New ATLAS Higgs Results

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(On behalf of the ATLAS Collaboration)
An Opening Thought

- This talk is being taped.
- What trouble could that possibly cause?
- Seriously, these results are new (first shown today), I haven’t had time to triple-check that these are the absolutely final plots and numbers.
  - I believe it’s right, but...
- If you’re going to get a plot or number, please take it from the ATLAS note (on the web) rather than from here.
Scope of this Talk

I am going to discuss the new ATLAS results in the $\gamma\gamma$ and $Z^*$ channel, especially significances, masses and spin-parity.

I refer you to Jianming’s talk on WW, bb and $\tau\tau$. 
Outline

- Introduction
- Results
  - Gamma-gamma channel
  - ZZ* Channel
  - Combination
- Interpretation
  - Consistency of Mass Results
  - Spin and Coupling
- Conclusions

I did my best to keep this talk short so there would be plenty of time for discussion.

I ask your indulgence not to place this talk on the web for a day or two.
Introduction: Understanding ATLAS Plots

The blue-and-white plots show the signal strength $\mu = \sigma/\sigma_{SM}$ as a function of mass.

This is the base plot from which the others are derived.
In the black and white plots, we test how compatible $\mu$ is with 0.

Appropriate for Discovery.

In the green and yellow plots, we test how compatible $\mu$ is with 1.

Appropriate for Exclusion.
Two-Photon Channel
Here we are plotting events. However, the fact that different events are “worth” more than others is hidden. The effect of dividing into 10 categories is not evident.

Here we are plotting weights – not events.
Outcome

\[ \mu = 1.8 \pm 0.5 \]

(at 126 GeV)

A significance in this channel of \(~4\frac{1}{2}\sigma\) (5.9\(\sigma\) in all channels)
What’s New?

- 4.8+13.0 fb\(^{-1}\) of data vs. 4.8+5.9 fb\(^{-1}\).
  - This is an update, not an independent dataset.

- We have gone from 10 to 12 categories
  - One added with a lepton (enhances ttH and VH)
  - One added with a low-mass dijet (also enhances VH)
  - Reminder: A SM Higgs hypothesis is built into the weights, combinations and thus the significance of these searches

- We have improved the isolation and vertex requirements
Updated Results

Reminder: Here we are plotting events. However, the fact that different events are “worth” more than others is hidden. The effect of dividing into 12 categories is not evident.

Reminder: Here we are plotting weights. However, it looks like we are plotting events.
Updated Results II

\[ \mu = 1.8 \pm 0.3^{+0.29}_{-0.21} \]

(Was 1.8 \pm 0.5)

A significance in this channel of 6.1\(\sigma\) (was \(\sim 4\frac{1}{2}\sigma\))
Higgs to ZZ(*) (4 leptons - e’s and μ’s)
**From The Discovery Paper**

- We’re obviously dealing with small statistics.
  - At 125 GeV, it’s 13 events over a predicted background of 5.

- The background is almost entirely ZZ and ZZ*.
  - Except under the peak at 125 GeV: more on that later.

- There are some interesting features in this plot.

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**ATLAS Preliminary**

- Data
- Background $ZZ^{(*)}$
- Background $Z + \text{jets, } t\bar{t}$
- Signal ($m_H = 125 \text{ GeV}$)
- Signal ($m_H = 190 \text{ GeV}$)
- Signal ($m_H = 360 \text{ GeV}$)
- Syst. Unc.

$H \rightarrow ZZ^{(*)} \rightarrow 4l$

$\sqrt{s} = 7 \text{ TeV}: \int Ldt = 4.8 \text{ fb}^{-1}$

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

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**Graph Details**

- **Axes:**
  - Y-axis: Events/10 GeV
  - X-axis: $m_{4\ell}$ [GeV]

- **Legend:**
  - Data
  - Background $ZZ^{(*)}$
  - Background $Z + \text{jets, } t\bar{t}$
  - Signal ($m_H = 125 \text{ GeV}$)
  - Signal ($m_H = 190 \text{ GeV}$)
  - Signal ($m_H = 360 \text{ GeV}$)
  - Syst. Unc.
Interesting Feature #1: Z → 4 leptons

- There are 6 events that are radiative + internal conversion (i.e. 4 lepton) Z decays.
  - Two each in the 4e, 2e2μ and 2μ2e categories.
  - ATLAS considers a “Z” to be between 50-106 GeV
- These events occur with about the same frequency as a SM Higgs.
Interesting Feature #2: Decay Modes

- The excess is not coming from a single channel.
  - Not much more to say with this level of statistics.

- The only channels with significant non ZZ* background are the ones where the off-shell Z* decays to electrons.
  - The higher probability for a jet to fake an isolated electron over an isolated muon comes into play.
  - The mass constraint for the on-shell pair removes most of this.
  - Much of the note concerns itself with the proper assessment of this background.
Outcome

A value for $\mu$ is not quoted, but from the graph one can see the $1\sigma$ range: $\sim 0.75$-2.25, peaking near 1.4-ish.

A significance in this channel of $3.4\sigma$ ($5.9\sigma$ in all channels)
What’s New?

- 4.8+13.0 fb$^{-1}$ of data vs. 4.8+5.9 fb$^{-1}$.
  - This is an update, not an independent dataset.

- Slightly better electron ID for 2012 data, especially at low $p_T$
  - More stringent pixel requirements (rejects against conversions)
  - Tighter ID in the transition region
  - Better bremsstrahlung recovery
Updated Results

In the signal region $125 \pm 5$ GeV

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>18 events</td>
</tr>
<tr>
<td>Expected from background only</td>
<td>8.3 ± 0.8</td>
</tr>
<tr>
<td>Expected from SM Higgs</td>
<td>9.9 ± 1.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>Data</th>
<th>Expected S/B</th>
<th>Irreducible/Total B</th>
</tr>
</thead>
<tbody>
<tr>
<td>4μ</td>
<td>8</td>
<td>1.7</td>
<td>85%</td>
</tr>
<tr>
<td>2e2μ</td>
<td>4</td>
<td>1.7</td>
<td>68%</td>
</tr>
<tr>
<td>2μ2e</td>
<td>2</td>
<td>0.9</td>
<td>37%</td>
</tr>
<tr>
<td>4e</td>
<td>4</td>
<td>0.1</td>
<td>35%</td>
</tr>
</tbody>
</table>

\[ \sqrt{s} = 7 \text{ TeV}: \int L dt = 4.6 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV}: \int L dt = 13.0 \text{ fb}^{-1} \]
Updated Results

\[ \mu = 1.3^{+0.6}_{-0.4} \]

(At 125 GeV)

A significance in this channel of 4.1 \( \sigma \)

Sorry, not quite ready
Updated Combined Results

\[ \mu = 1.35 \pm 0.19 \pm 0.15 \]

(Was 1.4 ± 0.3)

A combined significance of 7\(\sigma\) (was 5.9) – one in a trillion.
One expects 3 of 5 points to be within $1\sigma$ and all within $2\sigma$. That’s what we see.
Meet The New Mass(es)

- \( M(ZZ^*) \)
  - Discovery: “Around 125 GeV”
  - Update: \( 123.5 \pm 0.9 \pm 0.4/-0.2 \)
  - Difference: Downward shift

- \( M(\gamma\gamma) \)
  - Discovery: “Around 126.5 GeV”
  - Update: \( 126.6 \pm 0.4 \pm 0.4 \)
  - Difference: Small

- Combination:
  - Discovery: \( 126.0 \pm 0.4 \pm 0.4 \)
  - Update: \( 125.2 \pm 0.3 \pm 0.6 \)
  - Difference: -0.8 GeV (with comparable uncertainty)

The “change”, if there is one, comes from the \( ZZ^* \) channel, which is dominated by the 4\( \mu \) mode.

That channel has 8 observed events, with an expected 4 from signal and 4 from background.

My conclusion? Mass results are consistent within our sensitivity.
How Consistent are the Masses?

- These plots make no assumption about consistency of cross-sections.
- These plots (slightly) overestimate the significance of the discrepancy.
  - It is difficult to precisely quantify this – if we could, we would already have done this.
  - Assume systematics are distributed according to a Gaussian.
  - Use asymptotic formulas instead of Toy Monte Carlos to gauge the ZZ* uncertainty.
    - This is a 10-15% effect on that uncertainty (not the difference).
Mass and Cross-Section Consistency

One can stare at this plot for hours and think of all sorts of interesting questions.
Asking the Right Questions

- That plot lets one ask all sorts of questions: i.e. the statistical significances against various hypotheses, such as:
  - $ZZ^*$ and $\gamma\gamma$ have a common mass and $\mu = 1.0000000$ times the SM cross-section
  - $ZZ^*$ and $\gamma\gamma$ have a common mass and $\mu$ is within 7% of the SM cross-section
  - $ZZ^*$ and $\gamma\gamma$ have a common mass and common $\mu$ (which can be anything)
  - $ZZ^*$ and $\gamma\gamma$ have a common mass without any constraints on $\mu$.
  - Etc.

- The significances vary from $<1\%$ to $>10\%$. 
Spin-Parity ($\gamma\gamma$)

- It is difficult to distinguish an unpolarized* spin-2 particle from a spin-0 particle.
- The clever observation (by many folks) is that it is actually difficult to prepare such a state by collisions of spin-1 gluons and spin-$\frac{1}{2}$ quarks. This gives a polar angle dependence to the photon direction in the Higgs-like frame.
  - Flat in $\cos(\theta^*)$ for spin-0
  - $1+6\cos^2(\theta^*)+\cos^4(\theta^*)$ for $gg$ fusion to a graviton-like tensor

* I am misusing the word here. I don’t mean $\langle p_z \rangle = 0$; I mean an equally populated density matrix.

Exclude $2^+$ at 91%CL
Compatible with $0^{\pm}$. 

$\theta^*$ is defined in Collins-Soper frame
Spin-Parity (ZZ*)

Using the distributions of 5 production and decay angles combined in BDT or Matrix Element (MELA) discriminants

- $0^+$ vs $0^-$: Expected Exclusion of $0^-$ at the 96% CL
- Observed exclusion of $0^-$ at the 99% CL

Observation fully compatible with spin 0 (within 0.5 $\sigma$)
Spin-Parity ($ZZ^*$)

Using the distributions of 5 production and decay angles combined in BDT or Matrix Element (MELA) discriminants

- $0^+$ vs $2^+$: (Low) Expected Exclusion of $2^+$ at the 80% CL
- Observed exclusion of spin $2^+$ at the 85% CL

Observation fully compatible with spin $0^+$ (within 0.18 $\sigma$)
Conclusions

- The updated ATLAS results are qualitatively similar to the discovery results – we didn’t get a surprise.

- There is some tension in the mass measurements in the two precision channels
  - It’s driven by a few low mass $ZZ^* \rightarrow 4\mu$ events
  - There are 8 events here, over a background of 4
  - It was a good opportunity to give our systematics a closer look, but I wouldn’t call it a hint of new physics. Or even a hint, at this stage. Not with $8-4=4$ events.

- Spin/parity analyses are underway
  - We don’t have enough data for a definitive statement, but there is no evidence for anything but $0^+$. Not even hints.

Thanks to the organizers, KITP and Marumi Kado (who helped with this talk)!