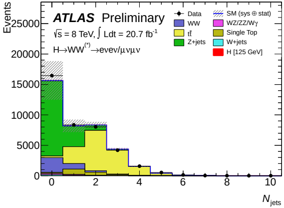
	$e\mu + \mu e$	$ee + \mu\mu$
$N_j = 0$	$m_{\ell\ell} > 10$ GeV $E^{miss}_{T,rel} > 25$ GeV	$m_{\ell\ell} > 12$, $\lvert m_{\ell\ell} - m_Z \rvert > 15$ GeV $E^{miss}_{T,rel} > 45$ GeV, $p^{miss}_{T,rel} > 45$ GeV $f_{\text{recoil}} < 0.05$
	$\Delta\phi_{\ell\ell,E^{miss}_T} > \pi/2$ $p^{\ell\ell}_T > 30$	
$N_j = 1$	$m_{\ell\ell} > 10$ GeV $E^{miss}_{T,rel} > 25$ GeV $\lvert m_{\tau\tau} - m_Z \rvert > 25$	$m_{\ell\ell} > 12$, $\lvert m_{\ell\ell} - m_Z \rvert > 15$ GeV $E^{miss}_{T,rel} > 45$ GeV, $p^{miss}_{T,rel} > 45$ GeV $f_{\text{recoil}} < 0.2$
	$N_{b-tag} = 0$	
$N_j \geq 2$	$m_{\ell\ell} > 10$ GeV $E^{\text{miss}}_{\text{T}} > 20$ GeV	$m_{\ell\ell} > 12$, $\lvert m_{\ell\ell} - m_Z \rvert > 15$ GeV $E^{\text{miss}}_{\text{T}} > 45$ Gev, $E^{miss}_{T,STVF} > 35$ GeV
	$m_{jj} > 500$ GeV, $\Delta y_{jj} > 2.8$ central jet, outer lepton veto $p^{\text{tot}}_T < 45$ GeV, $N_{b-tag} = 0$	





- exploit spin-0 nature with $\Delta\phi_{\ell\ell} < 1.8$, $m_{\ell\ell} < 50$ cuts
- $m_T = \sqrt{(E^{\ell\ell}_T + E^{\text{miss}}_{\text{T}})^2 - \lvert \mathbf{p}^{miss}_T + \mathbf{E}^{miss}_T \rvert^2}$ is discriminating variable in all channels

Background Estimation

Process
$Z^{(*)}Z^{(*)} \to 4l$
$W(Z/\gamma^*)$, $W\gamma$
WW
$t\bar{t}$
single top
Z/γ^* (+ jets)
W+jets

Legend:

- prediction from simulation
- validated in data sample
- normalised in data sample
- derived from data

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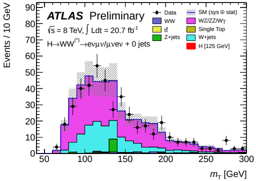

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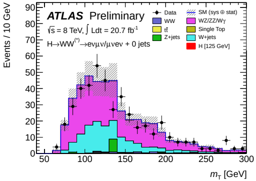

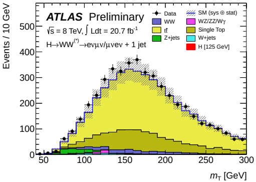

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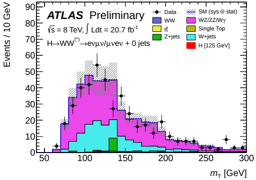

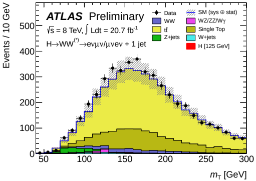

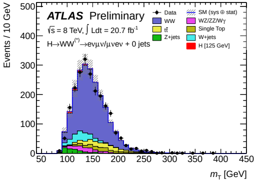

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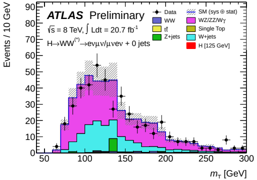

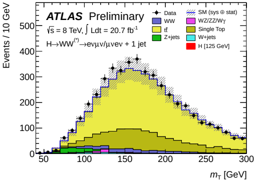

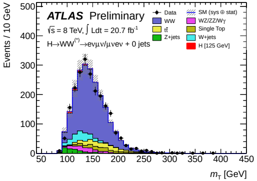

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- Z/γ^* yield in $ee/\mu\mu$ channels is estimated using efficiency measurements in m_Z window

Signal Yield

- largest systematic uncertainties are theoretical (QCD scale, parton shower modeling)
  - dominant experimental uncertainty is jet energy scale/resolution, b-tagging

	$N_j = 0$	$N_j = 1$	$N_j \geq 2$
Observed	831	309	55
Signal	100 ± 21	41 ± 14	10.9 ± 1.4
Total background	739 ± 39	261 ± 28	36 ± 4
WW	551 ± 41	108 ± 40	4.1 ± 1.5
Other VV	58 ± 8	27 ± 6	1.9 ± 0.4
Top-quark	39 ± 5	95 ± 28	5.4 ± 2.1
Z+jets	30 ± 10	12 ± 6	22 ± 3
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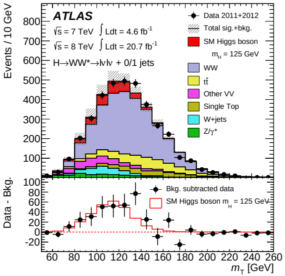

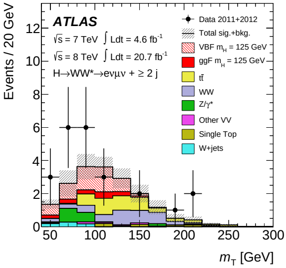

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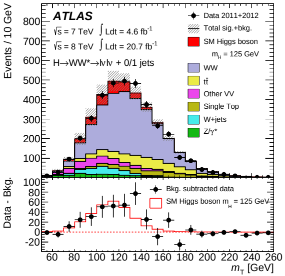
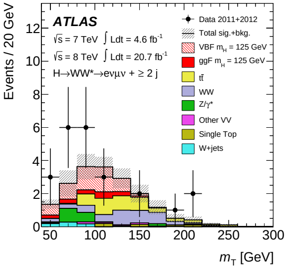
- maximal observed Z_0 is 4.1σ for $m_H = 140$ GeV
- at $m_H = 125$ GeV, $Z_0 = 3.8\sigma$ (obs. & exp.)





Mass Measurement

Submitted to PRD NEW

- mass measurement is performed in $ZZ \to 4\ell$ and $\gamma\gamma$ channels
- allow the signal strengths $\mu_{4\ell}$, $\mu_{\gamma\gamma}$ to float
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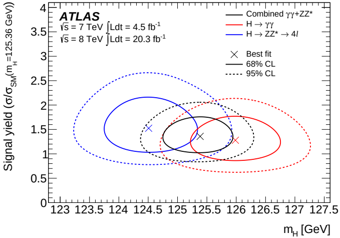
  - best overall $m_H = 125.4 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{sys})$ GeV
- consistency of $\gamma\gamma$ and ZZ masses is at the 4.8% level

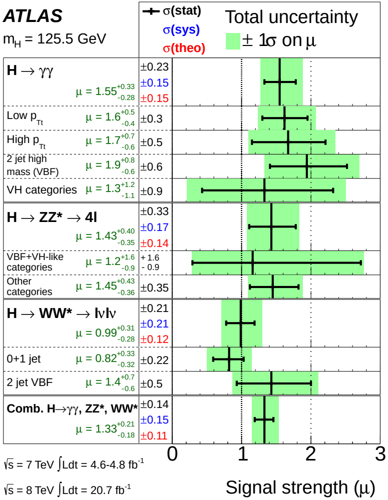
$$\Delta m_H = 1.47 \text{ GeV}$$

- **many** cross-checks performed, dedicated sub-group
- investigate systematics on e/γ scales with $Z, Z\gamma, J/\psi$ samples
- improved γ, electron, μ calibrations



Combined Rate

- use best-fit mass hypothesis $m_H = 125.5$ GeV maximum likelihood fit
- $\mu = 1.33 \pm 0.14\,(\text{stat}) \pm 0.15(\text{sys})$
  - consistent with SM $\mu = 1$ at $\sim$ 7% level
  - largest deviation in $H \to \gamma\gamma$ at 1.9σ



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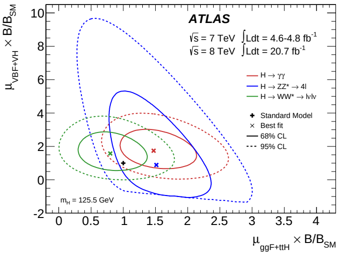
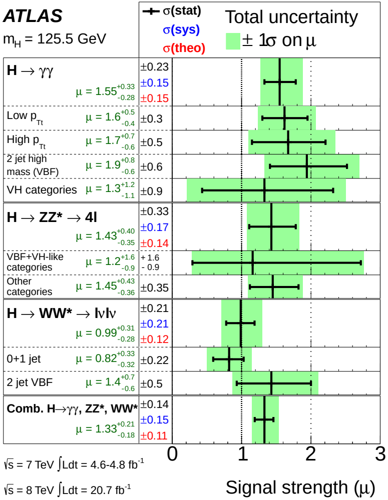
  - consistent with SM $\mu = 1$ at $\sim 7\%$ level
  - largest deviation in $H \to \gamma\gamma$ at 1.9σ





- evidence for VBF production at 3.3σ level
- best-fit VBF to ggF+ttH ratio is $1.4^{+0.4}_{-0.3}(\text{stat})^{+0.6}_{-0.4}(\text{sys})$

Fermionic Production and Decay Modes

Overview NEW

Ref: http://cds.cern.ch/record/1632191

- $H \to \tau\tau$ is the only fermionic decay channel with strong experimental evidence
  - *adds important contraints on Yukawa coupling*

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  - *adds important contraints on Yukawa coupling*
- diverse backgrounds for each of the τ decay combinations

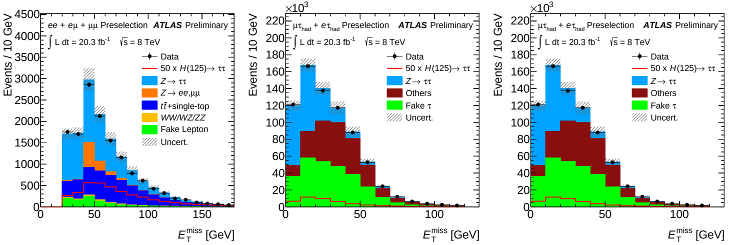

Figure: $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions for $\ell\ell$ for $\ell = e, \mu$ (left), $\ell\tau_{\mathrm{had}}$ (middle) and $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ (right)

- necessitates **heavy usage of MVA techniques**
  - τ triggering
  - discrimination of abundant background processes
- separate $\ell\ell$, $\ell\tau_{\mathrm{had}}$, and $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channels
- use two categories with improved S/B: VBF-like (large $m_{jj}, \Delta\eta_{jj}$) and boosted ggF (large $p_T^{\tau\tau}$)

BDT

- dedicated BDT for each decay channel in boosted & VBF categories

backgrounds

- $Z \to \tau\tau$ background modeled using novel "embedding" technique
  - simulated τ decays replace μ in $Z \to \mu\mu$ data sample
- $t\bar{t}$ background is constrained using b-tagged control sample
- W+jet(s) is estimated using a fake factor for jets $\to$ τ determined in data

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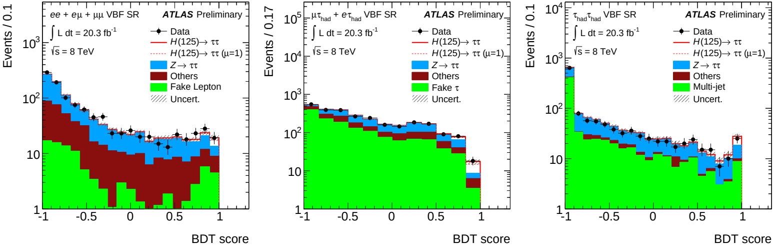
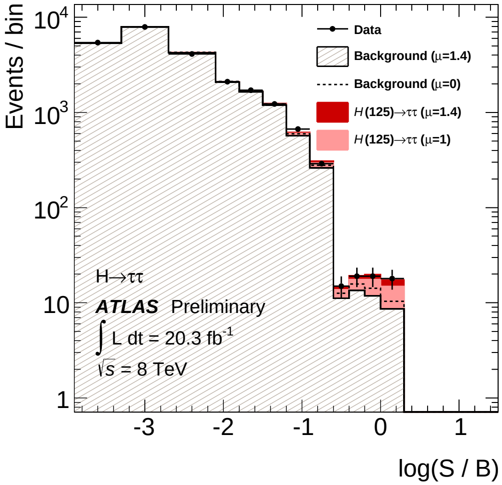
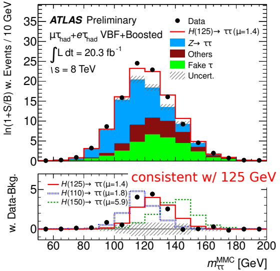
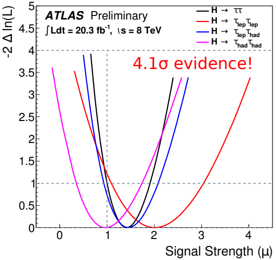




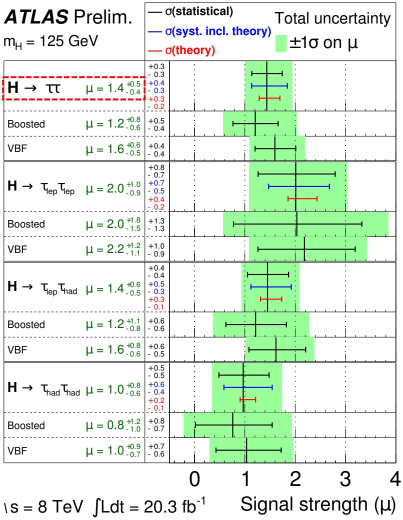
distribution of $\log(S/B)$ for all events, where S/B is taken from the expected purity in the BDT bin

$H \to \tau\tau$ Results





fully consistent with SM (☺ or ☹?)

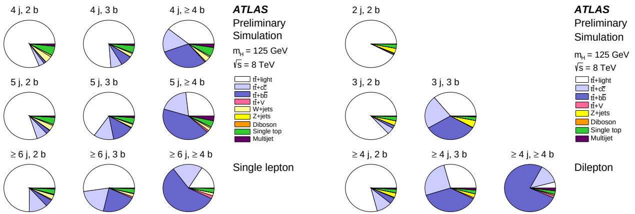


Overview

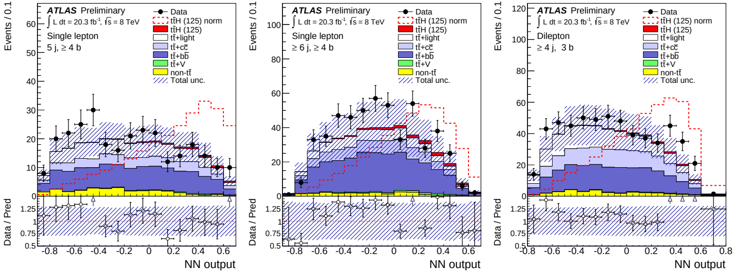
Ref: http://cds.cern.ch/record/1670532

- very interesting b/c production & decay are via fermion couplings
- ... but *very* challenging because of small signal and huge $t\bar{t}$ background
- considered semi-leptonic and dilepton $t\bar{t}$ signatures
  - sub-divide into jet and b-tag multiplicities for control samples and enhanced S/B
- utilize neural network to discriminate background and ttH signal

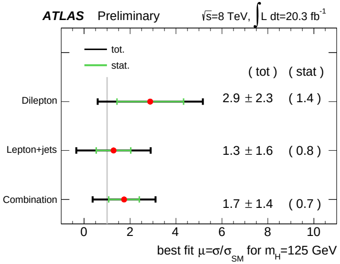
categories



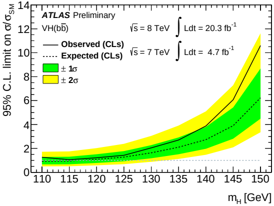
Results



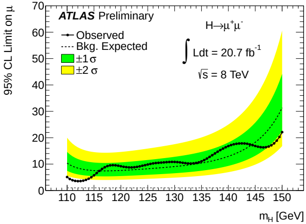
- large uncertainty on $t\bar{t} + b\bar{b}$ production
  - *need improvements in theory*
- set 95% limit on $t\bar{t}H$ production $4.1\times$ SM
- **key channel** to study in LHC Run II



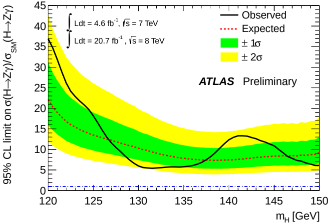
W/ZH



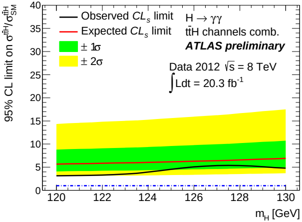
$\mu\mu$



$Z\gamma$



$ttH(\gamma\gamma)$



Final Remarks

- complex Higgs searches and measurements in many final states
  - enhance different production modes
  - sensitivity to fermion, gauge boson couplings
- Run I @ ATLAS has been **very successful**
- many interesting advances expected for Run II
  - couplings at few % level
  - new decay channels
  - high mass reach for 2HDM, SUSY, other BSM
- Canadian collaborators are leading the way in detector design & construction, theory, analysis and physics interpretation

Thank you for your attention!

Extra Material

Note on $\gamma\gamma$ Vertexing

- use fine calorimeter granularity to "point" back to production vertex
  - utilise vertex for converted photons
- combine in neural network with
  - $\sum p_T^2$ (8 TeV analysis)
  - $\sum p_T$, $\Delta\phi(\gamma\gamma,\ \mathbf{p}_T)$ (7 TeV analysis)
- vertexing performance from $Z \to ee$ events by removing electron tracks

$H \to \tau\tau$ BDT

Variable	VBF $\tau_{lep}\tau_{lep}$	VBF $\tau_{lep}\tau_{had}$	VBF $\tau_{had}\tau_{had}$	Boosted $\tau_{lep}\tau_{lep}$	Boosted $\tau_{lep}\tau_{had}$	Boosted $\tau_{had}\tau_{had}$
$m_{\tau\tau}^{\mathrm{MMC}}$	•	•	•	•	•	•
$\Delta R(\tau,\tau)$	•	•	•		•	•
$\Delta\eta(j_1,j_2)$	•	•	•			
m_{j_1,j_2}	•	•	•			
$\eta_{j_1} \times \eta_{j_2}$		•	•			
$p_{\mathrm{T}}^{\mathrm{Total}}$		•	•			
sum p_{T}					•	•
$p_{\mathrm{T}}(\tau_1)/p_{\mathrm{T}}(\tau_2)$					•	•
$E_{\mathrm{T}}^{\mathrm{miss}}\phi$ centrality		•	•	•	•	•
$x_{\tau 1}$ and $x_{\tau 2}$						•
$m_{\tau\tau,j_1}$				•		
m_{ℓ_1,ℓ_2}				•		
$\Delta\phi_{\ell_1,\ell_2}$				•		
sphericity				•		
$p_T^{\ell_1}$				•		
$p_T^{j_1}$				•		
$E_{\mathrm{T}}^{\mathrm{miss}}/p_T^{\ell_2}$				•		
m_{T}		•			•	
$\min(\Delta\eta_{\ell_1\ell_2,\mathrm{jets}})$	•					
j_3 η centrality	•					
$\ell_1 \times \ell_2$ η centrality	•					
ℓ η centrality		•				
$\tau_{1,2}$ η centrality			•			