Observation of a Narrow Resonance at ATLAS

Jianming Qian (University of Michigan)

On behalf of the ATLAS collaboration

Introduction

$H \rightarrow \gamma\gamma$

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

$H \rightarrow WW^* \rightarrow e\mu\nu\nu$

Combination

new

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SLAC Seminar, July 20, 2012
CERN Higgs Search Update

July 4, 2012:
Planned as an update...
going out with a bang!

“We have now found the missing cornerstone of particle physics. We have a discovery. We have observed a new particle that is consistent with a Higgs boson.”

- Rolf Heuer
Standard model does not answer all the questions, but it does describe existing data remarkably well.

Nevertheless, there are a few known anomalies:
- $t\bar{t}b$ F-B charge asymmetry
- $\mu^+\mu^-$ charge asymmetry

The EW symmetry breaking mechanism in the SM is not confirmed.

$\Rightarrow$ Hunting for Higgs boson
Higgs Boson Mass Constraint

Direct searches at LEP:

$$m_H > 114.4 \text{ GeV @ 95\% CL}$$

Precision electroweak data are sensitive to Higgs mass

Preferred value from global fit:

$$m_H = 94^{+29}_{-24} \text{ GeV}$$

and 95\% CL upper bound

$$m_H < 152 \text{ GeV}$$

Existing data suggests a low mass standard model Higgs boson and direct experimental searches exclude all except the narrow mass window of 114.4-127 GeV!
Higgs Boson Production

Gluon-gluon fusion gg→H and vector-boson fusion qq→qqH diagrams dominate.

\[ \sigma_{\text{ggH}} = 19.5 \text{ pb}, \quad \sigma_{\text{VBF}} = 1.6 \text{ pb}, \]
\[ \sigma_{\text{WH}} = 0.70 \text{ pb}, \quad \sigma_{\text{ZH}} = 0.39 \text{ pb}, \quad \sigma_{\text{ttH}} = 0.13 \text{ pb} \]

⇒ ~230k events in 2011 and 2012 samples!
Higgs Boson Decay

To all particles kinematically allowed, but two dominant modes:

- $H \rightarrow b\bar{b}$ for $m_H < 135$ GeV;
- $H \rightarrow WW$ for $m_H > 135$ GeV

Neither is ideal for the search and the study of properties
- $b\bar{b}$ by itself suffers from huge QCD backgrounds
- $WW$: easy identification in dilepton mode, complex backgrounds and no full reconstruction

Branching ratios at 125 GeV

- $b\bar{b}$: 57.7%
- $WW$: 21.5%
- $\tau\tau$: 6.3%
- $ZZ$: 2.6%
- $\gamma\gamma$: 0.23%

Difficulty level (least to most):

- $\gamma\gamma$, $ZZ \rightarrow 4l$,
- $WW \rightarrow llvv$

$bb$ and $\tau\tau$
ATLAS Collaboration

• Detector: A Toroidal LHC ApparatuS
  - 7000 tons, 25m high, 46m long and 100 million electronic channels

• Collaboration:
  - ~3000 collaborators;
  - ~1000 students;
  - 178 institutions;
  - 38 countries

20+ years of worldwide collaborative effort
ATLAS Detector
Data Samples

2011 data taking at 7 TeV
5.3 fb\(^{-1}\) recorded
\(~4.8\ fb\(^{-1}\) for analysis

2012 data taking at 8 TeV
“ICHEP” dataset
6.3 fb\(^{-1}\) recorded till 22/6
\(~5.8\ fb\(^{-1}\) for analysis

Data-taking efficiency: \(~94\%
Good data fraction: \(~93\%\)
Challenging pileup issues:
- Lepton reconstruction and isolation
- Primary vertex identification
- Jet energy and multiplicity
- ETmiss resolution

In particular, understanding ETmiss takes time...
Cross Section Measurements

Higgs searches are built upon the successes of numerous studies/measurements of Standard Model physics.

These measurements validate detector/physics simulation, object reconstructions, event selections and in general analysis techniques.
### Search Overview

#### High resolution channels: clean signature, full reconstruction, good mass resolution. *updated with 2012 data for the July 4th seminar.*

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mass range (GeV)</th>
<th>Key detector requirements</th>
<th>Main backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma \gamma$</td>
<td>110-150</td>
<td>photon</td>
<td>$\gamma\gamma$, $\gamma j$, $jj$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
<td>110-600</td>
<td>lepton</td>
<td>$ZZ$, $Z+jets$, top</td>
</tr>
<tr>
<td>$H \rightarrow bb$ (WH/ZH)</td>
<td>110-130</td>
<td>jets, b-tagging</td>
<td>$W/Z+jets$, top</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$ ($ll$, $l_\tau$, $\tau_\tau$, $\tau_\tau$)</td>
<td>100-150</td>
<td>lepton, jets, ETmiss</td>
<td>$Z+jets$, jets</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow ll\nu\nu$</td>
<td>110-600</td>
<td>lepton, jets, ETmiss, b-veto</td>
<td>$WW$, $W/Z+jets$, top, $W\gamma$</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow llqq$</td>
<td>300-600</td>
<td>lepton, jets, ETmiss, b-veto</td>
<td>$W+jets$, jets</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow ll\nu\nu$</td>
<td>200-600</td>
<td>lepton, ETmiss</td>
<td>$Z+jets$, $ZZ$, top</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow llqq$</td>
<td>200-600</td>
<td>lepton, jets, ETmiss, b-veto</td>
<td>$Z+jets$, $ZZ$, top</td>
</tr>
</tbody>
</table>

#### Low resolution channels: poor mass resolution, strong dependence on jet and ETmiss performance, *only WW*→$l\nu l\nu$ *updated with 2012 data.*
\[ H \rightarrow \gamma\gamma \]

- Very simple signature, but small rate \( \text{Br}(H \rightarrow \gamma\gamma) \sim 2 \times 10^{-3} \);
- Important decay mode for the low mass region (100-140 GeV)

\[ \sigma_H \times \text{Br}(H \rightarrow \gamma\gamma) \sim 50 \text{ fb} \]
\[ @ m_H = 125 \text{ GeV} \]
\[ \sim 500 \text{ events in 2011+2012 sample!} \]

- Irreducible background from \( \gamma\gamma \) production

\[ \sigma(\gamma\gamma) \sim 40 \text{ pb} \]

- Reducible background from \( \gamma j \) and \( jj \) productions

\[ \sigma(\gamma j) \sim 3 \times 10^5 \text{ pb} \]
\[ \sigma(jj) \sim 6 \times 10^8 \text{ pb} \]

Theoretical uncertainty \( \Delta \sigma/\sigma \sim 30\% \), not reliable!
Photon identification
- Longitudinal and lateral shower profiles;
- No track or tracks consistent with photon conversions (~40% γ converts!);
- Main background: π⁰ from jets;
- Neural network ID used for 2011, Cut-based ID for 2012
⇒ 85+% efficiency

Energy calibration
- Calibrating from Z, J/ψ→ee and W→ev events;
- Extrapolating to photon using MC;
- Energy scale at M_Z known to ~0.3%;
- Linearity better than 1%;
- Stable within 0.1% in 2011
Two isolated high pT photons with $E_T > 40, 30$ GeV and $|\eta| < 2.37$
(exclude $1.37 < |\eta| < 1.52$)

efficiency ~ 40%
$S/B$ ratio ~ 3%

New since 2011:
2-jet selection $\Rightarrow$ VBF process
$S/B$ ~ 20%

Keys to the search
$\gamma\gamma$ mass resolution;
Background suppression
and modeling
Taking advantage of different mass resolutions and signal-background ratios, data sample is split into 10 categories:

- Converted photons vs unconverted photons;
- Detector regions: central, transition and forward;
- Low and high $p_{Tt}$

$\Rightarrow$ improve sensitivity by $\sim 20\%$
Full reconstruction of the Higgs decay final state, very little else to distinguish signal from backgrounds other than mass:

\[ m^2 = 2E_{\gamma_1}E_{\gamma_2}\left(1 - \cos \Delta \phi_{\gamma \gamma}\right) \]

Mass resolution is the key, dominated by the energy resolution.

<table>
<thead>
<tr>
<th>Category</th>
<th>(\sigma_{CB}) [GeV]</th>
<th>FWHM [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>1.63</td>
<td>3.87</td>
</tr>
<tr>
<td>Unconverted central, low (p_{Tt})</td>
<td>1.45</td>
<td>3.42</td>
</tr>
<tr>
<td><strong>Unconverted central, high (p_{Tt})</strong></td>
<td><strong>1.37</strong></td>
<td><strong>3.23</strong></td>
</tr>
<tr>
<td>Unconverted rest, low (p_{Tt})</td>
<td>1.57</td>
<td>3.72</td>
</tr>
<tr>
<td>Unconverted rest, high (p_{Tt})</td>
<td>1.51</td>
<td>3.55</td>
</tr>
<tr>
<td>Converted central, low (p_{Tt})</td>
<td>1.67</td>
<td>3.94</td>
</tr>
<tr>
<td>Converted central, high (p_{Tt})</td>
<td>1.50</td>
<td>3.54</td>
</tr>
<tr>
<td>Converted rest, low (p_{Tt})</td>
<td>1.93</td>
<td>4.54</td>
</tr>
<tr>
<td>Converted rest, high (p_{Tt})</td>
<td>1.68</td>
<td>3.96</td>
</tr>
<tr>
<td>Converted transition</td>
<td>2.65</td>
<td>6.24</td>
</tr>
<tr>
<td>2-jets</td>
<td>1.57</td>
<td>3.70</td>
</tr>
</tbody>
</table>

\((m_H=125 \text{ GeV})\)
H → γγ

LHC beam size $\delta z \sim 5-6$ cm, vertex reconstruction through

**Unconverted photon:**
- Calorimeter pointing of longitudinal samplings
- Resolution: $\delta z \sim 1.5$ cm

**Converted photon:**
- Calorimeter pointing and conversion vertex extrapolation

Calorimeter pointing alone sufficient for a good di-photon mass resolution

![Diagram](image.png)
The $\gamma\gamma$, $\gamma j$ and $jj$ contributions can be decomposed through the analysis of photon identification and isolation.

- Determine the shape of these variables for real and fake photons from control samples and MC simulation;
- Fit the observed distribution to the sum of three components

**2012 breakdowns**
- $\gamma\gamma$: 75%
- $\gamma j$: 22%
- $jj$: 3%

**Background models:**
- $\gamma\gamma$: RESBOS, DIPHOX, SHERPA
- $\gamma j$: SHERPA
- $jj$: PYTHIA6
Signal: Crystal-Ball function (core) + Gaussian (outlier)
Backgrounds: exponentials, polynomials, ...

Category-dependent, choose the ones with best sensitivities and assign systematics based on spurious signals from MC studies

Low statistics categories: Exponential
High statistics categories: Exponential of 2\textsuperscript{nd} order polynomials

<table>
<thead>
<tr>
<th>Category</th>
<th>Parametrization</th>
<th>Uncertainty [$N_{\text{evt}}$]</th>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>4th order pol.</td>
<td></td>
<td>7.3</td>
<td>10.6</td>
</tr>
<tr>
<td>Unconverted central, low $p_{T\ell}$</td>
<td>Exp. of 2nd order pol.</td>
<td></td>
<td>2.1</td>
<td>3.0</td>
</tr>
<tr>
<td>Unconverted central, high $p_{T\ell}$</td>
<td>Exponential</td>
<td></td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Unconverted rest, low $p_{T\ell}$</td>
<td>4th order pol.</td>
<td></td>
<td>2.2</td>
<td>3.3</td>
</tr>
<tr>
<td>Unconverted rest, high $p_{T\ell}$</td>
<td>Exponential</td>
<td></td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Converted central, low $p_{T\ell}$</td>
<td>Exp. of 2nd order pol.</td>
<td></td>
<td>1.6</td>
<td>2.3</td>
</tr>
<tr>
<td>Converted central, high $p_{T\ell}$</td>
<td>Exponential</td>
<td></td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
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<td>4th order pol.</td>
<td></td>
<td>4.6</td>
<td>6.8</td>
</tr>
<tr>
<td>Converted rest, high $p_{T\ell}$</td>
<td>Exponential</td>
<td></td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Converted transition</td>
<td>Exp. of 2nd order pol.</td>
<td></td>
<td>3.2</td>
<td>4.6</td>
</tr>
<tr>
<td>2-jets</td>
<td>Exponential</td>
<td></td>
<td>0.4</td>
<td>0.6</td>
</tr>
</tbody>
</table>

10-20% uncertainties on signal yields from background modeling
A total 59059 events selected, expect ~170 signal events at 126 GeV with a S/B ~ 3%

(The background is parameterized using 4th order Bernstein polynomial)
Exclusions: 112-122.5 GeV, 132-143 GeV (observed); 110-139.5 GeV (expected)

A minimum $p_0$ at 126.5 GeV

$p_0 = 2 \times 10^{-6} \Rightarrow 4.5\sigma$

(Expected: 2.4$\sigma$ from a SM Higgs boson)

(Global observed significance: 3.6$\sigma$ over 110-150 GeV)
Consistent excesses are observed in both 2011 and 2012 data.

The measured signal strength, the excess relative to the SM expectation, at 126.5 GeV:

$$\mu = \frac{\sigma \cdot Br}{(\sigma \cdot Br)_{SM}} = 1.9 \pm 0.5$$
The gold-plated channel over a wide range of potential Higgs mass.

Clean signature:
- 4 isolated leptons, full reconstruction;
- Mass peak over backgrounds, good mass resolution.

Small backgrounds:
- Irreducible SM ZZ* production and reducible Z+jets, top, ...

But even smaller signal rate:
@125 GeV

\[
\text{BR}(ZZ \to 4\ell) = 0.45\%, \quad \text{BR}(H \to ZZ^*) = 2.6\%
\]

\[
\Rightarrow \quad \sigma_H \times \text{BR}(H \to ZZ \to 4\ell) = 2.6 \text{ fb}
\]

Selection efficiency to the 4\textsuperscript{th} power of lepton efficiency:
0.7\textsuperscript{4} \sim 0.25, 0.8\textsuperscript{4} \sim 0.41 \Rightarrow \text{critical to improve lepton selection!}
H → ZZ* → 4l

Two same-flavor and opposite-sign isolated lepton pairs:

4 leptons with $p_T > 20, 15, 10, 7 \,(6 \, \text{for } \mu) \, \text{GeV};$

$50 < m_{12} < 106 \, \text{GeV and } m_{\min} (m_{4\ell}) < m_{34} < 115 \, \text{GeV}$

$m_{\min} (m_{4\ell}) = 17.5 - 50 \, \text{GeV}$

$m_{\ell\ell} > 5 \, \text{GeV for same-flavor and opposite-charge pair}$

(Leading lepton pair: the pair with its closest to $M_Z$)

Analysis improvements since 2011 publication

- Relax $m_{12}$ requirement;
- Increased electron efficiency at low $p_T$ through the recovery of hard Bremsstrahlung radiation

$\Rightarrow 20-30\% \text{ gain in sensitivity for a low mass Higgs boson.}$

Selection efficiency ($m_H = 130 \, \text{GeV}$): 41% (4$\mu$), 27% (2e/2$\mu$), 23% (4e)
Improving resolution by applying a Z-mass constraint for the leading dilepton pair:

$4\mu: 2.13 \rightarrow 1.78 \text{ GeV}, \ 2e/2\mu: 2.33 \rightarrow 2.02 \text{ GeV}, \ 4e: 2.76 \rightarrow 2.46 \text{ GeV}

10-20% improvement
SM ZZ* background:
irreducible and estimated through MC simulation

Z+jets and top backgrounds:
reducible and estimated from data

Control sample for $\ell\ell + \mu\mu$
For sub-leading dimuon pair:
- Remove isolation requirement
- At least one $\mu$ failing IP cut

The $m_{12}$ distribution clearly shows a Z peak (Z+jets) over a continuum (top)
- Fit the $m_{12}$ distributions to Z+jets and top components;
- Extrapolate to the signal region

Both background shape and extrapolation from MC
### $H \rightarrow ZZ^* \rightarrow 4l$

<table>
<thead>
<tr>
<th></th>
<th>$4\mu$</th>
<th>$2e2\mu/2\mu2e$</th>
<th>$4e$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low mass</td>
<td>High mass</td>
<td>Low mass</td>
</tr>
<tr>
<td><strong>Int. Luminosity</strong></td>
<td>5.8 fb$^{-1}$</td>
<td>5.8 fb$^{-1}$</td>
<td>5.9 fb$^{-1}$</td>
</tr>
<tr>
<td>$ZZ^{(*)}$</td>
<td>6.3±0.3</td>
<td>27.5±1.9</td>
<td>3.7±0.2</td>
</tr>
<tr>
<td>$Z +$ jets, and $t\bar{t}$</td>
<td>0.4±0.2</td>
<td>0.15±0.07</td>
<td>3.9±0.9</td>
</tr>
<tr>
<td><strong>Total Background</strong></td>
<td>6.7±0.3</td>
<td>27.6±1.9</td>
<td>7.6±1.0</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>4</td>
<td>34</td>
<td>11</td>
</tr>
<tr>
<td>$m_H = 125$ GeV</td>
<td>1.4±0.2</td>
<td>1.7±0.2</td>
<td>0.8±0.1</td>
</tr>
<tr>
<td>$m_H = 150$ GeV</td>
<td>4.5±0.6</td>
<td>5.9±0.8</td>
<td>2.7±0.4</td>
</tr>
<tr>
<td>$m_H = 190$ GeV</td>
<td>8.2±1.0</td>
<td>12.5±1.7</td>
<td>5.3±0.8</td>
</tr>
<tr>
<td>$m_H = 400$ GeV</td>
<td>3.9±0.5</td>
<td>6.6±0.9</td>
<td>2.9±0.4</td>
</tr>
</tbody>
</table>

**Int. Luminosity**

<table>
<thead>
<tr>
<th></th>
<th>4.8 fb$^{-1}$</th>
<th>4.8 fb$^{-1}$</th>
<th>4.9 fb$^{-1}$</th>
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<tbody>
<tr>
<td>$ZZ^{(*)}$</td>
<td>4.9±0.2</td>
<td>18.1±1.3</td>
<td>3.1±0.2</td>
</tr>
<tr>
<td>$Z +$ jets, and $t\bar{t}$</td>
<td>0.2±0.1</td>
<td>0.07±0.03</td>
<td>2.1±0.5</td>
</tr>
<tr>
<td><strong>Total Background</strong></td>
<td>5.1±0.2</td>
<td>18.2±1.3</td>
<td>5.1±0.5</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>8</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>$m_H = 125$ GeV</td>
<td>1.0±0.1</td>
<td>1.0±0.1</td>
<td>0.37±0.05</td>
</tr>
<tr>
<td>$m_H = 150$ GeV</td>
<td>3.0±0.4</td>
<td>3.4±0.5</td>
<td>1.4±0.2</td>
</tr>
<tr>
<td>$m_H = 190$ GeV</td>
<td>5.1±0.6</td>
<td>7.4±1.0</td>
<td>2.8±0.4</td>
</tr>
<tr>
<td>$m_H = 400$ GeV</td>
<td>2.3±0.3</td>
<td>3.8±0.5</td>
<td>1.6±0.2</td>
</tr>
</tbody>
</table>

**S ~3.9 events**

**S ~2.4 events**

Low mass: $m_{4l} < 160$ GeV, high mass: $m_{4l} > 160$ GeV
H→ZZ*→4l

See significantly more events than expected:
2011: 88 observed with 71±5 expected
2012: 142 observed with 109±7 expected

The excess is mostly for m_{4l}>160 GeV ⇒ significantly higher measured ZZ cross section

Measured \( \sigma (ZZ) = 9.3 \pm 1.2 \text{ pb} \)
SM (NLO) \( \sigma (ZZ) = 7.4 \pm 0.4 \text{ pb} \)
H→ZZ*→4l

A small cluster of events populates around 125 GeV

Single resonant contributions
Enhanced by relaxing mass and pT requirements
H → ZZ* → 4l

**Exclusion:** 131-162 GeV and 170-460 GeV (observed)
124-164 GeV and 176-500 GeV (expected)

*Global significance: 2.5σ over 110-141 GeV*

A minimum $p_0$ at 125 GeV

$$p_0 = 3 \times 10^{-4} \Rightarrow 3.4\sigma$$

(Expected: 2.6σ from a SM Higgs boson)
Excess is seen in both 2011 and 2012 at about the same mass.

Signal strength at the lowest $p_0$ (125 GeV): $\mu = 1.3 \pm 0.6$

<table>
<thead>
<tr>
<th>Samples</th>
<th>Mass (GeV)</th>
<th>p-value</th>
<th>Obs. Sig.</th>
<th>Exp. Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>125</td>
<td>1.10%</td>
<td>2.3$\sigma$</td>
<td>1.5$\sigma$</td>
</tr>
<tr>
<td>2012</td>
<td>125.5</td>
<td>0.40%</td>
<td>2.7$\sigma$</td>
<td>2.1$\sigma$</td>
</tr>
<tr>
<td>Combined</td>
<td>125</td>
<td>0.03%</td>
<td>3.4$\sigma$</td>
<td>2.6$\sigma$</td>
</tr>
</tbody>
</table>
H→ZZ*→4l

$m_{4\ell} = 125.1$ GeV

$p_T = 71.7, 47.5, 36.1, 26.4$ GeV

$m_{12} = 86.3$ GeV, $m_{34} = 31.6$ GeV
\[ H \rightarrow WW^* \rightarrow l\bar{\nu}lv \nu \] 

The SM WW is said to be “irreducible”

The spin correlation leads to a smaller average opening angle between the two leptons

\[ \sigma(H \rightarrow WW^* \rightarrow l\bar{\nu}lv\nu) \approx 220 \text{ fb} \] 

(8 TeV, \( m_H = 125 \text{ GeV} \))

\implies \approx 2300 \text{ events in 2011+2012 samples}

Main background:
- WW, \( t\bar{t} \), W/Z+jets, WZ/ZZ/Wγ,...
- Main background:
- \( \gamma, tt, W/Z+jets, WZ/ZZ/W\gamma,... \)
H$\rightarrow$WW$^*$$\rightarrow$e$\mu$$\nu\nu$

Due to large pileups in 2012, only $e\mu$ final state has been analyzed

6 categories: $(e\mu, \mu e) \otimes (0$-jet, 1-jet, 2-jet)

(Separate final states with leading electron or leading muon)

Preselection:

- $p_T^{\ell_1, \ell_2} > 25,15$ GeV with $|\eta| < 2.5$;
- $E_{T,\text{miss}} > 25$ GeV;
- Jets: $p_T > 25$ GeV and $|\eta| < 2.5$ otherwise $p_T > 30$ GeV
H → WW* → eμνν

Significant background remains after pre-selection, apply topological selections for further background reduction:

0-jet selections
- $p_T^{ℓℓ} > 30$ GeV;
- $m_{ℓℓ} < 50$ GeV;
- $Δφ_{ℓℓ} < 1.8$

⇒ Focus on low mass region.
No change in the selections from 2011.

Similar for 1-jet analysis, with additional b-jet veto
H$\rightarrow$WW$^*\rightarrow$e$\mu$\nu$\nu$

Non-WW dibosons (WZ/ZZ/W$\gamma$) and Z/DY:

Diboson: real leptons, real ETmiss; Z/DY: real lepton, fake or real ETmiss

Both normalization and $m_T$ shape from MC

W+jets

Fake leptons, real ETmiss: both normalization and $m_T$ shape from data

Non-WW dibosons and W+jets processes contribute to both same- and opposite-sign dilepton events $\Rightarrow$ validation with same-sign events
H→WW*→eμνν

Top and WW backgrounds: real leptons and real ETmiss
Normalization from data and m_T shape from MC

Estimating WW and top background from data:

\[ N_{S.R.}^{\text{est.}} = \left( \frac{N_{S.R.}}{N_{C.R.}} \right)_{MC} \times N_{C.R.}^{\text{Data}} = \alpha_{MC} \times N_{C.R.}^{\text{Data}} \]

scaling using data control regions (C.R.):

- **WW**: \( m_{\ell\ell} > 80 \) GeV and no topological selection;
- **Top**: reverse b-jet veto (1j, 2j)

**ATLAS Preliminary**

\( \sqrt{s} = 8 \) TeV, \( \int L dt = 5.8 \) fb\(^{-1}\)

- WW 0j C.R.
- top 1j C.R.
**H → WW^* → eμνν**

The transverse mass as the final discriminant

\[ m_T = \sqrt{(E_\ell^\ell + E_T^{miss})^2 - (p_T^\ell\ell + E_T^{miss})^2} \]

125 GeV: 0.75\(m_H\) < \(m_T\) < \(m_H\) (illustration only)

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>WW</th>
<th>WZ/ZZ/Wγ</th>
<th>t\bar{t}</th>
<th>tW/tb/tqbc</th>
<th>Z/γ* + jets</th>
<th>W + jets</th>
<th>Total Bkg.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H+ 0-jet</strong></td>
<td>20 ± 4</td>
<td>101 ± 13</td>
<td>12 ± 3</td>
<td>8 ± 2</td>
<td>3.4 ± 1.5</td>
<td>1.9 ± 1.3</td>
<td>15 ± 7</td>
<td>142 ± 16</td>
<td>185</td>
</tr>
<tr>
<td><strong>H+ 1-jet</strong></td>
<td>5 ± 2</td>
<td>12 ± 5</td>
<td>1.9 ± 1.1</td>
<td>6 ± 2</td>
<td>3.7 ± 1.6</td>
<td>0.1 ± 0.1</td>
<td>2 ± 1</td>
<td>26 ± 6</td>
<td>38</td>
</tr>
<tr>
<td><strong>H+ 2-jet</strong></td>
<td>0.34 ± 0.07</td>
<td>0.10 ± 0.14</td>
<td>0.10 ± 0.10</td>
<td>0.15 ± 0.10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.35 ± 0.18</td>
<td>0</td>
</tr>
</tbody>
</table>

**Significant excess over estimated background in both 0j and 1j channels!**
H$\rightarrow$WW$^*$\rightarrow$eµνν

After $\Delta\phi < 1.8$ cut

<table>
<thead>
<tr>
<th></th>
<th>0-jet $e\mu$</th>
<th>0-jet $\mu e$</th>
<th>1-jet $e\mu$</th>
<th>1-jet $\mu e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total bkg.</td>
<td>177 ± 4</td>
<td>162 ± 4</td>
<td>43 ± 2</td>
<td>40 ± 3</td>
</tr>
<tr>
<td>Signal</td>
<td>18.7 ± 0.3</td>
<td>14.9 ± 0.2</td>
<td>4.3 ± 0.1</td>
<td>4.2 ± 0.1</td>
</tr>
<tr>
<td>Observed</td>
<td>213</td>
<td>194</td>
<td>54</td>
<td>52</td>
</tr>
</tbody>
</table>

All four categories show excess

No strange feature about the excess ...
$H \rightarrow WW^* \rightarrow e\mu\nu\nu$

Fit the observed $m_T$ distributions to improve sensitivity:
5 bins for 0-jet, 3 bins for 1-jet and 1 bin for 2-jet

Broad excess due to the limited mass resolution

@120 GeV: $p_0 = 6 \times 10^{-4} \Rightarrow 3.2 \sigma$

@125 GeV: $p_0 = 8 \times 10^{-4} \Rightarrow 3.1 \sigma$

(cut-and-count: 3.0s at 125 GeV)

Signal strength

$\mu = 2.1^{+0.8}_{-0.7} \mbox{ @ 125 GeV}$
H → WW* → eμνν

Combining with the published 2011 results (http://arxiv.org/abs/1206.0756)

A minimum $p_0$ value at 125 GeV

$p_0 = 3 \times 10^{-3} \Rightarrow 2.8\sigma$

(Expected: $p_0 = 0.01$ and $2.3\sigma$)

Combined p-value

Data-background
$H \rightarrow WW^* \rightarrow e\mu\nu\nu$

With a combined signal strength consistent with the SM expectation

$$\mu = \frac{\sigma \cdot Br}{(\sigma \cdot Br)_{SM}} = 1.4 \pm 0.5$$

Confirmed through signal injection:

The observation is within one-sigma band of the expected signal

2011: $\mu = 0.5 \pm 0.7$

2012: $\mu = 2.1^{+0.8}_{-0.7}$

Compatible within 1.5 $\sigma$
$H \to WW^* \to e\mu\nu\nu$

$m_T(e\mu E_T^{\text{miss}}) = 94 \text{ GeV}$
Combination inputs

- $2011 + 2012 \, H \rightarrow \gamma \gamma$
- $2011 + 2012 \, H \rightarrow ZZ^* \rightarrow 4\ell$
- $2011$ results for the rest
  (2012 results not yet available)

- $2011 \, H \rightarrow WW^* \rightarrow \ell\ell\nu\nu$
  2012 results approved this week,
  approval of its combination in process
Combination

Individual Channel Limits

**ATLAS** Preliminary 2011 + 2012 Data

$\int L \, dt \sim 4.6-4.8 \, fb^{-1}$, $\sqrt{s} = 7 \, TeV$  
$\int L \, dt \sim 5.8-5.9 \, fb^{-1}$, $\sqrt{s} = 8 \, TeV$

- **Exp. Comb.**
- **Obs. Comb.**
- **Exp. H $\rightarrow$ ZZ$^*$ $\rightarrow$ IIII**
- **Obs. H $\rightarrow$ ZZ$^*$ $\rightarrow$ IIII**
- **Exp. H $\rightarrow$ ZZ$^*$ $\rightarrow$ llvv**
- **Obs. H $\rightarrow$ ZZ$^*$ $\rightarrow$ llvv**
- **Exp. H $\rightarrow$ WW$^*$ $\rightarrow$ llqq**
- **Obs. H $\rightarrow$ WW$^*$ $\rightarrow$ llqq**
- **Exp. H $\rightarrow$ bb**
- **Obs. H $\rightarrow$ bb**
- **Exp. H $\rightarrow$ ZZ$^*$ $\rightarrow$ llqq**
- **Obs. H $\rightarrow$ ZZ$^*$ $\rightarrow$ llqq**
- **Obs. H $\rightarrow$ tt**
Combined Limits

Expected exclusion at 95% CL: 110-582 GeV
Observed exclusion: 110-122.6 GeV and 129.7-558 GeV

A SM Higgs boson is excluded:

110-122.6 GeV and 129.7-558 GeV @ 95% CL
111.7-121.8 GeV and 130.7-523 GeV @ 99% CL
Combination

Individual Channel p-Values

**ATLAS** Preliminary 2011 + 2012 Data

\[ \int L \, dt \sim 4.6-4.8 \, fb^{-1}, \sqrt{s} = 7 \, TeV \quad \int L \, dt \sim 5.8-5.9 \, fb^{-1}, \sqrt{s} = 8 \, TeV \]

- Exp. Comb.
- Obs. Comb.
- Exp. H → ZZ* → IIII
- Obs. H → ZZ* → IIII
- Exp. H → WW* → IVVV
- Obs. H → WW* → IVVV
- Exp. H → γγ
- Obs. H → γγ
- Exp. H → bb
- Obs. H → bb
- Exp. H → ZZ* → IIqq
- Obs. H → ZZ* → IIqq
- Exp. H → ττ
- Obs. H → ττ
Combination

Combined p-Values

The combined results are consistent with background-only hypothesis over the entire search range except the mass region around 125 GeV.

The significance of the excess at ~126 GeV is $5.1\sigma$

(including energy scale systematics in $\gamma\gamma$ reduces it to $5.0\sigma$)
Combination

Excess breakdowns

The excess is seen in both 2011 and 2012 data:
- 2011: 3.5σ (obs.) and 3.1σ (exp.)
- 2012: 4.0σ (obs.) and 3.3σ (exp.)

But is dominated by high-resolution channels: γγ and 4l.
(2012 H→WW∗→eμνν not included)
**Combination**

**Signal strength: rate relative to the SM expectation**

The value at the lowest $p_0$

$\mu = 1.2 \pm 0.3$

Consistent with the expectation of a SM Higgs boson

<table>
<thead>
<tr>
<th>-2$\ln \lambda(\mu)$&lt;1 Intervals</th>
<th>2011 + 2012 Data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS Preliminary</strong></td>
<td></td>
</tr>
<tr>
<td>$W, Z, H \rightarrow bb$</td>
<td></td>
</tr>
<tr>
<td>$\gamma = 7 \text{ TeV}; \int dt = 4.6 - 4.7 \text{ fb}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td></td>
</tr>
<tr>
<td>$\gamma = 7 \text{ TeV}; \int dt = 4.7 \text{ fb}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW^{(*)} \rightarrow \ell\ell\nu\nu$</td>
<td></td>
</tr>
<tr>
<td>$\gamma = 8 \text{ TeV}; \int dt = 5.9 \text{ fb}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td></td>
</tr>
<tr>
<td>$\gamma = 7 \text{ TeV}; \int dt = 4.8 \text{ fb}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow ZZ^{(*)} \rightarrow \ell\ell\ell\ell$</td>
<td></td>
</tr>
<tr>
<td>$\gamma = 8 \text{ TeV}; \int dt = 5.9 \text{ fb}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$\gamma = 7 \text{ TeV}; \int dt = 4.8 \text{ fb}^{-1}$</td>
<td></td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td></td>
</tr>
<tr>
<td>$\gamma = 8 \text{ TeV}; \int dt = 5.8 - 5.9 \text{ fb}^{-1}$</td>
<td>$\mu = 1.2 \pm 0.3$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>m$_{H}$ [GeV]</th>
<th>2011 + 2012 Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>ATLAS Preliminary</strong></td>
</tr>
<tr>
<td></td>
<td>-2$\ln \lambda(\mu)$ &lt; 1</td>
</tr>
<tr>
<td>m$_{H}$ [GeV]</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>Best fit</td>
</tr>
<tr>
<td>200</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
</tr>
<tr>
<td>600</td>
<td></td>
</tr>
</tbody>
</table>
Combination

Consistency among individual channels

**ATLAS Preliminary** $H \rightarrow WW^{(*)} \rightarrow ll\nu\nu$

$\sqrt{s} = 7$ TeV: $\int L dt = 4.7$ fb$^{-1}$

$\sqrt{s} = 8$ TeV: $\int L dt = 5.8$ fb$^{-1}$

- $-2\ln \lambda(\mu,m_H) = 2.3$
- $-2\ln \lambda(\mu,m_H) = 6.0$

- $H \rightarrow WW^{(*)} \rightarrow ll\nu\nu$ (2011+2012)
- $H \rightarrow \gamma\gamma$ (2011+2012)
- $H \rightarrow ZZ^{(*)} \rightarrow llll$ (2011+2012)
Combination

Time evolution

![Graph showing time evolution of local $p_0$ for different data sets.](image)
Summary

We have observed a narrow resonance at ~126 GeV, consistent with the Standard Model Higgs boson!

July 31: publication with $H \rightarrow \gamma \gamma$, $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow WW^* \rightarrow lvlv$

Fall: results of $H \rightarrow bb$ and $H \rightarrow \tau \tau$
Observation of an excess of events in the search for the Standard Model Higgs boson in the gamma-gamma channel with the ATLAS detector

Observation of an excess of events in the search for the Standard Model Higgs boson in the $H \to ZZ^* \to 4l$ channel with the ATLAS detector

Observation of an Excess of Events in the Search for the Standard Model Higgs boson with the ATLAS detector at the LHC

Observation of an Excess of Events in the Search for the Standard Model Higgs Boson in the $H \to WW(*) \to \ell^+\ell^-\nu\bar{\nu}$ Channel with the ATLAS Detector
Higgs Boson Width

Strong mass dependence

\[ \Gamma_H = 3.5 \text{ MeV} @ 120 \text{ GeV}, \]
\[ 1.43 \text{ GeV} @ 200 \text{ GeV}, \]
\[ 8.43 \text{ GeV} @ 300 \text{ GeV}, \]
\[ 68.0 \text{ GeV} @ 500 \text{ GeV} \]

At low mass (<300 GeV),
detector resolution dominates
mass resolution.

At higher mass, intrinsic width
goes dominant.

\[ \Gamma_H \approx \frac{3G_F M_H^3}{16\pi \sqrt{2}} \]
\[ \approx 500 \text{ GeV} \cdot \left( \frac{M_H}{1 \text{ TeV}} \right)^3 \]
Construct likelihood from Poisson probabilities:

\[ L(\text{data} | \mu, \theta) = \text{Poisson}(\text{data} | \mu \cdot s(\theta) + b(\theta)) \times p(\tilde{\theta} | \theta) \]

\[ \mu : \text{signal strength; } \theta: \text{'nuisance' parameters (efficiencies...)} \]

Compare data with background-only and signal+background models using test statistics

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

Calculate the ratio of these two p-values

\[ CL_s(\mu) = \frac{CL_{s+b}}{CL_b} = \frac{P(q_\mu > q^{\text{obs}}_\mu | s + b)}{P(q_\mu > q^{\text{obs}}_\mu | b)} \]

The signal model is excluded at 95% CL if

\[ CL_s(\mu = 1) < 5\% \]

For significance calculation, the background only p-value is computed from test statistics \( q_0 \):

\[ p_0 = P(q_0 > q^{\text{obs}}_0 | b) \Rightarrow Z = \Phi^{-1}(1 - p_0) \]
H → γγ

Photon reconstruction and γγ mass resolution are stable against pileup

Degrading primary vertex identification no effect on most of the categories, only needed for jet association of the 2jet analysis.
Numbers of expected signal and background events in a mass window around 126.5 GeV that contains 90% expected signal

2012 analysis

<table>
<thead>
<tr>
<th>Category</th>
<th>$\sigma_{CB}$ [GeV]</th>
<th>Observed $N_{evt}$</th>
<th>S $N_{evt}$</th>
<th>B $N_{evt}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>1.63</td>
<td>3693</td>
<td>100.4</td>
<td>3635</td>
</tr>
<tr>
<td>Unconverted central, low $p_T$</td>
<td>1.45</td>
<td>235</td>
<td>13.0</td>
<td>215</td>
</tr>
<tr>
<td>Unconverted central, high $p_T$</td>
<td>1.37</td>
<td>15</td>
<td>2.3</td>
<td>14</td>
</tr>
<tr>
<td>Unconverted rest, low $p_T$</td>
<td>1.57</td>
<td>1131</td>
<td>28.3</td>
<td>1133</td>
</tr>
<tr>
<td>Unconverted rest, high $p_T$</td>
<td>1.51</td>
<td>75</td>
<td>4.8</td>
<td>68</td>
</tr>
<tr>
<td>Converted central, low $p_T$</td>
<td>1.67</td>
<td>208</td>
<td>8.2</td>
<td>193</td>
</tr>
<tr>
<td>Converted central, high $p_T$</td>
<td>1.50</td>
<td>13</td>
<td>1.5</td>
<td>10</td>
</tr>
<tr>
<td>Converted rest, low $p_T$</td>
<td>1.93</td>
<td>1350</td>
<td>24.6</td>
<td>1346</td>
</tr>
<tr>
<td>Converted rest, high $p_T$</td>
<td>1.68</td>
<td>69</td>
<td>4.1</td>
<td>72</td>
</tr>
<tr>
<td>Converted transition</td>
<td>2.65</td>
<td>880</td>
<td>11.7</td>
<td>845</td>
</tr>
<tr>
<td>2-jets</td>
<td>1.57</td>
<td>18</td>
<td>2.6</td>
<td>12</td>
</tr>
</tbody>
</table>

16% 2nd best S/B

15% 3rd best S/B

22% Best S/B
$H \rightarrow \gamma\gamma$

**ATLAS Preliminary**

**Data 2011**

$\sqrt{s} = 7$ TeV, $\int L dt = 4.8$ fb$^{-1}$

$\text{SM } H \rightarrow \gamma\gamma$

(m$_H$ = 126.5 GeV)

**Signal strength**

---

**ATLAS Preliminary**

**Data 2012**

$\sqrt{s} = 8$ TeV, $\int L dt = 5.9$ fb$^{-1}$

$\text{SM } H \rightarrow \gamma\gamma$

(m$_H$ = 126.5 GeV)

**Signal strength**

---

**Local $p_0$**

$m_H$ [GeV]

---

**Local $p_0$**

$m_H$ [GeV]
$H \rightarrow \gamma\gamma$

Reanalysis of 2011 data

Data 2011, $\sqrt{s} = 7$ TeV, $\int L dt = 4.8$ fb$^{-1}$

ATLAS Preliminary

SM $H \rightarrow \gamma\gamma$

- Observed $p_0$
- Expected $p_0$
- Observed $p_0$ 2011 February paper
- Expected $p_0$ 2011 February paper

$m_H$ [GeV]

- $1\sigma$
- $2\sigma$
- $3\sigma$
- $4\sigma$
H → γγ

<table>
<thead>
<tr>
<th>Samples</th>
<th>Mass (GeV)</th>
<th>p-value</th>
<th>Observed sig.</th>
<th>Expected sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>126</td>
<td>3×10^{-4}</td>
<td>3.5σ</td>
<td>1.6σ</td>
</tr>
<tr>
<td>2012</td>
<td>127</td>
<td>3×10^{-4}</td>
<td>3.4σ</td>
<td>1.9σ</td>
</tr>
<tr>
<td>Combined</td>
<td>126.5</td>
<td>2×10^{-6}</td>
<td>4.5σ</td>
<td>2.4σ</td>
</tr>
</tbody>
</table>
$\text{H} \rightarrow \gamma\gamma$

2012 individual categories
2012 individual categories
**H \rightarrow ZZ^* \rightarrow 4l**

Same requirements as the nominal selection except no isolation requirement on the subleading lepton pair

⇒ Let in a lot more Z+jets and top backgrounds;
⇒ Data overshoot the expectation in ZZ dominated phase space
H→ZZ*→4l

Excess is seen in both 2011 and 2012 at about the same mass. It is the most significant excess over the entire search range.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Mass (GeV)</th>
<th>p-value</th>
<th>Observed sig.</th>
<th>Expected sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>125</td>
<td>1.10%</td>
<td>2.3σ</td>
<td>1.5σ</td>
</tr>
<tr>
<td>2012</td>
<td>125.5</td>
<td>0.40%</td>
<td>2.7σ</td>
<td>2.1σ</td>
</tr>
<tr>
<td>Combined</td>
<td>125</td>
<td>0.03%</td>
<td>3.4σ</td>
<td>2.6σ</td>
</tr>
</tbody>
</table>
\[ H \rightarrow ZZ^* \rightarrow 4l \]

Floating ZZ normalization reduces the significance slightly

4\(\mu\) contributes the most to the excess