Search for long-lived particles with the ATLAS detector
Overview of talk

- Introduction to LLP search motivations and typical signatures
- Outline of recent analyses performed using run-1 data at ATLAS
  - Mostly concentrate on decay length covered by each analysis
- Description of challenges with triggering for such analyses
  - Introduce some new solutions being worked on for run-2
Long-lived particle searches

- Many proposed extensions to the Standard Model predict new massive particles with measurable lifetimes.
  - SUSY, Hidden Valley, Extra Dimensions, Monopoles, etc.

- Exotic particle lifetime can originate from various features of the model
  - Signature depends greatly on particle lifetime, mass and charge
  - => LLPs subject of many different searches at the LHC detectors.

- Usually more useful to talk about proper decay length ($c\tau$) than lifetime
  - Typical signatures searched for:

<table>
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<th>Short decay length (~10 - 100mm)</th>
<th>Medium decay length (~0.1 - 1m)</th>
<th>Long decay length (&gt;~1m)</th>
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<td>Disappearing/Kinked track</td>
<td>Stable massive particle</td>
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<td>secondary vertex</td>
<td>$\pi^+/e^+$</td>
<td>low $\beta$</td>
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<td>primary vertex</td>
<td>Missing momentum</td>
<td>high dE/dx</td>
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<tr>
<td>LLP</td>
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<td>Stoped heavy particle</td>
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Physics models

- Long lived particle lifetimes may originate from:
  - Low coupling between the LLP and the next state
  - Decay via a heavy virtual particle
  - Approximated mass degeneracy between the two states

- Some examples:
  - Neutralinos in various R-Parity Violating (RPV) SUSY scenarios
  - V-hadrons in Hidden Valley (HV) models
  - Chargino in Anomaly Mediated SUSY Breaking (AMSB)
ATLAS detector

- A general purpose detectors on the LHC consisting of concentric cylinders of different detector systems.
- From innermost to outermost:
  - Inner Detector (tracking) (ID)
  - Electromagnetic calorimeter (EMCal)
  - Hadronic calorimeter (HCal)
  - Muon spectrometer (MS)

- Charged particle momentum is measured in the ID and MS through track bending in magnetic fields.
<table>
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<th>Recent ATLAS analyses</th>
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Two ATLAS searches for promptly decaying SUSY are re-interpreted in the context of models with metastable (\(\sim\)ps – ns lifetime) gluinos

- **“7 – 10 jets” analysis**
  - 19 signal regions based on: \([7, 8, 9, \geq 10]\) jets, \([0,1, \geq 2]\) b-tagged jets, \(E_T^{miss}\)

- **“2 – 6 jets” analysis**
  - 15 signal regions based on: \([2, 3, 4, 5, \geq 6]\) jets, \(E_T^{miss}\)

Decay models considered

- stop is lightest squark
  - \(\tilde{g} \rightarrow t\tilde{\chi}_1^0\)

- squarks are mass degenerate
  - \(\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0\)
  - \(\tilde{g} \rightarrow g\tilde{\chi}_1^0\)
Metastable Gluinos

- For $ttbar$ decay model both analyses can be used to set limits
- For $qqbar/g$ model the “7-10 jets” analysis has no sensitivity
  - Jet multiplicity is too low
- No decrease in acceptance for short $c\tau$
  - Analysis does not use effect of vertex displacement as a handle
- Longer $c\tau \Rightarrow$ lower acceptance
  - Low reconstruction in Inner Detector for more displaced vertices
Muon + Displaced vertex

- Analysis conducted in the framework of long-lived neutralino decay in RPV SUSY
  - Search for displaced vertices inside the ID

- Vertex requirements:
  - Must be inside Inner Detector fiducial region, but transversely **displaced** from Primary Vertex
    - \((r_{DV}<180\text{mm}, |z_{DV}|<300\text{mm}, dr_{xy}>4\text{mm})\)
  - Must have matching high \(p_T\) **displaced** muon candidate
    - \((p_T>55\text{GeV}, |d_0|>1.5\text{mm})\)

- Signal region for search requires:
  - High vertex mass to reduce background
  - High number of tracks to reduce fake vertex rate
  - No events are observed in the signal region
Muon + Displaced vertex

- Result is interpreted against 3 benchmark points:
  - **MH**: medium-mass squark, heavy neutralino
  - **ML**: medium-mass squark, light neutralino
  - **HL**: heavy squark, light neutralino

- The effectiveness of this analysis is strongly linked to DV reconstruction efficiency
  - => Most effective at $c\tau \approx 10\text{mm}$

- Shorter $c\tau$: Vertex and muon displacement requirements decrease acceptance
- Longer $c\tau$: Fiducial region requirement decreases acceptance
Long-lived neutral particles

- In model considered; a Higgs boson decays to two long-lived neutral particles ($\pi_v$), which each decay to an $f\bar{f}$ pair.

- Events are selected using the specialist LLP Cal-ratio trigger:
  - searches for jets with high HCal:EMCal energy deposition ratio

- Require exactly 2 jets with:
  - Both jets:
    - $\log_{10}(E_H/E_{EM}) > 1.2$
    - No good tracks in ID with $p_T > 1 \text{GeV}$
  - At least one jet matching the Cal-ratio trigger
  - Leading jet $E_T > 60 \text{GeV}$
Long-lived neutral particles

- No excess observed over SM background expectation
- Analysis acceptance requires that DV is inside the Calorimeter system
  - Shorter $\tau$: jets deposit energy in EMCal, H:EMCal ratio is low
  - Longer $\tau$: no energy deposition in either calorimeter
- Exclusion strength approximately matches acceptance
  - Most effective at $\tau \approx 0.5 - 2m$
Displaced lepton-jets

- Two models where Higgs boson decays into a hidden sector
  - The resulting shower ends with dark photons ($\gamma_d$) and Hidden Lightest Stable Particles (HLSP)
  - Dark photons decay into SM lepton/pion pairs, leading to 3 main signature types:
    - TYPE0: All $\gamma_d$ decay to $\mu^+\mu^-$
    - TYPE1: $\gamma_d$ decay to $\mu^+\mu^-$ and $e^+e^-/\pi^+\pi^-$
    - TYPE2: All $\gamma_d$ decay to $e^+e^-/\pi^+\pi^-$

- Events are obtained with:
  - Multi-muon trigger for decays to $\mu^+\mu^-$
  - Calorimeter ratio trigger for $e^+e^-/\pi^+\pi^-$ decays
Displaced lepton-jets

- **Short $c\tau$:** Low acceptance due to requirements that:
  - $\mu$ have no associated inner tracks
  - Inner Detector activity is low inside jet cone
  - EMCal deposition is low for $e^+e^-/\pi^+\pi^-$ jets

- **Long $c\tau$:** Low acceptance due to $\gamma_d$ leaving the detector fiducial region

- **Best acceptance at** $c\tau \approx 50$mm
Non-pointing photons

- GMSB model where $\tilde{\chi}_1^0$ decays to $\tilde{G} + \gamma$
  - Results in events with two displaced $\gamma$ and $E_T^{\text{miss}}$
  - $\Rightarrow$ Search for $\gamma$ that:
    - Do not point back to Primary Vertex
    - Have delayed detection time

- Search is performed by fitting pointing and timing distribution templates from MC simulations of signal to data
  - **Signal region from** $E_T^{\text{miss}} > 75\text{GeV}$ events
    - Background is modeled from $E_T^{\text{miss}} < 20\text{GeV}$ events
    - Validation and control from $20\text{GeV} < E_t^{\text{miss}} < 75\text{GeV}$ events

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Non-pointing photons

- No evidence of non-pointing or delayed photons is observed in the signal region
- Analysis is most effective at $c\tau \approx 0.6m$
  - Shorter $c\tau$: Decreased change in pointing & timing distributions
  - Longer $c\tau$: DV is outside of EMCal

Results

arXiv:1409.5542
ATLAS is primarily designed to study particles produced at the Primary Vertex

=> Efficient triggering is a major issue for most LLP searches

Triggering in LLP analyses:
- Metastable Gluinos: Jet topology
- Muon + DV: Single high $p_T$ muon
- Displaced lepton jets: Multiple muons, Calorimeter ratio
- Long-lived neutral particle: Calorimeter ratio
- Non-pointing photons: High $E_T$ photon (special case)
- Mass degenerate charginos: Jet topology
- Heavy long-lived sleptons: Single high $p_T$ “muon” (actually the LLP)
- Stopped R-hadrons: Empty BCID jets (special case)

Most analyses **must** use models with triggerable topologies unrelated to the displaced decay

Exceptions: Calorimeter ratio trigger, Non-pointing photons, Stopped R-hadrons
Run-1 displaced vertex triggers

- Three triggers in run-1
  - Trackless jets trigger (discontinued for run-2)
  - Calorimeter ratio trigger
  - Muon RoI trigger
- All triggers search for signals in outer detectors with little or no signals inwards
- No trigger available for short ($c\tau < 0.1m$) decays
  - Only possible to perform analyses on processes with otherwise trigger-able final states
    - High $p_T$ muons
    - High $E_T$ photons
    - $E_T^{\text{miss}}$, jet topologies, etc.
- $\Rightarrow$ Displaced vertex trigger inside the inner detector highly desirable
Run-2 triggers

- Calorimeter ratio trigger will remain a useful trigger in run-2
  - Muon RoI will also probably see some use

- Other DV oriented triggers are based around muon and jet topologies

- With discontinuation of Trackless Jet trigger, no existing generic trigger for DVs inside the Inner Detector

- However, the new ATLAS Fast Tracker (FTK) system being deployed for run-2 may allow for an entirely new trigger:
  - FTK reconstructs tracks for use in the High Level Trigger (HLT)
  - FTK is essentially a look-up database, trained with known tracks
    - Can only be trained over given parameter ranges. As standard:
      - $|\eta| < 2.5$
      - $p_T > 1\text{GeV}$
      - $|z_0| < 100\text{mm}$
      - $|d_0| < 2\text{mm}$ (main limitation for DV work)
FTK DV trigger

- Two main DV trigger possibilities:
  - High $d_0$ trigger: Use custom database with enlarged $d_0$ range to search for displaced tracks.
  - No-inner-hits trigger: Search for tracks originating from a DV past the innermost Inner Detector layers.

Viable vertex “Signal Region”
Summary

- Some proposed extensions to the Standard Model predict exotic particles with measurable lifetimes
  - Leads to rich phenomenological possibilities at the LHC experiments

- The ATLAS Collaboration has performed numerous searches for evidence of such particles during run-1
  - Will continue to do so during run-2

- Effective triggers with which to acquire data for these searches are essential
  - Several existing methods for medium to long decay lengths
  - The new FTK system allows new possibilities for triggering on shorter decay lengths
Backup slides
Mass degenerate charginos

- Analysis considers AMSB models with mass degenerate charginos and neutralinos
  - Leads to chargino LLPs that “disappear”

- Search for tracks with:
  - Inner silicon detector: Well measured
  - Outer straw tracks (TRT): Low (<5) number of hits
  - Must be isolated, $p_T > 75$ GeV

- Background sources
  - Interacting hadrons
  - Non-identified leptons
  - Mismeasured $p_T$ tracks

- In this analysis results can be interpreted in terms of $\Delta m_\chi$ as well as $c\tau$

Excluded (in decoupled AMSB): $m_{\tilde{\chi}^\pm} < 270$ GeV
Analysis searches for charged LLPs with $c\tau > 1\text{m}$
- Interpreted in the context of a GMSB stau ($\tilde{\tau}_1^\pm$)

Directly reconstruct the LLP and measure $\beta$ and $\beta\gamma$
- $\beta\gamma$ from $dE/dx$ measurements in the pixel detectors
- $\beta$ from Time of Flight measurements in the calorimeter and MS

Require two LLP candidate tracks with $p_T > 50\text{GeV}$ and $\beta < 0.95$

Signal region is set by calculating candidate masses and applying a mass cut
- Cut value depends on $\tilde{\tau}_1^\pm$ mass in GMSB model being evaluated

Background is primarily muons with mis-measured $\beta / \beta\gamma$

The LLP must decay outside of the calorimeter in this analysis
- There is no upper limit on $c\tau$
Analysis considers long-lived R-hadrons that “stop” in the ATLAS calorimeter.

Search for jets in “empty” bunch crossings from R-hadron decays.

Require:
- Veto events with reconstructed muon segments
  - (Rejects cosmics)
- Veto events with spike-like signals in the calorimeter
  - (Rejects random noise, also effective against cosmics & beam halo)
- Leading jet $E > 50$ GeV, no more than 6 jets total
- $E_T^{miss} / [leading\ jet\ p_T] > 0.5$

<table>
<thead>
<tr>
<th>Leading jet $E$</th>
<th>Muon veto</th>
<th>Cosmic bkgd</th>
<th>Beam-halo bkgd</th>
<th>Total bkgd</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 GeV</td>
<td>No</td>
<td>$4820 \pm 570$</td>
<td>$900 \pm 130$</td>
<td>$5720 \pm 590$</td>
<td>5396</td>
</tr>
<tr>
<td>50 GeV</td>
<td>Yes</td>
<td>$2.1 \pm 3.6$</td>
<td>$12 \pm 3$</td>
<td>$14.2 \pm 4.0$</td>
<td>10</td>
</tr>
<tr>
<td>100 GeV</td>
<td>Yes</td>
<td>$0.4 \pm 2.7$</td>
<td>$6 \pm 2$</td>
<td>$6.4 \pm 2.9$</td>
<td>5</td>
</tr>
<tr>
<td>300 GeV</td>
<td>Yes</td>
<td>$2.4 \pm 2.4$</td>
<td>$0.5 \pm 0.4$</td>
<td>$2.9 \pm 2.4$</td>
<td>0</td>
</tr>
</tbody>
</table>

Excluded (depends on other parameters):
- $m_{\tilde{g}} < 545 \text{ -- } 832$ GeV
- $m_{\tilde{q}} < 344 \text{ -- } 397$ GeV