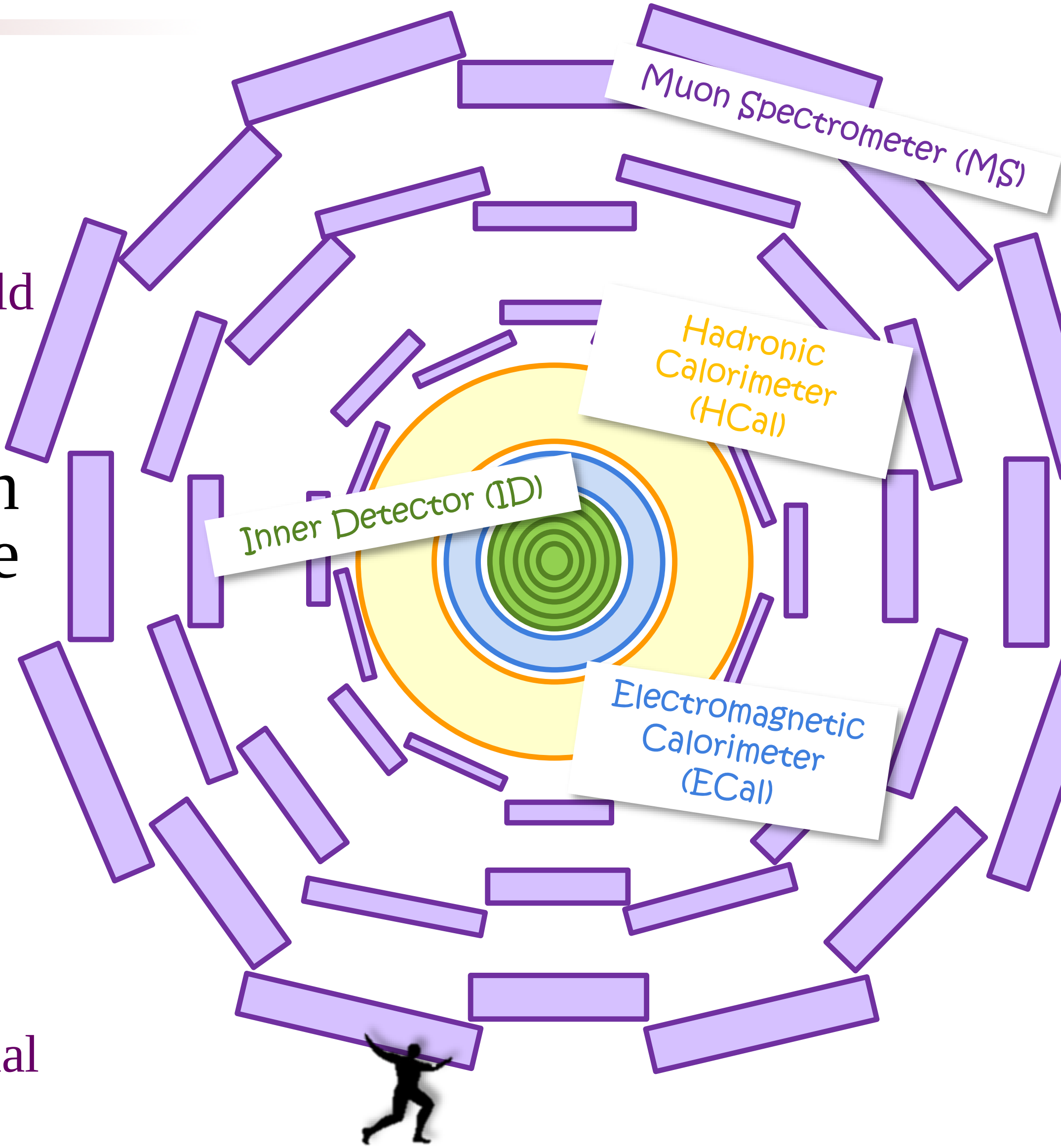
Search for New Physics through the Reconstruction of Challenging Signatures and for Long-lived particles with the ATLAS detector

Nora Pettersson (UMass) on behalf of
The ATLAS Experiment

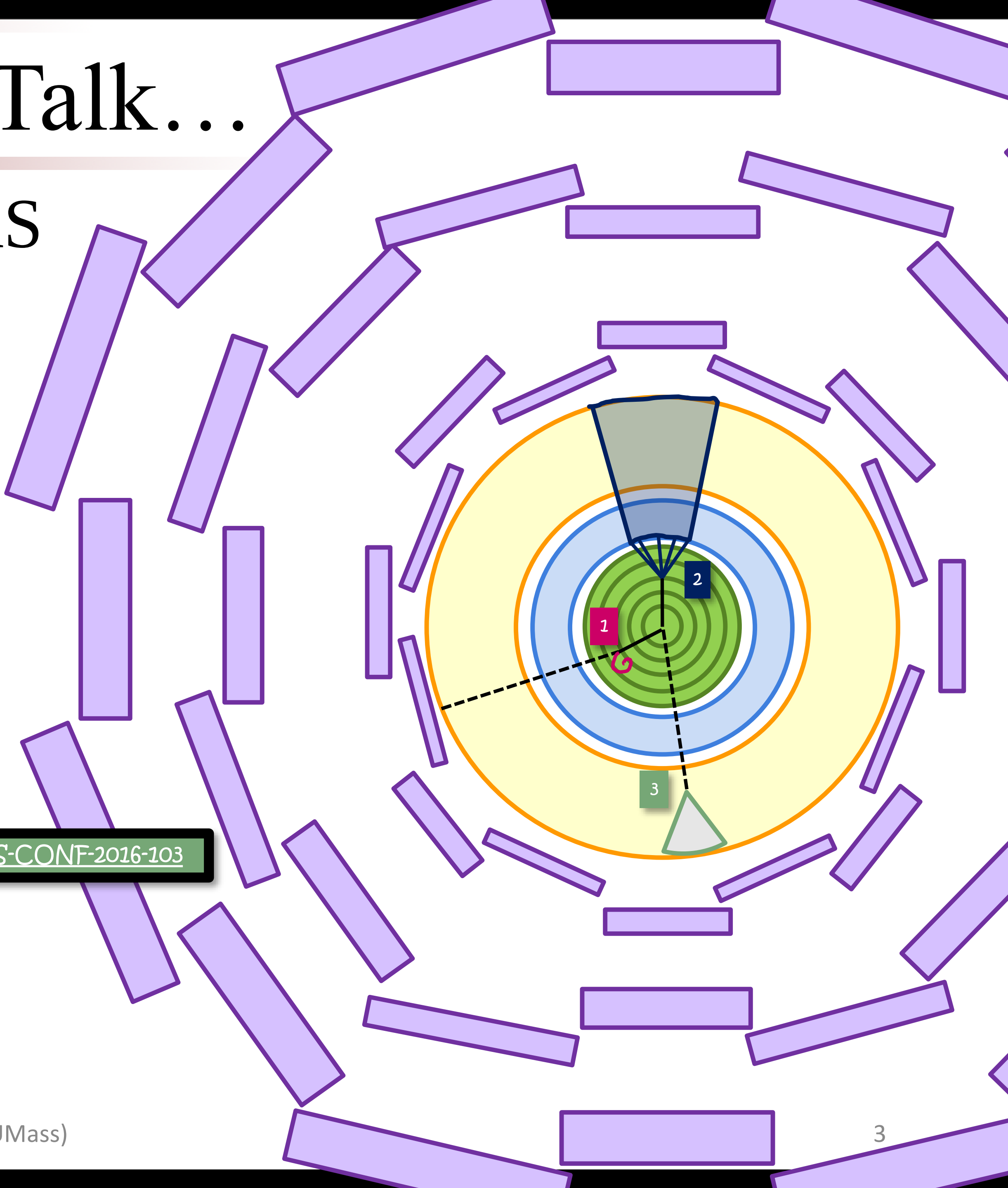
Introduction

- 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 ATLAS-CONF-2017-017

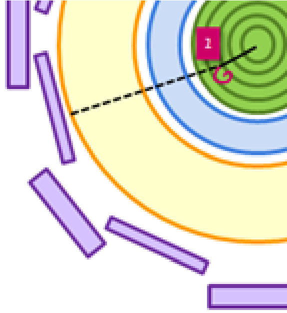
2 Displaced Vertex ATLAS-CONF-2017-026

3 Decays within the Calorimeter ATLAS-CONF-2016-103

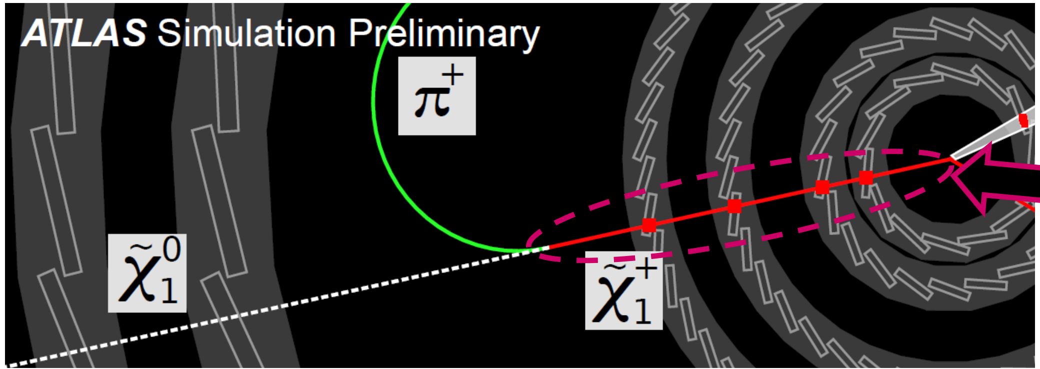
ATLAS-CONF-2017-017

Disappearing Track*

*Track = Charged Particle Trajectory



Event topology: high transverse momentum (p_T), large missing transverse energy (E_T^{miss}), high p_T jets and a ***short track***

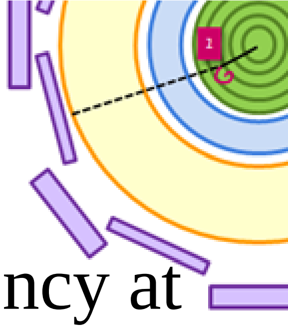


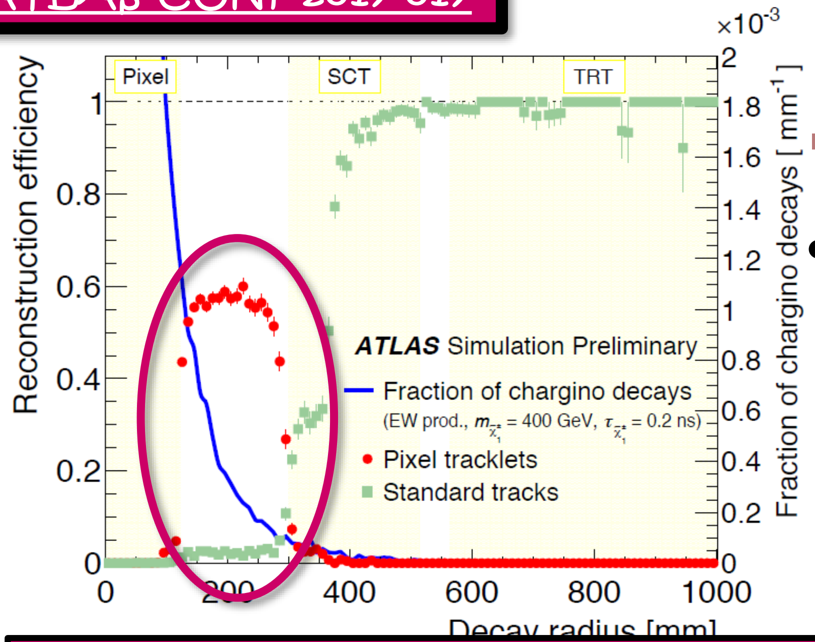
Short track

- Assume SUSY model where $\chi_1^\pm$ (NLSP) is nearly mass-degenerate with χ_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: ***at least four hits in the pixel layers***

ATLAS-CONF-2017-017

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

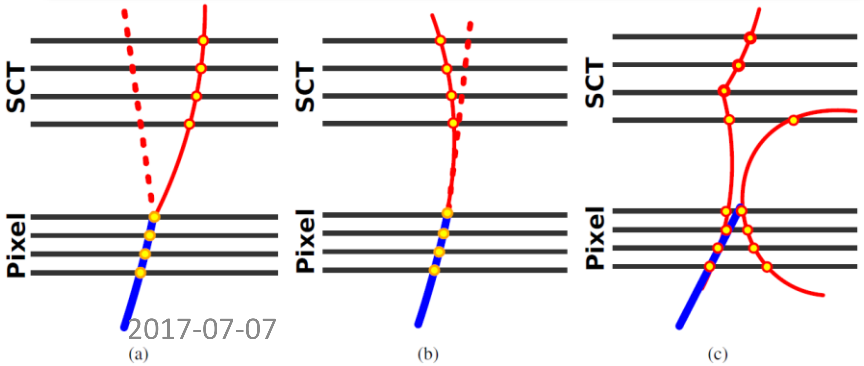
Red solid (dotted) shows neutral (charged) particles; thick blue represents the reconstructed tracklet

Background:

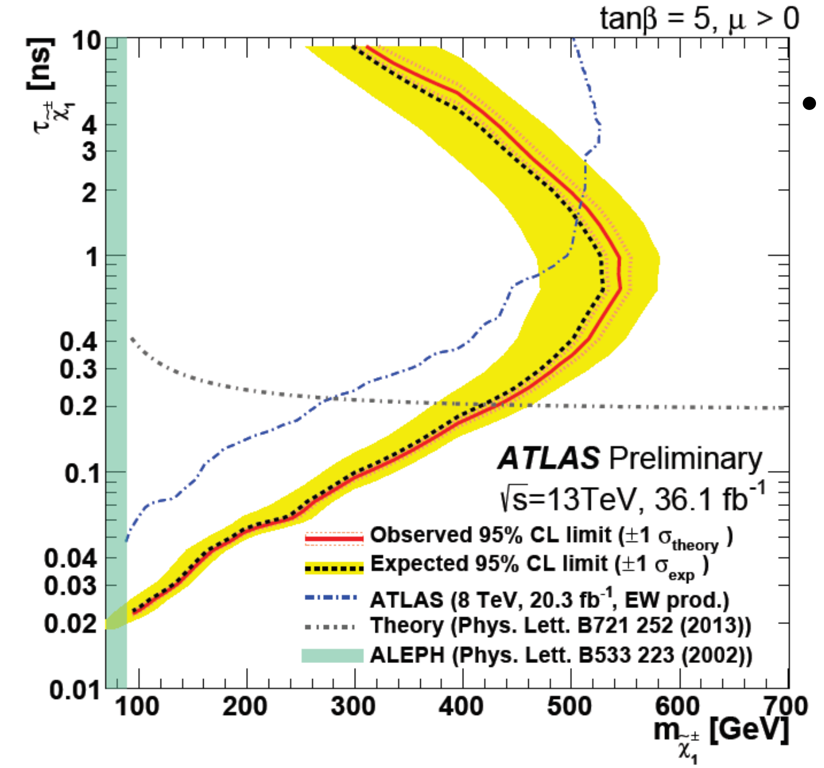
a) Hard scattering of a hadron

b) Lepton emitting a hard photon

c) Random combination of hits



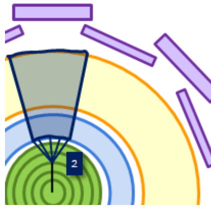
(a) (b) (c)



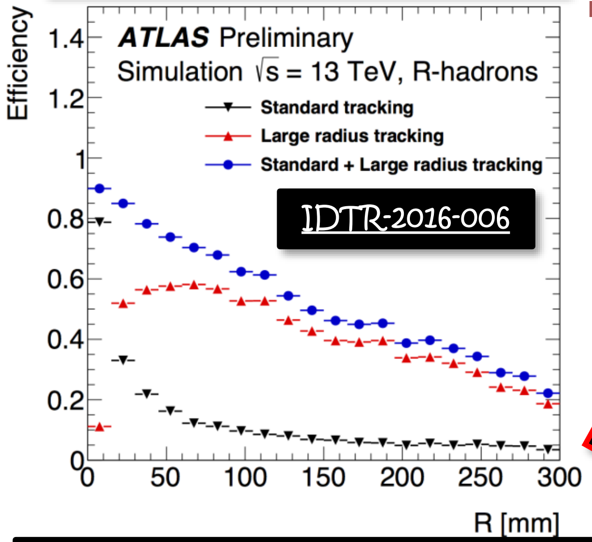
- Exclusion limits are presented as a function of the LLP lifetime and mass
  - ◀ Improved sensitivity to shorter lifetimes is visible comparing previous ATLAS results to the new set limits

ATLAS-CONF-2017-026

Displaced Vertex

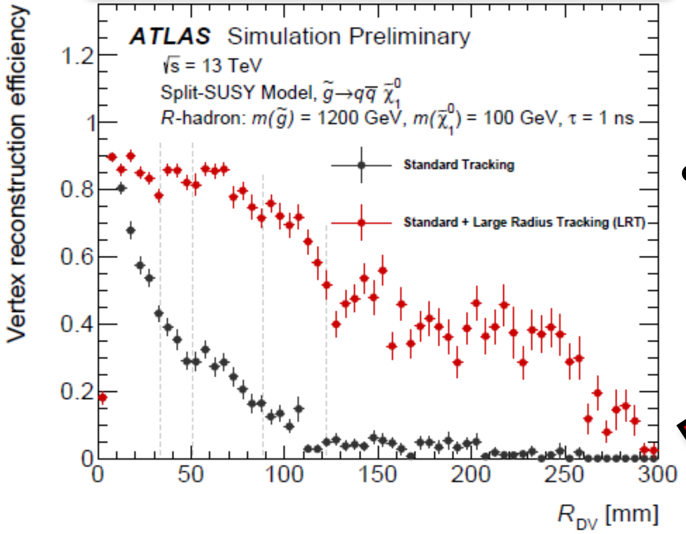


Track Reconstruction Efficiency



IDTR-2016-006

Vertex Reconstruction Efficiency

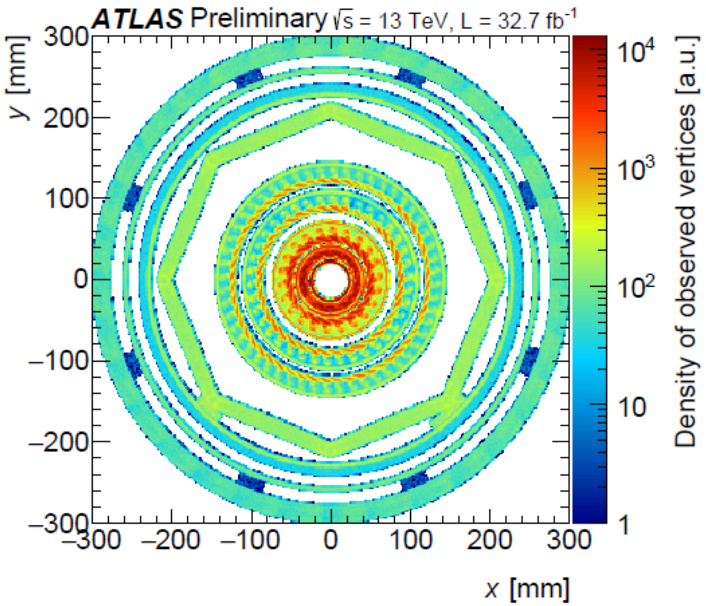


- R-hadrons decaying within the ID can be reconstructed as a Displaced Vertex (DV)
  - Long-lived Gluinos are present in Mini-split SUSY models
- Low track-reconstruction efficiency relying only on standard tracking
  - Strict cuts on transverse (d_0) and longitudinal (z_0) impact parameters with respect 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

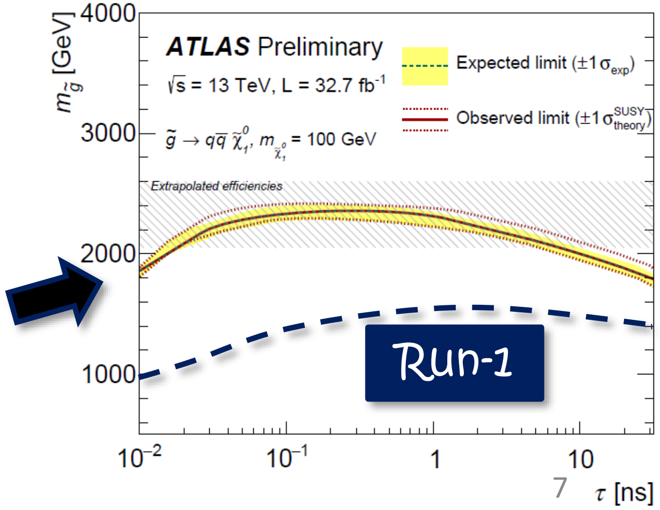
ATLAS-CONF-2017-026

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

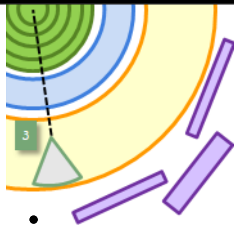


Material Veto:
Projection of all vertices in data vetoed by the material map in the x-y plane of the ATLAS ID

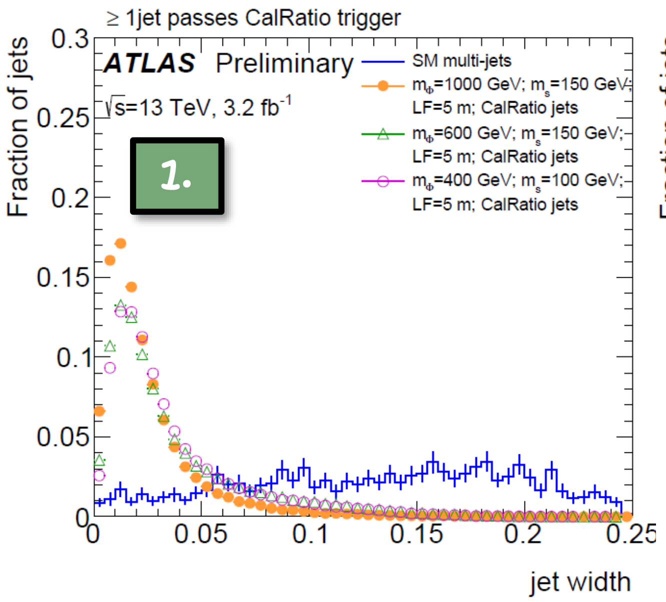


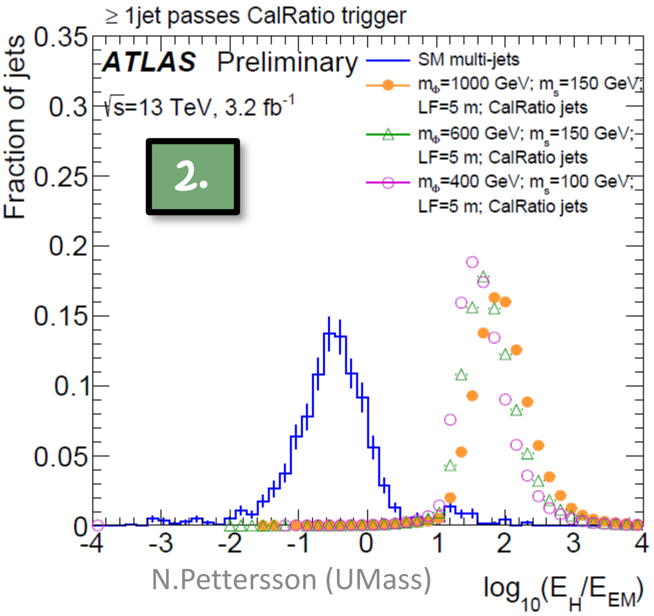
ATLAS-CONF-2016-103

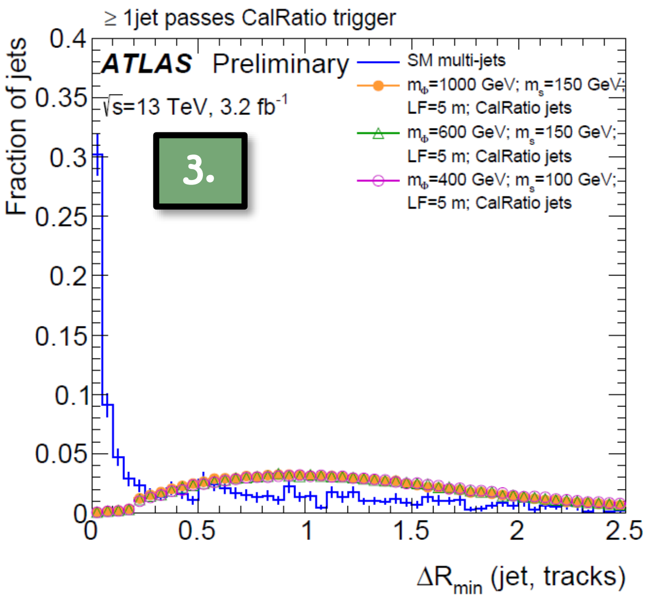
Decays within the Calorimeter



- 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_{H}) is large ($log_{10}(E_{\mathrm{H}}/E_{\mathrm{EM}})$ *CalRatio*)
      3. No associated ID tracks to the jet – large $\Delta R_{\min}$ between the jet direction and the tracks



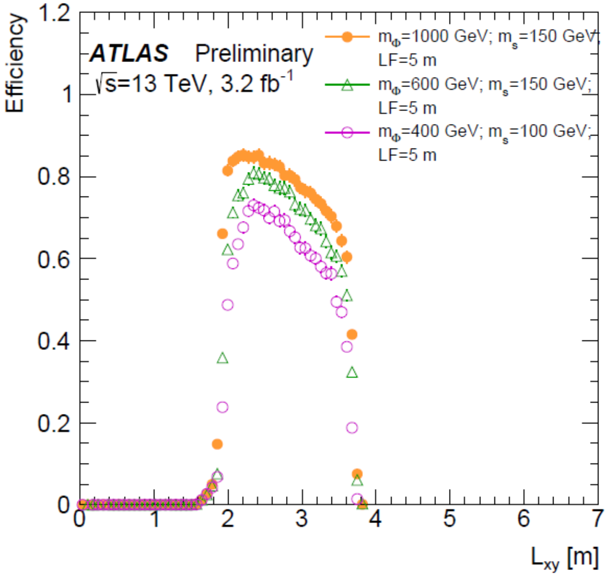




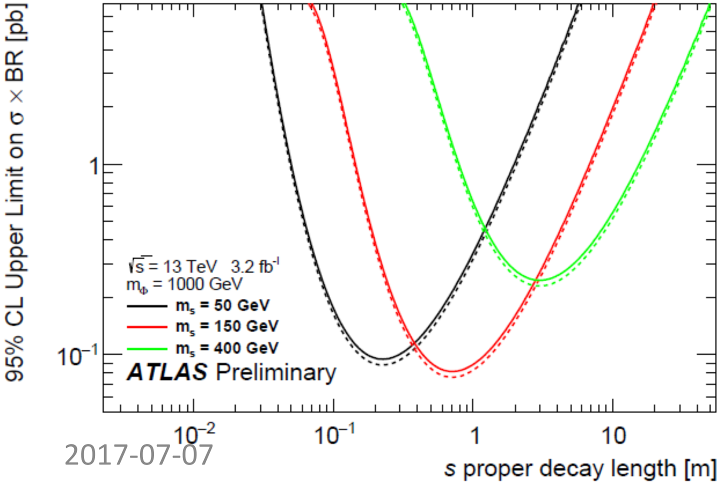
ATLAS-CONF-2016-103

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)
  - $log_{10}(E_{\mathrm{H}}/E_{\mathrm{EM}}) > 1.2$
    - 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



CalRatio Trigger Efficiency:
High efficiency (~70%) is obtained to trigger on decays within the calorimeter volume and for obvious reasons drops significantly outside the acceptance



- 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ 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

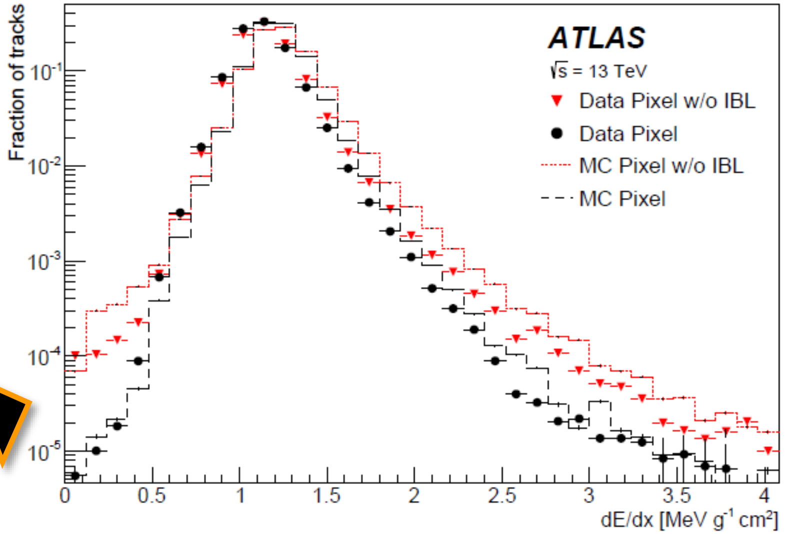
- Several interesting atypical searches have been conducted by the ATLAS Experiment – all using their unique techniques and methods for reconstruction, trigger, and object selections
  - Three of these analyses have been reviewed focusing on the technical aspects
    - Searches using signatures of Disappearing 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

Kinked Track:
Phys. Rev. D88 112006 (2013)
Late Photon:
Phys. Rev. D90 112005 (2014)
Displaced Vertices:
Phys. Rev. D92 072004 (2015)
HIP:
PLB 760 (2016) 647
Stopped Particles:
Phys. Rev. D88 112003 (2013)

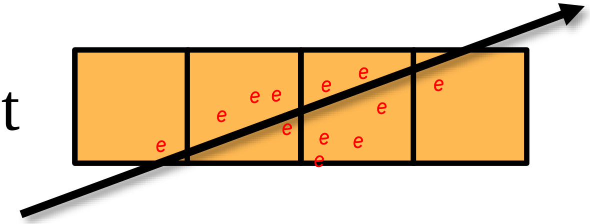
BACKUP

Phys. Rev. D 93, 112015 (2016)

Metastable Heavy Charge Particles

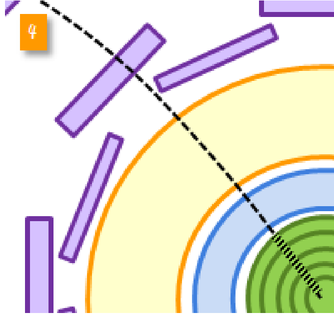


- LLP with a larger unit of charge than expected by SM particles
  - Measured by the energy loss in the pixel subsystem d*E*/dx
    - Targeting models predicting R-hadrons of a wide range of lifetimes
- Additional pixel layer in after run-1: Insertable B-Layer (IBL)
  - Improves d*E*/dx measurement capability
    - 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 d*E*/dx measurements are removed to reduce tails of the distribution



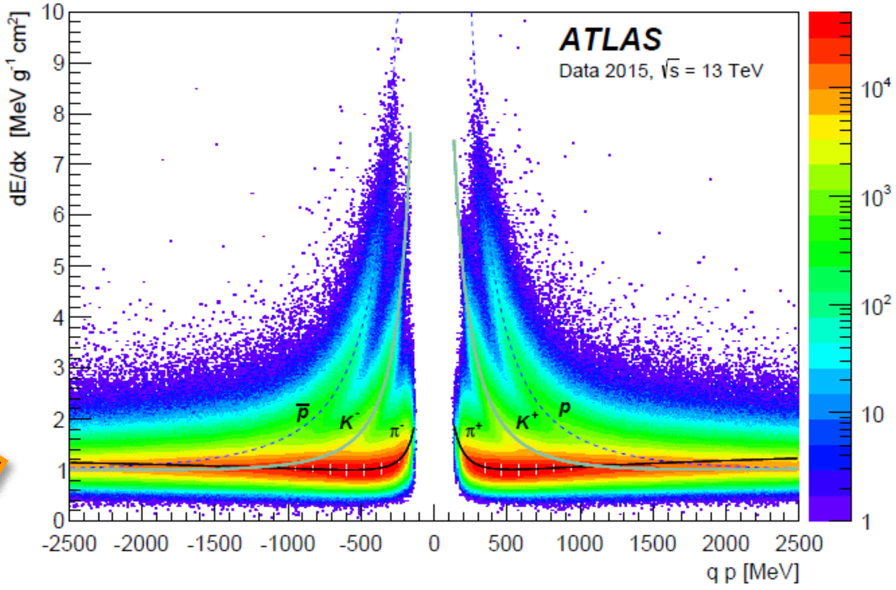
Phys. Rev. D 93, 112015 (2016)

Metastable Heavy Charge Particles



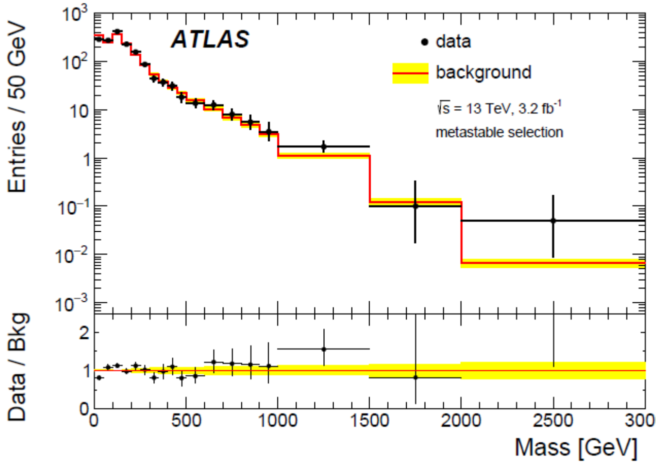
Average charge released:
20000 (16000) e in pixels (IBL) and
the threshold is set at 3500 (2500) e
The signal Time over Threshold (ToT):
is proportional to the ionisation charge
With a dynamic range of 8.5 (1.5)
times the average charge released by a
Minimum Ionising Particle (MIP) for
the pixel (IBL)

- 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
- d*E*/d*x* versus *qp* in collected minbias events
  - ◀Mass fits of the pions, kaons, and protons

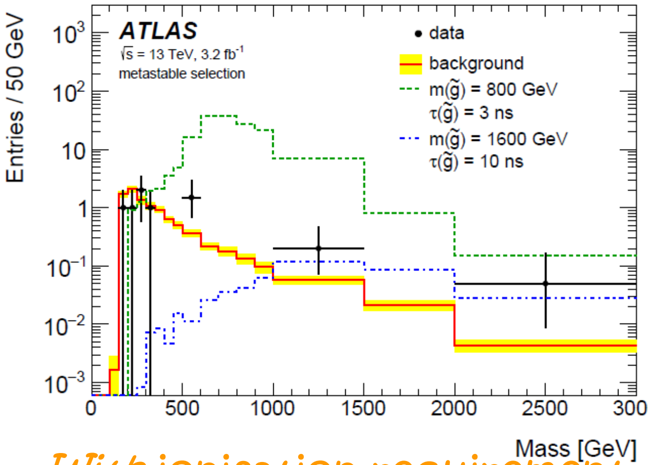


Phys. Rev. D 93, 112015 (2016)

Metastable Heavy Charge Particles



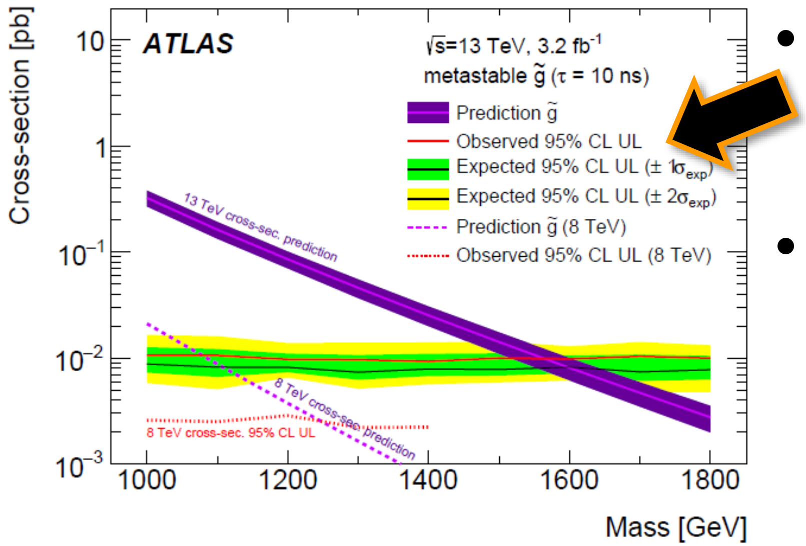
Without ionisation requirement



With ionisation requirement

- In addition to requirements on high track p_T, isolation and large E_T^{miss} - an η 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