Study of the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ channel with the full ATLAS detector simulation
$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ decay provides for one of the clearest Higgs signatures.

Evaluation of the discovery potential with ATLAS detector, using a detailed detector simulation (low luminosity runs up to 30 fb$^{-1}$):

- Data samples.
- Lepton reconstruction efficiency and resolution.
- Description of the analysis.
- Discriminating variables and cut optimizations.
- Results.
**Signal and background processes**

![Diagram of signal and background processes]

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma \times \text{BR (fb)}$ (after $4\ell$-filter)</th>
<th>$N_{30\text{fb}^{-1}}$</th>
<th>$N_{\text{reconstructed}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow 4\ell, 130$ GeV</td>
<td>1.624</td>
<td>48.72</td>
<td>60 000</td>
</tr>
<tr>
<td>$H \rightarrow 4\ell, 180$ GeV</td>
<td>1.656</td>
<td>49.68</td>
<td>15 000</td>
</tr>
<tr>
<td>$H \rightarrow 4\ell, 280$ GeV</td>
<td>4.397</td>
<td>131.9</td>
<td>32 000</td>
</tr>
<tr>
<td>reducible: $t\bar{t} \rightarrow \ell\nu b\ell\nu\bar{b}$</td>
<td>1311</td>
<td>39330</td>
<td>442 000</td>
</tr>
<tr>
<td>reducible: $Zb\bar{b} \rightarrow \ell\ell b\bar{b}$</td>
<td>519.9</td>
<td>15597</td>
<td>53 000</td>
</tr>
<tr>
<td>irreducible: $(ZZ^(<em>), Z\gamma^</em>) \rightarrow 4\ell$</td>
<td>33.36</td>
<td>1000.8</td>
<td>109 000</td>
</tr>
</tbody>
</table>

- Pythia($+$AcerMC) generator ($4\ell$-filter with $p_T > 5$ GeV/c, $|\eta| < 2.5$)
- Detailed simulation of processes in the detector (Athena 10.0.4).
- Largest data sizes produced so far, allow for the cut optimizations.
92% for muons: in agreement with previous (TDR) studies
86% for electrons: degradation w.r.t previous (TDR) studies
Lepton momentum- and angular resolution

- Default track parameters given by the combined information from the inner detector, calorimeter, muon spectrometer.

- Non-intuitive improvement: use the inner detector alone for $(p_T, \eta, \phi)$ of muons and $(\eta, \phi)$ of electrons.
  - due to the software bugs in the combining procedures
### Analysis Flow

**Isolated leptons impact significance cut**

<table>
<thead>
<tr>
<th></th>
<th>4e-combinations</th>
<th>4μ-combinations</th>
<th>2e2μ-combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 4e</td>
<td>≥ 4μ</td>
<td>≥ 2e, 2μ</td>
<td></td>
</tr>
</tbody>
</table>

**Charge cut:** total charge = 0

**Kinematic cut:** 2 leptons with \( p_T > 20 \) GeV, other two with \( p_T > 7 \) GeV (\(|\eta| < 2.5|\)

Select the best combination:

1. LEADING LEPTONS: \((l^+,l^-)\)-pair with mass \( m_{12} \) closest to the Z-resonance
2. FOLLOWING LEPTONS: second \((l^+,l^-)\)-pair with largest mass \( m_{34} \)

**Selected 4-lepton combination**

- **Z-mass cut:** \((m_Z - m_{12,\text{low}}) < \delta m_{12} < (m_Z + \delta m_{12,\text{upp}})\)
- **\(Z^(*)\)-mass cut:** \( m_{34,\text{low}} < m_{34} < m_{34,\text{upp}} \)
- **\(p_T\) cut:** \( p_T^{4l} > p_T^{4l,cut} \)
- Kinematic fit of the Z-mass (convolution of Breit-Wigner distribution and momentum resolution)

**Selected Higgs candidate**

- **Mass-window cut:** select events within a mass window \((m_H \pm 3\sigma)\)
  - i) + \(E_T^{\text{miss}}\) cut: \( E_T^{\text{miss}} < E_T^{\text{miss,cut}} \)
  - ii) + \(n_{\text{bjet}}\) cut: \( n_{\text{bjet}} = 0 \)
Lepton isolation

Provides the strongest rejection against the $t\bar{t}$ and $Zb\bar{b}$ background (2 of 4 leptons surrounded by the jet particles coming from b-decays).

- $\Rightarrow$ maximum energy $E_T^{\text{max}}(\Delta R)$ deposited in a cone of size $\Delta R$ around the lepton candidate, separately for electrons and muons:

<table>
<thead>
<tr>
<th>Lepton Type</th>
<th>$E_T(\Delta R)$ Limit</th>
<th>Signal Efficiency</th>
<th>Rejection Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons</td>
<td>$E_T(\Delta R = 0.2) &lt; 6$ GeV</td>
<td>0.68</td>
<td>320</td>
</tr>
<tr>
<td>Muons</td>
<td>$E_T(\Delta R = 0.4) &lt; 9$ GeV</td>
<td>0.72</td>
<td>420</td>
</tr>
</tbody>
</table>
Leptons from b-quarks are displaced from the primary vertex.

- $d_0$ - reconstructed distance from the primary vertex
- impact significance $a_0^{max} = \frac{d_0}{\sqrt{\text{Var}(d_0)}}$:

<table>
<thead>
<tr>
<th></th>
<th>signal efficiency</th>
<th>rejection factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrons: $a_0^{max} &lt; 7$</td>
<td>0.90</td>
<td>2.0</td>
</tr>
<tr>
<td>muons: $a_0^{max} &lt; 3.4$</td>
<td>0.95</td>
<td>4.5</td>
</tr>
</tbody>
</table>
Additional discriminating variables

- missing energy, number of b-jets, invariant mass of leading- and following lepton pairs

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**MISSING ENERGY**

- **signal**
- **Zbb**
- **tt**
- **ZZ**

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**LEADING LEPTON PAIR**

very loose cut, same for all Higgs masses

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**FOLLOWING LEPTON PAIR**

- **mH = 130 GeV**
- **mH = 180 GeV**
- **mH = 280 GeV**
Higgs mass resolution

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma$ for $m_H=130$ (GeV/c$^2$)</th>
<th>$\sigma$ for $m_H=180$ (GeV/c$^2$)</th>
<th>$\sigma$ for $m_H=280$ (GeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to 4\mu$</td>
<td>1.94 (1.74)</td>
<td>2.82 (2.36)</td>
<td>7.79 (7.29)</td>
</tr>
<tr>
<td>$H \to 4e$</td>
<td>2.29 (2.26)</td>
<td>2.81 (2.53)</td>
<td>6.90 (6.68)</td>
</tr>
<tr>
<td>$H \to 2e2\mu$</td>
<td>2.18 (2.00)</td>
<td>2.79 (2.52)</td>
<td>7.11 (6.81)</td>
</tr>
<tr>
<td>$H \to 4\ell$</td>
<td>2.07 (1.85)</td>
<td>2.81 (2.45)</td>
<td>7.30 (6.81)</td>
</tr>
<tr>
<td>$\Delta m$ (GeV/c$^2$)</td>
<td>5.6</td>
<td>7.3</td>
<td>20.4</td>
</tr>
</tbody>
</table>

- In brackets: numbers after the kinematic fit of the Z-mass.
- Mass window for the signal significance: $\Delta m = \pm 3\sigma$
### Signal significance at 30 fb$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>$m_H = 130$ GeV/c$^2$</th>
<th>$m_H = 180$ GeV/c$^2$</th>
<th>$m_H = 280$ GeV/c$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{signal}$</td>
<td>19.7$\pm$0.1</td>
<td>23.4$\pm$0.3</td>
<td>53.0$\pm$0.1</td>
</tr>
<tr>
<td>$N_{ZZ}$</td>
<td>12.0$\pm$0.3</td>
<td>31.8$\pm$0.5</td>
<td>35.2$\pm$0.6</td>
</tr>
<tr>
<td>$N_{Zbb}$</td>
<td>4$\pm$2</td>
<td>1$\pm$1</td>
<td>0$\pm$2</td>
</tr>
<tr>
<td>$N_{t\bar{t}}$</td>
<td>0.7$\pm$0.4</td>
<td>0.5$\pm$0.4</td>
<td>0.4$\pm$0.4</td>
</tr>
<tr>
<td>Significance</td>
<td>4.0$\pm$0.3</td>
<td>3.5$\pm$0.2</td>
<td>7.3$\pm$0.4</td>
</tr>
<tr>
<td>TDR study</td>
<td>4.8</td>
<td>11.2</td>
<td>14.5</td>
</tr>
</tbody>
</table>

- after all cuts the irreducible $ZZ$ background dominates
- big discrepancy with previous (TDR) studies for $m_H \geq 180$ GeV/c$^2$: only $ZZ^*$ background was taken into account, no $ZZ$ contribution
- degradation of the electron reconstruction efficiency and resolution reflects itself on the signal significance:

<table>
<thead>
<tr>
<th></th>
<th>$H \rightarrow 4e$</th>
<th>$H \rightarrow 4\mu$</th>
<th>$H \rightarrow 2e2\mu$</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance $m_H = 130$ GeV/c$^2$</td>
<td>1.5</td>
<td>1.9</td>
<td>2.6</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Space left for the improvements of the reconstruction.
Invariant mass distributions

- Distributions scaled down to the number of events at 30 fb$^{-1}$:

  \[ m_H = 130 \text{ GeV/c}^2 \]

  \[ m_H = 180 \text{ GeV/c}^2 \]

  \[ m_H = 280 \text{ GeV/c}^2 \]

- actual data at 30 fb$^{-1}$ will look more like this (for 130 GeV/c$^2$): if we’re lucky

  \[ \text{Entries 98} \]

  Data sample nr.5

  \[ \text{signal} \]

  \[ \text{sig + bck} \]

  \[ \text{m}_{4\ell} (\text{GeV/c}^2) \]

  \[ \text{events / (2 GeV/c}^2 \text{)} \]

- if we’re not so lucky

  \[ \text{Entries 126} \]

  Data sample nr.17

  \[ \text{signal} \]

  \[ \text{sig + bck} \]

  \[ \text{m}_{4\ell} (\text{GeV/c}^2) \]

  \[ \text{events / (2 GeV/c}^2 \text{)} \]

(2 independent data subsets)
Ensemble test with data subsets of 30 fb$^{-1}$

Extracting the signal from the fit to the invariant mass distribution:

- Testing the two hypotheses,

1.) "Background only" fit function:

$$f_b(x_b[3], m_k) = N_b \cdot \alpha^2 (m_k - \epsilon) e^{-\alpha (m_k - \epsilon)}$$

2.) "Signal+Background" fit function:

$$f_{sb}(x_{sb}[6], m_k) = \frac{N_s}{\sqrt{2 \pi \sigma}} \cdot e^{-\frac{(m_k - \mu)^2}{2 \sigma^2}} + N_b \cdot \alpha^2 (m_k - \epsilon) e^{-\alpha (m_k - \epsilon)}$$

- The goodness-of-the-fit determines the most probable hypothesis.
- Signal significance = \( \frac{N_s}{\text{Error}(N_s)} \).

The stability of the fit has been tested on 60 independent data subsets, each with the statistics corresponding to 30 fb$^{-1}$ ($m_H=130$ GeV/$c^2$).
Ensemble test: minimization procedures

DATA SAMPLE nr.3: signal + background hypothesis

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| DATA | Sample | nr.3: | signal + background hypothesis | background only hypothesis |

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- **a)** equidistant binning
- **b)** unbinned
- **c)** bins with constant density

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- **a)** $k$ equidistant bins, $\chi^2 = \sum \frac{[N_{k}^{\text{obs}} - f(x, m_k)]^2}{N_{k}^{\text{obs}}}$
  
  Unstable, not reliable for low statistics.

- **b)** unbinned maximum likelihood: $-\ln \mathcal{L} = - \sum \ln f(x, m_k)$
  
  Stable, but difficult to extract the goodness-of-the-fit.

- **c)** $k$ bins of constant density, $\chi^2 = \sum \frac{[N_{k}^{\text{obs}} - f(x, m_k)]^2}{N_{k}^{\text{obs}}}$
  
  Very stable, reliable goodness-of-the-fit for the hypothesis test.
Ensemble test: fit results

<table>
<thead>
<tr>
<th>Fit result</th>
<th>equidistant</th>
<th>unbinned</th>
<th>const. dens.</th>
<th>remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{\text{good fits}} ) (of 60)</td>
<td>45</td>
<td>54</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>( &lt;N_s - N_s^{\text{true}} &gt; ) (RMS)</td>
<td>-1 (6)</td>
<td>-3 (6)</td>
<td>2 (6)</td>
<td>( N_s^{\text{true}} = 23 ) (3)</td>
</tr>
<tr>
<td>( &lt;N_b - N_b^{\text{true}} &gt; ) (RMS)</td>
<td>56 (33)</td>
<td>-6 (6)</td>
<td>3 (12)</td>
<td>( N_b^{\text{true}} = 86 ) (10)</td>
</tr>
<tr>
<td>( \frac{\chi^2_b - \chi^2_{sb}}{\chi^2_{sb}} ) (RMS)</td>
<td>0.7 (0.4)</td>
<td>0.2 (0.3)</td>
<td>1.6 (1.0)</td>
<td>hypotheses test</td>
</tr>
<tr>
<td>( &lt;\text{Signf.}&gt; ) (RMS)</td>
<td>3.1 (1.1)</td>
<td>2.3 (0.6)</td>
<td>2.9 (0.6)</td>
<td></td>
</tr>
</tbody>
</table>

- best results provided by the \( \chi^2 \)-minimization using the bins of constant density
Summary

We evaluate the ATLAS potential for an early Higgs discovery in the $H \to ZZ(\ast) \to 4\ell$ decay channel by means of a detailed, up-to-date simulation of detector properties.

Large size of data samples allows for the cut optimizations and for a precise evaluation of the signal significance:

- Degradation of the significance w.r.t the initial ATLAS studies, due to the changes in the detector layout and still-to-be-done improvements of the reconstruction algorithms.

- Signal significance obtained with full Monte-Carlo statistics confirmed by an ensemble test with data subsets corresponding to an integrated luminosity of 30 fb$^{-1}$ (for $m_H=130$ GeV/c$^2$).