Higgs searches with leptons in ATLAS

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Higgs searches in ATLAS - current status

The first evaluation of the Higgs discovery potential in ATLAS has been published already in 1999 (Technical Design Report, TDR).

Since then:

- The detector layout was modified, affecting detector performance.
- ATLAS software is approaching the final detector description.
  ⇒ Necessary to update or improve the existing analyses.
  Also, some new, promising channels have been spotted.

A busy period has started (Computing System Commissioning, CSC):

Demonstrate the physics readiness by detailed studies of key channels.

Studies are mainly concentrated to the preparation for the first data and the low-luminosity running period.

Final physics and performance notes to appear early next year.
Reconstructing Leptons in ATLAS
Why to look for leptonic signatures?

Leptons (≡ electrons and muons) are

- most efficiently reconstructed objects in the detector,
- with a very low fake rate
- and with the highest momentum resolution.

Lepton reconstruction performance can be well understood from data, using $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ processes as a reference.

$Z \rightarrow \mu\mu$: $\sim 40000$ events at $100\text{ pb}^{-1}$ (in few days - weeks)
- statistics similar to TEVATRON today.

Some of the cleanest Higgs signatures are those having leptons as the final Higgs decay products.
Lepton reconstruction in ATLAS detector

Muons:
- Muon spectrometer track
  (MS: trigger + drift-tube chamb.),
  can be combined with the inner detector track.
  (ID: silicon detector + TRT)
- Low-$p_T$ muons: ID track combined with MS hits.

Electrons:
- Shower-shape analysis in the fine-granularity calorimeter,
  clusters are always matched with the ID track.
- Low-$p_T$ electrons:
  ID combined with clusters.

Isolation criteria (given by the calorimeter or by the inner detector):
suppressing leptons which come from jets.
Lepton reconstruction efficiency

Muon reconstruction efficiency
<efficiency> = 96%

Electron reconstr. efficiency
<efficiency> = 90%

Low-$p_T$ algorithms help to improve the reconstruction efficiency. Electrons more difficult than muons (Brehmsstrahlung, dead material).
(TDR: $<\epsilon>=95\%, \ p_T\text{-res.}=3\%$) → Performance now degraded w.r.t. TDR. Reconstruction algorithms still to undergo slight improvements.
Lepton Reconstruction

Searches:
- SM ($H \rightarrow 4\ell$, $H \rightarrow WW$, $H \rightarrow \tau\tau$)
- MSSM ($A/H \rightarrow \mu\mu$)

Outlook
Menu of leptonic Higgs decays

Standard Model Higgs boson:

Purely leptonic decay:
- $H \rightarrow ZZ^{(*)} \rightarrow (\ell^+\ell^-)(\ell^+\ell^-)$

Leptons $+$ missing transverse energy:
- $H \rightarrow W^+W^- \rightarrow (\ell^+\nu)(\ell^-\nu)$,
- VBF: $qqH, H \rightarrow W^+W^- \rightarrow (\ell^+\nu)(\ell^-\nu)$
- VBF: $qqH, H \rightarrow \tau^+\tau^- \rightarrow (\ell^+\nu\nu)(\ell^-\nu\nu)$

Heavy neutral MSSM Higgs boson:

Purely leptonic decay:
- $(bb)H/A \rightarrow \mu^+\mu^-$, most promising after the $\tau\tau$-mode.

At large $\tan\beta$:
- decays into WW, ZZ and $\gamma\gamma$ are suppressed.
Highly sensitive to the lepton reconstruction efficiency, $\epsilon_{4\ell} = (\epsilon_{\ell})^4$. 

$\epsilon_{4\mu} = 0.85$, $\epsilon_{4e} = 0.66$
$H \rightarrow ZZ^{(*)} \rightarrow (\ell^+\ell^-)(\ell^+\ell^-)$

Highly sensitive to the lepton reconstruction efficiency, $\epsilon_{4\ell} = (\epsilon_\ell)^4$.

$\epsilon_{4\mu} = 0.85$, $\epsilon_{4e} = 0.66$

- Lepton isolation (cut on $E_T^{\max}(\Delta R)$) optimized separately for electrons and muons - rejects most of the $t\bar{t}$ and $Zb\bar{b}$ events.
$H \rightarrow ZZ^{(*)} \rightarrow (\ell^+ \ell^-)(\ell^+ \ell^-)$

Highly sensitive to the lepton reconstruction efficiency, $\epsilon_{4\ell} = (\epsilon_{\ell})^4$.

$\epsilon_{4\mu} = 0.85, \epsilon_{4e} = 0.66$

- **Lepton isolation** (cut on $E_T^{\text{max}}(\Delta R)$) optimized separately for electrons and muons - rejects most of the $t\bar{t}$ and $Zb\bar{b}$ events.

- **Additional cuts**: primary vertex, $Z$-mass, $Z^*$-mass, $E_T^{\text{miss}}$, $p_T^{4\ell}$; optimized for the highest signal significance.
$H \rightarrow ZZ^{(*)} \rightarrow (\ell^+ \ell^-)(\ell^+ \ell^-)$: Results for 30 fb$^{-1}$

<table>
<thead>
<tr>
<th>FULL SIMULATION</th>
<th>$m_H =130$ GeV/($c^2$)</th>
<th>$m_H =160$ 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>$N_{signal}$ (gg+VBF)</td>
<td>21.5±0.1</td>
<td>26±1</td>
<td>28.1±0.3</td>
<td>67.4±0.1</td>
</tr>
<tr>
<td>$N_{qq\rightarrow ZZ}$ (×1.3 f. gg → ZZ)</td>
<td>11.3±0.3</td>
<td>11.4±0.3</td>
<td>27.3±0.5</td>
<td>40.4±0.6</td>
</tr>
<tr>
<td>$N_{Zbb}$</td>
<td>2±2</td>
<td>2±2</td>
<td>1±1</td>
<td>0±2</td>
</tr>
<tr>
<td>$N_{tt}$</td>
<td>0±0.4</td>
<td>0±0.4</td>
<td>0.5±0.4</td>
<td>0±0.4</td>
</tr>
<tr>
<td>Significance (no K)</td>
<td>5.0±0.3</td>
<td>5.5±0.5</td>
<td>4.7±0.2</td>
<td>8.8±0.4</td>
</tr>
<tr>
<td>$L$ for 5σ discovery</td>
<td>30 fb$^{-1}$</td>
<td>25 fb$^{-1}$</td>
<td>37.5 fb$^{-1}$</td>
<td>11 fb$^{-1}$</td>
</tr>
</tbody>
</table>

Differences between muon and electron reconstruction ⇒

<table>
<thead>
<tr>
<th>FULL SIMULATION</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>1.9</td>
<td>2.6</td>
<td>3.2</td>
<td>5.0</td>
</tr>
</tbody>
</table>
$H \rightarrow ZZ^{(*)} \rightarrow (\ell^+ \ell^-)(\ell^+ \ell^-)$: Ensemble test

Actual 4$\ell$-mass distribution at 30 fb$^{-1}$ will look more like this:

Small number of entries $\Rightarrow$ variable bin width instead of equidistant bins for the fit of the (S+)B-functions.

Ensemble test of the fit performance (60 subsamples, 25 fb$^{-1}$ each):

$$f_b (m_k) = N_b \cdot \alpha^2 (m_k - \epsilon) e^{-\alpha (m_k - \epsilon)}; \quad f_s (m_k) = \frac{N_s}{\sqrt{2\pi \sigma}} \cdot e^{-\frac{(m_k - \mu)^2}{2\sigma^2}}$$

$$\begin{array}{|c|c|c|}
\hline
\text{fit results} & \text{remark} \\
\hline
N_{\text{good fits}} & 54 & \text{max. 60} \\
\langle N_s - N_s^{\text{true}} \rangle & 2 & \langle N_s^{\text{true}} \rangle = 23 \\
\langle N_b - N_b^{\text{true}} \rangle & 3 & \langle N_b^{\text{true}} \rangle = 86 \\
\langle \chi^2_{b} - \chi^2_{s+b} \rangle & 1.6 & \text{hypothesis test} \\
\langle \text{Signif.} \rangle & \frac{N_s}{\sqrt{\text{Var}(N_s)}} & 2.9\pm 0.6 \quad \text{"$\delta m$"-signf.} \\
\hline
\end{array}$$

Outline/ Lepton Reconstruction/ Searches: SM ($H \rightarrow 4\ell$, $H \rightarrow WW$, $H \rightarrow \tau\tau$), MSSM ($A/H \rightarrow \mu\mu$) / Outlook
\[ H \rightarrow W^+ W^- \rightarrow (\ell^+ \nu)(\ell^- \nu) \]

<table>
<thead>
<tr>
<th>Dominant backgrounds</th>
<th>Rejection cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>( qq/gg \rightarrow WW ) ( t\bar{t} \rightarrow WbWb ) ( Z \rightarrow \ell\ell ) ( W + \text{jets} )</td>
<td>irreducible ( M_{\ell\ell} &lt; 300 \text{ GeV} ), b-jet veto ( M_{\ell\ell} \notin (82, 98) \text{ GeV} ), ( E_T^{\text{miss}} &gt; 30 \text{ GeV} ) no hard jets</td>
</tr>
</tbody>
</table>

- Azimuthal angle between the leptons, \( \Delta \Phi_{\ell\ell} < 1.5 \) (leptons emitted in the same direction, due to spin correlations).
- Transverse mass, \( M_T = \sqrt{2p_T^{\ell\ell} \cdot E_T^{\text{miss}} \cdot (1 - \cos \theta)} \): \( M_T \in (50, M_H + 10) \text{ GeV} \).

Counting experiment: excess of signal over the expected background (good knowledge of background distributions needed).

Recently: comparison of generators (PYTHIA, MC@NLO, SHERPA, ALPGEN) - good agreement observed
**VBF:** $qqH, H \rightarrow W^+W^- \rightarrow (\ell^+\nu)(\ell^-\nu)$

New promising signature from the Vector Boson Fusion (VBF) process.

Typical topology:
- two forward jets
- leptons inbetween
- rapidity gap
  (no central jets)

50% improvement of the signal significance with Neural Network:

**Outline**
- Lepton Reconstruction
- Searches: SM ($H \rightarrow 4\ell, H \rightarrow WW, H \rightarrow \tau\tau$), MSSM ($A/H \rightarrow \mu\mu$)
- Outlook
VBF: $qqH, H \rightarrow \tau^+\tau^- \rightarrow (\ell^+\nu\nu)(\ell^-\nu\nu)$

This channel is only visible in the VBF mode:

without the jet-cuts, the contribution from $Z \rightarrow \tau\tau$ is too large.
VBF: $qqH, H \to \tau^+\tau^- \to (\ell^+\nu\nu)(\ell^-\nu\nu)$

Mass peak reconstructed by means of the collinear approximation:

- $m_H \gg m_\tau$, so products of $\tau$-decays fly in the direction of $\tau$-s.
- Possible to calculate the four-momenta for $\tau$-s.

![Diagram](image)

Similar sensitivity observed also in the semi-leptonic channel, $H \to \tau\tau \to (\ell\nu\nu)(hadrons)$.
Remark on the VBF signatures

The searches in the VBF channels strongly rely on a good understanding of the jet distributions:

- **Theory:** underlying event uncertainties.
- **Experiment:**
  - Pile-up affects the rapidity gap between two forward jets.
  - Jet energy calibration (cross-section depends on the $p_T^{\text{jet}}$ -cuts).

Comparison of different generators → hint for systematic uncertainties:

<table>
<thead>
<tr>
<th>Delta Eta of two leading jets</th>
<th>PT of central jets</th>
<th>PYTHIA 6.323, new showering model; BUG</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.Rottlaender</td>
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<td>PYTHIA 6.323, old showering model; BUG</td>
</tr>
<tr>
<td>PYTHIA 6.403, new showering model</td>
<td>PYTHIA 6.403, old showering model</td>
<td></td>
</tr>
<tr>
<td>HERWIG</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Final evaluation of the generators and det. perf. to be done with data.

$(Z + \text{jets})$: handle for the jet distributions;
reference for the Higgs VBF cross-section (same depend. on the $p_T^{\text{jet}}$ -cuts).

V.A.Khoze et al., hep-ph/0207365v3
Performance of an up-to-date detector is similar to the TDR.
Performance of an up-to-date detector is similar to the TDR.
Vector boson fusion channels largely improve the discovery reach.
MSSM \((bb)A/H \rightarrow \mu^+\mu^−\)

The power of the lepton reconstruction performance:

The most promising \(A/H\) signature is the \(\tau\tau\)-decay mode.

The \(\mu\mu\)-decays are suppressed by the factor

\[
\frac{BR(A/H \rightarrow \mu\mu)}{BR(A/H \rightarrow \tau\tau)} = \left(\frac{m_\mu}{m_\tau}\right)^2 = \frac{1}{282}.
\]

However, the muons provide a much narrower Higgs resonance:
**MSSM \((bb)A/H \rightarrow \mu^+\mu^-\): Event selection**

- **Associated production with two b-jets dominates at larger** \(tan\beta\) **values (>10).**
- **b-tag essential for the suppression of the** \(Z/\gamma^* \rightarrow \mu^+\mu^-\) **background.**
- **\(t\bar{t}\) suppressed by the cuts on** \(E_T^{\text{miss}}\) **and** \(p_T^{b-\text{jet}}\) **(b-jets more energetic than in signal).**

**Outline**

- Lepton Reconstruction
- Searches: SM (\(H \rightarrow 4\ell, \ H \rightarrow WW, \ H \rightarrow \tau\tau\)), MSSM (\(A/H \rightarrow \mu\mu\))
For the first time analysis performed using the full simulation:

<table>
<thead>
<tr>
<th>Significance ((\tan\beta=30))</th>
<th>200 GeV</th>
<th>300 GeV</th>
<th>350 GeV</th>
<th>450 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLFAST</td>
<td>6.5</td>
<td>1.9</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td>FULL</td>
<td>5.4</td>
<td>1.7</td>
<td>–</td>
<td>0.4</td>
</tr>
</tbody>
</table>

\(\Rightarrow\) Only a factor of 2-3 worse than for the \(\tau\tau\) decay mode.
Di-muon mode gives narrow resonances \(\rightarrow\) separation of \(h/A/H\) peaks.
The evaluation of the Higgs discovery potential for the key channels in ATLAS approaches the final stage. Leptonic signatures have a large contribution to the overall signal significance, VBF channels are especially promising.

**To Do List:**

- Fine-tune the reconstruction algorithms.
- Include the detailed information on the trigger performance.
- Study the pile-up effects (especially for VBF).
- Include the misalignment effects (mainly for the Higgs properties).
- Prepare for the detector calibration and background estimation with the first data.

...  

The **ATLAS detector** is growing large, installation on schedule. →

- Pray for the first collisions.
- Enjoy (the sleepless nights with) the real data.