Measurement of properties of the Higgs boson in bosonic decay channels using the ATLAS detector

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Outline

- Introduction
  - Production and decay modes
  - Channels overview
    - Selection
    - Event categories
    - Backgrounds
- Properties (see also the talk of Florian Bernlochner)
  - Mass
  - Coupling strengths
  - Production mechanisms
- Summary
Introduction

- Most striking result from ATLAS and CMS experiments, so far:
  4\textsuperscript{th} July, 2012: “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”

- Since then: compare the properties of the new particle with the SM predictions for the Higgs boson:
  - “Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC”
  - “Evidence for the spin-0 nature of the Higgs boson using ATLAS data”
  - Other topics: couplings to fermions, differential cross section,...

- ATLAS results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
### Production and decay

- $\Gamma_H \sim 4 \text{ MeV } @ \ m_H = 125 \text{ GeV}$
- $H \rightarrow WW$: allow a broad range of masses to be “scanned”
- $H \rightarrow ZZ/\gamma\gamma$: distinct signatures, but low statistics

- Couplings determined by the mass: $g_{Hff} = \frac{m_f}{v}$; $g_{HVV} = \frac{2m_V^2}{v}$; ...
**H → γγ overview**

- **L = 20.7(4.7) fb⁻¹** (2012 (2011), √s = 8(7) TeV)

- **Simple signature**: pair of high-\(p_T\) isolated photons

- **Mass**: \(m_{γγ}^2 = 2p_γ₁p_γ₂ (1 − \cos θ) \approx p_γ₁p_γ₂ θ^2\)

- **Electron energy scale**: stability with pile-up and with time

- **Photon ID**: main syst. unc. on signal yield (2.4%)
  \((ε_{ID}(E_T, η) \sim 85% − 95\%, \text{ for } E_T^γ > 30 \text{ GeV})\)

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A. Palma (LIP & FCUL)  ●  Higgs properties @ ATLAS
$H \rightarrow \gamma\gamma$ sub-channels

**di-photon selection**

- One-lepton
  - $W(\rightarrow l\nu)H$, $Z(\rightarrow ll)H$
- $E_T^{miss}$ significance
  - $W(\rightarrow l\nu)H$, $Z(\rightarrow \nu\nu)H$
- Low-mass two-jet
  - $W(\rightarrow jj)H$, $Z(\rightarrow jj)H$
- High-mass two-jet
  - VBF
  - Tight
  - Loose
- 9 $p_{Tt}$-η-conversion
  - ggF

**Event categorization:** increase sensitivity to signal and to separate Higgs production mechanisms

Diphoton thrust axis in the transverse plane:

$$p_{Tt} = |(\vec{p}_T^{\gamma_1} + \vec{p}_T^{\gamma_2}) \times \hat{t}| \Leftrightarrow \hat{t} = (\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2})/|\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2}|$$
$H \rightarrow \gamma\gamma$ background

- Irreducible background: QCD $\gamma\gamma$ production ($\sim 75\%$)
- Reducible background: $\gamma j$ and $jj$ (jets misidentified as photons), and DY (mis-reconstruction of electrons) ($\sim 25\%$)
- Shape parameters and the normalization of the background determined by a fit to the data

$\star m_{\gamma\gamma} = 126.8 \pm 0.2\text{(stat.)} \pm 0.7\text{(syst.)} \text{GeV}$

$\star$ main syst. unc.: photon energy scale

$\star$ significance of the observed peak is 7.4$\sigma$
**Signature:** 2 pairs of same-flavour, opposite-charged, isolated leptons

- Leptons assigned to **quadruplets** of the same flavour and opposite charge, with $p_T > 20, 15, 10$ GeV for leading leptons

- **Electron ID & reco:** main syst. unc. on signal yield (2.4% - 9.4%)

### Diagram:

- $H \rightarrow ZZ^* \rightarrow 4\ell$ overview

- **Higgs properties @ ATLAS**

### Figures:

- **Reconstruction Efficiency:**
  - $15 < E_T < 50$ GeV
  - **ATLAS** Preliminary
  - 2011 data $\sqrt{s}=7$ TeV $\int L dt = 4.7$ fb$^{-1}$
  - 2011 MC
  - 2012 data $\sqrt{s}=8$ TeV $\int L dt = 20.3$ fb$^{-1}$
  - 2012 MC

- **Efficiency:**
  - ATLAS Preliminary
  - $|\eta| < 2.47$
  - $L dt = 20.3$ fb$^{-1}$
  - $\sqrt{s} = 8$ TeV $Z \rightarrow ee$
  - $|\eta| < 2.47$
  - Loose
  - LooseLLH
  - Medlepton
  - Medlepton
  - Tight
  - VeryTightLLH
H → ZZ* → 4ℓ backgrounds

- **Irreducible**: continuum ZZ production is the largest background
- Normalization and $m_{4\ell}$ shape both taken from simulation
- Single resonant Z peak and high mass resonance used to constrain ZZ contribution
**H → ZZ* → 4ℓ backgrounds**

- **Reducible:** mainly $Z + \text{jets}$ and $\bar{t}t$ processes (jets faking leptons)
  - composition depends on the flavour of the sub-leading lepton pair ($\ell\ell + \mu\mu$, $\ell\ell + ee$)

- **Approach:**
  - Normalization from data-driven methods: signal yields extrapolated from CRs using transfer factors obtained from simulation control samples
  - $m_{4\ell}$ shape derived from background simulation using relaxed lepton selection

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**ATLAS Preliminary**

$\mu^+\mu^-/e^+e^- + \mu^+\mu^-$

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

$\sqrt{s} = 8$ TeV: $\int L dt = 20.7$ fb$^{-1}$
Each $H \rightarrow ZZ^* \rightarrow 4\ell$ candidate is assigned to one of the three categories:

- **VBF-like**: 2 high-$p_T$ jets; $|\Delta \eta_{jj}| > 3; m_{jj} > 350$ GeV
- **VH-like**: not VBF-like; additional isolated lepton with $p_T > 8$ GeV
- **ggF-like**: not VH- or VBF-like

* $m_{4\ell} = 124.3^{+0.6}_{-0.5} \text{ (stat.)}^{+0.5}_{-0.3} \text{ (syst.)}$ GeV

* significance of the observed peak is 6.6$\sigma$
**Signature:** 2 oppositely charged isolated leptons and $E_T$

- $e\mu$ pair: dominates sensitivity to the Higgs boson signal
- same flavour: larger backgrounds (DY)
- cannot reconstruct a narrow mass peak due to neutrinos:

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T)^2 - |p_T^{\ell\ell} + \vec{E}_T|^2}$$

(with $E_T^{\ell\ell} = p_T^{\ell\ell} + m_{\ell\ell}$)

**Higgs spin 0:** collinear leptons (low $m_{\ell\ell}$ and $\Delta \phi_{\ell\ell}$) $\Rightarrow$ suppress WW background

**Production mechanism:** ggF (0 or 1 jet); VBF ($\geq$ 2 jets; low bkg and low theory uncertainty)

- VBF: $|\Delta y_{jj}| > 2.8$; $m_{jj} > 500$ GeV

Jet energy scale and resolution and b-tagging efficiency are the main sources of experimental systematic uncertainty
**H → WW^* → ℓνℓν** background

<table>
<thead>
<tr>
<th>Background</th>
<th>Why fake signal?</th>
<th>criteria to reduce</th>
<th>normalized from</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>large irreducible bkg</td>
<td>low (m_{ℓℓ})</td>
<td>data</td>
</tr>
<tr>
<td>top (tt and single top)</td>
<td>lose a b-jet</td>
<td>b-jet veto</td>
<td>data</td>
</tr>
<tr>
<td>W+jets</td>
<td>jet fakes (ℓ)</td>
<td>tight iso &amp; (ℓ) ID</td>
<td>data</td>
</tr>
<tr>
<td>Z+jets</td>
<td>fake/real (E_T)</td>
<td>(E_T) + low (m_{ℓℓ})</td>
<td>data</td>
</tr>
<tr>
<td>other diboson</td>
<td>lost/misidentified (ℓ)</td>
<td>veto extra (ℓ)</td>
<td>MC</td>
</tr>
</tbody>
</table>

| \(H\) to WW* to \(ℓνℓν\) background |

- **ATLAS**
  - \(\sqrt{s} = 8\) TeV
  - \(\int Ldt = 20.7\) fb\(^{-1}\)
  - \(H\to WW^* \to eνμν + 0\) jets

- Data 2012
- Total sig.+bkg.
- SM Higgs boson
  - \(m_H = 125\) GeV

<table>
<thead>
<tr>
<th>Events / 10 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>300</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

\(m_{ℓℓ}\) [GeV]

- WW CR, \(N_{jet} \leq 1\) final states:
  - \(\Delta\phi_{ℓℓ}\) criteria is removed
  - \(m_{ℓℓ}\) bounds are modified

A. Palma (LIP & FCUL)  - Higgs properties @ ATLAS
**$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ transverse mass**

- Excess of events observed in data
- VBF contributes 81% of the predicted signal in the $N_{jet} \geq 2$ final states
- Maximum deviation ($4.1\sigma$) at $m_H = 140$ GeV

**ATLAS**

- Data 2011+2012
- Total sig.+bkg.
- SM Higgs boson $m_H = 125$ GeV
- $\sqrt{s} = 7$ TeV $\int L dt = 4.6$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV $\int L dt = 20.7$ fb$^{-1}$
- $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu + 0/1$ jets

- $H \rightarrow WW^* \rightarrow e\nu\mu\nu + 2$ j

- ATLAS
- $\sqrt{s} = 7$ TeV $\int L dt = 4.6$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV $\int L dt = 20.7$ fb$^{-1}$
- $H \rightarrow WW^* \rightarrow e\nu\mu\nu + 2$ j
Mass measurements and signal strengths

**Signal strength:** \( \mu = \frac{\sigma_{\text{observed}}}{\sigma_{\text{SM}}} \)

**ATLAS**

- \( m_H = 125.5 \text{ GeV} \)

<table>
<thead>
<tr>
<th>Process</th>
<th>( \mu ) (stat)</th>
<th>( \mu ) (sys)</th>
<th>( \mu ) (theo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \to \gamma\gamma )</td>
<td>1.55(^{+0.33}_{-0.28})</td>
<td>0.23 ( -0.22 )</td>
<td>0.18 ( +0.18 )</td>
</tr>
<tr>
<td>( H \to ZZ^* \to 4l )</td>
<td>1.43(^{+0.40}_{-0.35})</td>
<td>0.35 ( -0.32 )</td>
<td>0.20 ( +0.20 )</td>
</tr>
<tr>
<td>( H \to WW^* \to 4l \nu \nu )</td>
<td>0.99(^{+0.31}_{-0.28})</td>
<td>0.20 ( -0.21 )</td>
<td>0.15 ( +0.15 )</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td>1.33(^{+0.21}_{-0.18})</td>
<td>0.13 ( -0.14 )</td>
<td>0.12 ( +0.12 )</td>
</tr>
</tbody>
</table>

**Total uncertainty** ± 1\( \sigma \) on \( \mu \)

- \( \sigma_{\text{stat}} \)
- \( \sigma_{\text{sys}} \)
- \( \sigma_{\text{theo}} \)

**\( \mu \) largest deviation (\( \sim 1.9\sigma \)) observed in**

\( H \to \gamma\gamma \)

**A. Palma (LIP & FCUL)  •  Higgs properties @ ATLAS**
Exploit sensitivity offered by categories to fit separately vector-boson mediated and gluon mediated processes
Data recorded by the ATLAS experiment in 2011/2012 allowed to test the fundamental properties of the discovered Higgs boson

Significance of the observed mass peak is $7.4\sigma$ in $H \rightarrow \gamma\gamma$ and $6.6\sigma$ in $H \rightarrow ZZ \rightarrow 4\ell$ channel (discovery level in each of these channels)

Mass of the Higgs boson measured to be $m = 126.8 \pm 0.2\text{(stat.)} \pm 0.7\text{(syst.)}$ in $H \rightarrow \gamma\gamma$ and $m = 124.3^{+0.6}_{-0.5}\text{(stat.)}^{+0.5}_{-0.3}\text{(syst.)}$ in $H \rightarrow ZZ \rightarrow 4\ell$ (better than 9 per mil)

All measurements are consistent with expectations for the SM Higgs boson

Acknowledgements:
References

Papers:

Conference notes:
- ATLAS-CONF-2013-034 (Couplings Combination)
- ATLAS-CONF-2013-030 (Higgs to $WW(\ell\nu\ell\nu)$)
- ATLAS-CONF-2013-014 (Combined of Mass)
- ATLAS-CONF-2013-012 (Higgs to Diphoton)
- ATLAS-CONF-2013-013 (Higgs to 4 leptons)
Backup Slides
Statistical method

- Construct a likelihood of Poisson probabilities, with expected numbers of events:

\[ N^k = n^k_{\text{sig}} + n^k_{\text{bkg}} \]

- For the analysis \( k \), signal scaling factors per each production \( i \) and decay \( f \):

\[ n^k_{\text{sig}} = \left( \sum_i \mu_i \times \sigma_i,\text{SM} \times A^k_{if} \times \epsilon^k_{if} \right) \times \mu_f \times BR_{f,\text{SM}} \times \mathcal{L}^k \]

  - cross section modifier: \( \mu_i = \sigma_i / \sigma_i,\text{SM} \)
  - branching ratio modifier: \( \mu_f = BR_f / BR_{i,\text{SM}} \)

- Test hypothesized values of parameter of interest \( \mu \) with profiled likelihood ratio:

\[ q_\mu = -2 \Delta \ln \mathcal{L} = -2 \ln \frac{\mathcal{L}(\text{data}|\mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})} \]

  - maximized likelihood for a fixed \( \mu \)
  - \( \mu \) and \( \theta \) that maximize likelihood

A. Palma (LIP & FCUL) - Higgs properties @ ATLAS