ATLAS Higgs Sensitivity for $1 \text{ fb}^{-1}$ at the LHC at 7 TeV

Malachi Schram
McGill University

on behalf of the ATLAS Collaboration
Outline

• Status of the Standard Model Higgs Search
• Review of Higgs Production and Decay Rates at the LHC
• Current expected sensitivity limits for SM Higgs using the ATLAS detector
• Current expected sensitivity limits for Charged Higgs using the ATLAS detector
• Road to the Higgs using the ATLAS detector
• Outlook
Introduction
• The Tevatron low mass sensitivity approaching LEP exclusion limit.
• Intermediate Higgs mass 95% C.L. exclusion between 158 and 175 GeV
LHC Plan and Status

- Currently running at 7 TeV CM
- Possibly increasing to 8 TeV CM
- End of 2010 we anticipate ~100 pb\(^{-1}\)
- End of 2011 we anticipate ~1 fb\(^{-1}\)

ATLAS Sensitivity

- Current results are obtained by scaling 10 and 14 TeV detailed analyses to 7 TeV
- Similar exercise for 8 TeV including more low mass Higgs modes
Standard Model Higgs Production & Decay

- Largest production cross-section is $gg \rightarrow H$ by a factor of $\sim 10$
- Requires clean signatures such as: di-photon, multi-leptons

- Current feasibility studies include $H \rightarrow WW$, $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$
- Studies are on-going to improve the low mass region by including decays such as $H \rightarrow t\bar{t}$ and $H \rightarrow bb$
- Studies are on-going in the $H \rightarrow ZZ \rightarrow ll\nu\nu$ and $llbb$ channels to provide improved sensitivity in the high mass region ($m_h > 200\text{GeV}$)

A. Djouadi, J. Kalinowski and M. Spira
arXiv:hep-ph/ 9704448v1

Wednesday, August 25, 2010
Expected Sensitivity Limits for 1 fb$^{-1}$ at 7 TeV for Standard Model Higgs
**Standard Model H → WW**

- Di-lepton (ee, eμ, μμ)+missing transverse energy + jets
- Study jet bins of 0, 1, and 2 separately then combine
- Common Event Selection:
  1. Two oppositely charged leptons
  2. Invariant di-lepton mass cut
  3. Missing Transverse Energy
  4. Lepton angular correlation from W decay
  5. Transverse Higgs candidate mass cut
- Main background: WW, W+jets, top
- Expected exclusion mass range ~145-180 GeV with 1 fb$^{-1}$

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<table>
<thead>
<tr>
<th>$M_H$ (GeV)</th>
<th>120</th>
<th>130</th>
<th>140</th>
<th>150</th>
<th>160</th>
<th>170</th>
<th>180</th>
<th>190</th>
<th>200</th>
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<tbody>
<tr>
<td>SM WW</td>
<td>26.3</td>
<td>35.4</td>
<td>43.8</td>
<td>50.1</td>
<td>55.2</td>
<td>58.5</td>
<td>60.6</td>
<td>61.7</td>
<td>62.4</td>
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<tr>
<td>top</td>
<td>4.9</td>
<td>6.7</td>
<td>9.1</td>
<td>11.6</td>
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<td>16.3</td>
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<td>18.2</td>
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<tr>
<td>W+jets</td>
<td>5.6</td>
<td>5.6</td>
<td>5.6</td>
<td>5.6</td>
<td>5.6</td>
<td>5.6</td>
<td>5.6</td>
<td>5.6</td>
<td>5.6</td>
</tr>
<tr>
<td>Total background</td>
<td>36.8</td>
<td>47.7</td>
<td>58.5</td>
<td>67.3</td>
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<td>80.4</td>
<td>83.4</td>
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<td>Signal</td>
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<td>10.4</td>
<td>18.5</td>
<td>26.3</td>
<td>39.5</td>
<td>35.4</td>
<td>26.2</td>
<td>16.8</td>
<td>11.0</td>
</tr>
</tbody>
</table>

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**ATLAS Preliminary**

(Simulation)

**95\% CL Limit / SM**

- Conservative systematics
  - 100 pb$^{-1}$
  - 250 pb$^{-1}$
  - 500 pb$^{-1}$
  - 750 pb$^{-1}$
  - 1000 pb$^{-1}$

**Fraction of events / 10 GeV**

\[ M_T = \sqrt{(E_T^{\ell\ell} + E_T^{VV})^2 - (P_T^{\ell\ell} + E_T^{miss})^2} \]
The $\alpha$ parameter of the background process is the ratio of its contribution to the signal and control regions.

The $\beta$ parameter of the background process to correct for contamination in the control region from other backgrounds.

Optimistic scenario places a 10% uncertainty for top and $W+$jets background.

<table>
<thead>
<tr>
<th>Analysis channel</th>
<th>$\sigma_{\alpha_{WW}}$</th>
<th>$\sigma_{\alpha_{top}}$</th>
<th>$\sigma_{\alpha_{W+jets}}$</th>
<th>$\sigma_{\beta_{top}}$</th>
<th>$\sigma_{\beta_{W+jets}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H + 0j$</td>
<td>7.3%</td>
<td>108%</td>
<td>100%</td>
<td>74%</td>
<td>100%</td>
</tr>
<tr>
<td>$H + 1j$</td>
<td>17%</td>
<td>52%</td>
<td>91%</td>
<td>20%</td>
<td>78%</td>
</tr>
<tr>
<td>$H + 2j$</td>
<td>54%</td>
<td>43%</td>
<td>-</td>
<td>18%</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$M_H$ (GeV)</th>
<th>Conservative Exclusion</th>
<th>Optimistic Exclusion</th>
<th>Conservative Discovery</th>
<th>Optimistic Discovery</th>
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<tbody>
<tr>
<td></td>
<td>120</td>
<td>210</td>
<td>1100</td>
<td>230</td>
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<tr>
<td></td>
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<td>95</td>
<td>36</td>
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<td></td>
<td>140</td>
<td>1.6</td>
<td>18</td>
<td>8.1</td>
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<td></td>
<td>150</td>
<td>0.68</td>
<td>16</td>
<td>5.5</td>
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<tr>
<td></td>
<td>160</td>
<td>0.28</td>
<td>4.8</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>0.41</td>
<td>6.6</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>0.76</td>
<td>17</td>
<td>6.7</td>
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<td></td>
<td>190</td>
<td>2.7</td>
<td>68</td>
<td>31</td>
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<td></td>
<td>200</td>
<td>4.5</td>
<td>96</td>
<td>52</td>
</tr>
</tbody>
</table>

Table 9: Minimum integrated luminosities in fb$^{-1}$ required at $\sqrt{s} = 7$ TeV for a 95% CL exclusion and 5$\sigma$ discovery for the two systematic uncertainty assumptions in the $H \rightarrow WW$ channel.
Standard Model $H \rightarrow ZZ$

- Four-lepton ($4e, 2e2\mu, 4\mu$)
- Looking for at least one on-shell $Z$-candidate
- Requires excellent energy and momentum resolution for leptons
- Clear Higgs mass peak can be observed
- Key Event Selection:
  - i. Tracking isolation cut
  - ii. Transverse impact parameter significance
- $Z$-mass constraint improves Higgs mass resolution
- Main background: $ZZ, Z\bar{b}b, tt$

<table>
<thead>
<tr>
<th>$M_H$(GeV)</th>
<th>120</th>
<th>130</th>
<th>140</th>
<th>150</th>
<th>165</th>
<th>170</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM ZZ</td>
<td>0.090</td>
<td>0.094</td>
<td>0.083</td>
<td>0.089</td>
<td>0.121</td>
<td>0.147</td>
</tr>
<tr>
<td>Top &amp; $Z+$jets</td>
<td>0.005</td>
<td>0.004</td>
<td>0.005</td>
<td>0.004</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>Total background</td>
<td>0.095</td>
<td>0.098</td>
<td>0.088</td>
<td>0.093</td>
<td>0.126</td>
<td>0.152</td>
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<tr>
<td>Signal</td>
<td>0.105</td>
<td>0.319</td>
<td>0.595</td>
<td>0.713</td>
<td>0.185</td>
<td>0.192</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>$M_H$(GeV)</th>
<th>200</th>
<th>220</th>
<th>240</th>
<th>260</th>
<th>300</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM ZZ</td>
<td>1.29</td>
<td>1.18</td>
<td>0.92</td>
<td>0.89</td>
<td>0.72</td>
<td>0.48</td>
</tr>
<tr>
<td>Signal</td>
<td>1.60</td>
<td>1.46</td>
<td>1.25</td>
<td>1.08</td>
<td>0.88</td>
<td>0.67</td>
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</table>
Standard Model H→ZZ

• Maximal sensitivity is reached at ~200 GeV with ~2.5xSM
• Studies are on-going in the H→ZZ→llvv and llbb channels to provide improved sensitivity in the high mass region (m_h>200GeV)
Standard Model $H \rightarrow \gamma \gamma$

- Initial focus is on gluon-fusion production
- Di-photon resonance can be observed over smooth background
- Background is estimated from side-band fit
- Main background: $\gamma \gamma$, $\gamma$+jets, Di-Jet, Drell Yan

<table>
<thead>
<tr>
<th>$M_H$ (GeV)</th>
<th>110</th>
<th>115</th>
<th>120</th>
<th>130</th>
<th>140</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma \gamma$</td>
<td>5540</td>
<td>5540</td>
<td>5540</td>
<td>5540</td>
<td>5540</td>
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<tr>
<td>$\gamma j$</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
</tr>
<tr>
<td>$jj$</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td>Drell Yan</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Total background</td>
<td>8490</td>
<td>8490</td>
<td>8490</td>
<td>8490</td>
<td>8490</td>
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<tr>
<td>Signal</td>
<td>12.6</td>
<td>12.8</td>
<td>13.0</td>
<td>12.0</td>
<td>9.2</td>
</tr>
</tbody>
</table>

**Mass resolution ~1.1%**

- $H \rightarrow \gamma \gamma$ ($m_H = 120$ GeV)
- $\sqrt{s} = 7$ TeV
- 1 fb$^{-1}$

**ATLAS Preliminary**

1 fb$^{-1}$ $\sqrt{s} = 7$ TeV (Simulation)

- Signal
- $H \rightarrow \gamma \gamma$ ($m_H = 120$ GeV)
- All Backgrounds
Standard Model $H \rightarrow \gamma \gamma$

- Expected upper limit of $\sim 5\times$SM between 110-140 GeV
• Current feasibility studies include $H \rightarrow WW, H \rightarrow γγ, H \rightarrow ZZ$
• Dominant contribution is $H \rightarrow WW$
• Systematics include:
  i. Reconstruction: lepton, jet, missing transverse energy momentum and energy resolution, and PID efficiency
  ii. Theoretical uncertainty: PDF, renormalisation/factorization scale
  iii. Luminosity 10%
• ATLAS should be able to exclude at 95% C.L. the Higgs within 135-190 GeV with 1 fb$^{-1}$ of data
Expected Sensitivity Limits for 1 fb$^{-1}$ at 7 TeV Charged Higgs
MSSM $H^+ \rightarrow \tau \nu$ in Di-Lepton $t\bar{t}$bar

- Di-Lepton+MET+2jets
- Event Selection:
  i. Two oppositely charged leptons
  ii. Two jets with the highest likelihood of being b-jets are assumed to be daughters of the top and anti-top quarks
  iii. Missing Transverse Energy
  iv. Transverse mass of charge Higgs candidate
  v. Lepton helicity angle
- Main background is: $t\bar{t}$bar (~90%)
- Expected exclusion $\text{Br}(H^+ \rightarrow \tau \nu) > 10\%$ for mass range ~90-150 GeV with 1 fb$^{-1}$

### Expected Number of Events

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of events after no cut</th>
<th>Number of events after all cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal $m_{H^+} = 90$ GeV</td>
<td>$2.5 \times 10^3$</td>
<td>282</td>
</tr>
<tr>
<td>Signal $m_{H^+} = 110$ GeV</td>
<td>$2.5 \times 10^3$</td>
<td>330</td>
</tr>
<tr>
<td>Signal $m_{H^+} = 130$ GeV</td>
<td>$2.5 \times 10^3$</td>
<td>326</td>
</tr>
<tr>
<td>Signal $m_{H^+} = 150$ GeV</td>
<td>$2.5 \times 10^3$</td>
<td>284</td>
</tr>
<tr>
<td>SM $t\bar{t}$ not hadronic</td>
<td>$87.3 \times 10^3$</td>
<td>1194</td>
</tr>
<tr>
<td>Single top $Wt$-channel</td>
<td>$5.7 \times 10^3$</td>
<td>55</td>
</tr>
<tr>
<td>Single top $t$-channel</td>
<td>$20.4 \times 10^3$</td>
<td>43</td>
</tr>
<tr>
<td>Single top $s$-channel</td>
<td>$0.9 \times 10^3$</td>
<td>3</td>
</tr>
<tr>
<td>$Z \rightarrow ll +$ jets</td>
<td>$3.1 \times 10^6$</td>
<td>4</td>
</tr>
<tr>
<td>$W \rightarrow l\nu +$ jets</td>
<td>$3.2 \times 10^7$</td>
<td>42</td>
</tr>
<tr>
<td>$Wbb +$ jets</td>
<td>$8.7 \times 10^3$</td>
<td>12</td>
</tr>
<tr>
<td>$Zbb +$ jets</td>
<td>$2.8 \times 10^4$</td>
<td>11</td>
</tr>
</tbody>
</table>

$$\mathcal{B}(t \rightarrow bH^+) = 10\%$$
MSSM $H^+ \rightarrow cs$ in Semi-Leptonic $tt\bar{t}$

- **Lepton+MET+2jets+2bjets**
- **Event Selection:**
  i. One high $p_T$ lepton
  ii. Reconstruct $m_{H^+}$ with non-bjets
  iii. Missing Transverse Energy
  iv. Improve dijet mass using top mass constraint
- **Main background is $tt\bar{t}$ (95%)**
- **Expected exclusion $Br(H^+ \rightarrow cs)>5\text{-}15\%$ for mass range $\sim 90\text{-}150$ GeV with 1 fb$^{-1}$

### Expected Br($H^+ \rightarrow cs$)

<table>
<thead>
<tr>
<th>$H^+ \rightarrow c\bar{s}$,GeV</th>
<th>no cut</th>
<th>all cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$90$</td>
<td>$9.5 \times 10^3$</td>
<td>$148$</td>
</tr>
<tr>
<td>$110$</td>
<td>$9.5 \times 10^3$</td>
<td>$144$</td>
</tr>
<tr>
<td>$130$</td>
<td>$9.5 \times 10^3$</td>
<td>$98$</td>
</tr>
<tr>
<td>$150$</td>
<td>$9.5 \times 10^3$</td>
<td>$56$</td>
</tr>
<tr>
<td>SM $t\bar{t}$, not all hadronic</td>
<td>$87.4 \times 10^3$</td>
<td>$1370$</td>
</tr>
<tr>
<td>Single top, $Wt$-channel</td>
<td>$5.7 \times 10^3$</td>
<td>$18$</td>
</tr>
<tr>
<td>Single top, $t$-channel</td>
<td>$20.4 \times 10^3$</td>
<td>$33$</td>
</tr>
<tr>
<td>Single top, $s$-channel ($e\nu$)</td>
<td>$448$</td>
<td>$1$</td>
</tr>
<tr>
<td>Single top, $s$-channel ($\mu\nu$)</td>
<td>$448$</td>
<td>$1$</td>
</tr>
<tr>
<td>$Wb\bar{b}$+jets</td>
<td>$5.6 \times 10^3$</td>
<td>$9$</td>
</tr>
<tr>
<td>$W \rightarrow e\nu$+jets</td>
<td>$39.2 \times 10^3$</td>
<td>$2$</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$+jets</td>
<td>$38.7 \times 10^3$</td>
<td>$3$</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu$+jets</td>
<td>$39.0 \times 10^3$</td>
<td>$0$</td>
</tr>
</tbody>
</table>

\[ \mathcal{B}(t \rightarrow bH^+) = 10\% \]
Road To The Higgs
Standard Model Processes

• LHC physicists are actively measuring key Standard Model processes and validating/improving the analysis machinery.
• Several of the measurements are very important to the Higgs search, such as:
  i. $W(\rightarrow l\nu)/Z(\rightarrow ll) + \text{jets}$
  ii. $t\bar{t}$
  iii. $W(\rightarrow l\nu)/Z(\rightarrow ll) + b\bar{b} + \text{jets}$
• We are now starting to work on various data-driven background methods.

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**ATLAS Preliminary**

- Data 2010 ($\sqrt{s} = 7$ TeV)
- $Z \rightarrow ee$

\[ L\ dt = 914\ \text{nb}^{-1} \]

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**Events**

\[ L\ dt = 0.9\ \text{pb}^{-1} \]

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**Events**

\[ L\ dt = 0.9\ \text{pb}^{-1} \]

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**ATLAS Preliminary**

- Data ($\sqrt{s} = 7$ TeV)
- $Z \rightarrow \tau\tau$
- $W \rightarrow ev, \mu\nu$
- QCD

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**McGill**

Wednesday, August 25, 2010
Summary

• The current expectation ATLAS should be able to exclude at 95% C.L. the Higgs within 135-190 GeV with 1 fb\(^{-1}\) of data.
• \(H \rightarrow WW\) should be able to exclude mass points with \(~250\) pb\(^{-1}\).
• Work is ongoing to improve the low mass Higgs searches using \(H \rightarrow \tau\tau\) and \(H \rightarrow bb\) decay modes.
• Studies are on-going in the \(H \rightarrow ZZ \rightarrow llvv\) and \(llbb\) channels to provide improved sensitivity in the high mass region \((m_h > 200 GeV)\).

• Expected exclusion \(\text{Br}(H^+ \rightarrow \tau\nu)\sim 10\%\) for mass range \(~90-150\) GeV with 1 fb\(^{-1}\).
• Expected exclusion \(\text{Br}(H^+ \rightarrow cs)\sim 5-15\%\) for mass range \(~90-150\) GeV with 1 fb\(^{-1}\).

• Work is ongoing to test/validate various data-driven background methods.
Extra Slides
Estimating the $W+jets$ Background In $H\rightarrow WW$ Search

- Looking for $W+jets$ events where something is faking the second lepton and passes the $H\rightarrow WW\rightarrow l\nu l\nu$ cuts.
- The data driven background extraction methods developed for $H\rightarrow WW\rightarrow l\nu l\nu$ are currently being adapted for the low data statistics and used for the observation of $W+jets\rightarrow ll\nu$ events
- Define a control sample enriched with $W+jets$
- Require one of the leptons to be “fakeable”, that is, loosen the lepton criteria
- Estimate and remove QCD contamination
- Determine the fake rate, $f_\ell$, using dijet or photon+jets samples:

$$f_\ell \equiv \frac{N_{id \text{ object}}}{N_{fakeable \text{ object}}}$$

- Estimation in the signal region is calculated:

$$N_{ee-ch \ one \ id + one \ fake} = f_e \times N_{one \ id \ e + one \ fakeable \ e}$$

$$N_{\mu\mu-ch \ one \ id + one \ fake} = f_\mu \times N_{one \ id \ \mu + one \ fakeable \ \mu}$$

$$N_{e\mu-ch \ one \ id + one \ fake} = f_e \times N_{one \ id \ \mu + one \ fakeable \ e} + f_\mu \times N_{one \ id \ e + one \ fakeable \ \mu}$$
Standard Model \( H \rightarrow ZZ (2) \)

- Selection efficiency between 7 and 10 TeV CM energies is ~2%
- Z-mass constraints improves Higgs mass constraint
- For \( m_h < 220 \) GeV, the mass resolution of Higgs candidate affects the sensitivity of Higgs search.
- For \( m_h > 220 \) GeV, the mass resolution is less important
- Impact parameter is key to reduce the Zbb background
MSSM $H^+ \rightarrow \tau \nu$ in Di-lepton $t\bar{t}b\bar{b}$

**ATLAS** Preliminary
(Simulation)

$\sqrt{s} = 7$ TeV, $1$ fb$^{-1}$

$m(H^+) = 130$ GeV

$H^+ \rightarrow \tau \nu$

$\mathcal{B}(t \rightarrow bH^+) = 17\%$

- **Signal**
- **$t\bar{t}$**
- **Single-top**
- **$Z \rightarrow ll$**
- **$W \rightarrow l\nu$**

$\cos \theta^*_H \approx \frac{4p_b \cdot p_\ell}{m_t^2 - m_W^2} - 1$

**Wednesday, August 25, 2010**
MSSM $H^+ \rightarrow cs$ in Semi-Leptonic $t\bar{t}$bar
Di-Muon Invariant Mass Scan

\[ \int L \approx 0.9 \text{ pb}^{-1} \]

\[ \omega/\rho \phi \quad J/\psi \quad \psi' \quad Y \quad Z \]

**ATLAS** Preliminary

Data 2010, \( \sqrt{s} = 7 \text{ TeV} \)

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

**McGill**
Di-Photon Invariant Mass

ATLAS preliminary

\[ \sigma_{\text{data}} = 19 \text{ MeV} \]

- Data
- Fit to data
- Non diffractive minimum bias MC

Uncorrected \( m_{\gamma\gamma} \) (MeV)

Entries / (10 MeV)

Wednesday, August 25, 2010
Di-Photon Double Converted Photon

Data 2010 ($\sqrt{s}=7.0$ TeV)
Monte Carlo
Truth-matched signal

$ATLAS$ Preliminary

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• After 2011 expect 2.4σ throughout the full mass range
• After “Run 3” expect 3σ or greater for Higgs mass range 100-185 GeV