H→ZZ* → 4ℓ search at the ATLAS experiment

Karoline Selbach
University of Edinburgh

IOP meeting

April 9, 2013
Many greetings from...

Karoline Selbach (University of Edinburgh)

April 9, 2013
Many greetings from...
H→ZZ* → 4ℓ with its **good mass resolution** is an ideal channel for the mass measurement.
Introduction

- **Four final states:** 4\(\mu\), 4e, 2e2\(\mu\) and 2\(\mu\)2e

- **Signal:**
  - **Production modes:** gg, VBF, ZH, WH & ttH
  - Shapes as a function of the Higgs mass by interpolating between simulation samples of discrete mass points

- **Backgrounds:**
  - **Irreducible:** ZZ\((*)\)
    - Taken from MC simulation normalised to the theoretical cross section
  - **Reducible:** Zbb, Z+jets and t\(\bar{t}\)
    - Evaluated by data-driven procedure
    - Suppressed with isolation and impact parameter cuts
Fitting the mass of $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$

- **New machinery for fitting** the data has been developed
- Consists of a “workspace” based on RooFit containing data events, systematics and probability density functions (p.d.f.s) for signal and background
- **Created for the needs** of this analysis and **flexible to use** additional models
- Helps facilitate the Higgs combination results
- **Rigorously validated** against the results published at ICHEP 2012 and used for the publications since then
- By using the new fitting machinery it was observed that splitting the analysis into different final states results in a gain of $\sim 7\%$
- The systematic uncertainties have been parametrised depending on $m_H$
Analytical models

- **Analytical functions** have been developed to model the background and signal e.g. the sum of a **Crystal ball** and Gaussian function (CB+GA)

- The **Pearson Type IV distribution** is a continuous probability function where $k$ is a normalization constant and $m$, $\nu$, $a$ and $\lambda$ are real-valued parameters:

  \[
  f(x) = k \left[1 + \left(\frac{x-\lambda}{a}\right)^2\right]^{-m} \exp\left[-\nu \arctan\left(\frac{x-\lambda}{a}\right)\right]
  \]
  for $-\infty < x < \infty$ where $m < \frac{1}{2}$

- The Pearson Type IV distribution models the error of the invariant mass of the 4 leptons allowing for an **asymmetric tail**
Per-event error for $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$

- Implementation of **per-event errors** for the reconstructed mass ($m_{4\ell}$) and the corresponding error ($m_{4\ell\text{err}}$) to take advantage of resolution information.

- **Conditional p.d.f.** is applied to ensure correlation due to differing signal and background shape is taken into account:

  $$ P_k(m_{4\ell}|m_{4\ell\text{err}})P_k(m_{4\ell\text{err}}) = P_k(m_{4\ell\text{err}}|m_{4\ell})P_k(m_{4\ell}) $$

- For the mass measurement applied to the low mass region $110 \text{ GeV} < m_H < 150 \text{ GeV}$.
Conditional p.d.f. for $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$

Models for the reconstructed mass $m_{4\ell}$ and the error on the reconstructed mass $m_{4\ell\text{err}}$:

- **Signal:**
  - $P_k(m_{4\ell}|m_{4\ell\text{err}})$: **Crystal ball** or sum of Crystal ball and Gaussian distribution
  - $P_k(m_{4\ell\text{err}})$: **Pearson Type IV distribution** or smoothed histogram

- **Background:**
  - $P_k(m_{4\ell})$: Polynomial function
  - $P_k(m_{4\ell\text{err}}|m_{4\ell})$: Pearson Type IV distribution

⇒ With the per-event error implementation the **resolution** is improved by $\sim 0.1\text{ GeV}$
**Profile likelihood** shown with mass scale systematics (solid curve) and without (dashed curve).

- Observed and expected signal and background events in [120 GeV, 130 GeV] show in table below.
- Strong contribution of 4µ channel with most expected signal events.

⇒ 4µ channel is most sensitive.

<table>
<thead>
<tr>
<th>Signal (m_H=125 GeV)</th>
<th>Expected: ZZ*</th>
<th>Z+jets, t̅t̅</th>
<th>Sum</th>
<th>Observed:</th>
</tr>
</thead>
<tbody>
<tr>
<td>4µ</td>
<td>6.3±0.8</td>
<td>2.8±0.1</td>
<td>0.55±0.15</td>
<td>9.6±1.0</td>
</tr>
<tr>
<td>2µ2e</td>
<td>3.0±0.4</td>
<td>1.4±0.1</td>
<td>1.56±0.33</td>
<td>6.0±0.8</td>
</tr>
<tr>
<td>2e2µ</td>
<td>4.0±0.5</td>
<td>2.1±0.1</td>
<td>0.55±0.17</td>
<td>6.6±0.8</td>
</tr>
<tr>
<td>4e</td>
<td>2.6±0.4</td>
<td>1.2±0.1</td>
<td>1.11±0.28</td>
<td>4.9±0.8</td>
</tr>
<tr>
<td>total</td>
<td>15.9±2.1</td>
<td>7.4±0.4</td>
<td>3.74±0.93</td>
<td>27.1±3.4</td>
</tr>
</tbody>
</table>

Karoline Selbach (University of Edinburgh)

H→ZZ* → 4l in ATLAS

April 9, 2013

10 / 17
Results are based on **4.6 fb\(^{-1}\) at \(\sqrt{s} = 7\) TeV** and **20.7 fb\(^{-1}\) at \(\sqrt{s} = 8\) TeV**

Best fitted mass of

\[ m_H = 124.3^{+0.6}_{-0.5} \text{(stat)}^{+0.5}_{-0.3} \text{(syst)} \text{ GeV} \]

Excess of background with a significance of 6.6 standard deviations

With a signal strength factor (fitted signal strength divided by expected SM strength):

\[ \mu = 1.7^{+0.5}_{-0.4} \]
Conclusion

- **New fitting framework** created exactly for $H \rightarrow ZZ^* \rightarrow 4\ell$ needs

- Results from **per-event error mass fit** and the standard fit are compatible

- **Improved resolution** by $\sim 0.1 \text{ GeV}$ with the per-event error implemented

$H \rightarrow ZZ^* \rightarrow 4\ell$ fit results:

$\mu = 1.7^{+0.5}_{-0.4}$

$m_H = 124.3^{+0.6}_{-0.5} \text{(stat)}^{+0.5}_{-0.3} \text{(syst)} \text{ GeV}$
I want to thank especially the following people for their work:

- Pierluigi Catastini$^1$
- Phil Clark$^2$
- Francisca Garay$^2$
- Robert Harrington$^2$
- Ben Wynne$^2$
Backup Slides
### Experimental systematic uncertainties:

<table>
<thead>
<tr>
<th>Systematic uncertainties</th>
<th>Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>1.8 (2011)/3.6 (2012)</td>
</tr>
<tr>
<td>Muon efficiency</td>
<td>0.4-0.8</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>0.1-0.2</td>
</tr>
<tr>
<td>Electron efficiency</td>
<td>1.6-9.4</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>0.2-0.4</td>
</tr>
</tbody>
</table>

### Theoretical systematic uncertainties:

<table>
<thead>
<tr>
<th>Process</th>
<th>QCD Scale (depend of $m_H$) in %</th>
<th>PDF+$\alpha_S$ in %</th>
<th>Total in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>+12/−7</td>
<td>±8</td>
<td>+20/−15</td>
</tr>
<tr>
<td>VBF</td>
<td>±1</td>
<td>±4</td>
<td>±5</td>
</tr>
<tr>
<td>WH/ZH</td>
<td>±1</td>
<td>±4</td>
<td>±5</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>±4</td>
<td>±4</td>
<td>±1</td>
</tr>
<tr>
<td>ZZ (SM)</td>
<td>±5 +10 (gg→ZZ)+shape</td>
<td>±4</td>
<td>±12</td>
</tr>
</tbody>
</table>
Cross checks

- Investigate systematic effects in the dominant muon channels:
  **Using the redundancy of the muon momentum measurement**
  - Comparing mass measurement results of muons only reconstructed by the ID to the results of combined muon measurement
  \[\Rightarrow\text{Consistent results}\]

- Check the leading lepton pair distribution in the $4\mu$ channel:
  $m_{4\mu}$ vs $m_{12}$ distribution for data and expected MC response for $m_H = 124$ GeV
  - Without Z-mass constraint (kinematic fit to the leading lepton pair for $m_{4\ell} < 190$ GeV)
  - Populated band, shown by horizontal lines (120 - 130 GeV), with both Z bosons off-shell and particularly populated where $m_{12}$ is on-shell
  \[\Rightarrow\text{Data and MC agree well within the statistical uncertainty}\]
SM $H \rightarrow ZZ^* \rightarrow 4\ell$ results released:

- ATLAS-CONF-2013-013 (March 2013)
- ATLAS-CONF-2012-162 (December 2012)
- ATLAS-CONF-2012-092 (July 2012)

All available at

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults