Combination of SM Higgs boson searches with the ATLAS detector at the LHC using up to 4.9 fb$^{-1}$ of pp collision data at $\sqrt{s} = 7$ TeV

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On behalf of the ATLAS collaboration

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Outline

• LHC Higgs Production and Decay modes

• Search Channels, their Mass Ranges and Uncertainties

• Combined results

• Compatibility with Signal Hypothesis

• Summary
Higgs Production/Decay at the LHC

- Dominant Higgs production@LHC are gluon-gluon fusion (ggF), vector boson fusion (VBF), and associated production (VH)

- High mass ($M_H > 135$ GeV), $H \to WW$ and $H \to ZZ$ decays dominate
- Low mass ($M_H < 135$ GeV), $H \to b\bar{b}$ and $H \to \tau^+\tau^-$ decays dominate
  - $H \to \gamma\gamma$ has tiny branching ratio but distinct signature
# Search Channels at ATLAS

<table>
<thead>
<tr>
<th>Higgs Decay</th>
<th>Subsequent Decay</th>
<th>$m_H$ Range</th>
<th>$L$ [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$\tau_{\text{lep}}\tau_{\text{lep}}4\nu$</td>
<td>110-150</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$\tau_{\text{lep}}\tau_{\text{had}}3\nu$</td>
<td>110-150</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$\tau_{\text{had}}\tau_{\text{had}}2\nu$</td>
<td>110-150</td>
<td>4.7</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>$\ell\ell\nu\bar{\nu}$</td>
<td>200-600</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$\ell\ell q\bar{q}$</td>
<td>200-600</td>
<td>4.7</td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>$\ell\nu\ell\nu$</td>
<td>110-600</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$\ell\nu q\bar{q}'$</td>
<td>300-600</td>
<td>4.7</td>
</tr>
<tr>
<td>$VH \rightarrow b\bar{b}$</td>
<td>$W \rightarrow \ell\nu$</td>
<td>110-130</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$Z \rightarrow \ell\ell$</td>
<td>110-130</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$Z \rightarrow \nu\bar{\nu}$</td>
<td>110-130</td>
<td>4.6</td>
</tr>
</tbody>
</table>
Higgs Mass Steps for Limits

- Steps driven by $m_H$ resolution ($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow llll$), Higgs half-width

![Graph showing Higgs boson mass steps and related resolutions](Graph.png)

- Smaller steps driven by observed excess

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Systematic Uncertainties

- Major uncertainties include

## Detector Uncertainties

<table>
<thead>
<tr>
<th>Object</th>
<th>Source</th>
<th>Uncertainty on signal yield</th>
<th>Channel(s) most affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>Luminosity</td>
<td>3.9%</td>
<td>All</td>
</tr>
<tr>
<td>Photons</td>
<td>Efficiency</td>
<td>11%</td>
<td>$H \rightarrow \gamma \gamma$</td>
</tr>
<tr>
<td>Electrons</td>
<td>Efficiency</td>
<td>$&lt; 3%$</td>
<td>$H \rightarrow ZZ \rightarrow 4\ell$</td>
</tr>
<tr>
<td></td>
<td>Energy scale</td>
<td>$&lt; 1%$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Energy resolution</td>
<td>$&lt; 0.5%$</td>
<td></td>
</tr>
<tr>
<td>Muons</td>
<td>Efficiency</td>
<td>$&lt; 1%$</td>
<td>$H \rightarrow ZZ \rightarrow 4\ell$</td>
</tr>
<tr>
<td></td>
<td>Momentum resolution</td>
<td>$&lt; 1%$</td>
<td></td>
</tr>
<tr>
<td>$\tau$-jets</td>
<td>Efficiency</td>
<td>Up to 8%</td>
<td>$H \rightarrow \tau \tau$</td>
</tr>
<tr>
<td>$b$-jets</td>
<td>Efficiency</td>
<td>Up to 15%</td>
<td>$H \rightarrow b\bar{b}, H \rightarrow ZZ \rightarrow \ell\ell qq$</td>
</tr>
<tr>
<td>Jets/MET</td>
<td>Energy scale/resolution</td>
<td>Up to 20%</td>
<td>$H \rightarrow \tau \tau, b\bar{b}, ZZ \rightarrow \ell\ell qq, WW \rightarrow \ell\nu qq$</td>
</tr>
</tbody>
</table>

## Theoretical Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>ggF</th>
<th>VBF</th>
<th>WH/ZH</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD scale</td>
<td>$^{+12%}_{-8%}$</td>
<td>$\pm 1%$</td>
<td>$\pm 1%$</td>
</tr>
<tr>
<td>PDF $+ \alpha_s$</td>
<td>$\pm 8%$</td>
<td>$\pm 4%$</td>
<td>$\pm 4%$</td>
</tr>
<tr>
<td>Mass lineshape</td>
<td>150% x $(m_H/\text{TeV})^3$ (0.3%@$125\text{GeV}$, 10%@$400\text{GeV}$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Individual Channels/Sub-Categories

- Sub-categories include jet multiplicity, lepton flavour, hi/lo pileup conditions, etc.

arXiv:1202.1414
arXiv:1202.1415
ATLAS-CONF-2012-012
ATLAS-CONF-2012-014
ATLAS-CONF-2012-015
ATLAS-CONF-2012-016
ATLAS-CONF-2012-017
ATLAS-CONF-2012-018

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Limit Setting Procedure

- $\mathcal{L}(\text{data} \mid \mu, \theta) = \text{Poisson}(\text{data} \mid \mu s(\theta) + b(\theta)) \cdot p(\tilde{\theta} \mid \theta)$

- **Likelihood**
  - Product over bins, channels
  - $\mu = \sigma/\sigma_{\text{SM}}$
  - signal strength parameter
- **No. of signal events**
- **No. of background events**
- **Gaussian constrained nuisance parameters $\theta$**

• Construct Test Statistic
  $$\tilde{q}_\mu = -2 \ln \frac{\mathcal{L}(\text{data} \mid \mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data} \mid \hat{\mu}, \hat{\theta})}$$
  (constraint $0 \leq \hat{\mu} \leq \mu$)

• 95% C.L. found by adjusting $\mu$ until
  $$CL_s(\mu) = \frac{p_\mu}{1 - p_b} = 0.05$$

- $p_\mu = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{\text{obs}} \mid \text{signal+background})$
- $1 - p_b = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{\text{obs}} \mid \text{background-only})$

• **Excess!?** Calculate local $p$-value to quantify the significance
  - $p_0$: the probability that background fluctuates to the observation
  - Expected $p_0$: the probability of $\mu=1$ w.r.t. $\mu=0$ hypothesis
Individual Search Channels

\[ \int L \, dt \sim 4.6-4.9 \, \text{fb}^{-1}, \sqrt{s}=7 \, \text{TeV} \]

**ATLAS 2011 Preliminary**

\[ m_H \, [\text{GeV}] \]

**ATLAS-CONF-2012-019**

• Expected exclusion at 95% CL: 120-555 GeV
• Observed exclusion at 95% CL: 110-117.5, 118.5-122.5, 129-539 GeV
• Observed exclusion at 99% CL: 130-486 GeV

➤ Note some excess in the low mass region
• Expected exclusion at 95% CL: 120-555 GeV
• Observed exclusion at 95% CL: 110-117.5, 118.5-122.5, 129-539 GeV
• Observed exclusion at 99% CL: 130-486 GeV

➤ Note some excess in the low mass region
Signal Hypothesis Compatibility

- $p_0$: the probability that background fluctuates to the observation
- Signal strength: best fit $\hat{\mu} = \sigma / \sigma_{SM}$

- Observed local significance for $m_H = 126$ GeV is $2.5\sigma$ (expected $2.9\sigma$)
- Global prob. to observe this fluctuation in 110-600 GeV is $30\%$ ($0.5\sigma$)

- Best-fit signal strength at $m_H = 126$ GeV is $\hat{\mu} = 0.9^{+0.4}_{-0.3}$
Local signal significance

- \( p_0 \): the probability that background fluctuates to the observation
- Signal strength: best fit \( \hat{\mu} = \sigma / \sigma_{SM} \)

- Observed local significance for \( m_H = 126 \text{ GeV} \) is 2.5\( \sigma \) (expected 2.9\( \sigma \))
- Global prob. to observe this fluctuation in 110-600 GeV is 30% (0.5\( \sigma \))

- Best-fit signal strength at \( m_H = 126 \text{ GeV} \) is \( \hat{\mu} = 0.9^{+0.4}_{-0.3} \)
Compatibility with Signal Hypothesis

- Signal strength: best fit $\hat{\mu} = \sigma / \sigma_{SM}$
- At 126GeV $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow llll$ are compatible with signal
  - other channels are compatible with both signal and null hypotheses
Excess is mainly observed in two high-resolution channels
- No big excess in $H \to WW \to l\nu l\nu$ or $H \to \tau^+\tau^-$ or $H \to b\bar{b}$

- $H \to \gamma\gamma$ and $H \to ZZ^* \to llll$ combined gives $3.4\sigma$ local significance
  - All channels combined gives $2.5\sigma$ local significance
Summary

• Searches for the Standard Model Higgs boson have been performed in a range of channels using the full 2011 dataset of up to 4.9 fb\(^{-1}\)

• Allowed Higgs boson mass is now limited to 117.5-118.5 GeV or 122.5-129 GeV in the low mass region

• See some hints of the Higgs boson at \(m_H=126\) GeV, observed local significance of 2.5\(\sigma\) (expected 2.9\(\sigma\))

• However, more data is needed to arrive at a definite conclusion

• Look forward to results using data collected this year at \(\sqrt{s}=8\) TeV!
• Look forward to results using data collected this year at $\sqrt{s}=8$ TeV!
References

- Limit setting and combination procedures: ATL-PHYS-PUB-2011-011
- Higgs combination using full 2011 dataset: ATLAS-CONF-2012-019
- H → ZZ* → llll: arXiv:1202.1415
- H → ZZ → llvv: ATLAS-CONF-2012-016
- H → ZZ → llqq: ATLAS-CONF-2012-017
- H → WW → lvlv: ATLAS-CONF-2012-012
- H → WW → lvqq: ATLAS-CONF-2012-018
- H → τ⁺τ⁻: ATLAS-CONF-2012-014
- VH(H → bb): ATLAS-CONF-2012-015
$H \rightarrow \gamma \gamma$ arXiv:1202.1414

- **Signal $m_{\gamma \gamma}$ modeling:**
  - Crystal Ball (core) and Gaussian function (tails)
  - Resolution for $m_{\gamma \gamma}$ approximately $\sigma_{CB} \approx 2$ GeV, FWHM $\approx 4$ GeV ($m_H$=120 GeV)

- **Total background from fit to $m_{\gamma \gamma}$ spectrum.**
  - Background modeled using exponential function
$H \rightarrow \gamma\gamma$ arXiv:1202.1414

- Observed Exclusion: 113-115, 134.5-136 GeV
- Excess of events observed around 126.5 GeV
  - Observed Local significance: 2.8\sigma
    - (1.5\sigma after the look-elsewhere-effect)

$p_0$: the probability that background fluctuates to the observation

\[ \int Ldt = 4.9 \text{ fb}^{-1} \]
$H \rightarrow ZZ^* \rightarrow llll$ arXiv:1202.1415

- Very clean: four leptons (e or $\mu$) “golden” channel
- Good mass resolution (for $m_H=130$ GeV $\sigma(m_H)/m_H$ is about 1.5-2%)
  - Above 350 GeV natural width dominates

- Two $2e2\mu$ candidates $m_{4l} = 123.6, 124.3$ GeV
- One $4\mu$ candidate $m_{4l} = 124.6$ GeV
$H \rightarrow ZZ^* \rightarrow llll$ arXiv:1202.1415

- Expected Exclusion: 137-157, 184-400 GeV

- Excess of events observed around 125 GeV
  - Observed Local significance: 2.1σ
Most sensitive channel in a broad mass range of 120-180 GeV

Require two opposite sign leptons and missing transverse energy

9 sub-channels
- (ee, μμ, eμ) x (0-,1-jet, VBF)

Use the shape of transverse mass ($m_T$) to extract limit

$$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - |\vec{p}_T^{ll} + \vec{p}_T^{miss}|^2}$$
• Expected exclusion: 127-234 GeV
• Observed exclusion: 130-260 GeV

• No significant excess seen in this channel
Use three different search channels:

- $H \rightarrow \tau^+ \tau^- \rightarrow l\nu l\nu l\nu$, uses $m_{\tau\tau}^{\text{eff}}$ in 0j channel and collinear approx. in 1 and 2j channels
- $H \rightarrow \tau^+ \tau^- \rightarrow l\tau_{\text{had}} 3\nu$, uses Missing Mass Calculator to calculate di-tau mass
- $H \rightarrow \tau^+ \tau^- \rightarrow \tau_{\text{had}} \tau_{\text{had}} 2\nu + 1\text{jet}$, uses collinear approx. to calculate the mass
Search in 3 channels:
- $ZH \rightarrow llbb$, $WH \rightarrow lvbb$, $ZH \rightarrow \nu\nu bb$

- Exactly two $b$-tagged jets
- Use leptons/$E_T^{\text{miss}}$ to trigger event
- Use $m_{bb}$ as the discriminating variable
H → ZZ → llvv ATLAS-CONF-2012-016

- Most sensitive channel in the high mass region
- Use $m_T$ as discriminating variable
- Different selections in low/high $m_H$ (< or >= 280 GeV) regions

$\frac{m_T}{(\text{GeV})} = \sqrt{m_Z^2 + \left| \vec{p}_T^{ll} \right|^2} + \sqrt{m_Z^2 + \left| \vec{p}_T^{\text{miss}} \right|^2} - \left[ \vec{p}_T^{ll} + \vec{p}_T^{\text{miss}} \right]^2$

- Expected exclusion: 260-490 GeV
- Observed exclusion: 320-560 GeV
**H → ZZ → lljj** ATLAS-CONF-2012-017

- Use $m_{lljj}$ as discriminating variable.
- Different selections in low/high $m_H$ ($< \text{or} \geq 300$ GeV) regions.
- Divide analysis into tagged and untagged categories.
  - Events with exactly two, and less than two $b$-tagged jets.

**Expected exclusion:** 360-400 GeV

**Observed exclusion:** 300-310, 360-400 GeV

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• Use $m_{WW}$ as discriminating variable
• Reconstruct $m_{WW}$ by imposing $m_{lv} = m_{W}$
• Divide search into events with 0/1/2 jets (in addition to the two arising from the W decay)
• Good mass resolution
  – for $m_H=400$ GeV $\sigma(m_H)/m_H$ is about 9%