Higgs Searches at ATLAS

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In the Standard Model, Higgs boson production primarily through gluon fusion and Weak Boson Fusion (WBF)
- Typical Feynman diagrams for $ggH$ and $WBF$ are shown above

In some searches (e.g. $H \rightarrow \gamma\gamma$, $bb$), $WH/ZH/ttH$ are important too
- Typical Feynman diagrams for $WH/ZH$ and $ttH$ are shown below
Right: cross-sections (top) and branching ratios (bottom) in the Standard Model (SM)

Decay modes which have been analyzed in data:
- $H \rightarrow WW$, $H \rightarrow ZZ$ at high mass
- $H \rightarrow bb$, $H \rightarrow \tau \tau$, and $H \rightarrow \gamma \gamma$ at low $m_H$

Cross-sections are taken from “Handbook of LHC Higgs Cross-sections,” arXiv:1101.0593
Requiring two leptons suppresses QCD multijet background to negligible levels.

Large background from Z is suppressed by requiring large \( E_{T,\text{miss}} \) in same-flavor events (left).

Top events are rejected by cut on jet multiplicity (right).

Presently, only \( N_{\text{jet}}=0 \) and \( N_{\text{jet}}=1 \) considered.
Event selection exploits different angular distributions caused by kinematics and by spin correlations. Above: $M_{ll}$ (left) and $\Delta\phi_{ll}$ (right) in events with no jets.

Backgrounds are estimated with control samples:
- Diboson: count events in a region with altered $M_{ll}$ and $\Delta\phi_{ll}$ cuts
- Top (in H+1j): reverse b-veto and drop cuts on $M_{ll}$, $M_T$, and $\Delta\phi_{ll}$

<table>
<thead>
<tr>
<th>Control Region</th>
<th>Expected BG</th>
<th>Observed</th>
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<tbody>
<tr>
<td>WW+0j</td>
<td>250±50</td>
<td>238</td>
</tr>
<tr>
<td>WW+1j</td>
<td>139±18</td>
<td>144</td>
</tr>
<tr>
<td>tt+1j</td>
<td>350±100</td>
<td>316</td>
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</table>
For major backgrounds (WW+0/1j and tt+1j), control samples are modeled in fit using ratio of cross-sections in signal region over control region taken from MC

- WW+1j control region has significant contamination from top, so use tt+1j control region to normalize it as well

Above: uncertainties on the ratio of cross-sections in the signal region over the listed control region.

- The last column shows the uncertainty in the ratio of top backgrounds in the WW+1j control sample and the top control region for H+1j.
Backgrounds which are small after cuts (ttbar in H+0j, W+jets, Z+jets) are also measured using control regions, but only the final estimate is modeled in the Likelihood, not the control sample itself:

- **W+jets**: loosened lepton selection. Derive a $p_T$-dependent extrapolation factor from dijet data to get estimate in signal region, accounting for contamination from real leptons.

- **Top in H+0j uses two control samples:**
  - Two leptons and $E_T^{\text{miss}}$ w/non-top backgrounds removed using MC
  - Two leptons and $E_T^{\text{miss}}$, w/ $\geq 1$ b-tagged jet; used to estimate an efficiency for the jet veto
  - Efficiency from second control sample and corrections from MC are applied to first control sample to estimate top in signal region

- **Z+jets**: use events on Z peak to derive a correction factor for the ratio of high-$E_T^{\text{miss}}$ to low-$E_T^{\text{miss}}$; apply it to events with small $m_{ll}$.
Upper bounds on production cross-section (left) and significance of excess over background (right).

- No significant excess, always less than about $2\sigma$
- Upper limit is set as a function of $m_H$, in units of the Standard Model prediction. ATLAS excludes $154 < m_H < 186$ GeV ($135 < m_H < 196$ GeV expected)
Select events with one lepton, two or three jets, and $E_T^{\text{miss}}$.

Two jets must have $m_{jj}$ close to $m_W$ (left)

- Contributes to large systematic from the jet $E$ scale uncertainty

Estimate background from jets misidentified as leptons using a sample of events in data with lepton isolation cut reversed.

- Can estimate the shapes of most kinematic variables by just plotting. See, for example, green region in upper right plot

- A normalization factor is estimated with a template fit to the $E_T^{\text{miss}}$ distribution (right). Shape of V+jets taken from MC, but it floats in the fit too and both contributions are rescaled for the final plots.
Estimate $P_{Z \nu}$ and $M_{WW}$ by solving $M_W = M_{lv}$. Require two real solutions; take one with smaller $|P_{Z \nu}|$.

Fit $M_{lvqq}$ distribution with a double exponential for background, hist PDF for signal.

Exclude $2.7 \times \text{SM}$ for $m_H = 400$ GeV.
Signature is two leptons and two jets, with small MET, and with $M_{ll}$ and $M_{qq}$ near $M_Z$.

- Divide the signal into events with fewer than two b-tagged jets (left) and events with two (right)
- For $m_H \geq 300$ GeV, also use angular information about the jets and leptons to suppress background.
  - Require $\Delta \phi_{ll} > \pi/2$ and $\Delta \phi_{jj} > \pi/2$
Background shape and normalization in MC is validated by data/MC comparisons in $m_{jj}$ sidebands (left) and $m_{ll}$ sidebands (not shown)

- Systematic error on the $Z$+jets normalization comes from comparisons of these sidebands, and ranges from 1.4% for low-$m_H$ untagged selection to 18% for high-$m_H$ b-tagged selection. Shape uncertainty comes from comparisons between Pythia and Alpgen.

- Observed limits are approaching the Standard Model prediction for $m_H$ near $\sim300$-$400$ GeV
Two leptons with \( m_{ll} = m_Z \) and very large MET (left)

Diboson BG is from MC

\( E_T^{\text{miss}} \) performance in top BG checked using events with \( m_{ll} \) outside Z peak (top right) and \( e\mu \) events (bottom right)

Z and W+jets evaluated from MC with data/MC comparisons
- **Left:** set limits based on the transverse mass distribution
  - Systematic errors on BG normalization: gluon fusion signal (+14/-10%), VBF signal (4%) and diboson background taken from theory; top quark production (9%), W+jets (100%), and QCD multijet (50%) are estimated from data

- **Right:** we are just starting to exclude a Standard Model Higgs boson around $360 < m_H < 420$ GeV
Very clean: four leptons (e or $\mu$)

Dilepton mass, lepton isolation, and impact parameter cuts suppress top and Z+jets

Good four-lepton mass resolution helps separate signal from otherwise irreducible continuum ZZ background
Background estimates:
- ZZ from MC prediction
- Top also from MC prediction, but validated in control region
- Z+jets normalized to data using control region based on loosened isolation cuts for second lepton pair

Very close to excluding a broad region of Standard Model parameter space

Some values of $m_H$ near 200 GeV are already excluded
H→γγ (1)

- H→γγ decay proceeds only via top and W loops, so BR(H→γγ) is small (~0.002). However, no subsequent decay as in the case of H→ZZ→4l.
- H→γγ signal is 0.04 pb, but background from continuum γγ is very large
  - Cross-section for qq→γγ is ~21 pb; for qg→γγ it's about 8 pb.
  - Background from γ+jet (before photon ID cuts) is ~1.8x10^5 pb
  - Background from dijets is ~5x10^8 pb.
  - Need large rejection, esp. against π^0 decays.
- Photon ID is based on lateral and longitudinal segmentation of the electromagnetic calorimeter.
Very good mass resolution of ~1.7 GeV helps distinguish between Higgs signal and continuum background.

Events are separated into categories based on the quality of photon reconstruction and location of photon candidates.

Resolution ranges from ~1.4 GeV for unconverted photons in the central region of the detector (left) to ~2 GeV with asymmetric tails for photons which land in the region between the barrel and endcap and also show signs of having converted to an $e^+e^-$ pair before reaching the calorimeter (right).
Improve mass resolution by using “pointing” information: positions of clusters in the different calorimeter layers can give an estimate of the photon's direction of flight, and identifies the primary vertex with a resolution of ~20-30 mm (left).

Signal is extracted using a fit to $M_{\gamma\gamma}$ (right). Plot shown above is inclusive, but fit treats pseudorapidity/conversion categories separately.

Normalization of background from jets is checked using loosened photon ID cuts.

- Measured background is compatible with predictions.
**Systematic Uncertainties:**
- Signal Yield (±12%)
- Invariant Mass Resolution (±14%)
- Background modeling (depends on $m_H$; ±5 events for $m_H=110$ GeV, ±3 events for $m_H=150$ GeV.)

**ATLAS currently excludes ~2-6 times the Standard Model prediction, depending on $m_H$.**
ggH and WBF are dominant Higgs production mechanisms, but for H→bb these modes are overwhelmed by background. WH/ZH (H→bb) is best for this decay mode.

- Select W→lν and Z→ll decays by requiring two leptons or one lepton and E_T^{miss}.
- Select two b-tagged jets with p_T>25 GeV.
- Dominant backgrounds for both are W+jets, Z+jets, top.
Top quark backgrounds are checked with control samples.

Left: control sample for WH consists of events with three jets (in the signal region only two are allowed)
- Top normalization in signal region comes from fit to sidebands in $m_{bb}$

Right: control sample for ZH consists of events with $m_{ll}$ outside the Z peak
- Assign 9% uncertainty to top in ZH based on this comparison; 6% for top in WH based on the fit to $m_{bb}$
**WH/ZH, $H \to bb$ (3)**

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<thead>
<tr>
<th>Uncertainty</th>
<th>ZH, 115 GeV</th>
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<td>Muon Res.</td>
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<td>$E_T^{\text{miss}}$ Res.</td>
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<tr>
<td>b-tagging eff.</td>
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<td>Luminosity</td>
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<td>Higgs x-sec</td>
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<tr>
<th></th>
<th>WH, 115 GeV</th>
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<th>WH, 130 GeV</th>
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<tbody>
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<td>1%</td>
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<tr>
<td>Jet E scale</td>
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<td>1%</td>
<td>3%</td>
</tr>
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- **Above:** major sources of background uncertainty. Several other sources contribute at the level of 1% or less
  - Electron E scale & resolution, Jet E res., electron and muon efficiency

- **Exclude Higgs production with cross-section $\sim$10-20 times the Standard Model prediction**
Promising channel for $110 < m_H < 140$ GeV

- In the H+1j final state considered here, both ggH and WBF contribute

- Require two leptons and at least one hard jet ($p_T > 40$ GeV).

Analysis is based on $m_{\tau\tau}$ assuming $\tau$ decay products are collinear with parent $\tau$ lepton (left)
Z→ττ is estimated by τ embedding (select Z→μμ in data and replace the reconstructed muons by simulated tau leptons)

- Top, Z→ee/μμ, and diboson backgrounds are taken from MC
- Backgrounds from jets misidentified as leptons are taken from control sample with reversed isolation, normalized by a template fit in the signal region

- Overall agreement is good. Example plots above: dilepton invariant mass (left) and $E_T^{miss}$ (right)
Dominant sources of systematic error on background are the jet energy scale uncertainty (-9.8/+7.0%) and MC statistics (8%).

No significant excess. Upper limits on cross-section are about 30x the Standard Model prediction (above).
Exclude a Standard Model Higgs boson with $m_H$ in the ranges 146-232 GeV, 256-282 GeV, or 296-466 GeV.

- Includes $H \rightarrow \gamma \gamma$, $H \rightarrow bb$, $H \rightarrow \tau \tau$, $H \rightarrow WW \rightarrow l\nu l\nu$, $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow ZZ \rightarrow ll \nu \nu$, and $H \rightarrow ZZ \rightarrow llqq$
With this year's data, expect only a small window of allowed Standard Model Higgs masses to remain near the LEP limit.

With another 5-10 fb$^{-1}$ next year, we should have a much stronger statement

...but a Higgs discovery in 114-130 GeV is challenging at this center-of-mass energy
Using the $H \rightarrow WW \rightarrow l\nu l\nu$ channel, ATLAS excludes the presence of a Higgs boson in the ranges 154-186 GeV.

The $H \rightarrow WW \rightarrow l\nu qq$ search excludes about 2.7 times the Standard Model cross-section at $m_H = 400$ GeV.

With $H \rightarrow ZZ \rightarrow ll\nu\nu$, exclude 360-420 GeV. Independent limits from $H \rightarrow ZZ \rightarrow llqq$ and $H \rightarrow ZZ \rightarrow 4l$ are approaching exclusion of the Standard Model for some masses.

$H \rightarrow \gamma\gamma$ search excludes $\sim 2-6 \times$SM.

$H \rightarrow \tau\tau$ search currently excludes $\sim 30 \times$ the SM prediction.

$WH/ZH \rightarrow bb$ search excludes $\sim 10-20$ times SM prediction.

Except for two holes (232-256 GeV and 282-296 GeV), the SM Higgs is excluded for $146 < m_H < 466$ GeV with current analyzed luminosity.