Searches for
long-lived particles with ATLAS

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UMass Amherst,
November 12th 2015
Introduction & Outline

• Signature-based review of BSM long-lived particles (LLP) searches in ATLAS

• Based on $\sqrt{s}=8$ TeV results (~all published, references therein)
  – Some earlier results may still be relevant(?), but not covered here

• Highlight experimental challenges and strengths of the detector

• No attempt to give details for each specific analysis
  – Especially if covered by a dedicated talk later in the workshop
  – List examples of benchmark models used, but won't be comprehensive
  – Highlight (attempt of) model-independence when possible

• Ending with a quick look at the future
**Direct** detection

- Through direct interaction with detector
- Energy loss, TOF, special track properties, …
- Mostly fit charged LLP

**Indirect** detection

- Through SM or invisible decay products
- “Isolated” activity inconsistent with prompt or expected instrumental / SM
- Natural fit for neutral LLP, but also sensitive to charged ones

- Various sub-detectors are sensitive to different life-time ranges
Direct detection

- Plot: lifetimes for which 20% decays after the outer radius of the sub-detector
**Direct detection**

- Plot: lifetimes for which 20% decays after the outer radius of the sub-detector

**Indirect detection**

- Plot: lifetimes for which 20% of decays within the inner/outer radius range of the sub-detector
The (non-obvious) ATLAS detector

**Ionization loss**: charge measured by:
- Pixel system
- Transition-Radiation Tracker (TRT)
- Monitored drift-tubes (MDT) in the muon system

**Time of flight**: time of arrival by
- Electromagnetic (EM) and Hadronic Calorimeters
- Muon system

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**Graph 1**: 
- ATLAS Preliminary
- Good Pixels & Barrel Only

**Graph 2**: 
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**Graph 3**: 
- ATLAS 13 = 8 TeV
- Ldt = 20.3 fb⁻¹
- EMB h·l·o·t = 0.4, High gain = 1.758 μ, 0.256
- EMB h·l·o·t = 0.4, Medium gain = 2.55 μ, 0.299

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### Outline of ATLAS searches

<table>
<thead>
<tr>
<th></th>
<th>ID</th>
<th>Calo</th>
<th>MS</th>
</tr>
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<tbody>
<tr>
<td><strong>Direct detection</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disappearing Track</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large ionization deposits</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Time-of-flight measurements</td>
<td></td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Prompt analysis (jets+E&lt;sub&gt;T&lt;/sub&gt;)</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Displaced vertices</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Non-prompt/delayed photons</td>
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<td>✓</td>
<td></td>
</tr>
<tr>
<td>&quot;Isolated&quot; jets</td>
<td></td>
<td>✓</td>
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</tr>
<tr>
<td>Collimated lepton-jets</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Indirect detection</strong></td>
<td></td>
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</tbody>
</table>
Experimental challenges

- Some signatures can't be exploited at trigger-level directly
  - Need rely on “collateral” features of the event (e.g. ISR, $E_T$, ..)
  - Develop dedicated trigger chains

- Many analyses targeting LLP require “non-standard” techniques
  - Detailed (low-level) detector information
  - Specific tracking setup to reconstruct highly displaced tracks
  - Custom vertexing algorithms for very displaced vertices
  - Careful balance of CPU timing and disk-space required

- Detector efficiency model-dependent
  - Limit by careful choice of fiducial region
  - What benchmark to provide
  - How to allow re-interpretation / boundaries?
Disappearing track

- Charged particle decaying within the ID into un-detected products
  - Manifest as “short” track
- Requires hard ISR to trigger: $E_T + \text{jet}$
- Isolated high-$p_T$ (> 75 GeV) track with at most few hits in the TRT
  - Dedicated tracking setup required
- Results by fitting $p_T$ spectrum
  - Main background at high-$p_T$: mis-measured tracks (data-driven)

- Signal model: AMSB SUSY
  \[ pp \to \tilde{\chi}^0_1 \tilde{\chi}^\pm_1 + \text{jet} \]
  \[ pp \to \tilde{\chi}^\pm_1 \tilde{\chi}^0_1 + \text{jet} \]
- 2-tracks signal region investigated
Large ionization tracks

- Heavy (→ slow) charged particles produce large ionization loss
  - Pixel detector provides accurate measurement; stability with p mass
- Trigger through calorimeter $E_T$
- Isolated high-$p_T$ (>80 GeV) track with large energy loss (dE/dx)
  - Background from hadrons and leptons in the tails of dE/dx (data-driven)

- Limits set for benchmark scenarios:
  - $\tilde{g}/\tilde{b}/\tilde{t}$ Stable R-hadrons, “stable” $\tilde{\chi}^\pm$
  - $\tilde{g}$ R-hadrons varying lifetime/mass/decay
    - Decay hypothesis vary limits to some extent
  - $\tilde{\chi}^\pm \to \tilde{\chi}^0 \pi^\pm$ (same as disappearing tracks)
- $\sigma$ vs mass, mass vs lifetime

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Large ionization tracks

- Multiply charged particles also produce larger ionization loss

- Search for **monopoles**
  - stop in EM calorimeter (special trigger)
- Analysis based on TRT high-threshold hits, no energy in calorimeter past first layers ($w$)
- Fiducial phase space defined to have uniform and > 90% efficiency
  - depends on material traversed

- Search for **multiply-charged particles**
  - Stable within ATLAS detector
- Combine Pixel, TRT and muon dE/dx measurements, depending on charge
  - Note: energy loss in calorimeter $\mu z^2 (q=ze)$
- Benchmark: Drell-Yan like pair production
  - $\sigma$ vs mass limits; $q=ze$, $z=2-6$
• Heavy charged particles travel with $\beta = v/c < 1 \rightarrow$ detect with TOF
  – Combine with information on ionization loss ($dE/dx$ from pixel detector) → $\beta \gamma$
• Average time measurements from calorimeter and muon system
  – Calibrated using $Z \rightarrow \mu\mu$, ad-hoc tracking setup to correctly associate hits in cases where $\beta \ll 1$
• Trigger on single-muon or calorimeter $E_T$
• Background mainly from muons with mis-measured $\beta$ or high $dE/dx$
  – Mostly rejected requiring consistency among independent detectors
  – Residual background estimated from random combination from the $\beta$ and momentum distributions measured in suitable regions

$$m = p/\beta \gamma$$
• Three sets of signal regions, selections targeted for each one

• Sleptons in GMSB (\(\tilde{\ell}_1\) NLSP) or LeptoSUSY simplified model (\(\tilde{\ell}\) degenerate, \(\tilde{\chi}^0\) LSP)
  - Investigate 1 and 2-tracks signal in both ID and muon system

• Charginos nearly mass degenerate with LSP (almost pure neutral wino) \(\epsilon \sim 15\% + 5\%\)
  - Investigate 1 and 2-tracks signal; expect significant \(E_T\) when \(\chi^\pm \chi^0\) production

• Squarks and gluinos forming R-hadrons
  - Use full detector or ignore muon system (charge → neutral interacting with calorimeter)
  - Optimized separately for gluino/stop/sbottom \(\epsilon \sim [10\%, 20\%]\)
Example of summary plot for a specific (SUSY) benchmark model

Useful for us for a quick overview, but need consistent benchmarks
• Re-interpret prompt analyses to target gluinos with ~short lifetime (~ < 1ns)
  – Actual sensitivity extends also for longer lifetimes
• Standard jets+$E_T$ analysis provides significant constraints
• Lepton and b-jet identification non-optimal for displaced decay

\[ \tilde{g} \rightarrow q\bar{q} \tilde{\chi}_1^0 / g \tilde{\chi}_1^0 \quad m(\tilde{\chi}_1^0)=100 \text{ GeV} \]
Displaced vertices

- Aim to reconstruct explicitly displaced decays of LLPs
  - Ad-hoc tracking (large $d_0$ tracks), veto known material (had. interactions)
  - Background: accidental crossing, merged vertices, jets punch-through

Inner-Detector analysis

- Multi-track: displaced vertex with either one $e, \mu, E_T$ or jets
- Di-lepton: displaced vertex from opposite charge $ee, \mu\mu$

Inner-Detector + Muon system analysis

- Dedicated muon-trigger for displaced vertices in the MS
  - Also using jet+$E_T$ trigger
- Two-vertices signal region
  - Aim for large efficiency

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Applicable topologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon RoI Cluster</td>
<td>IDVx+MSVx, 2MSVx</td>
</tr>
<tr>
<td>Jet+$E_T^{miss}$</td>
<td>2IDVx, IDVx+MSVx, 2MSVx</td>
</tr>
</tbody>
</table>
Indirect Detection

**Displaced vertices**

**Inner-Detector analysis**
- RPV, GMSB: $\tilde{\chi}^0 (N)$LSP long-lived
- Split-SUSY: $\tilde{g}$ into R-hadron

**Inner-Detector + Muon system analysis**
- Hidden Valley, $\Phi$ or $Z'$ mediator
- Stealth SUSY

- Non-trivial efficiency dependence on mass, boost, multiplicity, …
  - Weak dependence on originating particle given the above

Results presented for benchmark models as function of
- lifetime
- mass spectrum
- final state
• Nice complementarity of analyses shown in example SUSY benchmark summary plot (gluino R-hadron)
Non-prompt photons

- 2 photons pointing away from interaction and delayed in time
  - Additionally require $E_T^\gamma (>75$ GeV), low $E_T^\gamma$ region as control region
- Main background from prompt $\gamma$, jets
- Use calorimeter timing ($t_\gamma$) and pointing from shower profile ($z_{DCA}$)

<table>
<thead>
<tr>
<th>$\tau$ [ns]</th>
<th>$\Lambda = 80$ TeV</th>
<th>$\Lambda = 160$ TeV</th>
<th>$\Lambda = 320$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>8.4 ± 0.6</td>
<td>30 ± 1</td>
<td>46 ± 2</td>
</tr>
<tr>
<td>2</td>
<td>5.1 ± 0.3</td>
<td>21 ± 0.2</td>
<td>33.0 ± 0.3</td>
</tr>
<tr>
<td>6</td>
<td>1.7 ± 0.1</td>
<td>7.3 ± 0.1</td>
<td>12.5 ± 0.2</td>
</tr>
<tr>
<td>10</td>
<td>0.86 ± 0.03</td>
<td>3.71 ± 0.06</td>
<td>6.45 ± 0.09</td>
</tr>
<tr>
<td>40</td>
<td>0.089 ± 0.004</td>
<td>0.38 ± 0.01</td>
<td>0.70 ± 0.02</td>
</tr>
<tr>
<td>100</td>
<td>0.016 ± 0.001</td>
<td>0.070 ± 0.002</td>
<td>0.129 ± 0.004</td>
</tr>
</tbody>
</table>

- Exponential due to acceptance of decay before calorimeter
- Smaller $E_T^\gamma, E_T^\gamma$
- GMSB(SPS8), $\tilde{\chi}^0$ NLSP
- Limits on #events, $\sigma$
• Narrow jets in hadronic calorimeter with no activity before (EM+ID)
  – Well fit neutral LLPs, complements direct vertex reconstruction
• Dedicated trigger: narrow ($\Delta R=0.2$) jets with large $E_{\text{HAD}}/E_{\text{EM}}$ and no activity in ID
• $\geq 2$ jets required offline, low $E_T$
  – Loose timing requirement limits acceptance in $\beta$ (OK, for benchmark)
• Hidden Valley benchmark model with scalar communicator
• Acceptance 0.07%-0.6%, dominated by requiring both decays in calorimeter
• Limits on $\sigma(\Phi)\times\text{BR}(\Phi \rightarrow \pi \nu \pi \nu)$ for $m_\Phi$, $m(\pi \nu)$, $\tau(\pi \nu)$ hypotheses
  – Efficiency map vs $\pi \nu$ boost
**"Lepton"-jets**

- Collimated cluster of \( \mu/e/\pi \) (="jets")
  - Trigger: multi-\( \mu \) or jets in had. calorimeter
  - "Lepton"-jet types: 4\( \mu \), 2\( \mu \) + 2 "jets", 4 "jets"
- e/\( \pi \) "jets" ~as previous slide
  - Sensitive to decays in had. calorimeter
- Muons reconstructed in MS only for high efficiency when displaced
- Multi-jet and cosmic rays backgrounds data-driven

- Benchmark model: Higgs decaying to hidden sector, displaced decay of a light dark-photon (\( \gamma_D \))
  - \( H \rightarrow 2\gamma_D + X \), \( H \rightarrow 4\gamma_D + X \)
  - Efficiency depends strongly on number of \( \gamma_D \), decay length and angular distribution
Very-long lived R-hadrons

- Use bunch-structure of LHC: R-hadrons that decay in the calorimeter after a “long” time (jet+$E_T$ from $\tilde{\chi}^0$)
- Dedicated trigger; $\geq 1$ calorimeter jet (but $\leq 5$), no MS activity
  - Additionally, $E_T$ and loose jet shape requirements
- Main backgrounds: cosmic rays, beam halo
- Different models of R-hadrons and gluino-neutralino $\Delta M$ probed

![Graphs showing efficiency and gluino mass vs. neutralino mass](image-url)
• Very broad overview of lifetime sensitivity ranges
A brief look at the future

- Obvious: 7 TeV → 13 TeV :-)
- Key upgrades can help in LLPs searches
  - New pixel layer: IBL
    - E.g. better dE/dx measurement
  - L1 Topological trigger
    → correlation of L1 trigger primitives

![Graph showing fraction of tracks vs. dE/dx for different triggers](image-url)
A brief look at the future

- Obvious: 7 TeV → 13 TeV :-)  
- Key upgrades can help in LLPs search
  - ✓ New pixel layer: IBL
  - ✓ L1 Topological trigger
  - FTK to be commissioned during Run-2 → full-tracking in-between L1 and HLT
    - but tracks reconstructed tightly pointing to interaction region
  - Software and tracking algorithms speed-up a factor of 4, re-invest part of the gain
Conclusions (/Opening)

- A variety of complementary methods used in run-1 to hunt for LLPs

- Many of these analyses used the ATLAS detector in unique ways
  - Always looking for new innovative ways to hunt signatures that are theoretically well motivated and presently not fully covered

- Already towards end of Run-1, more systematic attempt to provide efficiency maps with results in simplified/benchmark models
  - However, very large model dependences are often found
  - How to specify “boundaries”?

- Looking forward to a fruitful workshop!
Including IBL in Overflow Tracks

ATLAS Preliminary

Pixel Only
Pixel+IBL
$\sqrt{s} = 13$ TeV

Fraction of tracks

$dE/dx$ [MeV g$^{-1}$ cm$^2$]