Search for New Physics through the Reconstruction of Challenging Signatures and for Long-lived particles with the ATLAS detector

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Introduction

- Many Beyond the Standard Model (BSM) theories predict atypical and unique signatures
  - These events often pose challenging to reconstruct
  - Detector responses to these signals are not what one would expect

- To this category belongs Long Lived Particles (LLP) of a wide range of lifetimes, particles with abnormal values of electrical charge and massive stable charged particles

- For example – an LLP decaying at a significant distance from the Interaction Point (IP) is strenuous for the tracking system
  - Standard tracking algorithms assume the particle trajectories arises from the IP
  - Need dedicated track reconstruction methods to gain signal significance for such signatures
In this Talk...

- Highlight three analyses from ATLAS
  - All using unique and dedicated, specialised methods of signal event selection and reconstruction

1. Disappearing-track
2. Displaced Vertex
3. Decays within the Calorimeter
Disappearing Track

- Assume SUSY model where $\chi_1^{\pm}$ (NLSP) is nearly mass-degenerate with $\chi_1^0$ (LSP) – Long-lived Chargino decays: $\chi_1^+ \rightarrow \chi_1^0 \pi^+$ (soft)
  - Common to wino LSP scenarios – vital to a large portion of SUSY dark matter searches
- Disappearing track – How does one reconstruct short tracks?
- Track reconstruction is done in two steps
  - Standard algorithms – e.g. to find mainly the primary tracks
    - Requiring at least seven measurements (hits) in the silicon detector layers
  - A second pass of the tracking is run
    - Only using leftover measurements from the first pass
    - The hit requirement is significantly looser and aimed at short tracks: \textit{at least four hits in the pixel layers}
Disappearing Track

- Pixel tracklets effectively increase the efficiency at decay radius < 300 mm from near 0% up to 60%
  - Remaining inefficiency is due to LLP decaying before obtaining 4 pixel hits

- Exclusion limits are presented as a function of the LLP lifetime and mass
  - Improved sensitivity to shorter lifetimes is visible comparing previous ATLAS results to the new set limits

Red solid (dotted) shows neutral (charged) particles; thick blue represents the reconstructed tracklet

**Background:**

a) Hard scattering of a hadron
b) Lepton emitting a hard photon
c) Random combination of hits

ATLAS Simulation Preliminary

Fraction of charged decays
(EW prod, m_{\tilde{g}} = 400 GeV, \tau_{\tilde{g}} = 0.2 ns)

Pixel tracklets
Standard tracks

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ATLAS Preliminary

\( \sqrt{s} = 13\text{TeV}, 36.1 \text{ fb}^{-1} \)

- Observed 95% CL limit (\( \pm 1 \sigma_{\text{theory}} \))
- Expected 95% CL limit (\( \pm 1 \sigma_{\text{exp}} \))
- ATLAS (8 TeV, 20.3 fb^{-1}, EW prod.)
Displaced Vertex

- R-hadrons decaying within the ID can be reconstructed as a Displaced Vertex (DV)
  - Long-lived Gluinos are present in Mini-split SUSY models
- Low track-reconstruction efficiency relying only on standard tracking
  - Strict cuts on transverse ($d_0$) and longitudinal ($z_0$) impact parameters with respect to the IP
    - Where as tracks from a displaced decay typical have significant large impact parameters
  - Yields low track reconstruction efficiency means low vertex reconstruction efficiency for displaced decays
- A dedicated second pass of the tracking is ran on leftover hits from the standard track - much like for the disappearing-track analysis - but with *looser cut on $d_0$ and $z_0*!
  - Greatly increase the signal vertex reconstruction efficiency
  - Analysis sensitive to decay length up to 300 mm
Displaced Vertex

• Signal regions defined for massive displaced vertices with large track multiplicity
  ◀ No SM background to the analysis

• Hadronic interactions with the material are the largest background - typically large impact parameters as well
  ◀ Create a 3D map of the dense material region of the ID
  ◀ Veto vertices in these regions

• Detector effects such as mis-reconstructions and combinatorics remains
  ◀ Fully data-driven background estimations

• The increase in energy and luminosity have greatly improved the analysis exclusions set for R-hadrons
Decays within the Calorimeter

- Weakly coupled Hidden Sector (HS) may communicate with the SM via neutral LLP that decays within the ATLAS detector
- Decays within the HCal give an unique signature of two atypical jets
  - Decays within the calorimeter volume:
    1. Produce *narrower cone* than typical SM jets originating from the IP (SM multi-jets)
    2. Ratio of energy in the HCal ($E_H$) to the energy in the ECal ($E_E$) is large ($\log_{10}(E_H/E_E) \text{ CalRatio}$)
    3. No associated ID tracks to the jet – large $\Delta R_{\text{min}}$ between the jet direction and the tracks

![Graphs showing jet width, $\log_{10}(E_H/E_E)$, and $\Delta R_{\text{min}}$](image-url)
Decays within the Calorimeter

- Dedicated *CalRatio* trigger developed on the topology of neutral LLP within the HCal
  - Narrow jets using cone radius R=0.2 (standard is R=0.4)
  - $\log_{10}(E_H/E_{EM}) > 1.2$
  - Small deposits are expected in the ECal
    - LLP decays at the outer edge of the ECal or contribution from pile-up
  - Requiring that no tracks are within the jet cone

- Boosted Decision tree (BDT) is used to select signal based on kinematics of the jets
  - Background purely data-driven ABCD method
  - Acceptance significantly improved by relaxing of $E_T^{miss}$ and using of the BDT for high mass LLP

- Exclusion are set for few mass points of a heavy scalar boson
  - $<1$ TeV and a wide range of decay lengths from 0.05 mm to 16 m
Conclusion

• Several interesting atypical searches have been conducted by the ATLAS Experiment – all using their unique techniques and methods for reconstruction, trigger, and object selections
  ◆ Three of these analyses have been reviewed focusing on the technical aspects
    ◆ Searches using signatures of Disappearing Track, Displaced Vertex, Decays within the HCal, and Highly Ionising Particles

• Many more interesting signatures
  ◆ Charged LLP decays to a light neutral and a heavy charged particle
    ◆ Results in a kinked track – opposite scenario of the disappearing track
  ◆ Neutral LLP decaying to neutral stable particles and a photon
    ◆ Gives a signature of a late photon
  ◆ More generic final states with Displaced Vertices
  ◆ Different types of HIP
    ◆ Stopped in the calorimeter, particle ID track, slow heavy ionising muon
  ◆ Stopped Particles
    ◆ Very, very, very slow particles – decays in a different bunch crossing

Late Photon: Phys. Rev. D90 112005 (2014)
HIP: PLB 760 (2016) 647
BACKUP
Metastable Heavy Charge Particles

- LLP with a larger unit of charge than expected by SM particles
  - Measured by the energy loss in the pixel subsystem $dE/dx$
  - Targeting models predicting R-hadrons of a wide range of lifetimes
- Additional pixel layer in after run-1: Insertable B-Layer (IBL)
  - Improves $dE/dx$ measurement capability
  - Reduces the tail of measurement and increasing the number of tracks with valid ionisation measurement
- A charged particle usually crosses several pixels and the deposits in adjoining pixels are combined into clusters
  - All pixels in a cluster are used to calculate the total charge
- And **finally the $dE/dx$** is measured as the charge in the cluster per unit length of the track in the sensor
  - Using all clusters associated to a track
- One or two of the highest $dE/dx$ measurements are removed to reduce tails of the distribution
Metastable Heavy Charge Particles

Average charge released:
20000 (16000) e in pixels (IBL) and the threshold is set at 3500 (2500) e
The signal Time over Threshold (ToT):
is proportional to the ionisation charge
With a dynamic range of 8.5 (1.5) times the average charge released by a Minimum Ionising Particle (MIP) for the pixel (IBL)

- Mass fit is performed on the energy loss measurement and the momentum of the reconstructed track
  - The fit used is a parametric Bethe-Bloch distribution
- $dE/dx$ versus $qp$ in collected minbias events
  - Mass fits of the pions, kaons, and protons
Metastable Heavy Charge Particles

- In addition to requirements on high track $p_T$, isolation and large $E_T^{\text{miss}}$ - an $\eta$ dependent ionisation cut is demanded
  - Greatly reduce the background

- Exclusions are set on the masses for lifetimes of 10 ns or greater which are the strongest yet
- The increase in luminosity, the additional pixel layer and improved analysis techniques have yielded significant extended exclusion with respect to Run-1