ATLAS/LHC 2011 highlights

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Outline

- LHC in 2011
- ATLAS Operations and Luminosity
- Detector Performance
- Physics Highlights
  - Standard Model/Top
  - SM Higgs Searches
  - Other Searches
- LHC Future Plans and Upgrades

Most results from Summer (~1 fb⁻¹)

All Physics being updated with full dataset for winter 2012 Conferences

https://twiki.cern.ch/twiki/bin/view/AtlasPublic
2011 proton-proton run

ATLAS Online Luminosity $\sqrt{s} = 7$ TeV

- LHC Delivered
- ATLAS Recorded

Total Delivered: 5.61 fb$^{-1}$
Total Recorded: 5.25 fb$^{-1}$
Peak and Integrated Luminosity

ATLAS Online Luminosity per Fill
- LHC Stable Beams

Peak Lumi: $3.65 \times 10^{33}$ cm$^{-2}$ s$^{-1}$

Peak Luminosity per Fill [10$^{-30}$ cm$^{-2}$ s$^{-1}$]

Day in 2011

Selected Records

Peak Lumi
Bunches Colliding
Max Lumi in 1 day
Max Lumi in 7 days

$3.65 \times 10^{33}$ cm$^{-2}$ s$^{-1}$
1331
135 pb$^{-1}$
580 pb$^{-1}$
Road to Luminosity

Luminosity = \( n_b \times f \times \frac{N^2}{A} \)

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
<th>2015 Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\text{beam}} ) (TeV)</td>
<td>3.5</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>( n_b ) (ATLAS/CMS)</td>
<td>36</td>
<td>1331</td>
<td>2808</td>
</tr>
<tr>
<td>( N ) (protons)</td>
<td>( 0.9 \times 10^{11} )</td>
<td>( 1.3 \times 10^{11} )</td>
<td>( 1.2 \times 10^{11} )</td>
</tr>
<tr>
<td>( 1/\beta^* ) (m(^{-1}))</td>
<td>0.3</td>
<td>1</td>
<td>~2</td>
</tr>
<tr>
<td>Peak Lumi (cm(^{-2}) s(^{-1}))</td>
<td>( 9 \times 10^{30} )</td>
<td>( 3.5 \times 10^{33} )</td>
<td>( 1 \times 10^{34} )</td>
</tr>
<tr>
<td>Stored Energy (MJ/beam)</td>
<td>~2.5</td>
<td>~100</td>
<td>~380</td>
</tr>
</tbody>
</table>

Currently at about 1/3 of design luminosity

\( f \) - revolution frequency
\( n_b \) - bunches colliding
\( N \) - protons per bunch
\( A \) - cross-sectional collision area
ATLAS Detector
ATLAS Detector

- Muon Detectors
- Tile Calorimeter
- Liquid Argon Calorimeter
- Toroid Magnets
- Solenoid Magnet
- SCT Tracker
- Pixel Detector
- TRT Tracker

Length: 46m
Radius: 12m
Weight: \(~7,000\) tons
\(~10^8\) electronic channels
TDAQ/Trigger

- 3-stage trigger
- Continual menu evolution during 2011
- Increasing use of multi-object triggers

2011 Peak Rates
- L1: 55 kHz
- EF: 550 Hz

<table>
<thead>
<tr>
<th>Stream Rates</th>
<th>Threshold (GeV)</th>
<th>Rate (Hz) @ L = 3x10^{33}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single e</td>
<td>22</td>
<td>55</td>
</tr>
<tr>
<td>Single µ</td>
<td>18</td>
<td>100</td>
</tr>
<tr>
<td>Two e</td>
<td>2x12</td>
<td>1.3</td>
</tr>
<tr>
<td>Two T</td>
<td>20, 30</td>
<td>15</td>
</tr>
<tr>
<td>MET</td>
<td>70</td>
<td>5</td>
</tr>
<tr>
<td>Jet+MET</td>
<td>75, 55</td>
<td>20</td>
</tr>
</tbody>
</table>

Average well above design
200 Hz to tape

Soft limit driven by world-wide disk storage

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Operational Efficiency

- Recording Efficiency
  - Trigger/DAQ problems
  - Trigger Deadtime
  - Start-of-fill preparations

- Data Quality Efficiency
  - Detector-specific problems
  - Shown after reprocessing

Over ~90% overall efficiency for physics
Luminosity Calibration

- Dedicated (fast) luminosity detectors measuring inelastic pp rate
- Absolute luminosity from ‘van der Meer’ beam separation scans, and bunch charge
- Can calibrate each detector/algorithm

\[
\sigma_{vis} = \frac{2\pi \sum_x \sum_y n_1 n_2}{\mu_{vis} \text{MAX}}
\]

Scan Widths
Peak Rate
Bunch Charges

- Extensive consistency checks in extrapolation to entire 2011 data sample

**Summer 2011 result:** \( dL/L = 3.7\% \) (preliminary)

Dominated by uncertainty in bunch charge product
Luminosity per crossing

- Luminosity per 25 ns ‘BCID’
- One snapshot like this every minute

- Mean number of inelastic interactions per crossing
- Increased pileup significant challenge for jets, MET, taus
- Not really an issue for electrons, muons, photons
- Now simulating this in MC
20 primary interactions per bunch crossing!

A lot of work goes in to disentangle these “pile-up” interactions.
Pile-up in jets/MET

- ATLAS LAr uses bi-polar shaping to average out pileup
- Not perfect with bunch trains - needs detailed corrections for Jets/MET
$Z \rightarrow \mu\mu$ candidate event display

**ATLAS EXPERIMENT**

Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST

$p_T(\mu^-) = 27$ GeV  $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV  $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV

$Z \rightarrow \mu\mu$ candidate in 7 TeV collisions
Standard Model boson production

- In 1 fb$^{-1}$: Millions of $W$s, hundreds of thousands of $Z$s
- $W$ or $Z$ cross-sections already systematics limited in 35 pb$^{-1}$
- LHC is a **Boson Factory**, high precision differential measurements underway
W and Z measurements

\[ \frac{\sigma(W^+) - \sigma(W^-)}{\sigma(W^+) + \sigma(W^-)} \]

2010 analyses established techniques, expect updates on all differential analyses this winter

\[ \frac{\sigma(W \rightarrow e\nu + 1\text{jet})}{\sigma(Z \rightarrow ee + 1\text{jet})} \]
ttbar – 2 b-tags 1e/1µ
ttbar yields

\[ \sim 2k \ ttbar \rightarrow \text{di-lepton in 1 fb}^{-1} \]

\[ \sim 10k \ \text{lepton+jet in 1 fb}^{-1} \]
Top studies

Di-lepton ttbar spin correlation

W Polarization

Top mass measurements

Rich program of detailed top quark measurements ahead
SM cross sections

\[ \sigma_{\text{total}} \text{ [pb]} \]

\[ \int L \, dt = 0.035 - 1.04 \, \text{fb}^{-1} \]

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

- **Theory**
- **Data 2010 (~35 pb\(^{-1}\))**
- **Data 2011**
SM cross sections

\[ \sigma_{\text{total}} \] [pb]

\[ 10^5 \]
\[ 10^4 \]
\[ 10^3 \]
\[ 10^2 \]
\[ 10 \]

\[ \int L \, dt = 0.035 - 1.04 \, \text{fb}^{-1} \]
\[ \sqrt{s} = 7 \, \text{TeV} \]

**ATLAS Preliminary**

- Theory
- Data 2010 (~35 pb\(^{-1}\))
- Data 2011

Experimental errors (including Lumi) at or below theory errors

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SM cross sections

\[ \sigma_{\text{total}} \] [pb]

\[ 10^5 \]
\[ 10^4 \]
\[ 10^3 \]
\[ 10^2 \]
\[ 10 \]

\[ \int L \, dt = 0.035 - 1.04 \, \text{fb}^{-1} \]
\[ \sqrt{s} = 7 \, \text{TeV} \]

- **ATLAS Preliminary**
- Theory
- Data 2010 (~35 pb\(^{-1}\))
- Data 2011

\[ \sigma_B \sim 40 \, \text{fb} \]
ZZ -> 4 leptons

Combined eeee, eemm, μμμμ

ZZ → 4l: 12 events in 1 fb⁻¹, very clean
Candidate $ZZ \rightarrow \mu\mu\mu\mu$
Updated Standard Model Higgs Boson results:

- Made public last night!
- Will show only some of the results
- Everything is still preliminary
- For more details, see the presentations:
  
  https://indico.cern.ch/conferenceDisplay.py?confId=164890
SM Higgs searches

- Low Mass ( < 120 GeV)
  - $H \rightarrow \gamma\gamma$ - best at low mass
  - $H \rightarrow \tau\tau$ - needs more lumi
- Intermediate ( < 200 GeV)
  - $H \rightarrow W^*W \rightarrow lvlv$
    high rate, poor resolution
- High Mass ( > 200 GeV)
  - $H \rightarrow ZZ \rightarrow llll$ - golden channel
  - $H \rightarrow ZZ \rightarrow llvv$ - higher stats, higher backgrounds

Some new results include full 2011 dataset!!
SM Higgs: cross section and decay modes

- Experimentally most sensitive channels vs $m_H$

- Cross-sections computed to NNLO in most cases $\rightarrow$ theory uncertainties reduced to $< 20\%$
- Huge progress also in the theoretical predictions of numerous and complex backgrounds $\rightarrow$ Excellent achievements of the theory community; very fruitful discussions with the experiments (e.g. through LHC Higgs Cross Section WG, LPCC, etc.)
SM Higgs by channel

Limits from Lepton-Photon

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Present Status (as of ~1 day ago)

First ATLAS+CMS combination: based on data recorded until end August 2011: up to ~2.3 fb⁻¹ per experiment

Excluded 95% CL : 141-476 GeV
Excluded 99% CL : 146-443 GeV (except ~222, 238-248, ~295 GeV)
Expected 95% CL : 124-520 GeV \( \rightarrow \) max deviation from background-only: \( \sim 3\sigma \) (\( m_H \sim 144 \text{ GeV} \))
## Higgs updates

<table>
<thead>
<tr>
<th>Channel</th>
<th>$m_H$ range (GeV)</th>
<th>Int. lumi fb$^{-1}$</th>
<th>Main backgrounds</th>
<th>Number of signal events after cuts</th>
<th>S/B after cuts</th>
<th>Expected $\sigma/\sigma_{SM}$ sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>110-150</td>
<td>4.9</td>
<td>$\gamma\gamma, \gamma j, jj$</td>
<td>~70</td>
<td>~0.02</td>
<td>1.6-2</td>
</tr>
<tr>
<td>$H \to \tau\tau \to ll+\nu$</td>
<td>110-140</td>
<td>1.1</td>
<td>$Z \to \tau\tau$, top</td>
<td>~0.8</td>
<td>~0.02</td>
<td>30-60</td>
</tr>
<tr>
<td>$H \to \tau\tau \to lT_{had}$</td>
<td>100-150</td>
<td>1.1</td>
<td>$Z \to \tau\tau$</td>
<td>~10</td>
<td>~5 $10^{-3}$</td>
<td>10-25</td>
</tr>
<tr>
<td>$W/ZH \to bb(l)$</td>
<td>110-130</td>
<td>1.1</td>
<td>$W/Z+\text{jets}, \text{top}$</td>
<td>~6</td>
<td>~5 $10^{-3}$</td>
<td>15-25</td>
</tr>
<tr>
<td>$H \to WW(*) \to ll\nu\nu$</td>
<td>110-300</td>
<td>2.1</td>
<td>$WW, \text{top}, Z+\text{jet}$</td>
<td>~20 (130 GeV)</td>
<td>~0.3</td>
<td>0.3-8</td>
</tr>
<tr>
<td>$H \to ZZ(*) \to 4l$</td>
<td>110-600</td>
<td>4.8</td>
<td>$ZZ^*, \text{top}, Zbb$</td>
<td>~2.5 (130 GeV)</td>
<td>~1.5</td>
<td>0.7-10</td>
</tr>
<tr>
<td>$H \to ZZ \to llvv$</td>
<td>200-600</td>
<td>2.1</td>
<td>$ZZ, \text{top}, Z+\text{jets}$</td>
<td>~20 (400 GeV)</td>
<td>~0.3</td>
<td>0.8-4</td>
</tr>
<tr>
<td>$H \to ZZ \to llqq$</td>
<td>200-600</td>
<td>2.1</td>
<td>$Z+\text{jets}, \text{top}$</td>
<td>2-20 (400 GeV)</td>
<td>0.05-0.5</td>
<td>2-6</td>
</tr>
<tr>
<td>$H \to WW \to l\nuqq$</td>
<td>240-600</td>
<td>1.1</td>
<td>$W+\text{jets, top, jets}$</td>
<td>~45 (400 GeV)</td>
<td>$10^{-3}$</td>
<td>5-10</td>
</tr>
</tbody>
</table>

- Use “cut-based” analyses,
- estimate backgrounds with data-driven techniques using signal-free control regions
H → WW(*) → lνlν (e+e−, μ+μ−, e+μ−)

- Most sensitive channel over ~ 130-180 GeV (σ ~ 200 fb)
- However: challenging: 2ν → no mass reconstruction/peak → “counting channel”
- 2 isolated opposite-sign leptons, large E_T^{miss}
- Main backgrounds: WW, top, Z+jets
  → m_νν ≠ m_Z, b-jet veto, ...
  → Topological cuts against “irreducible” WW background:
    p_T^{ll}, m_νν, Δφ_νν (smaller for scalar Higgs), m_T (ll, E_T^{miss})

Crucial experimental aspects:
- understanding of E_T^{miss} (genuine and fake)
- excellent understanding of background in signal region → use signal-free control regions in data to constrain MC → use MC, extrapolate to signal region

<table>
<thead>
<tr>
<th>Control region</th>
<th>MC expectation</th>
<th>Observed in data</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW 0-jet</td>
<td>296±36</td>
<td>296</td>
</tr>
<tr>
<td>WW 1-jet</td>
<td>171±21</td>
<td>184</td>
</tr>
<tr>
<td>Top 1-jet</td>
<td>270±69</td>
<td>249</td>
</tr>
</tbody>
</table>

Expected signal contamination: ~ 1 event/region
$H \rightarrow WW(*) \rightarrow \ell\nu\ell\nu$ ($e\nu e\nu, \mu\nu\mu\nu, e\nu\nu\nu$)

$E_{T,\text{miss}}$ spectrum in data for inclusive events with a lepton pair well described (over 5 orders of magnitude) by the various background components. Dominated by real $E_{T,\text{miss}}$ from $\nu$’s for $E_{T,\text{miss}} \sim 60$ GeV → little tails from detector effects

After all cuts (selection for $m_H = 130$ GeV)

<table>
<thead>
<tr>
<th>Observed in data</th>
<th>94 events (10 $ee$, 42 $e\mu$, 42 $\mu\mu$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected background</td>
<td>76 ($\pm 11$)</td>
</tr>
<tr>
<td>Expected signal $m_H = 130$ GeV</td>
<td>19 ($\pm 4$)</td>
</tr>
</tbody>
</table>

Transverse mass spectrum after all cuts (except $M_T$)

$$m_T = \sqrt{(E_{T,\ell}^\ell + E_{T,\text{miss}})^2 - (P_{T,\ell}^\ell + P_{T,\text{miss}})^2}$$
H \rightarrow WW(*) \rightarrow \ell\ell\nu\nu (e\ell\nu, \mu\mu\nu, e\mu\nu)

- Excluded (95% CL): $145 < m_H < 206$ GeV (expected: 134-200 GeV)
- Observed limit within 2\sigma of expected: max deviation 1.9 \sigma for $m_H \sim 130$ GeV

Consistency of the data with the background-only expectation

**ATLAS**

- Observed
- Expected
- $\pm 1\sigma$
- $\pm 2\sigma$

\[ \int Ldt = 2.05 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

Vertical lines indicate points where selection changes
**H → γγ**

- **Small cross-section:** $\sigma \sim 40$ fb
- **Simple final state:** two high-$p_T$ photons
  $E_T(\gamma_1, \gamma_2) > 40, 25$ GeV
- **Main background:** $\gamma\gamma$ continuum (irreducible, smooth, ..)
- **Events divided into 9 categories based on $\eta$-photon** (e.g. barrel, end-cap, ..), converted/unconverted, $p_T^{\gamma\gamma}$ along thrust axis
- **~70 signal events expected in 4.9 fb$^{-1}$** after all selections for $m_H=125$ GeV
  ~ 4000 background events in signal mass window $\rightarrow S/B \sim 0.02$

**Crucial experimental aspects:**
- excellent $\gamma\gamma$ mass resolution to observe narrow signal peak above irreducible background
- **powerful $\gamma$/jet separation** to suppress $\gamma j$ and $jj$ background with jet $\rightarrow \pi^0$ faking single $\gamma$

More information in back-up material
H → γγ

- 22489 events with 100 < m_{γγ} < 160 observed in the data
- expected signal efficiency: ~ 35% for m_H=125 GeV

m_{γγ} spectrum fit with exponential function for background plus Crystal Ball + Gaussian for signal in 1 GeV steps
→ background determined directly from data

Excluded (95% CL):
114 ≤ m_H ≤ 115 GeV, 135 ≤ m_H ≤ 136 GeV

Consistency of the data with the background-only expectation

Maximum deviation from background-only expectation observed for m_H~126 GeV:
- local p₀-value: 0.27% or 2.8σ
- global p₀-value: includes probability for such an excess to appear anywhere in the investigated mass range ("Look-Elsewhere-Effect"): ~7% (1.5σ)
- expected from SM Higgs: ~1.4σ
\[ \text{H} \to \text{ZZ}(\ast) \to 4l \ (\text{eeee, } \mu \mu \text{ee, } \mu \mu \mu \mu) \]

- \( \sigma \sim 2-5 \text{ fb} \)
- However:
  - mass can be fully reconstructed \( \rightarrow \) events would cluster in a (narrow) peak
  - pure: S/B \( \sim 1 \)
- 4 leptons: \( p_T^{1,2,3,4} > 20,20,7,7 \text{ GeV} \); \( m_{12} = m_Z \pm 15 \text{ GeV} \); \( m_{34} > 15-60 \text{ GeV} \) (depending on \( m_H \))
- Main backgrounds:
  - \( \text{ZZ}(\ast) \) (irreducible)
  - \( m_H < 2m_Z \): Zbb, Z+jets, tt with additional leptons from b/q-jets \( \rightarrow l \)
  - Suppressed with isolation and impact parameter cuts on two softest leptons
- Signal efficiency: \( \sim 15 \% \) for \( m_H \sim 125 \text{ GeV} \)

Crucial experimental aspects:
- High lepton reconstruction and identification efficiency down to lowest \( p_T \)
- Good lepton energy/momentum resolution
- Good control of reducible backgrounds (Zbb, Z+jets, tt) in low-mass region:
  - cannot rely on MC alone (theoretical uncertainties, b/q-jet \( \rightarrow l \) modeling, ..)
  - need to compare MC to data in background-enriched control regions (but: low statistics ..)
  - Conservative/stringent \( p_T \) and \( m(ll) \) cuts used at this stage
H → ZZ(*) → 4l (eeee, μμee, μμμμ)

In the region $m_H < 141$ GeV (not already excluded at 95% C.L.) 3 events are observed: two 2e2μ events ($m=123.6$ GeV, $m=124.3$ GeV) and one 4μ event ($m=124.6$ GeV)

In the region $117 < m_{4l} < 128$ GeV (containing ~90% of a $m_H=125$ GeV signal):
- similar contributions expected from signal, background: ~ 1.5 events each
- S/B ~ 2 (4μ), 1 (2e2μ), ~0.3 (4e)
- Background dominated by ZZ* (4μ and 2e2μ), ZZ* and Z+jets (4e)

Observed in data: 71 events: 24 4μ + 30 2e2μ + 17 4e
Expected from background: 62±9
$H \rightarrow ZZ^{(*)} \rightarrow 4\mu$ ($\mu\mu\mu\mu$)

4$\mu$ candidate with $m_{4\mu} = 124.6$ GeV

$p_T(\mu^-, \mu^+, \mu^+, \mu^-) = 61.2, 33.1, 17.8, 11.6$ GeV : $m_{12} = 89.7$ GeV, $m_{34} = 24.6$ GeV
$H \rightarrow ZZ(*) \rightarrow 4l$ ($\mu\mu ee$)

$p_T (e^+, e^-, \mu^-, \mu^+) = 41.5, 26.5, 24.7, 18.3 \text{ GeV} : m (e^+e^-) = 76.8 \text{ GeV}, m (\mu^+\mu^-) = 45.7 \text{ GeV}$

$2e2\mu$ candidate with $m_{2e2\mu} = 124.3 \text{ GeV}$
H → ZZ(*) → 4l (eeee, µee, µµµµ)

From fit of signal and background expectations to 4l mass spectrum

Excluded (95% CL): 135 < m_H < 156 GeV and 181 < m_H < 415 GeV (except 234-255 GeV)
Expected (95% CL): 137 < m_H < 158 GeV and 185 < m_H < 400 GeV


Combined Constraints

**Expected if no signal**

- $112.7 < m_H < 115.5$ GeV (local deficit in $\gamma\gamma$ mass spectrum)
- $131 < m_H < 453$ GeV, except 237-251 GeV

**Excluded at 99% CL**

- $133 < m_H < 230$ GeV, $260 < m_H < 437$ GeV

**Excluded at 95% CL**

- $124.6-520$ GeV (identical to expected limit of ATLAS+CMS combination for $\sim 2$ fb$^{-1}$)

**ATLAS Preliminary**

- Observed
- Expected
- $\int L dt = 1.0-4.9$ fb$^{-1}$
- $\sqrt{s} = 7$ TeV

**CLs Limits**

- $10^{-1}$
- $10$ to $600$ GeV

**ATLAS+CMS Combination**

- Observed
- Expected
- $\int L dt = 1.0-4.9$ fb$^{-1}$
- $\sqrt{s} = 7$ TeV

- New ATLAS limits

**H → γγ, H → ττ**

- $H → WW(\ast) → l l ν ν$
- $H → ZZ(\ast) → 4l, H → ZZ → l l ν ν$
- $H → ZZ → l l q q, H → WW → l l q q$
- $W/ZH → l b b + X$ not included

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Combined Constraints

Local $p_0$-value: $2.2 \times 10^{-4}$
$
\rightarrow$ significance of the excess: $3.6\sigma$
$
\sim 2.8\sigma H \rightarrow \gamma\gamma, 2.1\sigma H \rightarrow 4l, 1.4\sigma H \rightarrow l\nu l\nu$

Global $p_0$-value: $\sim 1\% \rightarrow 2.3\sigma$

Expected from SM: $\sim 2.4\sigma$ ($\sim 1.4\sigma$ per channel)
Combined Constraints

Compatibility with the expected strength of a SM Higgs signal

The observed excess is slightly larger (2±0.8) than expected in the $H \rightarrow \gamma\gamma$ channel and compatible within 1σ for the other channels and the combined result.
Evolution with time

ATLAS 2010: \( \int L \, dt \sim 35 \text{ pb}^{-1}, 7 \text{ TeV} \)

ATLAS 2011: \( \int L \, dt \sim 1.0-2.3 \text{ fb}^{-1}, 7 \text{ TeV} \)

ATLAS and CMS: up to 2.3 fb^{-1}/expt (November 2011)

ATLAS Preliminary 2011: \( \int L \, dt \sim 1.0-4.9 \text{ fb}^{-1}, 7 \text{ TeV} \)

ATLAS 2010 data (35 pb^{-1})

ATLAS today

\( \text{CL}_{s} \) Limits

Observed

Expected

\( m_{H} \) [GeV]
Expected Sensitivity

ATLAS Preliminary (Simulation)

- $5\sigma \sqrt{s}=7$ TeV
- $5\sigma \sqrt{s}=8$ TeV
- $3\sigma \sqrt{s}=7$ TeV
- $3\sigma \sqrt{s}=8$ TeV
- 95% CL $\sqrt{s}=7$ TeV
- 95% CL $\sqrt{s}=8$ TeV

Integrated Luminosity, fb$^{-1}$

$m_H$ [GeV]
Results from CMS

Updated results to full data in all 8 channels studied
- $H\rightarrow bb$ and $\tau\tau$ particularly impressive (hard to do!)

$H \rightarrow \gamma\gamma$:
Local excess at $\sim 124$GeV, consistent with ATLAS? (to be confirmed)
A lot of masses ruled out... but no discovery!

- The excess is most compatible with a SM Higgs hypothesis in the vicinity of 124 GeV and below, but the statistical significance (2.6σ local and 1.9σ global after correcting for the LEE in the low mass region) is not large enough to say anything conclusive.
What do the results mean?

• ATLAS sees an excess of events at ~126GeV in channels where mass can be reconstructed (γγ and ZZ) and resolution is ~1-2GeV
  – “Excess” in 3 decay channels studied
  – Suggestive of SM Higgs….but not evidence

• CMS rules out masses above 127GeV
  – Modest excess of events from 115-127GeV
  – The slight excess exists in all 5 channels sensitive at low Higgs mass

• 2012 LHC running should prove definitive
# LHC future

Rough draft 10-year plan (not approved)

<table>
<thead>
<tr>
<th>Year</th>
<th>LHC Upgrades</th>
<th>ATLAS Upgrades</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td></td>
<td></td>
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<td>2019</td>
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</table>

- **LHC Upgrades**
  - **LS1:** Interconnect Repair
  - **LS2:** Collimation Crab Cavities RF Cryo
  - **LS3:** Lumi Upgrade?

- **ATLAS Upgrades**
  - **Phase 0:** Insertable B-Layer
  - **Phase 1:** Trigger/DAQ
  - **Phase 2:** New tracker

<table>
<thead>
<tr>
<th>Year</th>
<th>E$_{beam}$ ~ 7 TeV</th>
<th>~ 4 TeV</th>
<th>3 x 10$^{33}$</th>
<th>L$_{int}$ ~ 80 fb$^{-1}$</th>
<th>L ~ 1 x 10$^{34}$</th>
<th>L$_{int}$ ~ 100 fb$^{-1}$</th>
</tr>
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<tbody>
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<td>2012</td>
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</table>
ATLAS Upgrade

• Phase 0 - LS1: 2012-2014
  - Insertable B-layer (new pixel layer)
  - New cooling for pixels/SCT
  - Replace LAr LV power supplies
  - Finish EE chamber installation (muons)
  - New beam pipes (Be and Al)

• Phase 1 - LS2: 2018, some in LS1 as ready?
  - Higher granularity L1 Calo trigger, topological L1 triggers
  - Adaptation of TDAQ electronics and HLT configuration (network)
  - Fast track trigger (FTK)
  - New small wheels (muons)
  - New forward physics instrumentation

• Phase 2 - LS3: 2022
  - Major detector replacements (e.g.: new inner tracker), ...
Conclusions

- LHC exceeded all expectations in 2011
  - achieved $L = 3.65 \times 10^{33}$ cm$^{-2}$ s$^{-1}$, over 5 fb$^{-1}$ delivered to ATLAS
- ATLAS detector performing well
  - High operational efficiency for entire year

We have looked for a SM Higgs boson
- over the mass region 100-600 GeV
- in 11 distinct channels
- using up to 4.9 fb$^{-1}$ of integrated luminosity

We have restricted the most likely mass region (95% CL) to:
116 - 131 GeV

We observe an excess of events around $m_H \sim 126$ GeV:
- local significance $3.5\sigma \rightarrow 2.3\sigma$ with LEE
- contributions from $H \rightarrow \gamma\gamma$ ($2.7\sigma$), $H \rightarrow 4l$ ($2\sigma$), $H \rightarrow l\nu l\nu$ ($1.4\sigma$)
- SM Higgs expectation: $2.4\sigma \rightarrow$ observed excess compatible with signal strength within $+1\sigma$
If confirmed: **very nice region for the Higgs** to be accessible at LHC in $\gamma\gamma$, $4l$, $l\nu l\nu$, $bb$, $\tau\tau$

It’s far too early to draw definite conclusions
More work and more data are needed
We have built solid foundations for the (exciting !) months to come
2012 likely to be a big year...good time to join ATLAS!
Additional Material

coepp.org.au
facebook.com/CoEPP
twitter.com/CoEPP
twitter.com/HEPAdelaide
Selected SUSY limits

ATLAS SUSY Searches* - 95% CL Lower Limits (Status: BSM-LHC 2011)

- MSUGRA/CMSSM: 0-lep + j's + E_{T,miss}:
  \[ q' = \tilde{g} \text{ mass} \]
  \[ \tilde{q} = \tilde{g} \text{ mass} \]
- MSUGRA/CMSSM: 1-lep + j's + E_{T,miss}:
  \[ m_{\tilde{q}} = 873 \text{ GeV} \]
- MSUGRA/CMSSM: multijets + E_{T,miss}:
  \[ m_{\tilde{q}} = 650 \text{ GeV} \]
- Simpl. mod. (light \tilde{\chi}_1^0): 0-lep + j's + E_{T,miss}:
  \[ m_{\tilde{\chi}_1^0} < 1.075 \text{ TeV} \]
- Simpl. mod. (light \tilde{\chi}_1^0): 0-lep + j's + E_{T,miss}:
  \[ m_{\tilde{\chi}_1^0} < 950 \text{ GeV} \]
- Simpl. mod. (light \tilde{\chi}_1^0): 0-lep + j's + E_{T,miss}:
  \[ m_{\tilde{\chi}_1^0} < 720 \text{ GeV} \]
- Simpl. mod. (light \tilde{\chi}_1^0): 0-lep + j's + E_{T,miss}:
  \[ m_{\tilde{\chi}_1^0} < 140 \text{ GeV} \]
- Pheno-MSSM (light \tilde{\chi}_1^0): 2-lep SS + E_{T,miss}:
  \[ m_{\tilde{\chi}_1^0} = 600 \text{ GeV} \]
- Pheno-MSSM (light \tilde{\chi}_1^0): 2-lep OS, SF + E_{T,miss}:
  \[ m_{\tilde{\chi}_1^0} = 508 \text{ GeV} \]
- Simpl. mod. (\tilde{g} \rightarrow q\tilde{\chi}_1^0): 1-lep + j's + E_{T,miss}:
  \[ m_{\tilde{\chi}_1^0} = 200 \text{ GeV} \]
- GMSB (GGM) + Simpl. model: \tilde{\chi}_1^0 + E_{T,miss}:
  \[ m_{\tilde{\chi}_1^0} = 778 \text{ GeV} \]
- GMSB: stable \tilde{t}:
  \[ m_{\tilde{t}} = 136 \text{ GeV} \]
- Stable massive particles: R-hadrons:
  \[ m_{\tilde{g}} = 562 \text{ GeV} \]
- Stable massive particles: R-hadrons:
  \[ m_{\tilde{b}} = 294 \text{ GeV} \]
- Stable massive particles: R-hadrons:
  \[ m_{\tilde{t}} = 309 \text{ GeV} \]
- Hypercolour scalar gluons: 4 jets, \( m_{\tilde{g}} = m_{\tilde{q}} \):
  \[ m_{\tilde{g}} = 185 \text{ GeV} \]
- RPV (\lambda'_{31}, \lambda'_{21} = 0.05): high-mass eq:
  \[ m_{\tilde{\chi}_2} = 1.32 \text{ TeV} \]
- Bilinear RPV (c_{\tilde{t}g}, < 15 mm): 1-lep + j's + E_{T,miss}:
  \[ m_{\tilde{\chi}_1^0} = 769 \text{ GeV} \]

*Only a selection of the available results leading to mass limits shown

\[ \int L dt = (0.034 - 1.34) \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

Paul D. Jackson
### Selected non-SUSY limits

<table>
<thead>
<tr>
<th>ATLAS Exotics Searches - 95% CL Lower Limits (Status: BSM-LHC 2011)</th>
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<tbody>
<tr>
<td><strong>Large ED (ADD): monojet</strong></td>
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<tr>
<td><strong>UED: ( \gamma \gamma + E_{T,\text{miss}} )</strong></td>
</tr>
<tr>
<td><strong>RS with ( k/M_{R} = 0.1 ): diphoton, ( m_{\gamma\gamma} )</strong></td>
</tr>
<tr>
<td><strong>RS with ( k/M_{R} = 0.1 ): dilepton, ( m_{l\nu} )</strong></td>
</tr>
<tr>
<td><strong>RS with ( g_{qgq}/g_{g} = 0.20: H_{T} + E_{T,\text{miss}} )</strong></td>
</tr>
<tr>
<td><strong>Quantum black hole (QBH): ( m_{\text{det}} F(x) )</strong></td>
</tr>
<tr>
<td><strong>QBH: High-mass ( \sigma_{\times} )</strong></td>
</tr>
<tr>
<td><strong>ADD BH (( M_{\chi}/M_{D} = 3 )): multijet ( \Sigma \chi_{N_{\text{jets}}} )</strong></td>
</tr>
<tr>
<td><strong>ADD BH (( M_{\chi}/M_{D} = 3 )): SS dimuon ( N_{\text{th. part.}} )</strong></td>
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<tr>
<td><strong>qqqq contact interaction: ( F_{1}(m_{\text{qqqq}}) )</strong></td>
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<tr>
<td><strong>qqμμ contact interaction: ( m_{\text{qqμμ}} )</strong></td>
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<tr>
<td><strong>χCM</strong></td>
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<tr>
<td><strong>SSM: ( m_{\text{eqgq}} )</strong></td>
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<tr>
<td><strong>SSM: ( m_{\text{eqgq}} )</strong></td>
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<tr>
<td><strong>5^{th} generation: ( c_{\ell_{\beta}} \Rightarrow W_{l}Q_{l} )</strong></td>
</tr>
<tr>
<td><strong>4^{th} generation: ( d_{\ell_{\beta}} \Rightarrow W_{l}Q_{l} )</strong></td>
</tr>
<tr>
<td><strong>5^{th} generation: ( T_{\ell_{4 \leftrightarrow 3}} \rightarrow 1\text{-lep + jets + } E_{T,\text{miss}} )</strong></td>
</tr>
<tr>
<td><strong>Techni-hadrons: ( m_{\text{eqgq}} )</strong></td>
</tr>
<tr>
<td><strong>Major. neutr. (LRSM, no mixing): ( 2\text{-lep + jets} )</strong></td>
</tr>
<tr>
<td><strong>Major. neutr. (LRSM, no mixing): ( 2\text{-lep + jets} )</strong></td>
</tr>
<tr>
<td><strong>Higgs (DY prod., BR[( H_{\ell_{\beta}} \rightarrow \mu^{+}\mu^{-} = 1 )] ( \sim \text{sign} )</strong></td>
</tr>
<tr>
<td><strong>Excited quarks: ( m_{\text{obj}} )</strong></td>
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<tr>
<td><strong>Axigluons: ( m_{\text{obj}} )</strong></td>
</tr>
<tr>
<td><strong>Color octet scalar: ( m_{\text{obj}} )</strong></td>
</tr>
</tbody>
</table>

*Only a selection of the available results leading to mass limits shown*

\[
\int L \, dt = (0.031 - 1.60) \, \text{fb}^{-1}
\]

\[\sqrt{s} = 7 \, \text{TeV}\]
Price to pay for the high luminosity: higher-than-expected pile-up

Pile-up = number of interactions per crossing
Tails up to ~20 → comparable to or larger than expected at design luminosity
(several machine parameters pushed beyond design)

LHC figures used over the last 20 years:
~ 2 (20) events/crossing at $L=10^{33}$ ($10^{34}$)

Challenging for trigger, computing resources, reconstruction of physics objects
(in particular $E_T^{\text{miss}}$, soft jets, ..)

Precise modeling of both, in-time and out-of-time pile-up, in simulation is crucial
\[ m_{\gamma\gamma}^2 = 2E_1 E_2 (1 - \cos \alpha) \]

**H \rightarrow \gamma\gamma**

<table>
<thead>
<tr>
<th>m_H = 120 GeV</th>
<th>( \sigma (m_{\gamma\gamma}) ) GeV</th>
<th>Event fraction in ( \pm 1.4 \sigma (m_{\gamma\gamma}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>1.7</td>
<td>80 %</td>
</tr>
<tr>
<td>Best category</td>
<td>1.4</td>
<td>84 %</td>
</tr>
<tr>
<td>Worst category</td>
<td>2.3</td>
<td>70 %</td>
</tr>
</tbody>
</table>

- **m_H**: 120 GeV
- **\( \sigma (m_{\gamma\gamma}) \)**: Energy scale and resolution transported to photons using MC
- **Event fraction**: Electron scale and resolution transported to photons using MC

Present understanding of calorimeter E response (from Z, J/\( \psi \rightarrow \) ee, W\( \rightarrow \) ee data and MC):

- Energy scale at m_Z known to ~ 0.5%
- Linearity better than 1% (over few Gev-few 100 GeV)
- “Uniformity” (constant term of resolution): 1% (barrel) -1.7 % (end-cap)
\[ m_{\gamma\gamma}^2 = 2E_1E_2(1 - \cos \alpha) \]

Use longitudinal (and lateral) segmentation of EM calorimeter to measure photon polar angle \( \vartheta \). Crucial at high pile-up: many vertices distributed over \( \sigma_Z \) (LHC beam spot) \( \sim 5.6 \, \text{cm} \) → difficult to know which one produced the \( \gamma\gamma \) pair.

Z-vertex as measured in \( \gamma\gamma \) events after selection from calorimeter “pointing”

Calorimeter pointing capability reduces vertex uncertainty from \( \sim 5.6 \, \text{cm} \) (LHC beam spot) to \( \sim 1.5 \, \text{cm} \) → Contribution to mass resolution from angular term is negligible with calorimeter pointing (\( \gamma \rightarrow ee \) vertex also used)

Robust against pile-up
Potentially huge background from $\gamma j$ and $jj$ production with jets fragmenting into a single hard $\pi^0$ and the $\pi^0$ faking single photon.

**Determined choice of fine lateral segmentation (4mm $\eta$-strips) of the first compartment of ATLAS EM calorimeter**

**However:** huge uncertainties on $\sigma (\gamma j, jj)$ !! $\rightarrow$ not obvious $\gamma j$, $jj$ could be suppressed well below irreducible $\gamma\gamma$ until we measured with data.
After all cuts: 22489 events with $100 < m_{\gamma\gamma} < 160$ observed in the data

Sample composition estimated from data using control samples

<table>
<thead>
<tr>
<th>$\gamma\gamma$</th>
<th>Num of events</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma j$</td>
<td>$16000 \pm 1120$</td>
<td>$71\pm5%$</td>
</tr>
<tr>
<td>$jj$</td>
<td>$5230 \pm 820$</td>
<td>$23\pm4%$</td>
</tr>
<tr>
<td>$jj$</td>
<td>$1130 \pm 600$</td>
<td>$5\pm3%$</td>
</tr>
<tr>
<td>DY</td>
<td>$165 \pm 8$</td>
<td>$0.7\pm0.1%$</td>
</tr>
</tbody>
</table>

- $\gamma j + jj \ll \gamma\gamma$ irreducible (purity $\sim 70\%$)
- Good agreement with theory
Photon identification efficiency: ~ 85±5% from MC, cross-checked with data (Z→ ee, Z→ eγ, μγ)

Photon isolation requirement: $E_T < 5$ GeV inside a cone $\Delta R < 0.4$ around $\gamma$ direction

Underlying event and pile-up contribution subtracted using an “ambient energy density” determined event-by-event.

If the subtraction is not perfect, a residual dependence of the corrected isolation energy on the bunch position in the train is observed, due to the impact of pile-up from neighbouring bunches convolved with the LAr calorimeter pulse shape.

Calorimeter bipolar pulse shape: average pile-up is zero over ~ 600 ns (~12 bunches)

Effect well described by the (detailed !) ATLAS simulation
5 methods of Higgs production

- $p p \rightarrow H$
- $p p \rightarrow q \bar{q} H$
- $p p \rightarrow W, Z H$
- $p p \rightarrow t \bar{t} H$
MSSM Higgs -> tautau

$e + \mu$

$\mu$ channel

$\ell + h$

$\ell_{\text{had}} + \mu_{\text{had}}$

$\tau_{\text{had}} + \tau_{\text{had}}$

$\tau_{\text{had}} + \tau_{\text{had}}$

$\ell + h$

$m_{\tau\tau}$ effective [GeV]

$\tau_{\text{had}} + \tau_{\text{had}}$

$\ell + h$

MMC $m_{\tau\tau}$ [GeV]

$h + h$

Events / 10 GeV

Events / 15 GeV

$\sqrt{s} = 7 \text{ TeV}, \int L = 1.06 \text{ fb}^{-1}$

$\sqrt{s} = 7 \text{ TeV}, \int L = 1.06 \text{ fb}^{-1}$

$\sqrt{s} = 7 \text{ TeV}, \int L = 1.06 \text{ fb}^{-1}$

ATLAS Preliminary

ATLAS Preliminary

ATLAS Preliminary

I+h dominates the limit

High $\tan \beta$ region excluded

Nice demonstration of tau trigger and reco abilities

Paul D. Jackson