Prospects for Higgs Boson Searches with ATLAS

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on behalf of the ATLAS Collaboration

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Review of Current Status of Searches
ATLAS Online Luminosity $\sqrt{s} = 7$ TeV

- LHC Delivered
- ATLAS Recorded

Total Delivered: 5.61 fb$^{-1}$
Total Recorded: 5.25 fb$^{-1}$
ATLAS Online Luminosity \( \sqrt{s} = 7 \text{ TeV} \)

- LHC Stable Beams
- Peak Lumi: \( 3.65 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \)

Peak Luminosity per Fill \( [10^{33} \text{ cm}^{-2} \text{ s}^{-1}] \)

Day in 2011

28/02 02/04 05/05 08/06 11/07 14/08 16/09 20/10 22/11
Sensitivity Predictions from 2011

For now, focus just on the expectations for $\sqrt{s} = 7$ TeV (2011 running) and the fact that analyses typically had 4.6-4.9 fb$^{-1}$ available for the Higgs searches. Based on that, we expected to exclude at better than 95% a SM Higgs across most of the mass space, or achieve better than 3σ significance for most of the masses (>130 GeV) should there be a Standard Model (SM) Higgs signal.

Inputs to the study:
- $H \rightarrow \gamma\gamma, ZZ^{(*)}$ [4l, 2l2ν, and 2l2b channels], $WW^{(*)}, \tau\tau$, and $bb$ were used in combination across the mass range.
# Summary of Channels (March 2012)

<table>
<thead>
<tr>
<th>Higgs Decay</th>
<th>Subsequent Decay</th>
<th>Additional Sub-Channels</th>
<th>$m_H$ Range</th>
<th>L [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>–</td>
<td>9 sub-channels ($p_T, \eta \eta, \text{conversion}$)</td>
<td>110-150</td>
<td>4.9</td>
</tr>
<tr>
<td>$H \to ZZ$</td>
<td>$\ell\ell\ell'$</td>
<td>${4e, 2e2\mu, 2\mu2e, 4\mu}$</td>
<td>110-600</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>$\ell\ell\nu\bar{\nu}$</td>
<td>${ee, \mu\mu} \otimes {\text{low pile-up, high pile-up}}$</td>
<td>200-280-600</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>${b\text{-tagged, untagged}}$</td>
<td>200-300-600</td>
<td>4.7</td>
</tr>
<tr>
<td>$H \to WW$</td>
<td>$\ell\nu\ell\nu$</td>
<td>${ee, e\mu, \mu\mu} \otimes {0\text{-jet, 1-jet, VBF}}$</td>
<td>110-300-600</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>${e, \mu} \otimes {0\text{-jet, 1-jet}}$</td>
<td>300-600</td>
<td>4.7</td>
</tr>
<tr>
<td>$H \to \tau^+\tau^-$</td>
<td>$\ell\ell4\nu$</td>
<td>${e\mu} \otimes {0\text{-jet}} \oplus {1\text{-jet, VBF, VH}}$</td>
<td>110-150</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>${e, \mu} \otimes {0\text{-jet}} \otimes {E_T^{\text{miss}} \geq 20 \text{ GeV}}$</td>
<td>110-150</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$\ell\tau_{\text{had}}3\nu$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{\text{had}}\tau_{\text{had}}2\nu$</td>
<td>${1\text{-jet}}$</td>
<td>110-150</td>
<td>4.7</td>
</tr>
<tr>
<td>$VH \to b\bar{b}$</td>
<td>$Z \to \nu\bar{\nu}$</td>
<td>$E_T^{\text{miss}} \in {120 - 160, 160 - 200, \geq 200 \text{ GeV}}$</td>
<td>110-130</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>$W \to \ell\nu$</td>
<td>$p_T^W \in {&lt; 50, 50 - 100, 100 - 200, \geq 200 \text{ GeV}}$</td>
<td>110-130</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$Z \to \ell\ell$</td>
<td>$p_T^Z \in {&lt; 50, 50 - 100, 100 - 200, \geq 200 \text{ GeV}}$</td>
<td>110-130</td>
<td>4.7</td>
</tr>
</tbody>
</table>

For details about these specific channels, please see all the previous speakers' talks.
ATLAS Preliminary

2011 Data

\[ \int L dt = 4.6-4.9 \text{ fb}^{-1} \]

\( \sqrt{s} = 7 \text{ TeV} \)

95\% CL Limit on \( \sigma/\sigma_{\text{SM}} \)

- Obs.
- Exp.
- \( \pm 1 \sigma \)
- \( \pm 2 \sigma \)

CLs Limits

\( \sqrt{s} = 7 \text{ TeV} \)

ATLAS-CONF-2012-019
Improvements to LHC Energy and Luminosity
The increase in LHC proton-proton collision energy to 8 TeV brings expected 20-50% increases in Standard Model (SM) production cross-sections depending on the Higgs mass and the production process.
Integrated Luminosity in 2012

ATLAS Online Luminosity $\sqrt{s} = 8$ TeV

- LHC Delivered
- ATLAS Recorded

Total Delivered: 0.67 fb$^{-1}$
Total Recorded: 0.62 fb$^{-1}$
As of Thursday (4/19), the LHC has already demonstrated they can operate the LHC in Stable Beam conditions with the maximum compliment of bunches (1380) for 2012 running.
Average Interactions per Bunch Crossing

(Lines in the above plot added by speaker)
LHC is rapidly pushing up the instantaneous luminosity. In two weeks we have integrated 0.62 fb\(^{-1}\). I'll have more to say about targets later.
Standard Model Higgs Bosons: Prospects for 2012
Inputs to the plot:
- $H \rightarrow \gamma\gamma$, $ZZ^{(*)}$ [4l, 2l2$\nu$, and 2l2$\bar{b}$ channels], $WW^{(*)}$, $\tau\tau$ (ll, lh), and $bb$ were used in combination across the mass range.

Optimizations Also Considered:
- mass-dependent cuts on $p_T$ and angular constraints.
- these significance expectations do not assume such optimizations.

### Integrated luminosity needed to give 50% probability of obtaining a 95% CL exclusion, 3$\sigma$ evidence or 5$\sigma$ discovery:

<table>
<thead>
<tr>
<th>Type</th>
<th>E.C.M.</th>
<th>$m_H$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>115</td>
<td>120</td>
</tr>
<tr>
<td>95% CL</td>
<td>7 TeV</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>8 TeV</td>
<td>3.1</td>
</tr>
<tr>
<td>3$\sigma$</td>
<td>7 TeV</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>8 TeV</td>
<td>9.7</td>
</tr>
<tr>
<td>5$\sigma$</td>
<td>7 TeV</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>8 TeV</td>
<td>33</td>
</tr>
</tbody>
</table>
Assuming the SM Higgs actually does have a mass of ~125 GeV, then a 5σ discovery by either ATLAS or CMS alone will require about 12 fb\(^{-1}\) in the 8 TeV data; taking into account the 7 TeV data, achieving this sensitivity requires 7-8 fb\(^{-1}\).

Depending on the progress of the LHC instantaneous luminosity over the next few weeks, we'll have a clearer sense of the data sample anticipated before the June break (and the data sample capable of being analyzed for ICHEP). The hope, as targets are achieved, is to get to about 5-7 fb\(^{-1}\) by that time and 15-20 fb\(^{-1}\) by the end of the 2012 run.
Beyond-the-Standard Model Higgs Bosons
Beyond-the-SM Higgs Searches

- For the rest of the presentation
  - Focus on Beyond-the-SM Higgs searches where sensitivity projections are already available:
    - Search for $A/H/h \rightarrow \tau^+ \tau^- \ (\text{MSSM})$
    - Search for a charged Higgs boson, $H^\pm \ (\text{MSSM})$
  - Compare results to expectations
Expectations: $H/h/A \rightarrow \tau^+ \tau^-$

Inputs: $\sqrt{s} = 14$ TeV and only the 2l2v final state.

Discovery Potential of $h/A/H \rightarrow \tau^+\tau^- \rightarrow \ell^+\ell^-4\nu$

**ATLAS** $\sqrt{s}=14$ TeV, 30 fb$^{-1}$

$bb \ h/H/A \rightarrow \tau\tau \rightarrow 2 \ l + 4 \ \nu$

95% CL. Exclusion

$m_h^\text{max scenario}$
- Exp. Systematics only
- $+10\% \sigma(tt)$ Uncertainty
- Theoretical Uncertainty
More Expectations: $H/h/A \rightarrow \tau^+ \tau^-$

Inputs: $\sqrt{s} = 14$ TeV and only the $l\tau_{\text{had}}\nu\nu$ final state.
Results from 2011 data

Combined three di-tau final states: $e+\mu$, $l+\tau_{\text{had}}$, $\tau_{\text{had}}+\tau_{\text{had}}$

- More than projected from the 2009 study

2009 study considered a slightly more limited mass range of 110-450.

Expected sensitivity in actual analysis at 7 TeV was almost as sensitive across the entire mass range as the projections at 14 TeV and 30 fb$^{-1}$ done in 2009!

I've added orange stars to mark the location of points on the 14 TeV, 30 fb$^{-1}$ expectations
Expectations: $H^+ \to \tau^+ \nu$
(“low-mass region”) 

Inputs: $\sqrt{s} = 14$ TeV. Focused on production from top-pair decay (“low-mass Higgs”). “Scenario B” refers to the $m_{h\text{-max}}$ scenario of the MSSM.

Considered three final-state topologies:

- $tt \to (Wb)(Hb) \to$
  - $(bqq)(\tau^\text{had} \nu b)$
  - $(bqq)(l \nu \nu b)$
  - $(b l \nu)(\tau^\text{had} \nu b)$

A likelihood discriminant was constructed for each mass point, leading to a flattening of the sensitivity across the mass range from [90,130] GeV.
Results: individual channels

2009 studies suggested that tau+jets final state would yield the best single-channel sensitivity, but all channels are needed in order to understand any potential discoveries. Results suggest no evidence for a charged Higgs so far in the data for masses < 160 GeV, and pattern of sensitivity is confirmed (see next slide for combination).
Results from 2011 data

Combined all three channels:
- no optimization performed for masses near the W mass as compared to higher masses.

Expected sensitivity in actual analysis at 7 TeV, with 4.6 fb$^{-1}$, was almost as sensitive at the expectation for 1 fb$^{-1}$ at 14 TeV for Higgs masses above 120 GeV.

I've added stars ( ) to mark the location of boundaries on the upper and lower exclusions regions from the 14 TeV, 1 fb$^{-1}$ expectations
Results from data (but wait, there's more!)

There has also been an effort on a charged Higgs channel sensitive to low tan(β):

\[ H^+ \rightarrow c\bar{s} \]

This was last made public on a small ATLAS data sample (35pb⁻¹).
Heavy Charged Higgs: Expectations

For $m_{H^+} > m_t$, a dominant production mechanism is expected to be:

$$gg \rightarrow t[b]H^+$$

In 2008-2009, we considered the search for subsequent decays $t \rightarrow Wb \rightarrow qqb$ and either $H^+ \rightarrow \tau_{\text{had}} \nu$ or $H^+ \rightarrow (l \nu) \nu$, which look nearly identical to the low-mass tau+jets and lepton+jets channels.

The exclusion plot shown here only contains contributions from the tau+jets final state; the tau+lepton final state, by itself, was found to not contribute much exclusion power in this study.
Conclusions and Outlook for 2012
Outlook

- **2011 was an incredible year for the Higgs @ LHC**
  - Up to 4.9 fb$^{-1}$ was available for the Higgs searches
  - Multiple independent channels combined
    - SM Higgs excluded at 95% C.L. for masses between about 130-540 GeV
    - Interesting “hints” in the region 120-130 GeV
- **2012 will be another incredible year**
  - LHC already delivering collisions at 8 TeV – keep an eye on instantaneous luminosity
  - Aiming for ~5-7 fb$^{-1}$ for ICHEP and 15-20 fb$^{-1}$ by year’s end
  - Multiple improvements are expected to SM (and beyond) Higgs searches, extending both the sensitivity to existing mass ranges and expanding the mass ranges possible for searches.
  - If “hints” hold up, anticipate measurements with significances between 3-5σ and a very interesting combination of channels!
  - Continue to aggressively push the beyond-the-SM Higgs searches – already able to approach or meet sensitivity expectations predicted for $\sqrt{s} = 14$ TeV!
BACKUP SLIDES
Features of this channel

- sensitive to low Higgs masses

- uses unconverted and converted photons to make Higgs candidates. ATLAS calorimeter pointing allows good angular separation and better Z decay vertex determination

- candidate selection using a leading (pT>40GeV) and sub-leading photon (pT>25GeV), isolated in the calorimeter and passing a tight identification algorithm.

- Largest backgrounds are from real γγ production from proton-proton interaction, followed by γ+jet (jet faking photon)
H → γ γ (continued)

**ATLAS Preliminary**

\[ \int Ldt = 4.9 \text{ fb}^{-1} \]

### Plot Details:
- **Data-driven estimations**
- **γγ expected**
- **γj expected**
- **jj expected**
- **DY expected**

### Axes:
- **Number of Events**
- **γγ**, **γj**, **jj**, **DY**
Fermiophobic Higgs

There are extensions to the SM in which the coupling of the Higgs to fermions can be substantially suppressed.

A benchmark model can be assumed where the coupling is exactly zero. VBF and associated production then become the dominant production modes; decays to gauge bosons become the dominant final states.

For low masses the product $\sigma \times \text{BR}(H \to \gamma \gamma)$ is larger than expected in the SM, but decreases rapidly at higher masses. It can be 4x the SM rate for $m_H = 110$ GeV. In addition, the Higgs has a higher transverse momentum at production, which can be exploited.
**Features of this channel**

- sensitive to low Higgs masses – this is the dominant decay mode of the SM Higgs for low masses

- One of the critical channels in studying Higgs coupling – this channel helps prepare the ground for understanding SM vs. BSM Higgs models.

- large multi-jet background makes the final state an experimentally challenging one.

- current measurement uses associated Higgs production, (W/Z)+H, with final states $l\nu bb$, $l\ell bb$, and $\nu\nu bb$.
  - demonstrates that using this production mechanism is already fruitful

- current measurement already uses boosted Higgs and takes advantage of the favorable reduction of background at high pT.
Features of this channel

- sensitive to low Higgs masses
- Uses multiple final-states, including those with two leptons (e, μ), a single lepton and a tau hadronic jet, and two tau hadronic jets.
- Multiple production mechanisms are considered: gluon fusion, vector boson fusion, and associated production (where the associated boson decays to hadrons).
- This allows to different accompanying jet multiplicities and sub-categories defined by those multiplicities.
- Dominant backgrounds: Z → ll, top quark decays
H → WW(*) → l⁺ ν l⁻ ν

Features of this channel

• fairly wide range of good sensitivity for different Higgs masses

• experimentally challenging due to significant missing energy from neutrinos – need to use transverse mass instead of mass for reconstruction.

• Major backgrounds: WW, W+jets, top quarks, and Z+jets
$H \rightarrow WW^{(*)} \rightarrow l^+ \nu l^- \nu$

(continued)

### ATLAS Preliminary

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

**H → WW$^{(*)}$ → lνlν**

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>Signal</th>
<th>$WW$</th>
<th>$WZ/ZZ/W\gamma$</th>
<th>$t\bar{t}$</th>
<th>$tW/tb/tnq$</th>
<th>$Z/\gamma^* + $ jets</th>
<th>$W +$ jets</th>
<th>Total Bkg.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0+jet</td>
<td>125</td>
<td>25 ± 7</td>
<td>110 ± 12</td>
<td>12 ± 3</td>
<td>7 ± 2</td>
<td>5 ± 2</td>
<td>13 ± 8</td>
<td>27 ± 16</td>
<td>173 ± 22</td>
</tr>
<tr>
<td>0+jet</td>
<td>240</td>
<td>60 ± 17</td>
<td>432 ± 49</td>
<td>24 ± 3</td>
<td>68 ± 15</td>
<td>39 ± 9</td>
<td>8 ± 2</td>
<td>36 ± 24</td>
<td>607 ± 63</td>
</tr>
<tr>
<td>1+jet</td>
<td>125</td>
<td>6 ± 2</td>
<td>18 ± 3</td>
<td>6 ± 3</td>
<td>7 ± 2</td>
<td>4 ± 2</td>
<td>6 ± 1</td>
<td>5 ± 3</td>
<td>45 ± 7</td>
</tr>
<tr>
<td>1+jet</td>
<td>240</td>
<td>23 ± 9</td>
<td>99 ± 22</td>
<td>8 ± 1</td>
<td>73 ± 27</td>
<td>35 ± 19</td>
<td>6 ± 2</td>
<td>7 ± 7</td>
<td>229 ± 55</td>
</tr>
<tr>
<td>2+jet</td>
<td>125</td>
<td>0.4 ± 0.2</td>
<td>0.3 ± 0.2</td>
<td>negl.</td>
<td>0.2 ± 0.1</td>
<td>negl.</td>
<td>0.0 ± 0.1</td>
<td>negl.</td>
<td>0.5 ± 0.2</td>
</tr>
<tr>
<td>2+jet</td>
<td>240</td>
<td>2.5 ± 0.6</td>
<td>1.1 ± 0.7</td>
<td>0.1 ± 0.1</td>
<td>2.6 ± 1.3</td>
<td>0.3 ± 0.3</td>
<td>negl.</td>
<td>0.1 ± 0.1</td>
<td>4.2 ± 1.7</td>
</tr>
</tbody>
</table>

Stephen Sekula - SMU - ATLAS

Comparing Sensitivities: $H \rightarrow WW^{(*)} \rightarrow l\nu$ ($l\nu/qq$)
$H \rightarrow ZZ^{(*)} \rightarrow 4l$

**Features of this channel**

- currently most sensitive to SM Higgs above 130 GeV
- extremely low background - “the golden channel”
- high efficiency in the lepton final states
- challenging due to the low branching fraction for the 4l final state
- main background: $ZZ^{(*)}$
$H \rightarrow ZZ^{(*)} \rightarrow 4l$
H → ZZ\(^(*)\) → ll\(\nu\nu\)

Features of this channel
- wide range of good sensitivity at different Higgs masses
- cannot reconstruct Higgs mass; need to use transverse mass
- main backgrounds: ZZ, WZ, WW
H → ZZ(*) → llνν (continued)

ATLAS Preliminary

\[
\int L dt = 4.7 \text{fb}^{-1}, \sqrt{s} = 7 \text{TeV}
\]

95% CL limit on \( \sigma / \sigma_{\text{SM}} \)

\( m_H [\text{GeV}] \)
\[ \text{H} \rightarrow \text{ZZ} \rightarrow \ell\ell qq \]

**Features of this channel**

- currently, the best sensitivity is for high-mass Higgs bosons – the two Z bosons are on-mass-shell

- can fully reconstruct Higgs mass, with larger experimental resolution due to jet reconstruction

- main backgrounds: Z+jets and top

- can be looked at with and without b-jet tagging applied to the qq system

- the b-tagging takes advantage of the large Z branching fraction relative to the backgrounds.
$H \rightarrow ZZ \rightarrow llqq$

(continued)

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

95\% CL limit on $\sigma/\sigma_{SM}$
**A/H/h → τ⁺τ⁻**

**Expectations**
- two production mechanisms of interest from the MSSM: $gg \rightarrow A/H/h$ and $bb(H/A/h)$
- both are pursued
Expectations

- favored final state is a function of $\tan(\beta)$
- $\tan(\beta) > 1$ favors $H^+ \rightarrow \tau^+ \nu$
- current effort focuses on production from top events (tt)
**Expectations:**

- Expected to dominate for $\tan(\beta) < 1$

- Allows full reconstruction of the $H^+$ mass, albeit with wide resolution due to use of dijet system

- Current public ATLAS result uses only $35\text{pb}^{-1}$

- Dominant background: multijet events and $W$+jets
Expectations

- CP-odd Higgs in MSSM, could be very light in extensions of the MSSM (e.g. the NMSSM)

- Very clean and experimentally resolvable final state