Combined ATLAS Standard Model Higgs Search with 1 fb⁻¹ of Data at 7 TeV

Kyle Cranmer, New York University on behalf of the ATLAS Collaboration
Introduction

Understanding of electroweak symmetry breaking is a major goal of the LHC physics program

- Initial focus: search for the Standard Model Higgs
  - drove the design of both the ATLAS and CMS detectors
  - stresses every major sub-system

ATLAS and LHC are running great!

- Analyses here are based on up to 1.2 fb⁻¹
- High pile-up environment

\[
V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4
\]

Goldstone modes (become longitudinal polarizations of massive W,Z)

vacuum expectation fluctuations

New Heavy Gauge Bosons:
- \( \text{Lepton+ET}\)
- \( \text{Dileptons}\)
- \( \text{Compositeness: dimuons}\)
- \( \text{Extra Dimensions}\)
  - \( \text{Same-sign dimuons (ADD)}\)
  - \( \text{Dileptons (RS)}\)
  - \( \text{Diphotons (RS)}\)
  - \( \text{Diphotons+ET}\)
  - \( \text{Leptoquarks}\)

Highly Ionising Particles
Channels Included in the Combination

Enhance sensitivity by combining all available searches channels in the context of the SM Higgs hypothesis

- some channels are composed of sub-channels and include control samples

<table>
<thead>
<tr>
<th>Channel</th>
<th>btag (veto)</th>
<th>Jets</th>
<th>MET (GeV)</th>
<th>Shape</th>
<th>Mass Range (GeV/c²)</th>
<th>Main backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>γγ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>γγ (from sidebands)</td>
</tr>
<tr>
<td>WH</td>
<td>✓</td>
<td>2</td>
<td></td>
<td>M_{bb}</td>
<td>110-130</td>
<td>Top (3j - high M_{bb}) and W+jets (low M_{bb})</td>
</tr>
<tr>
<td>ZH</td>
<td>✓</td>
<td>2</td>
<td></td>
<td>M_{bb}</td>
<td>110-130</td>
<td>Z+jets (low M_{bb})</td>
</tr>
<tr>
<td>WW (lνlν)</td>
<td>0-jet</td>
<td>0</td>
<td>&gt;30</td>
<td></td>
<td>110-240</td>
<td>WW (control region M_{ll})</td>
</tr>
<tr>
<td></td>
<td>1-jet</td>
<td>veto</td>
<td>1</td>
<td>&gt;30</td>
<td>110-240</td>
<td>Top (from reverse btag) and WW (M_{ll} CR)</td>
</tr>
<tr>
<td>WW (lνqq)</td>
<td>0-jet</td>
<td>0</td>
<td>&gt;30</td>
<td>M_{WW}</td>
<td>200-600</td>
<td>W+jets (sidebands)</td>
</tr>
<tr>
<td></td>
<td>1-jet</td>
<td>veto</td>
<td>1</td>
<td>&gt;30</td>
<td>200-600</td>
<td>W+jets (sidebands)</td>
</tr>
<tr>
<td>ZZ (lννν)</td>
<td>✓</td>
<td></td>
<td>&gt;30</td>
<td>M_{T}</td>
<td>200-600</td>
<td>VV(from MC) and top (MC and checks)</td>
</tr>
<tr>
<td>ZZ (lνqqq)</td>
<td>✓</td>
<td>2</td>
<td>&lt;50</td>
<td>M_{llqq}</td>
<td>200-600</td>
<td>Z+jets (from MC) and top (from MC)</td>
</tr>
<tr>
<td>ZZ (4l)</td>
<td>IP</td>
<td></td>
<td></td>
<td>M_{4l}</td>
<td>110-600</td>
<td>ZZ (from MC), Z+jets (MC) and top (CR)</td>
</tr>
</tbody>
</table>
Detailed presentations on the channels

Higgs search in the Higgs to bb channel
inside Higgs and New Physics

11:30 - 11:45
Room: Dauphine
Location: Alpes Congrès - Alpexpo
Presenter(s): GONCALO, Ricardo

The decay of the Standard Model-like Higgs boson into bb is the dominant decay process in the region of low Higgs boson masses. The Higgs search in this channel requires an associated heavy objec...

Search for Higgs to ZZ (llll,llnnu,llqq)
inside Higgs and New Physics

12:15 - 12:35
Room: Dauphine
Location: Alpes Congrès - Alpexpo
Presenter(s): NIKOLOPOULOS, Konstantinos

The search for the Standard Model-like Higgs boson via its decays into two Z bosons is presented, based on the ATLAS data collected in 2011. The results obtained in the fully leptonic 'golden' deca...

Higgs search in the Higgs to gammagamma channel
inside Higgs and New Physics

11:45 - 12:00
Room: Dauphine
Location: Alpes Congrès - Alpexpo
Presenter(s): KADO, Marumi

The search for the Standard Model-like Higgs boson decaying to two photons is one of the best ways to identify a low mass Higgs boson at LHC. The results of the search in this channel are presente...

Search for Higgs to WW (lnulnu,lnuqq)
inside Higgs and New Physics

14:30 - 14:45
Room: Dauphine
Location: Alpes Congrès - Alpexpo
Presenter(s): STRANDBERG, Jonas

The search for the Standard Model-like Higgs boson via its decays into two W bosons is presented, based on the ATLAS data collected in 2011. The search in the dilepton final state is more powerful...
Low mass channels

\( H \rightarrow \gamma \gamma \) (110-150)

![Graph showing the invariant mass distribution for the candidate events selected, with data and MC predictions at \( \sqrt{s} = 7 \text{ TeV} \).]

WH and ZH, \( H \rightarrow bb \) (110-130)

![Graphs showing the m_{W,W} and m_{Z,Z} distributions for data and MC predictions at \( \sqrt{s} = 7 \text{ TeV} \).]

Kyle Cranmer (NYU)
The $H \rightarrow WW \rightarrow l\nu l\nu$ Channels

\[ m_T = \sqrt{(E_T^{\ell\ell} + E_{miss}^T)^2 - (P_T^{\ell\ell} + P_{miss}^T)^2}, \]

**ATLAS Preliminary**

- **Observed**
- **Expected**

\[ \int Ldt = 1.04 \text{ fb}^{-1} \]

$\sqrt{s} = 7$ TeV

**Broad excess >2\sigma**

126 <$m_H<$ 158 GeV/$c^2$
The High Mass Channels

\[ H \rightarrow WW \rightarrow l\nu qq \quad \text{H} \rightarrow ZZ \rightarrow llqq \quad \text{H} \rightarrow ZZ \rightarrow llvv \]

\[ \text{Data 2011, } \sqrt{s} = 7 \text{ TeV}, \int Ldt = 1.1 \text{ fb}^{-1} \]

\[ \text{Data 2011, } \sqrt{s} = 7 \text{ TeV}, \int Ldt = 1.04 \text{ fb}^{-1} \]

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\[ H \rightarrow ZZ^{(*)} \rightarrow llqq \]

\[ H \rightarrow ZZ^{(*)} \rightarrow llvv \]

\[ 95\% \text{ C.L. limit on } \alpha'_{SM} \]

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\[ M_{H} [\text{GeV}] \]

\[ m_{jj} [\text{GeV}] \]

\[ m_{ll} [\text{GeV}] \]

\[ m_{ll} [\text{GeV}] \]

\[ m_{ll} [\text{GeV}] \]

\[ m_{ll} [\text{GeV}] \]

H→ZZ channels able to exclude high-mass SM Higgs
The $H \rightarrow ZZ \rightarrow 4l$ Channel ($110 < M_H < 600$)

**Observed CL**

\[
\text{Observed CL} = 0.32
\]

\[
\text{Observed CL} = 0.64
\]

\[
\text{Expected CL} = 0.05
\]

\[
\text{Expected CL} = 0.10
\]

Data 2011, $\sqrt{s} = 7$ TeV, $\int L dt = 1.1$ fb$^{-1}$

ATLAS Preliminary

- Data
- $m_H = 210$ GeV, 1xSM
- Total background

95% C.L. limit on $\alpha/\alpha_{SM}$

- $\pm 1 \sigma$
- $\pm 2 \sigma$

m$_{4l}$ [GeV]

m$_H$ [GeV]

Kyle Cranmer (NYU)  
EPS-HEP 2011 - ATLAS Higgs Combination
Summary of individual channels’ limits

The situation prior to the combination

› Two individual channels are able to exclude by themselves
Systematics

The channels utilize three main strategies for addressing systematic uncertainties:

- **data-driven techniques**: eliminates dominant impact of uncertainty leaving uncertainties associated with extrapolation from control to signal region

- **implicit parametrization**: parametrized functions flexible enough to describe effect of uncertainty on distribution (eg. exponential + Crystal ball in H→γγ)

- **explicit parametrization**: variational histograms obtained from modifying simulated samples according to variations the source of uncertainty (eg. H→ZZ)

Uncertainties in normalization described by log-normal distributions

The combination requires relations between rates of different channels, thus it is subject to theoretical uncertainties. Prescription agreed upon by LHC-HCG & Higgs cross-section working group.

<table>
<thead>
<tr>
<th></th>
<th>H → γγ</th>
<th>H → b̅b̅</th>
<th>H → WW(+)</th>
<th>H → ZZ(+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>±3.7</td>
<td>±3.7</td>
<td>±3.7</td>
<td>±3.7</td>
</tr>
<tr>
<td>e/γ efficiency</td>
<td>±11.6</td>
<td>±2.3</td>
<td>±1.4</td>
<td>±0.9</td>
</tr>
<tr>
<td>e/γ energy scale</td>
<td>±10.4</td>
<td>±1.5</td>
<td>±0.1</td>
<td>±0.8</td>
</tr>
<tr>
<td>e/γ resolution</td>
<td>-1.6</td>
<td>-1.4</td>
<td>-1.0</td>
<td>-1.1</td>
</tr>
<tr>
<td>μ efficiency</td>
<td>-2.0</td>
<td>±0.6</td>
<td>±0.3</td>
<td>±0.8</td>
</tr>
<tr>
<td>μ resolution</td>
<td>±5.8</td>
<td>±2.4</td>
<td>±1.2</td>
<td>±0.6</td>
</tr>
<tr>
<td>Jet/MET energy scale</td>
<td>-2.1</td>
<td>-1.7</td>
<td>-0.9</td>
<td>-0.7</td>
</tr>
<tr>
<td>Jet resolution</td>
<td>±2.5</td>
<td>±1.5</td>
<td>±1.8</td>
<td>±2.1</td>
</tr>
<tr>
<td>MET</td>
<td>±5.5</td>
<td>±6.1</td>
<td>+3.3</td>
<td>+4.5</td>
</tr>
<tr>
<td>b-tag efficiency</td>
<td>±3.7</td>
<td>±0.6</td>
<td>±6.6</td>
<td>-</td>
</tr>
<tr>
<td>Theory</td>
<td>±15.0</td>
<td>±15.0</td>
<td>±15.0</td>
<td>±15.0</td>
</tr>
</tbody>
</table>

![Graph of Higgs production cross section](image)
Statistical Procedure

The full complexity of individual channels’ likelihood functions are packaged using RooFit/RooStats workspaces, and a combined probability model is formed by identifying nuisance parameters \( \nu \) associated to common systematic effects.

- the common parameter of interest is a cross-section scale factor: \( \mu = \sigma / \sigma_{SM} \)

The profile likelihood ratio is used as a test statistic:

\[
\lambda(\mu) = \frac{L_{s+b}(\mu, \hat{\nu})}{L_{s+b}(\hat{\mu}, \hat{\nu})}
\]

- nuisance parameters are “profiled” based on the data
- one-sided variants of the test statistic are used for upper-limits and discovery

The distribution of the test statistic is obtained in two ways:

- Ensemble tests with toy Monte Carlo using a fully frequentist procedure
  - randomize auxiliary measurements instead of randomizing nuisance parameters

- Using asymptotic distribution of likelihood ratio
  - used for primary result

Primary result based CLs, conservatism introduced to protect against downward fluctuations

- results based on power-constrained CLs+b (“PCL”) in backup
- Additional comparisons with Bayesian procedure with a uniform prior on \( \mu \)

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\( \lambda(\mu) = L_{s+b}(\mu, \hat{\nu}) / L_{s+b}(\hat{\mu}, \hat{\nu}) \)

Cowan, Cranmer, Gross, Vitells
**Limits in the low mass range**

Impressive sensitivity to a Higgs boson in the mass range 135-200 GeV

Excess in $H \rightarrow WW \rightarrow l\nu l\nu$ leads to weaker-than-expected limits near $M_H = 130-160$ GeV

---

**ATLAS Preliminary**

- Observed CLs
- Expected

$\int L dt = 1.0-1.2 \text{ fb}^{-1}$

$\sqrt{s} = 7 \text{ TeV}$

$155 < m_H < 190 \text{ GeV}/c^2$ excluded at 95% CL

---

Kyle Cranmer (NYU)
**Limits in the low mass range**

Impressive sensitivity to a Higgs boson in the mass range 135-200 GeV

Excess in $H \rightarrow WW \rightarrow l\nu l\nu$ leads to weaker-than-expected limits near $M_H = 130-160$ GeV

Extends exclusion range significantly beyond Tevatron from ~175 to 190

Not yet competitive near LEP limit
Background-only $p$-values at low-mass

Broad WW excess is modulated by local fluctuations in $\gamma\gamma$ and 4l

- local significance, no look-elsewhere effect correction applied

Test statistic defined such that downward fluctuation gives $p_0=50\%$

Largest excess has approximately 2.8$\sigma$ significance

![Graph showing background-only $p$-values at low-mass with observed and expected data points, indicating a large excess at approximately 2.8$\sigma$ significance.](image)
Background-only $p$-values at low-mass

Broad WW excess is modulated by local fluctuations in $\gamma\gamma$ and 4$l$

- local significance, no look-elsewhere effect correction applied

Test statistic defined such that downward fluctuation gives $p_0=50%$

Largest excess has approximately 2.8\(\sigma\) significance

- $\gamma\gamma$ deficit
- $\gamma\gamma$ excess
- 4$l$ candidate
- Broad WW$\rightarrow$l\(\nu\)l\(\nu\) excess

$\int Ldt = 1.0-1.2$ fb$^{-1}$
$s = 7$ TeV
**Limits full mass range**

Additional High-mass channels extend the H→ZZ→llνν exclusion

Noticeable excess around 250 GeV from H→ ZZ→4l candidates

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**ATLAS Preliminary**

- **Observed CLs**
- **Expected**

\[ \int Ldt = 1.0-1.2 \text{ fb}^{-1} \]

\[ \sqrt{s} = 7 \text{ TeV} \]

155<M_H<190 and 295 <M_H< 450 GeV/c² excluded at @ 95% CL
Approximately 8% chance of background-only fluctuation this large anywhere in range

No combined excess beyond 3σ is observed

Asymptotic approximation in good agreement with ensemble tests

\[ H \rightarrow ZZ \rightarrow 4l \] candidates

\[ \int L dt = 1.0-1.2 \, \text{fb}^{-1} \]
\[ \sqrt{s} = 7 \, \text{TeV} \]
**Cross-checks**

The full limit procedure was performed with toys to confirm the asymptotic distributions of the profile likelihood ratio

- Toy Monte Carlo is significantly more computationally intensive and sensitive to fit failures etc. Asymptotic results are robust

In addition, a Bayesian procedure, which is known to reproduce the CLs limit in simple problems, also yielded consistent results.
Conclusions

Thanks to the excellent LHC operations, ATLAS has collected more than 1 fb\(^{-1}\) of 7 TeV data leading to substantial gains in sensitivity to the Standard Model Higgs

- In the low-mass range (120 – 140 GeV) an excess of events with a significance of approximately 2.8\(\sigma\) is observed.

ATLAS has extended the 95% CL excluded region around 2M\(_W\) to 155<M\(_H\)<190 GeV and excluded a new range from 295<M\(_H\)<450 GeV

We congratulate the LHC for terrific performance and look forward to more successful running in 2011!

We also look forward to the results from CMS and the upcoming ATLAS+CMS Higgs combination
Backup
**Results with PCL**

While CLs is well a established technique in our field, it is considered a non-standard procedure by statistician mixing notions of power and coverage

- it intentionally over-covers to protect against setting limits beyond the experiments sensitivity due to downward fluctuations

An alternative approach (PCL) is based on purely frequentist CLs+b together with a “power-constraint” at the experiments sensitivity achieves the same protection without mixing the notions of coverage and power

![Graph](image.png)

Figure 5: The combined upper limits on the Standard Model Higgs boson production cross section normalized to the Standard Model value as a function of $m_H$ using the PCL 50% method is shown in the entire mass range (upper figure) and in the low mass range (lower figure).