Searches for the Standard Model Higgs Boson at ATLAS

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on behalf of the ATLAS collaboration

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Higgs Boson Production at the LHC


At the LHC (pp at 7 TeV):
- $gg \rightarrow H \sim 20-25$ times larger
- $qq \rightarrow W/Z + H \sim 4$ times larger

compared to the Tevatron (ppbar at 1.96 TeV)
At high mass (>135 GeV):
- Decay to $H \rightarrow WW$ and $H \rightarrow ZZ$ dominates

At low mass (<135 GeV):
- Dominant decay modes are into pairs of $b$-quarks and taus
- $H \rightarrow \gamma\gamma$ tiny branching ratio but distinct signature
Search Channels at ATLAS

Searches performed in 12 distinct channels using the full 2011 dataset

<table>
<thead>
<tr>
<th>Higgs Decay channel</th>
<th>$m_H$ Range</th>
<th>L [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>low-$m_H$, good mass resolution</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>110-150</td>
<td>4.9</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow ll\ell'\ell'$</td>
<td>110-600</td>
<td>4.8</td>
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<tr>
<td><strong>low-$m_H$, limited mass resolution</strong></td>
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<tr>
<td>$H \rightarrow WW \rightarrow \ell\nu\ell\nu$</td>
<td>110-200-300-600</td>
<td>4.7</td>
</tr>
<tr>
<td>$VH \rightarrow b\bar{b}$</td>
<td>110-130</td>
<td>4.6</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^- \rightarrow \ell 4\nu$</td>
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All exclusion limits shown are at 95% CL unless otherwise stated.
$H \rightarrow ZZ \rightarrow ll\nu\nu$

- Most sensitive in high mass
- 4 sub-channels: $(ee, \mu\mu) \times (\text{low-}, \text{high-pileup})$
- $m_T$ distribution for the limit setting
- Analysis divided into low and high mass selection

\[<\mu>=6.3\]

\[<\mu>=11.6\]
H → ZZ → llνν

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- 4 sub-channels: (ee, μμ)⊗(low-, high-pileup)
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Expected Exclusion: $260 < m_H < 490$ GeV

Observed Exclusion: $320 < m_H < 560$ GeV

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H → ZZ → llqq

- 2 sub-channels: (untag, b-tag)
- b-tagged channel requires 2 b-tags (Z→bbbar)
- $m_{lljj}$ distribution for the limit setting
- Analysis divided into low and high mass selection
H → ZZ → llqq

- 2 sub-channels: (untag, b-tag)
- b-tagged channel requires 2 b-tags (Z→bbbar)
- $m_{lljj}$ distribution for the limit setting
- Analysis divided into low and high mass selection

Expected Exclusion: $360 < m_H < 400$ GeV

Observed Exclusion: $300 < m_H < 310$ GeV
$360 < m_H < 400$ GeV
H → WW → lvqq

- Reconstruct Higgs mass ($M_{lvqq}$) by imposing $M_{lv}=M_W$ and $M_{qq}=M_W$
- Strategy is to search for a bump in the $M_{lvqq}$ distribution above the strongly falling background (modeled from fit to the data)
- Analysis split into 0, 1 and 2 (VBF) jets
H→WW→lνqq

- Reconstruct Higgs mass (M_{lνqq}) by imposing M_{lν}=M_W and M_{qq}=M_W
- Strategy is to search for a bump in the M_{lνqq} distribution above the strongly falling background (modeled from fit to the data)
- Analysis split into 0, 1 and 2 (VBF) jets

![Graphs showing the distribution of M_{WW} and M_{lνqq} with data and MC comparisons.](image)

ATLAS Preliminary

\[ \int L \, dt = 4.7 \, \text{fb}^{-1} \]

\[ \sqrt{s} = 7 \, \text{TeV} \]

H + 0j, H→μν qq

\[ \begin{array}{c}
\text{Entries / 20 GeV} \\
\text{Data / MC}
\end{array} \]

\[ m_W \text{ [GeV]} \]

\[ m_{WW} \text{ [GeV]} \]
H→ZZ(*)→4l

- Very clean: four leptons (e or μ); “golden” channel
- Good four-lepton mass resolution needed to separate signal from irreducible continuum ZZ background ($\sigma_{mH}/m_H \sim 1.5\text{-}2\%$ at $m_H = 130$ GeV)
  - Above 350 GeV natural width dominates
- High lepton reconstruction efficiency down to low $p_T$ (7 GeV)
- Lepton performance well modeled by the simulation, independent of pileup

### Event yields in full mass range

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**H → ZZ(*) → 4l**

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**H → ZZ(*) → 4l**

**Expected Exclusion:**
137 < m_H < 157 GeV
184 < m_H < 400 GeV

**Observed Exclusion:**
134 < m_H < 156 GeV
182 < m_H < 233 GeV
256 < m_H < 265 GeV
268 < m_H < 415 GeV

Small excess observed around 3 mass values

<table>
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<tr>
<th>Mass</th>
<th>125 GeV</th>
<th>244 GeV</th>
<th>500 GeV</th>
</tr>
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<td><strong>Expected significance</strong></td>
<td>1.3σ</td>
<td>3.0σ</td>
<td>1.5σ</td>
</tr>
<tr>
<td><strong>Observed significance</strong></td>
<td>2.1σ</td>
<td>2.2σ</td>
<td>2.1σ</td>
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H→γγ

- BR(H→γγ) is small (~0.2%), but distinct signature
- Good mass resolution is essential to separate signal from cont. background
- Divided in 9 exclusive categories with different m_{γγ} resolutions and S/B
  - (photon η ⊗ conversion status ⊗ p_T^{γγ(thrust)})
  - Signal is extracted using a fit to M_{γγ} simultaneous to all categories

- Background modeling: exponential function, free slope and normalization
- Signal m_{γγ} modeling: sum of Crystal Ball and Gaussian functions

σ_{CB} ranges from 1.4 to 2.3 GeV
H → γγ

Invariant \(m_{\gamma\gamma}\) distribution summed over all categories:

Excess of events observed around 126.5 GeV

Local significance: 2.9\(\sigma\) (1.5\(\sigma\) after the look-elsewhere-effect).
$H \rightarrow \gamma\gamma$

Invariant $m_{\gamma\gamma}$ distribution summed over all categories:

Excess of events observed around 126.5 GeV

Local significance: $2.9\sigma$ (1.5$\sigma$ after the look-elsewhere-effect).

Observed Exclusion:

$113 < m_H < 115$ GeV

$134.5 < m_H < 136$ GeV

$\int L dt = 4.9$ fb$^{-1}$

Data 2011, $\sqrt{s} = 7$ TeV

ATLAS
Search for $H \rightarrow bb$

- Select events with a $Z(W)$ boson in the leptonic final state
- Also invisible decay $Z \rightarrow \nu \nu$ is used
- The leptons/MET are also used to trigger the event
- Exactly two b-tagged jets
- Higgs boson recoil away with significant $p_T$
- Backgrounds: $W^+(b^-)$jets, $Z^+(b^-)$jets, Top, QCD jets
- Background systematic uncertainties are crucial
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- Background systematic uncertainties are crucial
**H → ττ**

- Collinear approximation to reconstruct mass/Missing Mass calculator

- Split in different jet categories
  - 0-jet, 1-jet, 2-jet VH, 2-jet VBF

- Irreducible Z→ττ estimated by embedding simulated τ’s into Z→μμ events
H→WW(*)→lνlν

- 9 sub-channels: (ee, µµ, eµ) ⊗ (0-,1-jet, VBF)
  - Different backgrounds
- Events with two isolated opposite sign leptons
- Require missing transverse energy
- Due to neutrinos no mass peak
  ⇒ use transverse mass ($m_T$) to extract limit

\[
m_T = \sqrt{(E_{T}^{\ell\ell})^2 + (E_{T}^{\nu\nu})^2 - (\vec{p}_{T}^{\ell\ell} + \vec{p}_{T}^{\nu\nu})^2}
\]

Signal $m_H = 125$ GeV
H → WW(*) → ℓνℓν

<table>
<thead>
<tr>
<th>Lepton Channels</th>
<th>0-jet ee</th>
<th>0-jet μμ</th>
<th>0-jet eμ</th>
<th>1-jet ee</th>
<th>1-jet μμ</th>
<th>1-jet eμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total bkg.</td>
<td>58 ± 5</td>
<td>114 ± 10</td>
<td>257 ± 13</td>
<td>21 ± 3</td>
<td>37 ± 5</td>
<td>76 ± 6</td>
</tr>
<tr>
<td>Signal</td>
<td>3.8 ± 0.1</td>
<td>9.0 ± 0.1</td>
<td>25 ± 0.2</td>
<td>1.1 ± 0.1</td>
<td>2.3 ± 0.1</td>
<td>6.0 ± 0.1</td>
</tr>
<tr>
<td>Observed</td>
<td>52</td>
<td>138</td>
<td>237</td>
<td>19</td>
<td>36</td>
<td>90</td>
</tr>
</tbody>
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Expected Exclusion: 127 < m_H < 234 GeV

Observed Exclusion: 130 < m_H < 260 GeV

ATLAS Preliminary

H → WW → ℓνℓν

\[ \int L dt = 4.7 \text{ fb}^{-1} \]

\(|s = 7 \text{ TeV}|
Combination

95% CL limit on $\sigma/\sigma_{SM}$

- $H \rightarrow \gamma\gamma$ (4.9 fb$^{-1}$)
- $H \rightarrow \tau\tau$ (4.7 fb$^{-1}$)
- $H \rightarrow bb$ (4.6-4.7 fb$^{-1}$)
- $H \rightarrow WW \rightarrow l\nu l\nu$ (4.7 fb$^{-1}$)

$\int L dt \sim 4.6-4.9$ fb$^{-1}$, $\sqrt{s}=7$ TeV

ATLAS 2011 Preliminary

CLs limits

$m_H$ [GeV]
Combination

Expected Exclusion:
120 < m_H < 555 GeV

Observed Exclusion:
110 < m_H < 117.5 GeV
118.5 < m_H < 122.5 GeV
129 < m_H < 539 GeV

Observed Exclusion:
130 < m_H < 486 GeV
@ 99% CL
Combination

**Expected Exclusion:**

\[ 120 < m_H < 555 \text{ GeV} \]

**Observed Exclusion:**

\[ 110 < m_H < 117.5 \text{ GeV} \]
\[ 118.5 < m_H < 122.5 \text{ GeV} \]
\[ 129 < m_H < 539 \text{ GeV} \]

@ 99% CL
- Observed local significance for $m_H = 126$ GeV is $2.5\sigma$ (expected $2.8\sigma$)
- Best-fit signal strength at $m_H = 126$ GeV is $\hat{\mu} = 0.9^{+0.4}_{-0.3}$
- Global probability to observe such a fluctuation in 110 - 600 GeV is 30%
- Observed local significance for $m_H = 126$ GeV is $2.5\sigma$ (expected $2.8\sigma$)
- Best-fit signal strength at $m_H = 126$ GeV is $\hat{\mu} = 0.9^{+0.4}_{-0.3}$
- Global probability to observe such a fluctuation in 110 - 600 GeV is 30%
Contributions of individual channels

- Excess mainly in two channels $H \rightarrow ZZ^{(*)} \rightarrow 4l$ and $H \rightarrow \gamma\gamma$
  - Combined local significance is 3.4$\sigma$ at 126 GeV
- No excesses in $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ ($H \rightarrow \tau\tau$, $H \rightarrow bb$)
  - All channels combined: 2.5$\sigma$ local significance
Summary

- Latest results on the search for the SM Higgs boson from ATLAS
  - 12 distinct channels, using the full 2011 data 4.7/fb
- No evidence yet for the Higgs boson
- Only small region for the SM Higgs boson mass range is still allowed from 117.5-118.5 GeV or 122.5-129 GeV
  - SM Higgs excluded from 129 < m_H < 539 GeV at 95% CL
- An excess of events has been observed in the region compatible with a SM Higgs boson hypothesis of 126 GeV
  - No excesses in H →WW(*) →lνlν (H →ττ, H →bb)
- Not yet possible to distinguish in low mass region between background fluctuations or a Higgs boson signal
- More data need - stay tuned, 2012 may reveal the truth
Bonus
Combination

\[ \int L dt = 4.6 - 4.9 \, fb^{-1} \]

\[ \sqrt{s} = 7 \, TeV \]

95\% CL Limit on \( \sigma/\sigma_{SM} \)

- Obs.
- Exp.
- \( \pm 1 \sigma \)
- \( \pm 2 \sigma \)

\( \text{ATLAS Preliminary} \)

2011 Data

\( \text{CLs Limits} \)

\( m_H \, [GeV] \)
H → ZZ → llνν

- Results based on shape of the transverse mass $m_T$
  - Pile-up dependent due to missing transverse energy
\( H \rightarrow ZZ^(*) \rightarrow 4l: \) Mass distributions
$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Background compatibility
H $\rightarrow \gamma\gamma$: $m_{\gamma\gamma}$ in 9 categories
H → γγ: Excess at 126.5 GeV

- Local significance: 2.9σ without ESS; 2.8σ with ESS
- Global significance: 1.5σ
H → γγ: Background modeling
H → γγ: Signal reconstruction with pileup
Combination Best-fit Signal Strength
Data Driven Background Estimation

$H \rightarrow WW(*) \rightarrow l\nu l\nu$

Backgrounds either partially or fully determined from data

$N_{S.R.} = \alpha \times N_{C.R.}$

**Signal Region**

- **Higgs (VBF+ggF)**
- **WW**
- **tt + single t**
- **W jets**

**0j:** estimate top background from b-jet survival probability

**WW control**

- $\alpha_{WW} = \frac{N_{WW}^{sig}}{N_{WW}^{ctrl}}$

**W jets**

- $\alpha_{Wj} = \frac{N_{dijet}^{SR}}{N_{dijet}^{CR}}$

**tt + single t**

- $\alpha_{tt} = \frac{N_{top}^{sig}}{N_{top}^{ctrl}}$

**top control**

- $\beta_{tt} = \frac{N_{top}^{ctrl}}{N_{top}^{ctrl}}$

**WW**

- $\beta_{Wj} = \frac{N_{Wj}^{ctrl}}{N_{Wj}^{Wj}}$

- remove $\Delta \phi$ and $m_T$ cuts, invert $m_\perp$ cuts

- 1j: remove topological cuts, invert b-jet veto

- require 2nd lepton to fail tight selection, but pass loose selection
H$\rightarrow$WW(*)$\rightarrow$l$\nu$l$\nu$; $E_{\text{miss}}$; VBF channel
$H \rightarrow WW(\ast) \rightarrow l\nu l\nu$: Control samples
$H \rightarrow WW(\ast) \rightarrow l\nu l\nu$: Background compatibility
(W/Z)H,H → b\bar{b}b\bar{b}: l\nu bb, llbb, v\nu bb
$H \rightarrow \tau \tau \rightarrow (ll, lh, hh)$
Collinear approximation for $m_{\tau\tau}$ by assuming
- Leptons arise from $Z \rightarrow \tau\tau$ decays
- Neutrinos are collinear with the leptons

\[ x_{1,2} = \frac{p_{vis1,2}}{(p_{vis1,2} + p_{mis1,2})} \]

\[ m_{\tau\tau} = \frac{m_{vis}}{\sqrt{x_1 x_2}} \]

MMC (Missing Mass Calculator), allows non-collinear $\nu$’s, mode of $m_{\tau\tau}$ from scanning over under-determined kinematic variables, weighted by pdf of 3D opening angle between visible and invisible decay products
$H \rightarrow WW \rightarrow l\nu jj$: $m_{l\nu qq}$
H → WW → ℓνjj: limits