Search for the SM Higgs boson in the 4 leptons channel with the ATLAS detector

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Higgs production:
- $gg$ fusion dominant
- VBF comes next ($\sim 10\%$), relative contribution increases with $m_H$.

4 leptons channel:
- Large BR for $ZZ$ above threshold
- Small fraction once $\text{BR}(ZZ \rightarrow 4\ell)$, $\ell = e, \mu$ included
- Cross-sections $\sim 1 - 10\, \text{fb}$: $\ll \sigma(H \rightarrow \gamma\gamma)$ at low mass

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H → 4\ell: characteristics

4 leptons \((e,\mu)\) in the final state:

⇒ Full reconstruction of the Higgs, with excellent experimental resolution (\(\sim 2\) GeV at low mass)

⇒ Clean channel, low background rates

Backgrounds:

- Irreducible SM ZZ continuum
- With leptons from Heavy-Flavour decays: \(Zb\bar{b}, t\bar{t}\)
- With fake leptons: \(Z+\) light jets, multijets

Cross-section in 1–10 fb over whole search range:

Important channel from 115 to 600 GeV.

- Low mass: complementary to \(\gamma\gamma\)
- High mass: Higgs width sizeable, experimental resolution less critical

Experimental challenges

- High lepton reconstruction efficiency and acceptance
- Good resolution on leptons
- Good measurement of lepton properties (cut reducible backgrounds): isolations, impact parameters, electron shower shapes

Search driven by lepton performance.
The ATLAS detector

**Inner Detector**: $(|\eta| < 2.5, B=2\mathrm{T})$
Si Pixels, Si Strips, Transition Radiation tracker provides precise tracking, vertexing, $e/\pi$ separation $\sigma/p_T \sim 3.8 \times 10^{-4} (\text{GeV}) \oplus 0.015$

**Hadronic Calorimeter**: 
Scint/Fe tiles in the central $(|\eta| < 3.2)$ W/Cu-LAr in the fwd region $(|\eta| < 4.9)$ provides trigger, jet measurement and $E_T^{\text{miss}}$
$\sigma/E \sim 50\%/\sqrt{E} \oplus 3\%$

**EM Calorimeter**: $(|\eta| < 3.2)$
Pb-LAr accordion structure provides $e/\gamma$ trigger, identification and measurement $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$

**Muon Spectrometer**: $(|\eta| < 2.7)$
air core toroids with gas chambers provides $\mu$ trigger and standalone momentum measurement resolution $< 10\%$ up to $E_T \sim 1 \text{ TeV}$
Data-taking in 2011

**Very efficient data-taking**

- 5.25 fb\(^{-1}\) recorded by ATLAS in 2011, with peak luminosity up to 3.65 \(10^{33}\) cm\(^{-2}\)s\(^{-1}\)
- Very high efficiency of all subdetectors
  - 4.9 fb\(^{-1}\) analysed in the 4e channel
  - 4.8 fb\(^{-1}\) analysed in the 2e2\(\mu\) and 4\(\mu\) channels

Pile-up conditions increasing with instantaneous luminosity:

- \(<\mu> \approx 6 \rightarrow <\mu> \approx 12\)
- ⇒ Simulations corrected to match observed distribution
**Electron performance**

**Reconstruction:**
- Good quality track matched to an EM cluster
- Track refitted, taking Bremsstrahlung possibility into account: improve track parameters in bending plane

**Energy scale and resolution:**
- Measured using Z decays
- Simulations corrected to match resolution in data
- Energy scale flat with pile-up
**Electron Identification**

**Identification:**
Set of cuts to reduce fakes
- track quality
- track-cluster matching
- cluster shower shapes, transverse and longitudinal

**Performance:**
- Over 90% efficiency
- Efficiencies measured in data with $W$, $Z$ and $J/\psi$
- Simulations corrected to match data
- Small efficiency dependance with pile-up, well reproduced by simulations
Muons performance

Reconstruction:
Two types of muons used
- Good quality track in ID, combined with spectrometer track
- Good quality track in ID, tagged in spectrometer
- Rejection of cosmic rays through impact parameter cuts (1 mm)

Efficiencies:
- Very high (~ 98%, measured with Z decays)
- Well reproduced by simulations
- Simulations corrected to match data

Resolution:
- Measured with Z decays
- Data/MC difference due to non-nominal alignment of MS and ID
  \[ \Rightarrow \text{Simulations corrected to match data} \]
- Small degradation with pile-up
Selection of a candidate

**Trigger:**
- Di-lepton: 2 muons $p_T > 10$ GeV, 2 electrons $E_T > 12$ GeV

**Lepton selection:**
- $p_T > 7$ GeV
- $|\eta| < 2.47$ (electrons), $|\eta| < 2.7$ (muons)

**Reconstruction of a candidate:**
- 2 same-flavor, opposite-sign pairs
- $p_T > 20$ GeV for 2 leptons
- Angular separation $\Delta R > 0.1$ between all leptons
- Pair with mass closest to $m_Z$: $|m_{12} - m_Z| < 15$ GeV
- Second pair: $m_{\text{min}} < m_{34} < 115$ GeV

<table>
<thead>
<tr>
<th>$m_{4\ell}$ (GeV)</th>
<th>$\leq 120$</th>
<th>130</th>
<th>140</th>
<th>150</th>
<th>160</th>
<th>165</th>
<th>180</th>
<th>190</th>
<th>$\geq 200$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{34}$ threshold (GeV)</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>50</td>
<td>60</td>
</tr>
</tbody>
</table>
Additional cuts

Aim: suppress reducible backgrounds

Lepton isolations. Target: $Z$+jets, multijets
- Relative track and calorimeter isolations in cones of size $\Delta R < 0.2$
- Corrected for pile-up
- Corrected for the other leptons of the candidate
  - track isolation: $(\sum p_T)/p_T^\ell < 0.15$
  - calorimetric isolation: $(\sum E_T)/E_T^\ell < 0.30$

Transverse impact parameters. Target: $Zb\bar{b}$, $tt$ $
-$ Used when $m_{4\ell} < 190$ GeV
- Applied on 2 lowest $p_T$ leptons
- $|d_0/\sigma(d_0)| < 3.5$ (muons), 6 (electrons)

Efficiencies.
- Checked with $Z \to \ell\ell$ decays (isolated leptons), $Z + \ell$ and heavy-flavor enriched di-jet sample (non-isolated leptons)
- Excellent data/MC agreement: ratio compatible with 1
- Dependence on pile-up also well represented
- Small systematic uncertainties; one exception: isolation of low-$p_T$ electrons. Uncertainty 5%.
Generators:
- Powheg+Pythia for $gg$ and VBF
- Pythia for $WH$ and $ZH$

Cross-sections
Follow LHC Higgs $\sigma$ working group recommendations:
- Use state-of-the-art computations: NNLO+NNLL (QCD) and NLO (EW) for $gg$, NNLO (QCD) and NLO (EW) for VBF
- Decays by Prophecy4f (NLO)
- Reweight $p_T$ spectrum of $gg$ production to prediction by HqT
- Theory uncertainty: envelope of PDF and $\alpha_s$ (8%), QCD scales (10%)

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>$\sigma(gg \rightarrow H)$ [pb]</th>
<th>$\sigma(qq' \rightarrow Hqq')$ [pb]</th>
<th>$\sigma(qg \rightarrow WH)$ [pb]</th>
<th>$\sigma(qg \rightarrow ZH)$ [pb]</th>
<th>$\text{BR}(H \rightarrow ZZ^{(*)} \rightarrow 4\ell)$ [$10^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>$14.1^{+2.7}_{-2.1}$</td>
<td>$1.154^{+0.032}_{-0.027}$</td>
<td>$0.501 \pm 0.020$</td>
<td>$0.278 \pm 0.014$</td>
<td>0.19</td>
</tr>
<tr>
<td>150</td>
<td>$10.5^{+2.0}_{-1.6}$</td>
<td>$0.962^{+0.028}_{-0.021}$</td>
<td>$0.300 \pm 0.012$</td>
<td>$0.171 \pm 0.009$</td>
<td>0.38</td>
</tr>
<tr>
<td>200</td>
<td>$5.2^{+0.9}_{-0.8}$</td>
<td>$0.637^{+0.022}_{-0.015}$</td>
<td>$0.103 \pm 0.005$</td>
<td>$0.061 \pm 0.004$</td>
<td>1.15</td>
</tr>
<tr>
<td>400</td>
<td>$2.0 \pm 0.3$</td>
<td>$0.162^{+0.010}_{-0.005}$</td>
<td>–</td>
<td>–</td>
<td>1.21</td>
</tr>
<tr>
<td>600</td>
<td>$0.33 \pm 0.06$</td>
<td>$0.058^{+0.005}_{-0.002}$</td>
<td>–</td>
<td>–</td>
<td>1.23</td>
</tr>
</tbody>
</table>
Reconstruction and selection efficiencies:

<table>
<thead>
<tr>
<th>Mass [GeV]</th>
<th>4μ</th>
<th>2e2μ</th>
<th>4e</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>27%</td>
<td>18%</td>
<td>14%</td>
</tr>
<tr>
<td>360</td>
<td>60%</td>
<td>52%</td>
<td>45%</td>
</tr>
</tbody>
</table>

Resolutions at 130 GeV:
2 GeV (4μ), 2.2 GeV (2e2μ), 2.5 GeV (4e)

4e: lower mean value and tails, due to energy losses from Bremsstrahlung.

Natural width of Higgs dominant from 350 GeV on: FWHM ~ 35 GeV at \( m_H = 400 \) GeV.
SM $ZZ^*$ production: irreducible background.

- Generated with Pythia (only double-resonant diagrams)
- $m_{ZZ}$ spectrum reweighted to MCFM prediction (single-resonant diagrams, leading $gg$)
- Uncertainties from QCD scales (5%) and PDF+$\alpha_s$ variations (4%)
- Additional normalisation (10%) + shape uncertainty from varying $gg$ contribution
Reducible backgrounds

Reducible backgrounds contributions derived using data-driven techniques.

\( t\bar{t} : \)

- Generated with MC@NLO
- Cross-section at NNLO (Hathor)
- Checked in control region with \( e^\pm \mu^\mp \) leading pairs
- Good data-MC agreement
- Sizeable contribution in \( Z + \mu\mu \) final states

\( Z + \text{jets} : \)

- Generated with Alpgen+Herwig
- Two types of samples :
  - \( Z + \text{light jets (incl. } c \text{)}, \) normalised to inclusive FEWZ NNLO cross-section
  - \( Zb\bar{b}, \) normalised to MCFM NLO cross-section
  - Overlap removed between samples
- Control regions : \( Z + \ell\ell, \) no isolation nor impact parameter cuts
- Dominant background depends on flavor of second pair
Z + μ⁺μ⁻ dominated by HF decays

- Z + light jets contribution in control region estimated using probabilities that tracks fake muons, checked on Z + μ
- Then Z + b b̄ (→ μμ) estimated by subtraction: good data/MC agreement
- Finally propagation to signal region

Distributions in control region:

\[
\begin{align*}
\text{Events per 2.5 GeV} & \\
\text{Events per 10 GeV} & \\
\end{align*}
\]
**Z+e⁺e⁻ dominated by light jets**

- Normalize $Z+ee$ events in MC using control region with reversed shower shape cut
- Compute isolation and impact parameter efficiencies in $Z+e$ samples: good data/MC agreement
- Extrapolate to signal region

**Distributions in control region:**

![Distributions graph](image)
Systematic Uncertainties

Normalizations:

- Effects of PDF, $\alpha_s$ and QCD scales computed correlated between signal and backgrounds.
- Additional systematics for high mass signal (off-shell effects): $150\% \times m_H^3 \,[\text{TeV}]$ for $m_H > 300 \text{ GeV}$.
- Luminosity: 3.9%.

Backgrounds:

- $t\bar{t}$: 10% cross-section, 10% selection efficiencies.
- $Zb\bar{b}$: 40%.
- $Z$+light jets: 45%.
  - Origin: statistics in control region, uncertainty on composition of control region, uncertainty on extrapolation.

Reconstruction and selection efficiencies:

- Muon efficiency: 0.22% (4$\mu$), 0.16% (2e2$\mu$), uniform with $m_{4\ell}$.
- Electron efficiency: 2.3% (4e), 1.6% (2e2$\mu$) at 600 GeV. 8.0% (4.1%) at 110 GeV.
- Lepton resolution: negligible.
- Electron energy scale: uncertainty 0.6% (4e) and 0.3% (2e2$\mu$) on mass scale.
- Isolations: negligible, except low-$p_T$ electrons (5%).
- Impact parameters: negligible.
- Modelling of Higgs $p_T$ spectrum: 2%.
71 candidate events observed in data, for $62 \pm 9$ estimated background events

Breakdown per channel, in low-mass ($m_{4\ell} < 180$ GeV) and high-mass ($m_{4\ell} > 180$ GeV) regions:

<table>
<thead>
<tr>
<th>Int. Luminosity</th>
<th>$\mu^+\mu^-\mu^+\mu^-$ and $e^+e^-\mu^+\mu^-$</th>
<th>$e^+e^-e^+e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-$m_{4\ell}$</td>
<td>2.1 ± 0.3</td>
<td>2.8 ± 0.6</td>
</tr>
<tr>
<td>High-$m_{4\ell}$</td>
<td>16.3 ± 2.4</td>
<td>25.2 ± 3.8</td>
</tr>
<tr>
<td></td>
<td>1.2 ± 0.3</td>
<td>10.4 ± 1.5</td>
</tr>
</tbody>
</table>

Good agreement between data and SM background prediction

Reducible backgrounds negligible in the high mass region

Significant contribution of reducible backgrounds in the low mass region in $4e$ and $2e2\mu$ channels
After the full selection:
Comparisons of data with SM backgrounds, separated into reducible and irreducible contributions.

Good agreement between data and SM expectations
Invariant mass

Good agreement between data and SM expectations
3 excesses of events in the mass range:

- around 125 GeV, with 3 events
- around 245 GeV
- around 500 GeV, with 3–4 events
2\(e2\mu\) candidate. \(m_{4\ell} = 124.3\) GeV. 
Masses of pairs: 76.8 GeV and 45.7 GeV
Limit-setting

- Limits set with $CL_s$ formalism.
- Test statistic: profile likelihood ratio, evaluated with binned maximum-likelihood fits of the signal and background distributions to the observed data.
- Observed 95% CL limit curve matches well expected one.
- Exclusion expected in 136–157 GeV and 184–400 GeV.
- Largest deviations from expected limit observed around 125 GeV, 244 GeV and 500 GeV.

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Discussion of results

Quantification of excesses: compute $p_0$ values

- Use pseudo-experiments, check with asymptotic formulae
- 1.6% (2.1 $\sigma$) at 125 GeV
- 1.3% (2.2 $\sigma$) at 244 GeV
- 1.8% (2.1 $\sigma$) at 500 GeV
- Expected in presence of a SM-like signal: 1.3, 3.0 and 1.5 $\sigma$ respectively
- Global $p_0$ around 50% when look-elsewhere effect included

Observed $p_0$ value and expected one in presence of a signal

Observed signal strength
Conclusions

Search for the SM Higgs boson in the 4 lepton channel with 4.8 fb$^{-1}$:

- Thanks to a very successful run of the LHC and efficient data-taking, 4.8 fb$^{-1}$ of data analyzed!
- Study of backgrounds shows good agreement with expectations
- 71 4 leptons candidates in data
- SM Higgs excluded by this channel in 134–156 GeV, 182–233 GeV, and ~ 256–415 GeV
- Small excesses at 125, 244 and 500 GeV, of probabilities around 2.1 – 2.2 $\sigma$
- None of them significant once look-elsewhere effect included
- Nevertheless intriguing when compared to other ATLAS results ($\gamma\gamma$)
- Look forward to 2012 data!

Backup
Lepton kinematics

\( p_T \) spectrum of leptons of candidates

\( \eta \) spectrum of leptons of candidates

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Invariant mass for different channels

In the plot on the left:
- The invariant mass distribution for 4μ candidates is shown.
- The 4μ channel is used to search for the Higgs boson.
- The Higgs boson can decay into ZZ, and the ZZ can further decay into 4μ.
- The data is compared with the ATLAS collaboration data.
- The background is also shown.

In the plot on the right:
- The invariant mass distribution for 2e2μ candidates is shown.
- The 2e2μ channel is used to search for the Higgs boson.
- The Higgs boson can decay into ZZ, and the ZZ can further decay into 2e2μ.
- The data is compared with the ATLAS collaboration data.
- The background is also shown.