Search for the SM Higgs boson through the $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu, \ell\ell qq$ decay channels with the ATLAS detector

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on behalf of the ATLAS Collaboration

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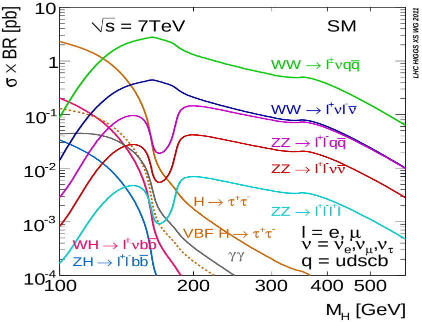
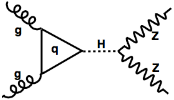
Introduction

- For a high mass Higgs boson the *ZZ* and *WW* decay modes dominate
- "Golden" $H \to ZZ \to 4\ell$ is very clean but suffers from low BF
- $H \to ZZ \to \ell\ell qq/\ell\ell\nu\nu$ have larger backgrounds but benefit from a significantly higher BF

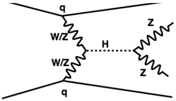


- Present results of the ATLAS Collaboration in these channels in the range $200 \leq m_H \leq 600$ GeV using full 2011 $\sqrt{s} = 7$ TeV dataset ($4.7\ \mathrm{fb}^{-1}$)
  - Signal modelled by NLO POWHEG+PYTHIA for ggF and VBF

gluon fusion (dominant)



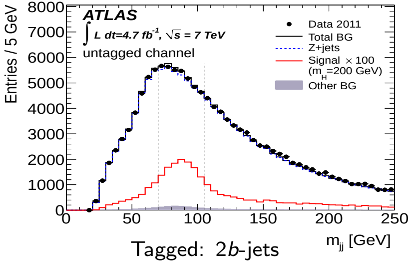
vector boson fusion (10-15%)



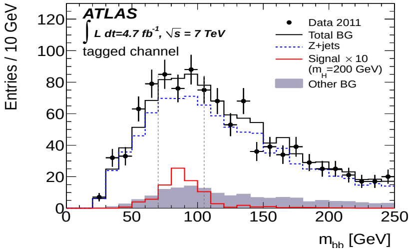
$H \to ZZ \to \ell\ell qq$ Selection

- $Z \to \ell\ell$: 2 leptons (e/μ) with
  - $p_T > 20$ GeV and $|\eta| < 2.5$
  - $83 < m_{\ell\ell} < 99$ GeV
- $E_T^{\text{miss}} < 50$ GeV
- $Z \to qq$: ≥ 2 jets with
  - $E_T^{\text{jet}} > 25$ GeV and $|\eta| < 2.5$
  - $70 < m_{jj} < 105$ GeV and $\Delta R_{jj} > 0.7$
- At high m_H the Z bosons from the H decay are boosted. For $m_H > 300$ GeV
  - $E_T^{\text{jet}} > 45$ GeV
  - $\Delta\phi_{ll} < \pi/2$ and $\Delta\phi_{jj} < \pi/2$
- Separate "untagged" and "tagged" channels to improve sensitivity
  - Lower background for $Z \to bb$

Untagged: $< 2b$-jets



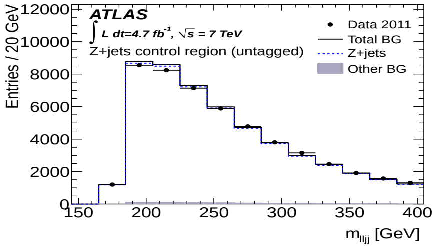
Tagged: $2b$-jets



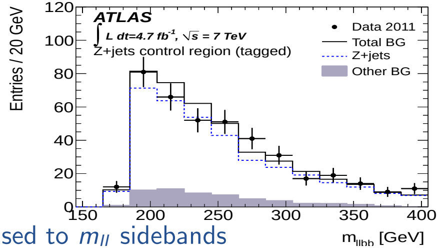
$H \to ZZ \to \ell\ell qq$ Background

- Shapes generally taken from MC but normalised to data where possible
- Z+jets is dominant background
  - Fraction of light/c/b determined by fit to b-tagging discriminant in data
  - Overall normalisation taken from fit to m_{jj} sidebands (untagged/tagged)
    - Uncertainty: 1.8-2.4% for untagged; 6.2-18% for tagged
  - m_{llqq} shape
    - Low m_H untagged: corrected using data/MC linear fit in m_{jj} sidebands
    - All: uncertainty from comparing fit in low/high m_{jj} SBs
- Top: m_{ll} SBs with reverted E_T^{miss} cut
- Diboson (ZZ/WZ): theory
- Multijet: loosened electron ID; normalised to m_{ll} sidebands

Z+jets (low-m_H untagged)



Z+jets (low-m_H tagged)

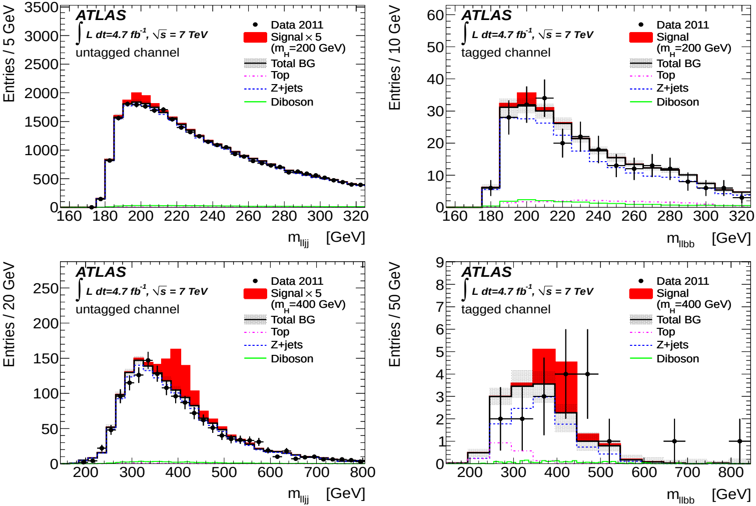


$H \to ZZ \to \ell\ell qq$ Results

- Discriminant: *llqq* invariant mass (with m_{jj} constrained to m_Z)

low-m_H

high-m_H



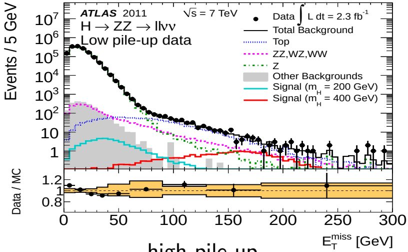
$H \to ZZ \to \ell\ell\nu\nu$ Selection

- $Z \to \ell\ell$: 2 leptons (e/μ) with
  - $p_T > 20$ GeV and $|\eta| < 2.5$
  - $|m_{\ell\ell} - m_Z| < 15$ GeV
- $Z \to \nu\nu$: Large E_T^{miss}
- Veto b-jets to reduce top background
- Separate low/high-m_H analyses to exploit boost of Z boson

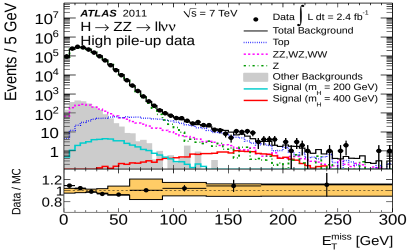
$m_H \leq 280$ GeV	$m_H > 280$ GeV
• $E_T^{\text{miss}} > 66$ GeV	• $E_T^{\text{miss}} > 82$ GeV
• $1 < \Delta\phi_{ll} < 2.64$	• $\Delta\phi_{ll} < 2.25$
• $\Delta\phi_{\text{jet},p_T^{\text{miss}}} < 1.5$	• $\Delta\phi_{\text{jet},p_T^{\text{miss}}} < 0.5$
	• $\Delta\phi_{ll,p_T^{\text{miss}}} \geq 1$

- Separate low/high pile-up analyses due to degradation of E_T^{miss} resolution

low pile-up

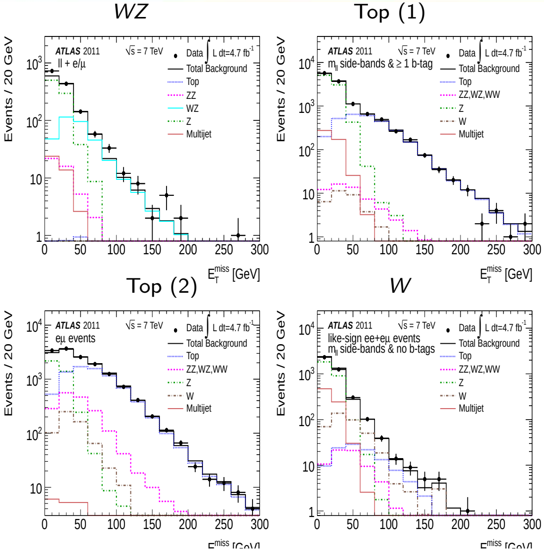


high pile-up



$H \to ZZ \to \ell\ell\nu\nu$ Background (1)

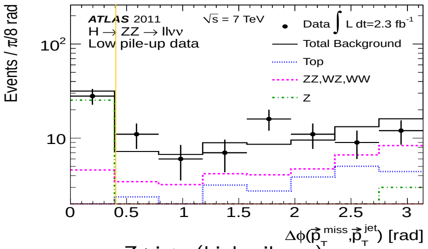
- Shapes from MC but where possible normalised to data
- Diboson (*WW*/*WZ*/*ZZ*)
  - Main contribution to high-m_H analysis
  - *WZ* normalisation checked in 3 lepton control sample
  - *WW*/*ZZ* from theory
  - *ZZ* shape uncertainty by compairing generators
- Top
  - Normalisation verified in 2 control samples:
    - m_{ll} sidebands + ≥ 1 b-jet
    - opposite-sign $e\mu$ pairs
- *W*
  - like-sign $ee/e\mu$ events
  - m_{ll} sidebands; no b-jets



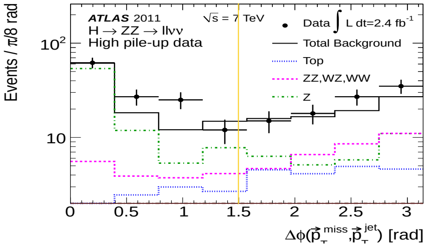
$H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ Background (2)

- Z is important in low-m_H analysis
  - Increases in high pile-up sample
  - Normalisation checked by reverting $\Delta\phi_{\text{jet},p_T^{\text{miss}}}$ after E_T^{miss} cut
  - Shape uncertainty from comparing different generators
- Multijet
  - Loosened electron ID; normalised to m_{ll} sidebands
- Normalisation uncertainties (dominant contribution):
  - Diboson 11% (theory)
  - Top 20-25% (b-tagging)
  - W 100% (CR)
  - Z 20-25% (JES + pile-up)
  - QCD (elec) 50% (CR)

Z+jets (low pile-up)



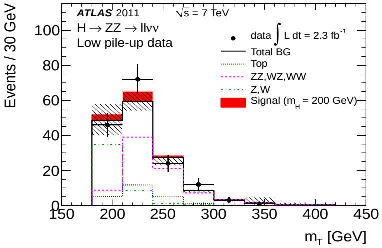
Z+jets (high pile-up)

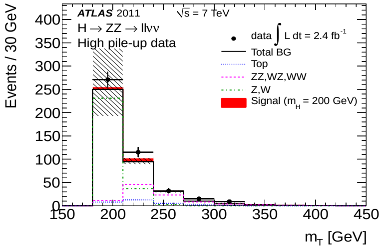


$H \to ZZ \to \ell\ell\nu\nu$ Results

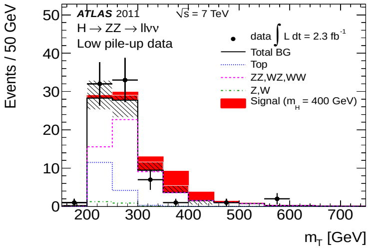
- Discriminant: Transverse mass $m_T^2 \equiv \left[\sqrt{m_Z^2 + |\vec{p}_T^{\,\ell\ell}|^2} + \sqrt{m_Z^2 + |\vec{p}_T^{\,\rm miss}|^2}\right]^2 - \left[\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,\rm miss}\right]^2$

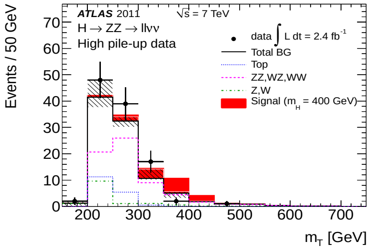
low-m_H





high-m_H





Limit Extraction and Systematics

- Set limits on σ/σ_{SM} at 95% CL using CL_s modified frequentist method [1] with profile likelihood test statistic [2]
- Bin-by-bin likelihood fit to full invariant/transverse mass distribution
  - Combine sub-channels by forming product of likelihood
  - Systematic uncertainties incorporated as nuisance parameters

Explanatory figure (not actual data)

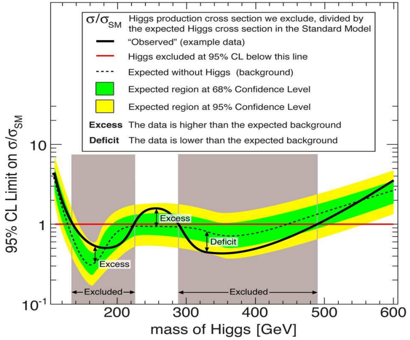


Figure A

- Systematic uncertainties
  - Signal
    - Normalisation: $15-20\%/3-9\%$ for ggF/VBF [3] + acceptance uncertainty
    - Uncertainty on H line shape and interference with SM background [3]
      - $1.5 \times m_H^3$ [TeV] for $m_H > 300$ GeV
      - Up to $\sim 30\%$ for $m_H = 600$ GeV
  - Background from CRs/theory
  - Luminosity + detector-related
    - Object efficiency, scale & resolution
    - Variations propagated to E_T^{miss}
    - b-tagging efficiency and mistag rate

[1] J. Phys. G **28** (2002) 2693-2704, [2] Eur. Phys. J. C **71** (2011) 1554, [3] Handbook of LHC Higgs Cross Sections

Exclusion Limits

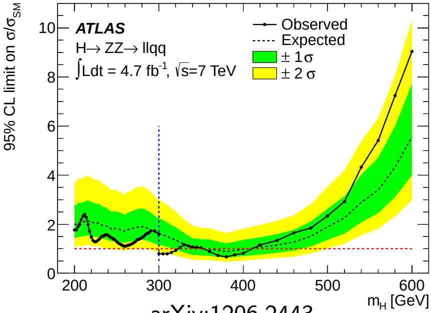
- Able to exclude a large range of heavy Higgs boson masses:
  - Sensitivity in this region is dominated by $H \to ZZ \to \ell\ell\nu\nu$

$H \to ZZ \to \ell\ell qq$

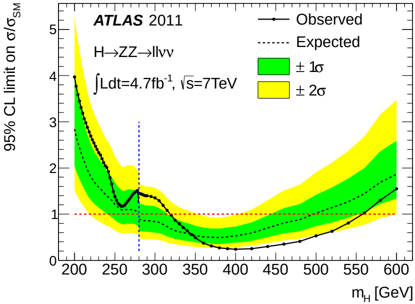
Observed: $300 \leq m_H \leq 322$ GeV
$353 \leq m_H \leq 410$ GeV
Expected: $351 \leq m_H \leq 404$ GeV

$H \to ZZ \to \ell\ell\nu\nu$

Observed: $319 \leq m_H \leq 558$ GeV
Expected: $280 \leq m_H \leq 497$ GeV



arXiv:1206.2443



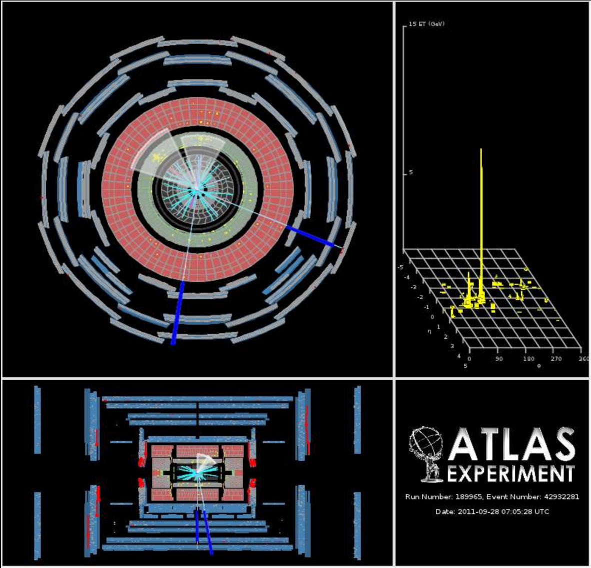
arXiv:1205.6744

Conclusion

- Have presented full $\sqrt{s} = 7$ TeV results in $H \to ZZ \to \ell\ell qq/\ell\ell\nu\nu$ channels
- $H \to ZZ \to \ell\ell\nu\nu$ dominates high-m_H sensitivity
- Together exclude a large region of heavy Higgs masses
- See R.Hawking's talk in plenary session on Monday for the combined ATLAS high-m_H limit from all channels
- LHC and ATLAS preforming well at $\sqrt{s} = 8$ TeV so look forward to improving limits and exploring possibilities to extend beyond $m_H = 600$ GeV!

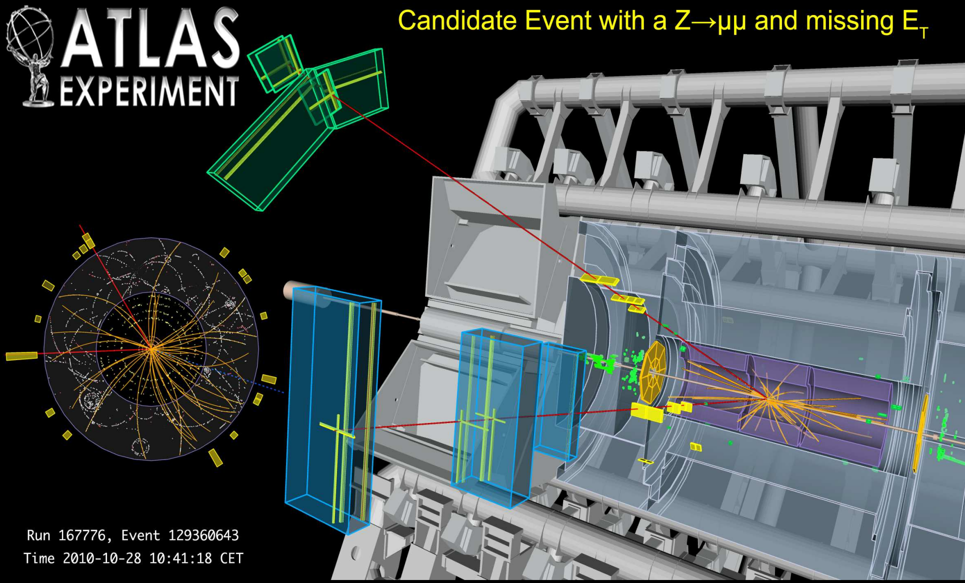
Additional Material

$H \to ZZ \to \ell\ell qq$ Candidate



Candidate event with a $Z \to \mu\mu$ and 2 b-jets

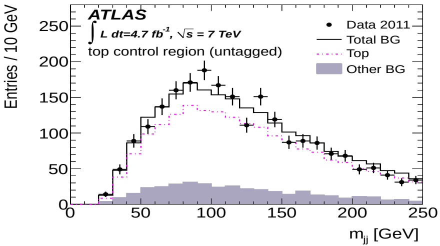
$H \to ZZ \to \ell\ell\nu\nu$ Candidate



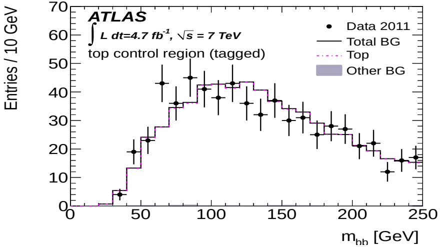
$H \to ZZ \to \ell\ell qq$ Background (2)

- Top
  - Important in tagged analysis
  - Normalised to m_{ll} sidebands with reversed E_T^{miss} cut
    - Separately for untagged/tagged
  - 2.7% (4.0%) uncertainty for untagged (tagged) channel
- Diboson (ZZ/WZ)
  - Normalisation taken from theory
  - 11% uncertainty
- QCD Multijet
  - Shape from loosened electron ID; normalised to m_{ll} sidebands
  - 50% uncertainty
  - Negligible in muon channel
- Detector uncertainties applied in addition to those above

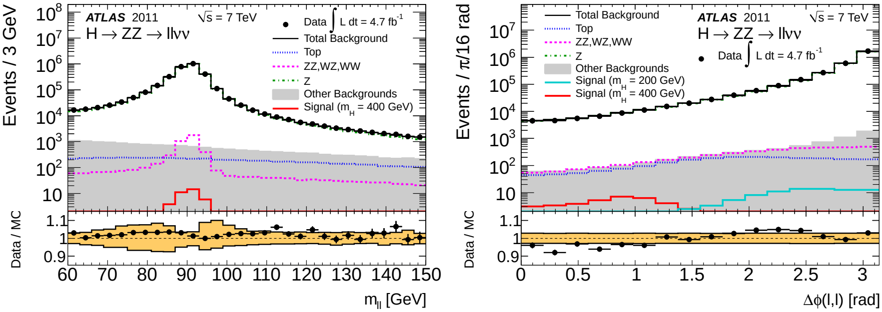
Top (low-m_H untagged)



Top (low-m_H tagged)



$H \to ZZ \to \ell\ell\nu\nu$ Plots



$H \to ZZ \to \ell\ell qq$ Results Table

ATLAS

The expected numbers of signal and background candidates in the $H \to ZZ \to \ell\ell qq$ channel, along with the numbers of candidates observed in data, for an integrated luminosity of 4.7 fb^{-1}. The low-m_H analysis is applied when searching for a Higgs boson with $m_H < 300$ GeV and the high-m_H analysis for $m_H \geq 300$ GeV. The first error indicates the statistical uncertainty, the second error the systematic uncertainty.

	Untagged		Tagged	
	Low-m_H	High-m_H	Low-m_H	High-m_H
Z+jets	$36190 \pm 80 \pm 640$	$1450 \pm 14 \pm 35$	$239 \pm 6 \pm 15$	$11 \pm 1 \pm 2$
Top	$85 \pm 3 \pm 10$	$7.1 \pm 0.7 \pm 0.8$	$23 \pm 1 \pm 3$	$1.9 \pm 0.4 \pm 0.5$
Multijet	$15 \pm 0 \pm 8$	$0.2 \pm 0.0 \pm 0.1$	< 0.1	< 0.1
ZZ	$348 \pm 3 \pm 47$	$25 \pm 1 \pm 3$	$22 \pm 1 \pm 4$	$2.3 \pm 0.3 \pm 0.4$
WZ	$434 \pm 4 \pm 70$	$45 \pm 1 \pm 7$	$0.7 \pm 0.2 \pm 0.3$	< 0.2
Total background	$37070 \pm 80 \pm 670$	$1530 \pm 14 \pm 37$	$285 \pm 6 \pm 18$	$15 \pm 1 \pm 2$
Data	36898	1444	286	18
Signal				
$m_H = 200$ GeV	$118 \pm 2 \pm 19$		$6.4 \pm 0.4 \pm 1.3$	
$m_H = 300$ GeV		$24.3 \pm 0.7 \pm 4.1$		$2.1 \pm 0.2 \pm 0.4$
$m_H = 400$ GeV		$40.5 \pm 0.5 \pm 6.4$		$4.4 \pm 0.2 \pm 1.0$
$m_H = 500$ GeV		$18.5 \pm 0.2 \pm 3.1$		$2.0 \pm 0.1 \pm 0.5$
$m_H = 600$ GeV		$6.3 \pm 0.1 \pm 1.1$		$0.7 \pm 0.0 \pm 0.2$

$H \to ZZ \to \ell\ell\nu\nu$ Results Table

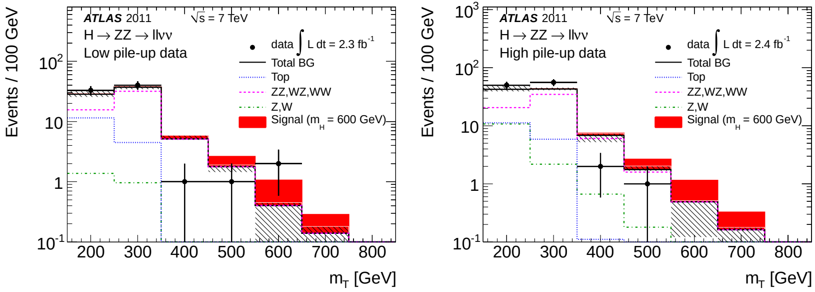
ATLAS

The expected number of background and signal events along with the observed numbers of candidates in the data, separated into the low and high m_H search regions and the low and high pile-up periods. The quoted uncertainties are statistical and systematic, respectively.

	low m_{H} search		high m_{H} search	
Source	Low pile-up data	High pile-up data	Low pile-up data	High pile-up data
Z	$40.1 \pm 5.0 \pm 7.9$	$265 \pm 13 \pm 67$	$0.8 \pm 0.3 \pm 0.8$	$11.6 \pm 2.1 \pm 2.9$
W	$4.6 \pm 2.2 \pm 4.6$	$5.8 \pm 1.8 \pm 5.8$	$1.5 \pm 0.8 \pm 1.5$	$2.2 \pm 1.3 \pm 2.2$
top	$23.2 \pm 1.3 \pm 5.4$	$27.9 \pm 1.3 \pm 5.3$	$16.0 \pm 1.1 \pm 4.0$	$17.2 \pm 1.0 \pm 3.9$
multijet	$1.1 \pm 0.2 \pm 0.5$	$1.1 \pm 0.2 \pm 0.6$	$0.1 \pm 0.1 \pm 0.0$	$0.1 \pm 0.1 \pm 0.0$
ZZ	$33.4 \pm 0.7 \pm 3.9$	$36.7 \pm 0.7 \pm 4.3$	$28.4 \pm 0.6 \pm 3.4$	$31.9 \pm 0.7 \pm 3.8$
WZ	$23.3 \pm 1.0 \pm 2.8$	$25.2 \pm 1.0 \pm 3.0$	$17.1 \pm 0.8 \pm 2.1$	$18.9 \pm 0.8 \pm 2.3$
WW	$25.5 \pm 0.8 \pm 3.0$	$32.4 \pm 0.9 \pm 3.8$	$9.4 \pm 0.5 \pm 1.1$	$13.3 \pm 0.5 \pm 1.6$
Total	$151 \pm 6 \pm 11$	$394 \pm 13 \pm 67$	$73.3 \pm 1.8 \pm 6.1$	$95.2 \pm 2.9 \pm 6.9$
Data	158	442	77	109
m_{H} [GeV]	Signal expectation			
200	$10.3 \pm 0.2 \pm 1.8$	$11.1 \pm 0.2 \pm 1.9$		
300			$16.4 \pm 0.3 \pm 2.9$	$17.5 \pm 0.3 \pm 3.1$
400			$14.4 \pm 0.2 \pm 2.5$	$15.4 \pm 0.2 \pm 2.7$
500			$6.2 \pm 0.1 \pm 1.1$	$6.5 \pm 0.1 \pm 1.1$
600			$2.7 \pm 0.0 \pm 0.5$	$2.9 \pm 0.0 \pm 0.5$

$H \to ZZ \to \ell\ell\nu\nu$ Results (2)

- High-m_H analysis with 600 GeV Higgs signal



Systematic Uncertainties: Details

- Detector-related:
  - Jet energy scale (1-6%) and resolution (1-4%); b-quark energy scale ($\leq 2.5\%$)
  - Electron reconstruction/ID efficiency, scale and resolution
  - Muon reconstruction/trigger efficiency, scale and resolution
  - b/c-tagging efficiency (5-19%) and mistag rate (18-50%)
  - E_T^{miss}: Propagate object uncertainties + additional uncertainties for soft jets and unassociated calorimeter cells
  - Vary number of additional interactions
  - Luminosity: 3.9% (3.7%/4.1% for low/high pile-up)
- $H \to ZZ \to \ell\ell\nu\nu$:
  - Signal:
    - Normalisation: 15-20%/3-9% for ggF/VBF
    - Acceptance: 8.4%/3.4% for low/high pile-up (ISR/FSR, fact/renorm scale, UE)
    - Higgs line shape: $1.5 \times m_H^3[TeV]$ for $m_H > 300$ GeV
  - Z: 2.5% normalisation; alternative generator
  - W normalisation: 100%
  - Top normalisation: 9%
  - Diboson: 11% normalisation; alternative generator for ZZ
  - QCD normalisation: 50% (electron channel)

Systematic Uncertainties: Details

- $H \to ZZ \to \ell\ell qq$:
  - Signal:
    - Normalisation: 15-20%/3-9% for ggF/VBF
    - Acceptance: 3%/12% for low/high m_H (ISR/FSR, fact/renorm scale, UE, generator)
    - Higgs line shape: $1.5 \times m_H^3[TeV]$ for $m_H > 300$ GeV
  - Z+jets:
    - Normalisation: 1.7%/2.2% for low/high-m_H untagged; 5.5% for tagged
    - Shape: vary m_{llqq}, m_{jj} and p_T^Z using m_{jj} SBs
    - Flavour composition: Vary relative fraction of $Z + c$-jets by $\pm 30\%$
  - Top normalisation: 2.7%/4.0% for untagged/tagged
  - Diboson normalisation: 11%
  - QCD normalisation: 50% (electron channel)
  - Effect of detector-related uncertainties on signal:
    - Tagged: dominated by b-tagging $\to$ 9% on average
    - Untagged: JES/JER $\to$ 3%/4% on average