Life at LHC in 2012

Candidate Z boson event  25 reconstructed vertices
# ATLAS and CMS Comparison

<table>
<thead>
<tr>
<th>Subsystem</th>
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<td>Pixel &amp; Si strips - Part. ID dE/dx $\sigma_{pT}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$</td>
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<tr>
<td>EM CAL</td>
<td>Pb-LAr Sampl. – longitudinal seg. $\sigma_E/E \sim 10%/\sqrt{E} \oplus 0.7%$</td>
<td>Pb Tungstate Cryst. – no long. seg. $\sigma_E/E \sim 3%/\sqrt{E} \oplus 0.5%$</td>
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<td>HCAL</td>
<td>Fe-Scint &amp; Cu-LAr fwd $\geq 11\lambda_0$ $\sigma_E/E \sim 50%/\sqrt{E} \oplus 3%$</td>
<td>Brass-Scint. $\geq 11\lambda_0$ tail catcher $\sigma_E/E \sim 100%/\sqrt{E} \oplus 5%$</td>
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<td>Air Core - drift tubes (stand alone) $\sigma_{pT}/p_T \sim 4%$ (at 50 GeV) $\sim 11%$ (at 1 TeV)</td>
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U. C. Davis  
May 22, 2012  
Henry Lubatti
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ATLAS Detector
- **Pixel Detector (Three layers - double sided)**
  - $|\eta| < 2.5$ with $\sigma_{r\phi} \sim 10 \, \mu m$, $\sigma_z \sim 115 \, \mu m$ (80M channels)
- **Semiconductor Tracker (SCT): single sided Si strips**
  - stereo pairs
  - Four barrel layers and 2x9 end-cap disks stereo
  - $|\eta| < 2.5$ with $\sigma_{r\phi} \sim 17 \, \mu m$, $\sigma_z \sim 580 \, \mu m$ (6.3M channels)
- **Transition Radiation Tracker (tracking and e/\pi separation)**
  - 73 barrel straw layers and 2x160 end-cap radial layers
  - $|\eta| < 2.0$ with $\sigma_{r\phi} \sim 130 \, \mu m$ (350k channels)
  - Average of 32 hits/track
- The ID is inside a 2 Tesla solenoidal magnetic field
Muon Spectrometer

Precision Chambers
- Monitored Drift Tube (MDT) chambers in barrel and most of forward spectrometer
  - Barrel MDTs ~ 4.5, 7 and 10 m
  - Forward MDTs ~ 7.5 and 14 m
- MDT chamber has two multilayers (ML) with 3 or 4 layers of MDT tubes
- Multilayers separated: up to 32 cm

Cathode Strip Chambers (CSC’s) for 2.0 < η < 2.7
- Resolution
  \[ \sigma_{p_T/p_T} \approx 4\% \text{ at } 50 \text{ GeV} \]
  \[ \approx 11\% \text{ at } 1 \text{ TeV} \]

Trigger Chambers
- RPC’s in barrel region \(|\eta|<2.4\) and TGC’s in Forward region \(2.0 < |\eta| < 2.7\)
- Trigger chambers provide second coordinate (ϕ) for track reconstruction

Air core toroidal magnetic field allows - stand-alone momentum measurements
Muon Spectrometer

Cross-section of the barrel MS (non-bending plane), showing the three concentric cylindrical layers of eight large and eight small chambers. OD is about 20 m

Cross-section MS in bend plane showing the three muon stations.
**MDT Chambers**

- MDT Chamber has two multilayers with three or four layers of drift tubes
- Tubes 30 mm diameter operating at 3 bar absolute
Calorimeters

- Electromagnetic Calorimeter (ECAL)
  - Lead accordion with liquid argon - uniform
  - Three longitudinal segments

- Hadronic Calorimeter (HCAL)
  - Barrel Fe Scintillator plates with polystyrene
  - Forward Cu Liquid Ar

- Barrel Dimensions
  - ECAL 1.1m < r < 2.25m
  - HCAL 2.25m < r < 4.25m
Features of Atlas Calorimeter

- Low energy hadronic jets with 50 to 100 GeV deposit most of the energy in the EM calorimeter material in ID plus ECAL.
- This feature used by ATLAS to search for long-lived particles that decay to hadron jets in HCAL.
- More later in the talk.
EM Calorimeter

Barrel Segmentation

Cumulative Material in units of $X_0$

U. C. Davis
May 22, 2012

Henry Lubatti
Photon ID based on longitudinal and lateral segmentation of the ECAL (shower shapes)

High granularity in S1 results in good rejection efficiency for $\pi^0 \rightarrow \gamma \gamma$

Photon direction from shower centroids in layers 1 & 2 gives longitudinal (z) position

For two $\gamma$ (cf. $H \rightarrow \gamma \gamma$) combine to improve z resolution of vertex

Get $\gamma$ direction in layers 1 & 2 for each $\gamma$ and get z find z of primary vertex (IP).

Vertex with pointing ~1.6-1.8 cm (without 5.6 cm)
Triggers

Level 1 (hardware)
- Uses Calo cells with reduced granularity and muon chambers e, μ, γ, τ, jet candidates
- Defines Regions of Interest (RoI)
- ~40 MHz
- ~300 Hz
- Latency ~2.5 ms
- Execution Time ~10 ms

Level 2
- Seeded by LVL 1 RoI
- Full granularity of the detector
- Performs Calo-track matching
- ~50 kHz
- ~5 kHz

High Level Trigger (HLT)
- Offline-like algorithms
- Refines LVL 2 decision
- Full event building
- ~1 s
### Triggers

#### Level 1
- Corse CAL & Muon Spectrometer granularity and no ID tracking
- Identifies Regions of Interest (RoI) for further processing at Level 2

#### Level 2
- The full detector granularity in RoI region
- Full tracking in RoI and all tracks required to connect to the Interaction Point
- Only one muon per RoI is reconstructed
Muon Level1 Trigger

- based on three trigger stations
- The algorithm requires a coincidence of hits in the different trigger stations
- Defines a road: tracks the path of a muon from the interaction point through the detector.
- Width of the road depends on the $p_T$ threshold.
L1 Muon Trigger Efficiency

L1 muon trigger efficiency - Barrel

L1 muon trigger efficiency - Forward
Level2 Triggers

- Both IP centric and muon stand alone triggers
- MSonly triggers (Muon stand alone triggers)
- Used in many analyses including long-lived decays of dark photons to lepton-jets
  - 3mu6_MSonly used to select decays to long-lived muon jets
  - 2mu6_MSonly_g10_loose used for selection of displaced decays to lepton jets (electrons/muons)
- Hidden Valley triggers
  - Select decays of neutral particles to hadron jets
Good understanding of material distribution from $\gamma$ conversions

Photon energy scale calibration from global fit to the 2011 data $Z \rightarrow e^+e^-$
Triggers

- ATLAS triggers were designed to be IP centric and generally require a connection to the IP (b-tagging an exception)
- But many extensions of the SM models have suggested the possibility of long-lived neutral particles with a wide range of lifetimes, final states and production mechanism*
- New triggers needed to select such events

Long-lived Decays

- Hidden Valley (HV) Scenarios in which a new, hidden sector is weakly coupled to the Standard Model through a communicator (Higgs, $Z'$, ...) used to benchmark triggers and for first search.
- Mixing between the SM and hidden sector Higgs boson.

- Long-lived particles $h_v \rightarrow \pi_v \pi_v \rightarrow b\bar{b} b\bar{b}$
- Life-time of $\pi_v$ unspecified by model
- First analysis searched for two displaced decays at end of HCAL or in MS.

Long-lived Particle Triggers

Signatures for displaced decays of neutral particles to $q\bar{q}$

Decays in or beyond ECAL gives $E_{HAD}/E_{EM}$ ratio larger than observed for jets originating at IP

L2 Trigger Object

Decays near end of HCAL & before 1$^{st}$ muon trigger plane give hadron clusters in small $\Delta R(\eta,\phi)$ region of muon spectrometer and L1 muon trigger returns multiple RoIs in this small $\Delta R$ region

L2 Trigger Object
**Long-lived Particle Triggers**

**Signature driven triggers**

- **Muon Spectrometer RoI cluster trigger**
  - Selects decays inside of MS (only active in barrel)
  - Events with at least 3 muon RoI’s in \( \Delta R < 0.4 \) cone
  - Isolation
    - Jets with \( E_T > 35 \) GEV in \( \Delta R < 0.4 \) around cluster center
    - ID tracks \((p_T > 5 \text{ GeV})\) in \( \Delta \eta \times \Delta \phi = 0.2 \times 0.2 \)

- **Calorimeter energy ratio trigger \((E_{\text{HAD}}/E_{\text{EM}})\)**
  - Selects decays at end of \( E_{\text{CAL}} \) or in \( H_{\text{CAL}} \)
  - \( \log[ E_{\text{HAD}}/E_{\text{EM}} ] > 1.2 \)
  - Isolation
    - No tracks > 1 GeV in \( \Delta R = 0.2 \) cone around the jet axis

- **Trackless jet trigger (decays in ID...)**
  - \( \mu \)-jet matching in \( \Delta R = 0.4 \)
  - Isolation: No tracks > 0.8 GeV in \( \Delta R = 0.2 \) around jet axis

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**Increasing proper decay length**

- 4 – 7 m
- 2 – 3 m
- 0.5 – 3 m
Long-lived Particle Triggers

Signature driven triggers

- **Muon Spectrometer RoI cluster trigger**
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  - Isolation
    - Jets with $E_T > 35$ GEV in $\Delta R < 0.4$ around cluster center
    - ID tracks ($p_T > 5$ GeV) in $\Delta \eta \times \Delta \phi = 0.2 \times 0.2$

- **Calorimeter energy ratio trigger ($E_{HAD}/E_{EM}$)**
  - Selects decays at end of $E_{CAL}$ or in $H_{CAL}$
  - $\log[E_{HAD}/E_{EM}] > 1.2$
  - Isolation
    - No tracks > 1 GeV in $\Delta R = 0.2$ cone around the jet axis

- **Trackless jet trigger (decays in ID...)**
  - $\mu$-jet matching in $\Delta R = 0.4$
  - Isolation: No tracks > 0.8 GeV in $\Delta R = 0.2$ around jet axis
Decay probabilities

- Probability for a $\pi_v$ to decay in each of the detector regions as a function of the $\pi_v$ proper decay length
- Depends on boost (masses of decaying particles)
- Generator level simulation of $h_v \rightarrow \pi_v \pi_v \rightarrow b\bar{b} b\bar{b}$

$m_h = 120 \text{ GeV/c}^2, m_{\pi_v} = 40 \text{ GeV/c}^2$

$m_h = 140 \text{ GeV/c}^2, m_{\pi_v} = 20 \text{ GeV/c}^2$

- Probability for decay in barrel and forward detectors ($|\eta| \leq 2.5$)
Fraction of $\pi_v$'s that decay at a given radius that result in a trigger

Trigger is 40 - 50% efficient in barrel MS

Lower efficiency for $m_h = 120\text{ GeV}/c$, $m_{\pi_v} = 40\text{ GeV}$ result of kinematics and trigger timing ($\pi_v$ arrives in next BC)
Search for Long-lived Particles in MS

Standalone MS vertex routine developed for displaced vertices in the MS

MC event shown with tracklets and reconstructed vertex

Reconstructed tracklets

8 m

6 m

5.3 m

Simulation

ATLAS

http://atlas.ch

True vertex position

Reconstructed Vertex position

MDT hits
Reconstruct single segments from $\geq 3$ MDT hits
- Segments pointing to second ML kept if $\chi^2 > 5$
- No $\phi$ information (too many hits in RPC's)
ML separation gives powerful handle for pattern recognition

Tracklets reconstructed by matching segments using the two parameters $\Delta b$ and $\Delta \alpha$
- $\Delta b$ is distance of closest approach at the mid-plane of MDT chamber
- $\Delta \alpha$ is amount of bending in the chamber and combined with the average magnetic field gives a measure of the tracklet momentum with uncertainty $\Delta p/p \approx [0.06 - 0.08]p$
Long-lived Particle Triggers

- Vertex resolution in the barrel MS is approximately 20 cm in $z$ and 30 cm in $R$
- Reconstruction efficiency
  - 40% in barrel MS
  - 50% in forward MS

Powerful tool for rejecting QCD jets punch through backgrounds
Analysis Strategy

- Search for events where two decays occur in the MS where one decays in the barrel
- Only events passing the Muon RoI cluster trigger
- Final event selection requires two good MS vertices separated by $\Delta R > 2$ (back-to-back)
- Each vertex required to
  - Point to the IP (sum of tracklet $p_z$ points to IP)
  - MDT and RPC/TGC hits in cone centered on vertex be in the range $200 \leq N_{MDT} \leq 3000$ and $N_{RPC/TGC} \geq 100$
  - Isolation: jets with $E_T \geq 15$ GeV and $\log_{10}[E_{HAD}/E_{EM}] \leq 0.5$
  - Vertex in the ID tracking volume - $|\eta_{vx}| < 2.2$
  - Isolation: ID tracks with $p_T \geq 5$ GeV
Expected number of $h^0 \rightarrow \pi_v \pi_v$ events, with two isolated MS vertices for an integrated luminosity of 1.94 fb$^{-1}$, as a function of the $\pi_v$ lifetime assuming 100% branching ratio for $h^0 \rightarrow \pi_v \pi_v$. 

**Expected decays**
Results

- No events in 1.94 fb\(^{-1}\) of 2011 LHC data pass the selection criteria requiring two back-to-back vertices in MS
- Expected background determined by data driven method: 0.03 ± 0.02 events

Limits

1. Expected number of signal events determined from trigger and reconstruction efficiencies
2. In essence, a counting experiment that is repeated for each \(\pi_V\) lifetime.
3. Take gluon fusion Higgs cross section (\(\sigma_{SM}\)) from LHC Higgs Cross Section Working Group, S Dittmaier, C. Mariotti, G. Passarino and R. Tanaka (Eds.) - CERN 2011-022
Limits

New

arXiv:1203.1303v2 accepted PRL

95% CL Limit on $\sigma/\sigma_{SM}$

$\int Ldt = 1.94 \text{ fb}^{-1}$

$\sqrt{s} = 7 \text{ TeV}$

ATLAS

95% CL Limit: $m_h=120 \text{ GeV}$, $m_{\chi} = 20 \text{ GeV}$

95% CL Limit: $m_h=120 \text{ GeV}$, $m_{\chi} = 40 \text{ GeV}$

95% CL Limit: $m_h=140 \text{ GeV}$, $m_{\chi} = 20 \text{ GeV}$

95% CL Limit: $m_h=140 \text{ GeV}$, $m_{\chi} = 40 \text{ GeV}$

$\pi_v \text{ proper decay length [m]}$
**Limits - summary**

- Observed no events in 1.94 fb\(^{-1}\) with back-to-back vertices in muon spectrometer
- Stringent exclusion limits obtained for \(\sigma_h \times \text{BR}(h^0 \rightarrow \pi_v \pi_v)/\sigma_{SM}\)
- Assuming 100% \(h^0 \rightarrow \pi_v \pi_v\) branching ratio we exclude \(\pi_v\) proper decay lengths in a broad range

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<th>(m_{\pi_v}) (GeV)</th>
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<tr>
<td>120</td>
<td>20</td>
<td>0.50 &lt; c(\tau) &lt; 20.65 m</td>
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<tr>
<td>120</td>
<td>40</td>
<td>1.60 &lt; c(\tau) &lt; 24.65 m</td>
</tr>
<tr>
<td>140</td>
<td>20</td>
<td>0.45 &lt; c(\tau) &lt; 15.8 m</td>
</tr>
<tr>
<td>140</td>
<td>40</td>
<td>1.10 &lt; c(\tau) &lt; 26.75 m</td>
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- **Model independent limits** on \(\sigma \times A \times \varepsilon_{\text{trig}} \times \varepsilon_{\text{reco}} < 3.6\) fb, where \(A\) is acceptance, \(\varepsilon_{\text{trig}}\) and \(\varepsilon_{\text{reco}}\) the trigger and reconstruction efficiencies
Contributors to first result

- University of Washington
  - HL, Dan Ventura*, A. Policicchio*, G. Watts
- University of Rome (La Sapienza)
  - G. Ciapetti, S. Giagu
- Matt Strassler (during initial stage)

* PhD thesis, now at U. Mass. Amherst
* Now at Università della Calabria (Italy)
Long-lived Particle II

- Currently working on search for decays at end of ECAL or in HCAL
- Large energy deposition in HCAL
- Little or no energy in ECAL
- Jets with no tracks reconstructed in ID with \( p_T > 1 \text{ GeV} \)
- Suggests ratio \( E_{\text{HCAL}}/E_{\text{ECAL}} \) may be good trigger object
\[ \log_{10}[E_{\text{HAD}}/E_{\text{EM}}] \]

- Normal Low \( p_T \) b-jets from IP or ID loose most of energy in \( E_{\text{CAL}} \) - \( \log_{10}[E_{\text{HAD}}/E_{\text{EM}}] \approx -1 \)
- BUT jets from \( \pi_v \) decays at end of \( E_{\text{CAL}} \) and beyond have \( \log_{10}[E_{\text{HAD}}/E_{\text{EM}}] \approx 1.5 \) - Trigger object at Level 2


**Efficiency**

- Efficiency 40 to 50% in barrel
- In Forward region about 15 - 20%

![Graphs showing efficiency vs. radius and distance](image_url)
Decays in $H_{\text{CAL}}$

- Currently completing this analysis on the full 2011 data set $\sim 4.6 \text{ fb}^{-1}$
- Do not have vertex handle to reduce backgrounds from QCD jets
- Require coincidence of two Cal Ratio triggers or one Cal Ratio trigger and a “trackless jet”
- Data driven background estimates
ATLAS Upgrades and LHC Shutdowns

- **Shutdown ~ 1 December 2012**
  - Ends 31st July 2014 (about 20 months)
  - *Machine development (13-14 TeV) operation to end 2014*

- **Phase 0 ATLAS upgrades**
  - **IBL (Insertable B Layer)**
    - 14 staves, located at $r \approx 33.4$ mm
    - loaded with silicon sensors new front-end (IC) FE-I4 *
    - Current pixels layer 1 at 50.5 mm (cf slide 5); nominal insertion clearance is about 2 mm radially

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Phase 0 Upgrade 2013-14

- Phase 0 activities

- Be Beam pipe
- AL VA, VT beam pipes
- IBL INSERTABLE B-LAYER
- nSQP/Pixel
- new diamond det. for monitors
- new evaporative cooling plant
- new CO2 IBL cooling plant
- remove MB scint, restore tiles readout
- new LVPS for LAr
- new LVPS for Tiles
- repair several Tiles drawers (connectors)
- finish EE installation
- RPC feet chambers electronics installation
- MDT+RPC chambers in sect 13 elevators
- substitute few TGC chambers in the BW
- new He dryer for magnet main refrigerator
- new redundant compressor for the main refriger.
- new He tank for Solenoid transfer line
- various electrical, vacuum and mechanical magnet consolidation
- new neutron shielding on the toroid endcap
- new neutron shielding wall UX15/USA15
- various access platforms (permanent, temporary, movement system,..)
- new visitors passage (cage)
- tool for removing at once the lower part of the JF
- interface FTK- SCT-PIXEL (Fast TracKer)
The longer term

- **Shutdown ~ 2018**
  - Upgrade for luminosities of \(>10^{34}\text{cm}^{-2}\text{s}^{-1}\)

- **Phase 1** ATLAS upgrades - active discussion and planning currently (examples)
  - New muon small wheel to replace CSCs
  - Target is to implement full digital read-out of the calorimeter at 40 MHz

- **Phase 2 (2022-2023)**
  - Major changes to tracking system \(5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}\) operation
  - Replace the complete strip detector system
    - electronics and sensors with finer granularity
    - greater radiation tolerance.
    - Project has such a large lead-time that it already is taking considerable R&D resources