# Searches for long-lived particles with a disappearing track signature at $\sqrt{s}$ = 13 TeV with ATLAS

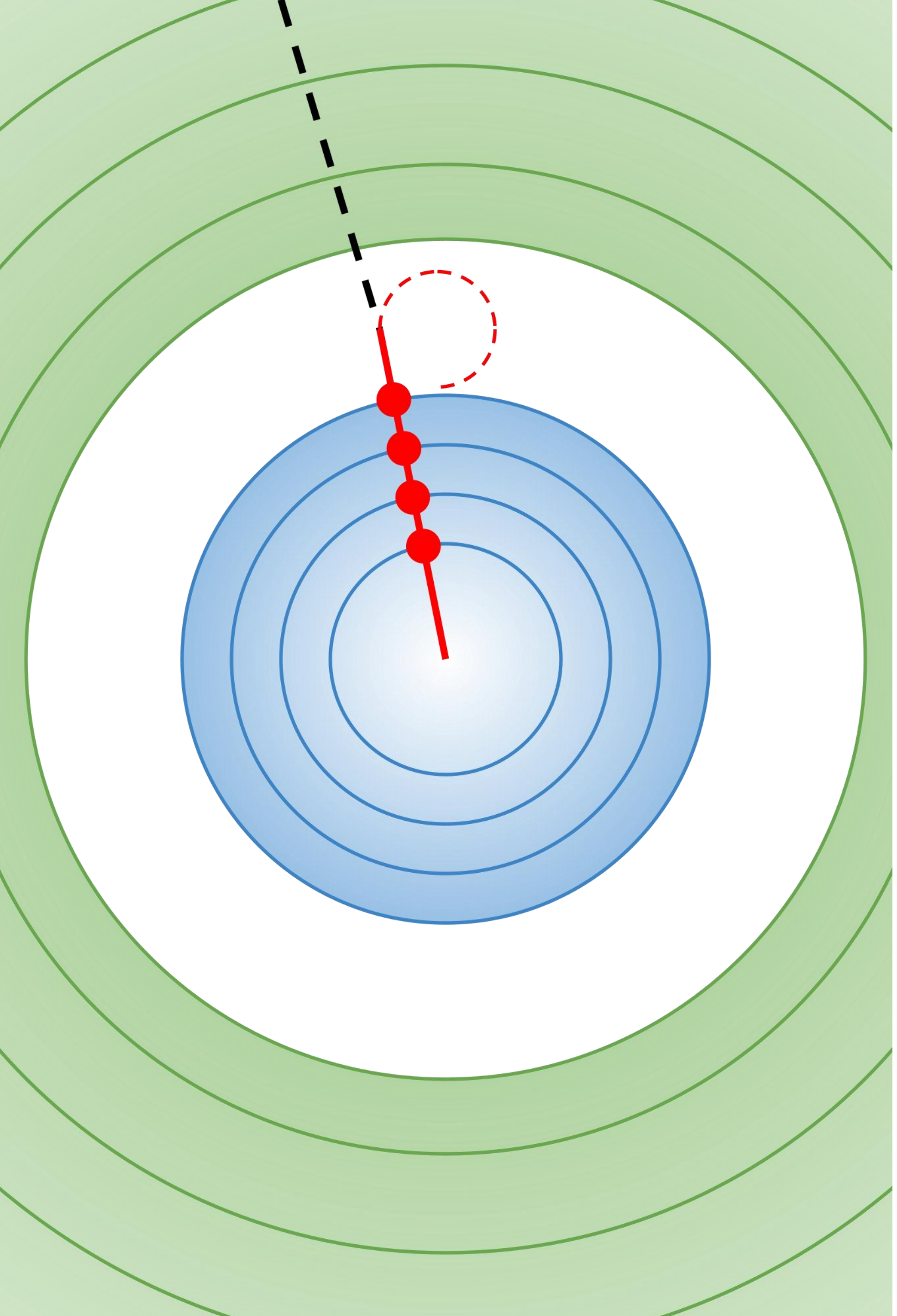

JAMES SMITH

UNIVERSITY OF LIVERPOOL / DESY


LIVERPOOL HEP ANNUAL MEETING 2021

19TH MAY 2022


SUPERVISORS: MONICA D'ONOFRIO, HELEN HAYWARD, NICK STYLES (DESY)



# Introduction

Long-lived particles are common in many BSM models
- Excellent dark matter candidates
- LLPs already exist in standard model!
- Unique signatures mean very low SM backgrounds
- Wide unexplored phase space due to challenging signatures

Many models predict a long-lived charged particle that decays to an almost-mass-degenerate invisible particle and a soft track
- Charged particle has lifetime 0.01→10 ns traveling $c\tau$=O(cm)

Signal: Short “tracklet” with no reconstructed objects after
- “Disappearing Track”

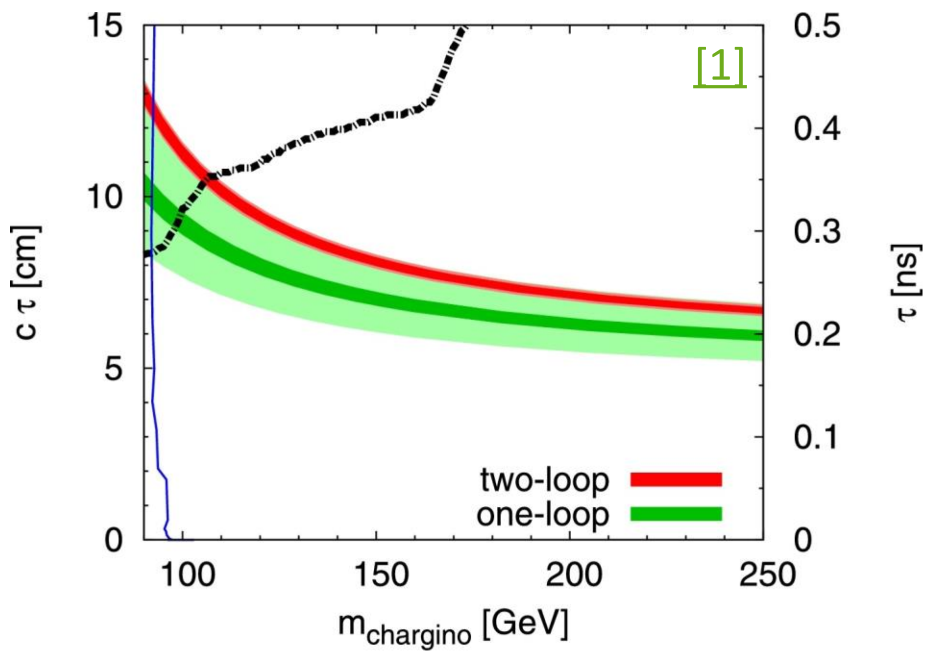
# Theory

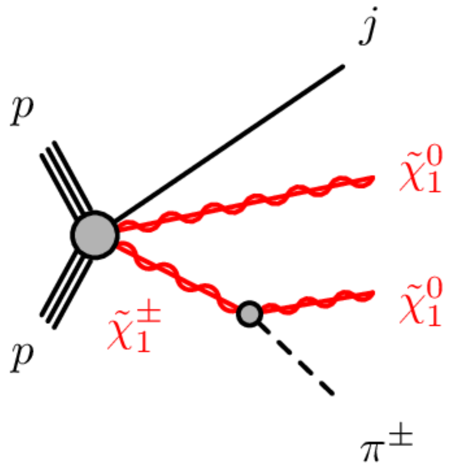
Anomaly-Mediated Supersymmetry Breaking (AMSB) model used as a benchmark[1]

- Charginos and neutralinos nearly mass degenerate, splitting of $\Delta$m=~200 MeV
- Chargino lifetime ~0.2ns ($c\tau$=~6cm)
- Direct electroweak production of either neutralinos, or charginos decaying to neutralinos and low-$p_T$ pions
- Cascade of gluino decays also possible

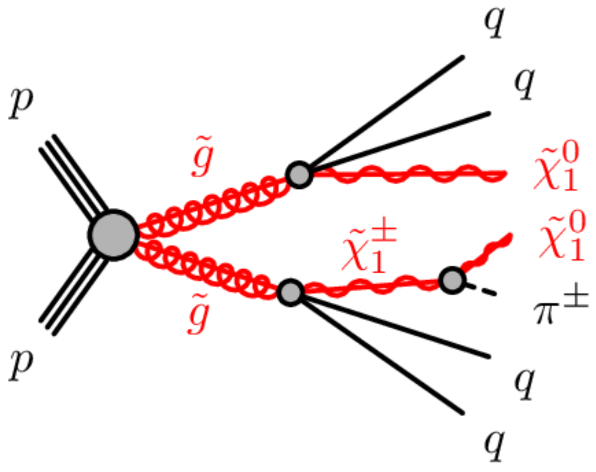
Beyond SUSY DM models predicting a DM thermal relic and doublets or triplets under SU(2) symmetry have also similar signatures

[1] Mass splitting between charged and neutral winos at two-loop level - M. Ibe, S. Matsumoto, R. Sato. DOI: 10.1016/j.physletb.2013.03.015




Electroweak




Strong

# New DT search

Tracklet candidates use dedicated reconstruction

- Second-pass reconstruction uses up to 4 pixel hits unused by standard tracking

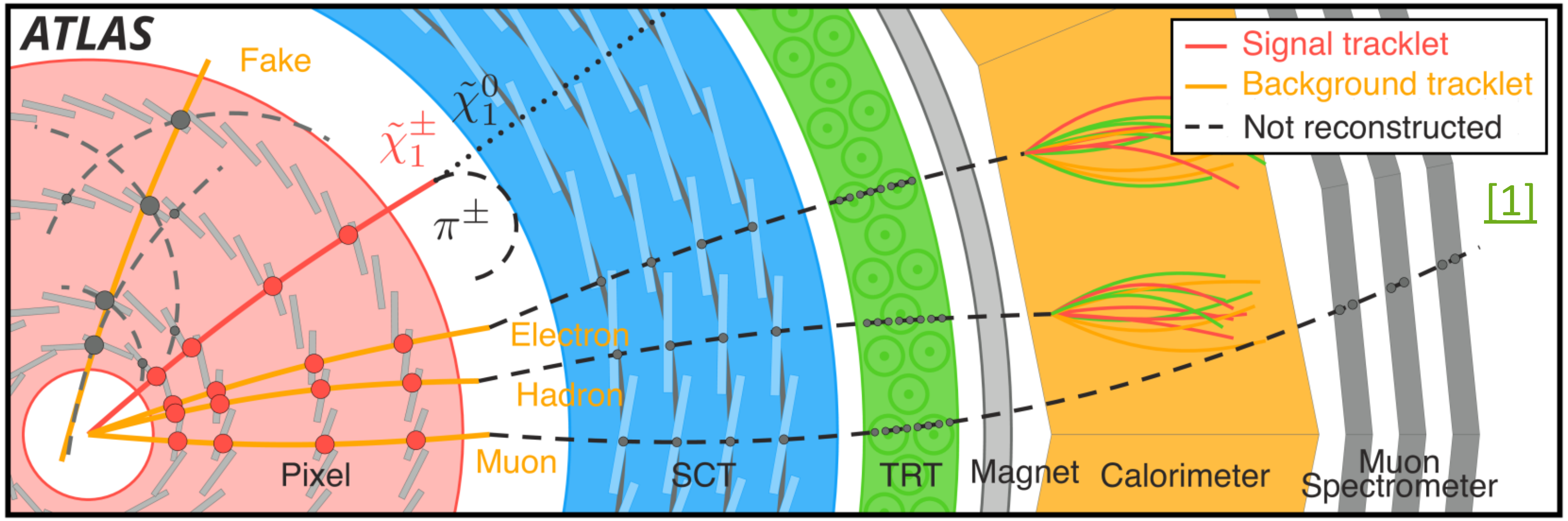
First search with full Run 2 ATLAS dataset

- [1] [arxiv:2201.02472] [SUSY-2018-19]

Primary background is combinatorial fake tracks, secondary backgrounds are partially-reconstructed scattered particles

- Fakes reduced with impact parameter cuts
- Scatters reduced with muon-spectrometer and calorimeter vetos – new in this analysis

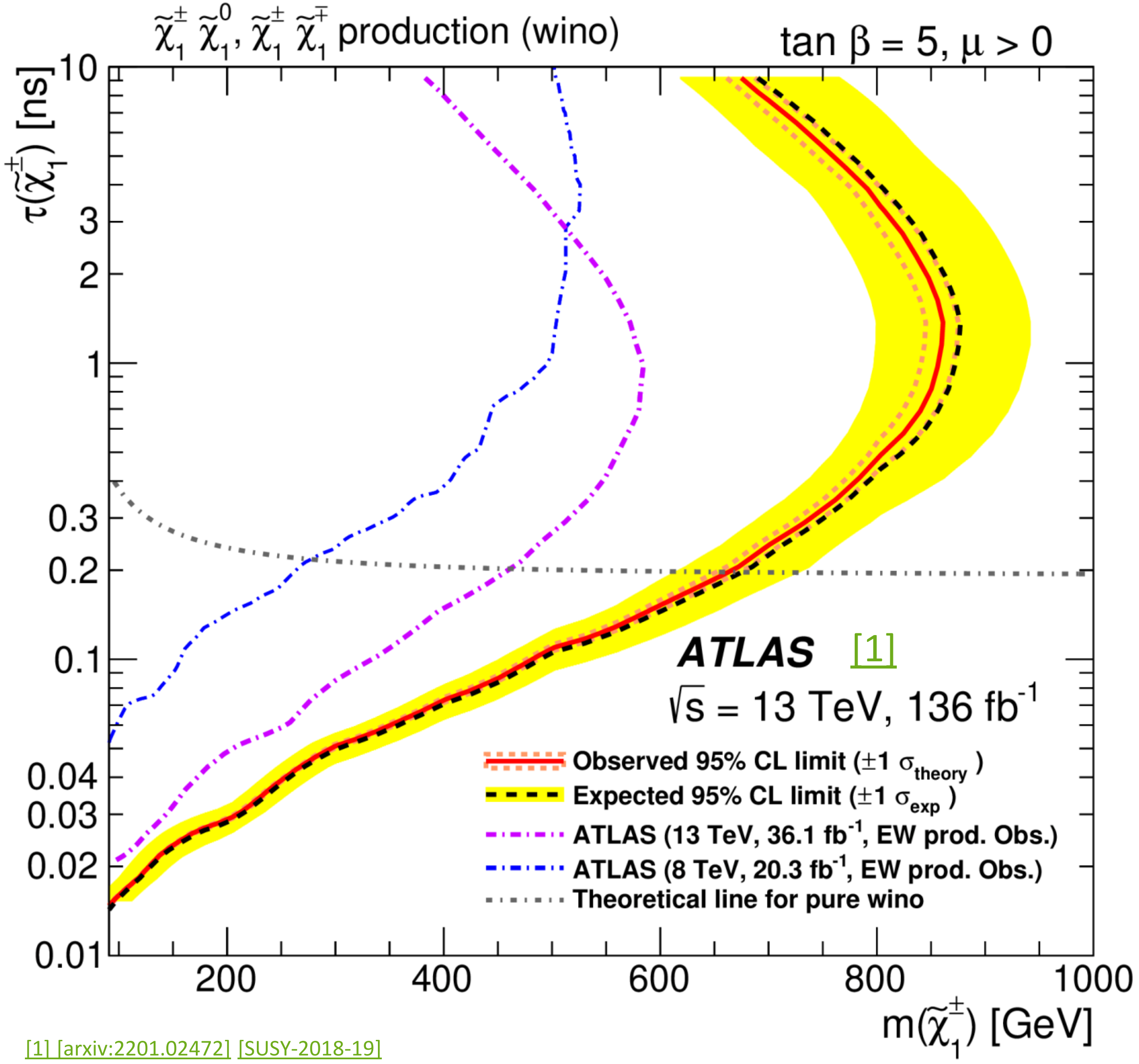
Background estimation fully data-driven, performed by estimating scatters in Z→ll events and deriving a $p_T$ fit template that can be used in the signal region




[1]

# New results

- No significant excesses identified
  - EWK: Observed **3**, Expected **3.0±0.7**
  - Strong: Observed **1**, Expected **0.84±0.33**
- Electroweak production excluded at 95% CL up to $m(\tilde{\chi}_1^{\pm})$ = 850 GeV
  - Wino (0.2ns): 670 GeV
  - Higgsino (0.035ns): 210 GeV
- Strong production excluded at up to $m(\tilde{g})$ = 2.1 TeV




[1] [arxiv:2201.02472] [SUSY-2018-19]

# Reinterpretation

Due to strong theoretical interest, robust and varied reinterpretation materials required

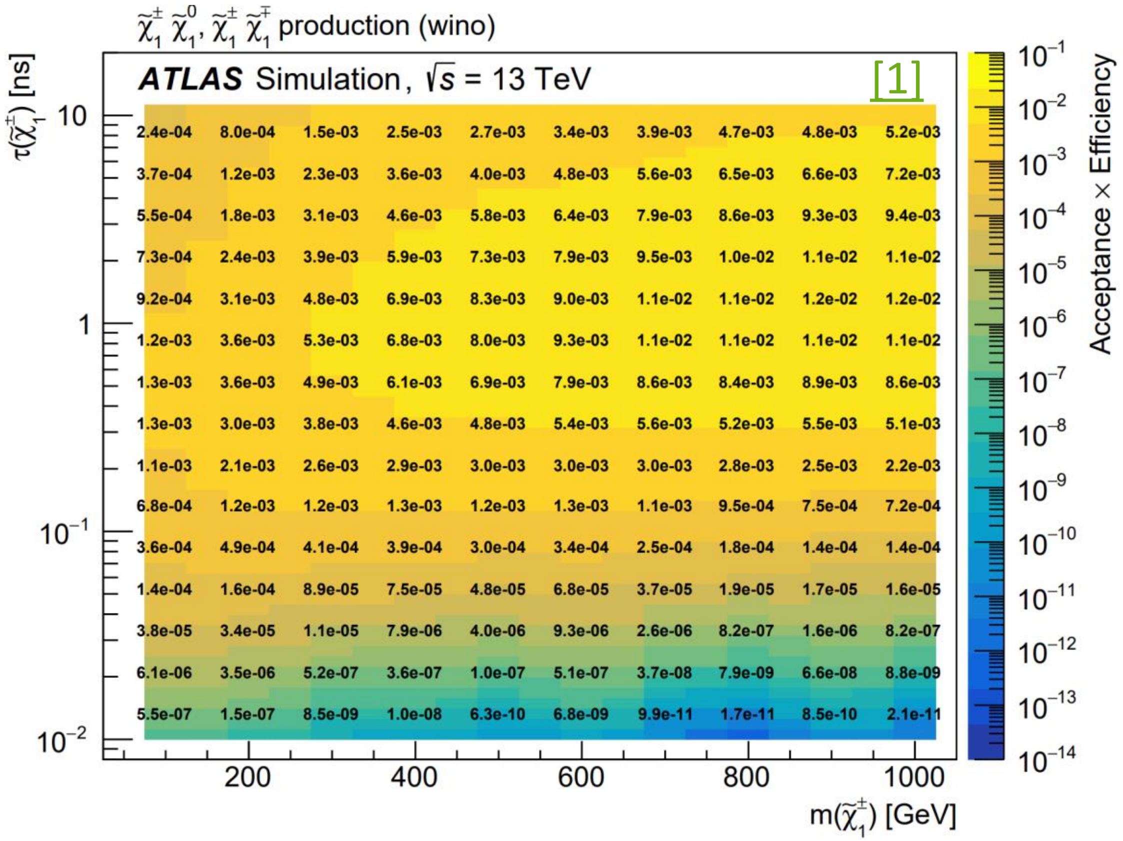
Three reinterpretation techniques developed [1] [HEPData PDF]

Overall acceptance, efficiency and acceptance-times-efficiency plots

- Simple, but model-dependent

Component event- and tracklet-level acceptance and efficiency values

- Allows for model independence
- Users calculate new acceptances for tracklets and events and use provided efficiencies



# SimpleAnalysis

SimpleAnalysis is a high-level analysis preservation framework allowing per-event truth-level analysis [PUB Note] [Website]

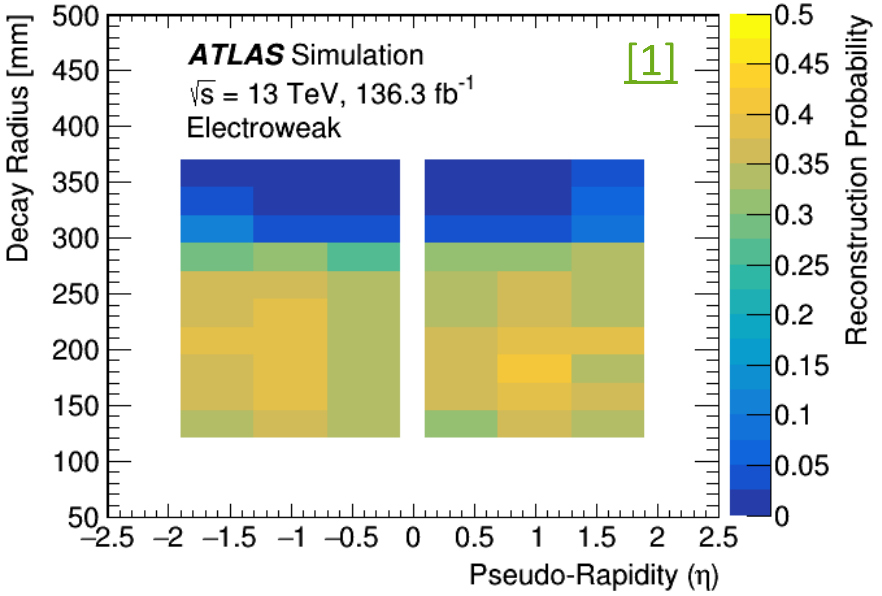
Event selection directly implemented

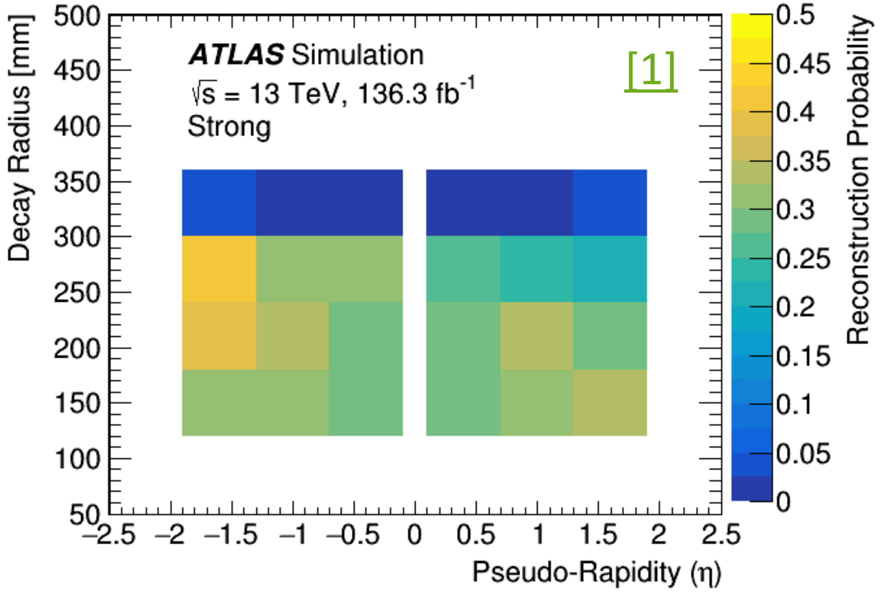
No low-level objects (i.e tracks) available in SimpleAnalysis, only truth charginos

- Tracklet selection emulated with reconstruction efficiency parameterisation
- Transverse momentum smearing also applied

Analysis results well-replicated by all methods within a few percent

[1] [HEPData PDF]



# Future Analysis

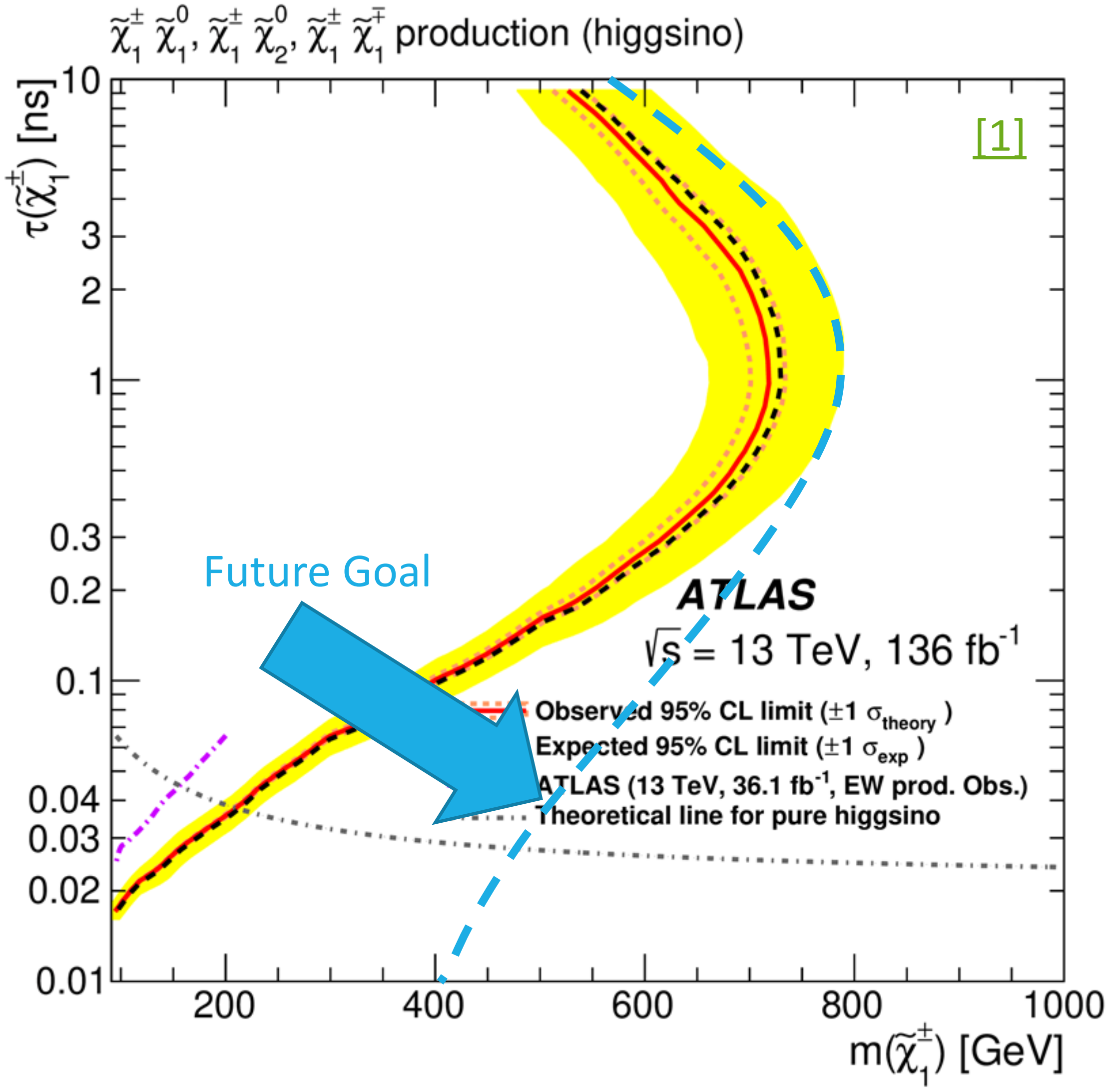
4-hit requirement reduces sensitivity at very short lifetimes

- Important for higgsino interpretations relevant for many dark matter models

Allowing 3-hit tracklets will significantly improve sensitivity

Large increase in combinatorial fakes must be controlled

- Use new soft track reconstruction methods
- Investigate new background estimation techniques




[1] [arxiv:2201.02472] [SUSY-2018-19]

# Low-$p_T$ Pions & Vertex Constraints

Reconstruction algorithm for low-$p_T$ tracks developed in 2019 [1]

Targets low-$p_T$ pions resulting from tracklets using hits leftover from standard tracking

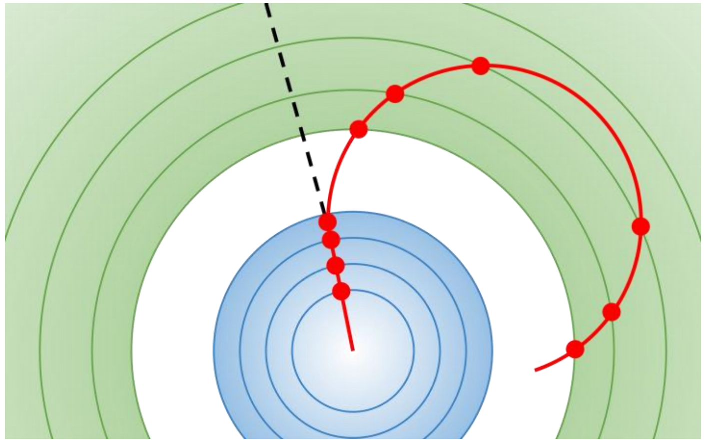
- Track seeds (3 SCT hits) in region of interest
  - $\Delta R<0.8$ of tracklet with $p_T>200$ MeV
- At least 6 SCT hits
  - No more than 2 shared with other tracks, no more than 2 missing hits.

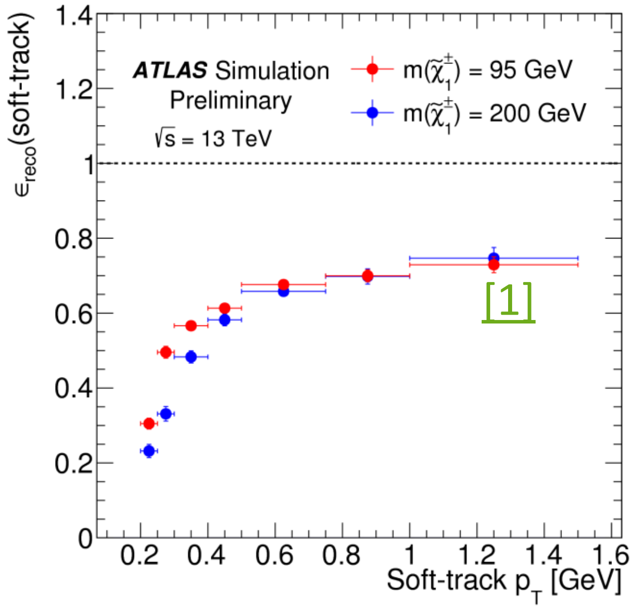
Good reconstruction efficiency above $p_T$=350MeV and with a small $d_0$. Not dependent on pileup or production radius.

Fit tracklets and low-$p_T$ tracks together to estimate decay vertex

- Decay vertex can be used to improve tracklet $p_T$ resolution

[1] Performance of tracking and vertexing techniques for a disappearing track plus soft track signature [CDS] [ATL-PHYS-PUB-2019-011]





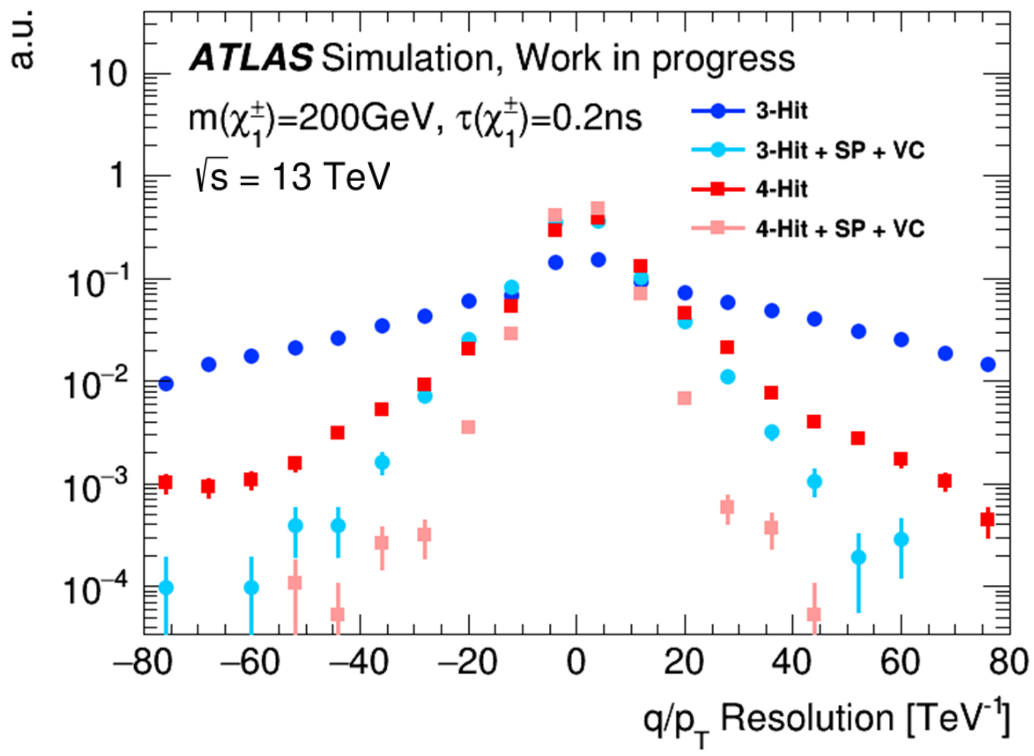
# Using 3-hit tracklets

3-hit tracklets heavily dominated by fakes in prior analyses and had poor $p_T$ resolution so not previously used

Aim to integrate low-$p_T$ track reconstruction and vertex constraints to make 3-hit analysis viable

- Reduce fake backgrounds
- Improve tracklet $p_T$ resolution
- Also apply to 4-hit tracklets

Variable d0/z0 cuts can also improve efficiency



# Background Estimations

Previous background estimation used the tracklet pT distribution in separate fake, hadronic and leptonic control regions and fitted to the signal region

- Complex fitting framework, sensitive to small changes
- Simpler & more robust approach planned for this analysis

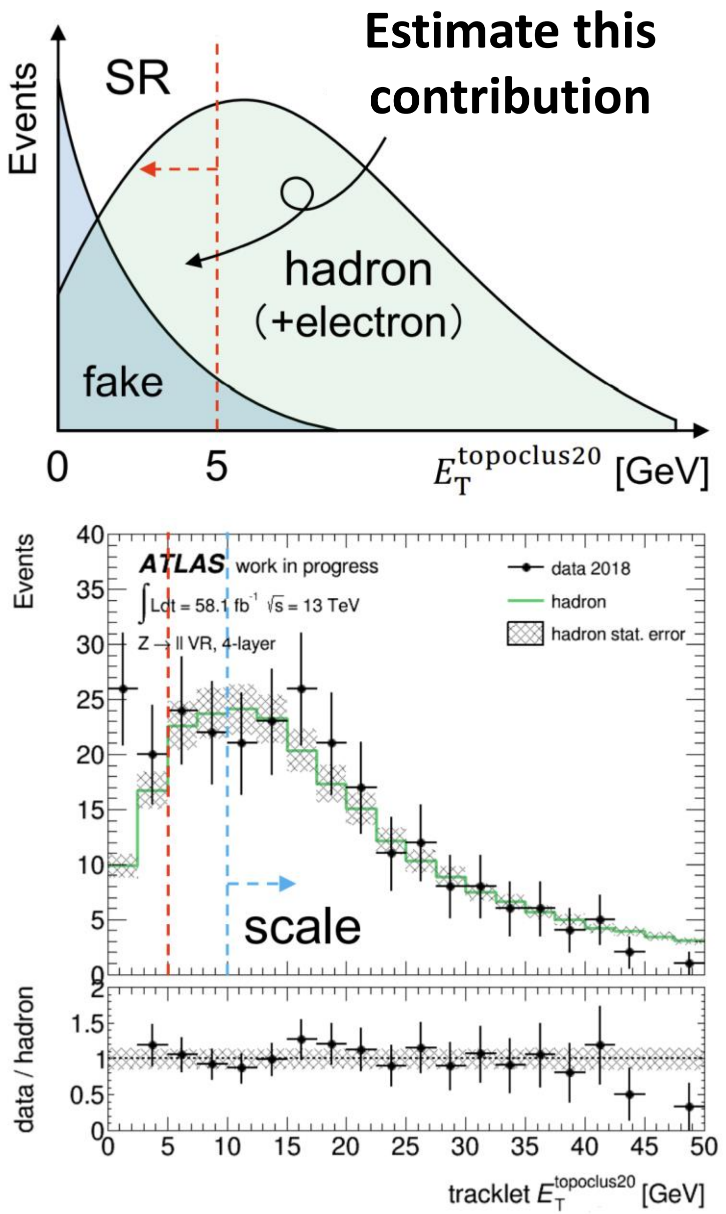
Plan to use separate fits for each background

- Hadronic: Sum of calorimeter energy in DR<0.2 of tracklet
- Fakes: Impact parameters

Early studies completed with single pion samples, waiting for V+Jets samples to be produced with dedicated reconstruction

Also considering simpler ABCD approaches and other improvements including ML

Plots: Daiya Akiyama, Waseda University



# Technical Work – Polar Co-Ordinates in ITk Strip Endcap Software

ATLAS tracking system to be replaced in 2024 with new, all-silicon Inner Tracker – the ITk

Ongoing efforts by team to adapt or replace existing software

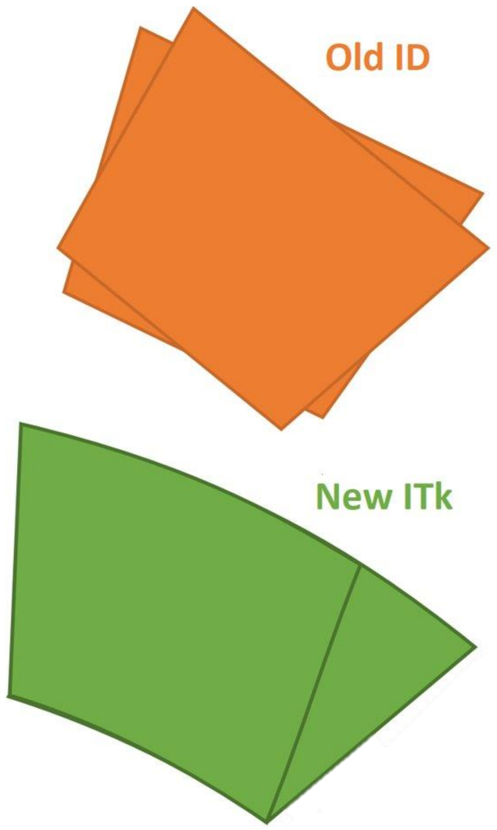
- Up until now, ATLAS used modified software from the existing detector for the ITk developments

Software representation has been modified to use a polar co-ordinate system for the new strip endcaps

- Digitisation working, Reconstruction being debugged
- Detailed performance profiling and optimisation planned
- Will also consider modifying conversion between disk and memory

Used to qualify as an ATLAS Author last Christmas

Also plan to take Inner Detector control room shifts in August



# Conclusions

Results of the first disappearing track search with full Run-2 ATLAS dataset are presented

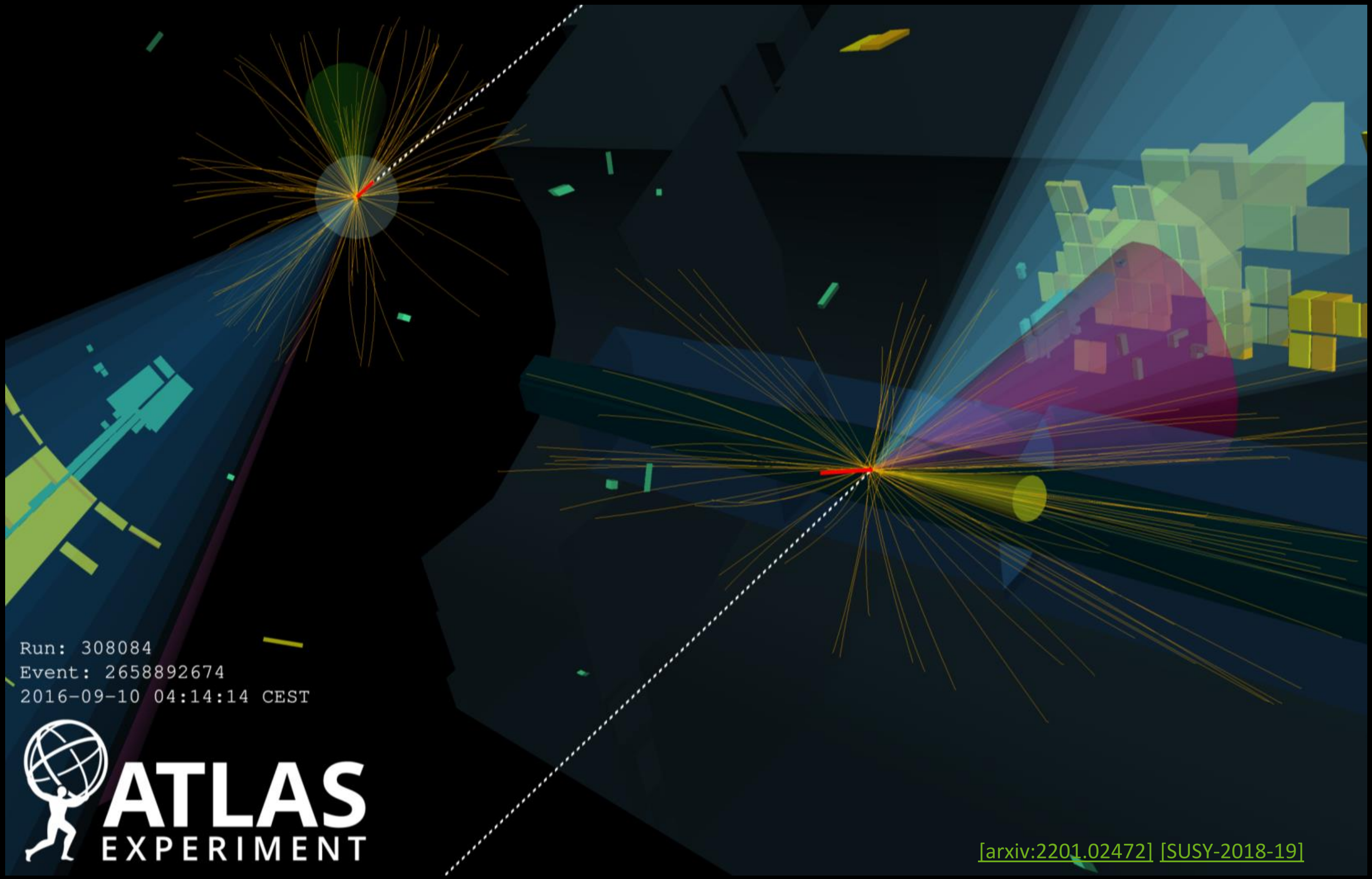
- New calorimeter veto to suppress scattered electron/hadron backgrounds
- No significant excess presented, strongest-ever limits set

Search has high potential for reinterpretation for DM due to general LLP signature

- Various reinterpretation methods developed and presented
- Tracklet reconstruction and selection probability parameterised and used in SimpleAnalysis implementation

New techniques being explored for future analysis on the same data

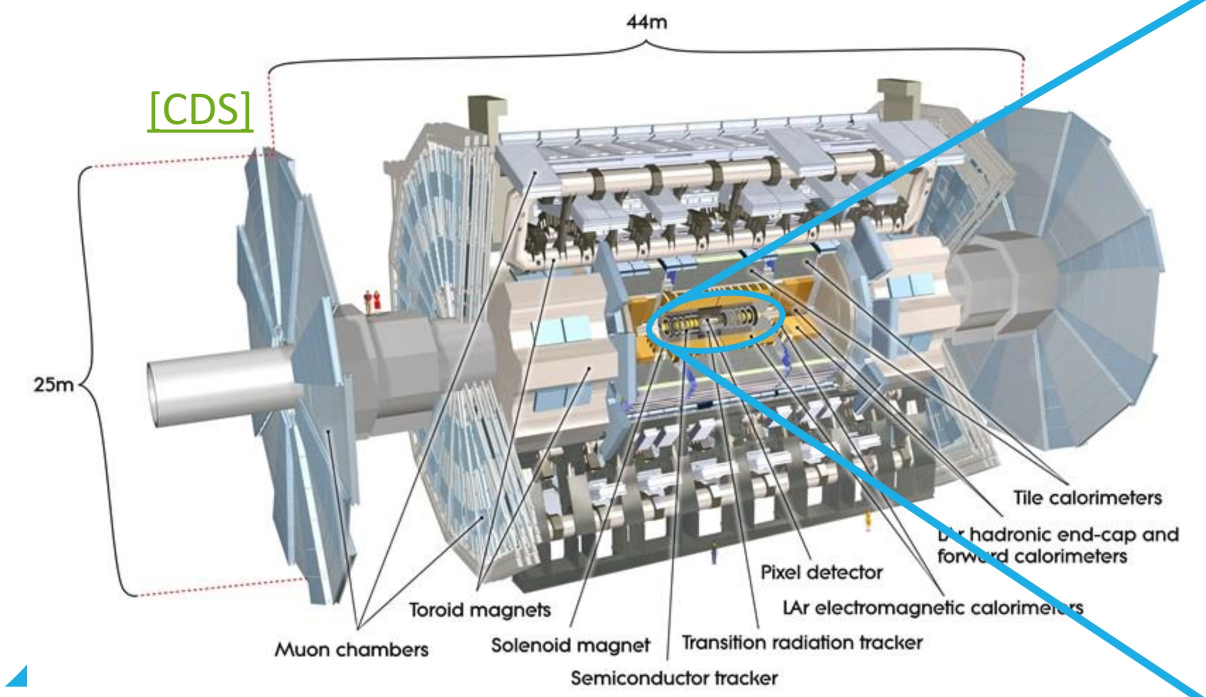
- Low-$p_T$ track reconstruction and vertex constraints to allow 3-hit analysis
- New background estimation techniques being explored



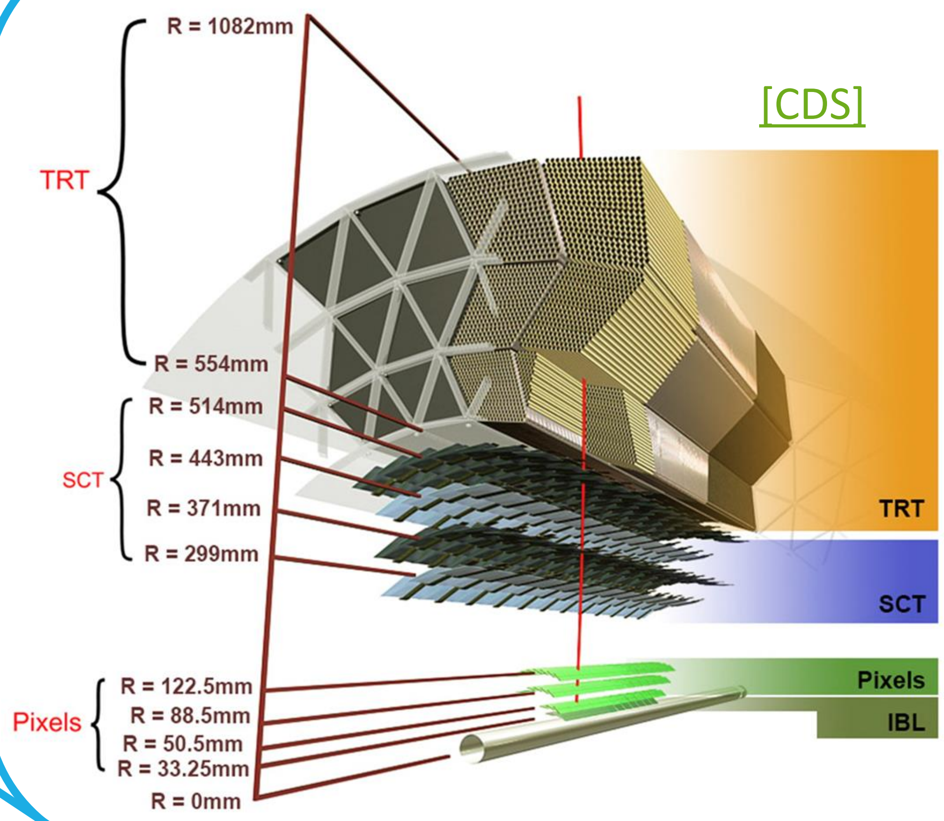

# Any Questions?

# ATLAS ID

[CDS]




[CDS]



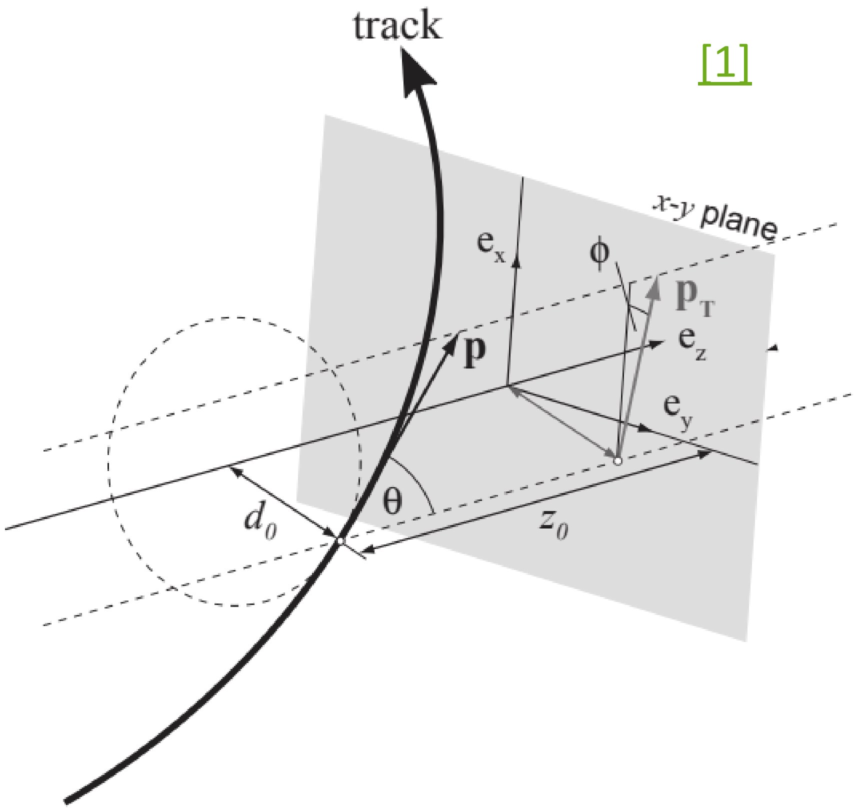
# Impact parameters

Measured from the beamspot position to the track's point of closest approach

$d_0$: radial distance to point of closest approach

$z_0$: longitudinal distance (parallel to beamline) to point of closest approach

$d_0$ Significance: $d_0$ / $d_0$ Uncertainty




[1]

[1] ATLAS Tracking Software Tutorial | ATLAS Track Reconstruction -- General Overview (cern.ch)

# Signal Region Selection

Separate event pre-selections for electroweak (strong) channels

- No leptons
- Pass missing $E_T$ trigger
- Missing $E_T$ > 200 (250) GeV
- At least 1 (3) jets with $p_T$ > 20 GeV
- Leading Jet $p_T$ > 100 GeV
- (2nd, 3rd Jet $p_T$ > 20 GeV)
- $\Delta\phi_{min}^{jets_{1\to4} - E_T^{miss}} > 1.0$ (0.4)

Tracklet selection:

- $p_T$ > 20 GeV
- Disappearing (4 pixel hits, no SCT hits, no bad hits)
- Tight impact parameter cuts
- Isolated from other ID tracks ($\Delta R < 0.4$)
- Isolated from jets, muon spectrometer tracks ($\Delta R < 0.4$)
- Good fit quality
- $0.1 < |\eta| < 1.9$
- Calorimeter activity veto ($\Delta R < 0.2$)

# Signal Selection

Event-level preselection and tracklet selection

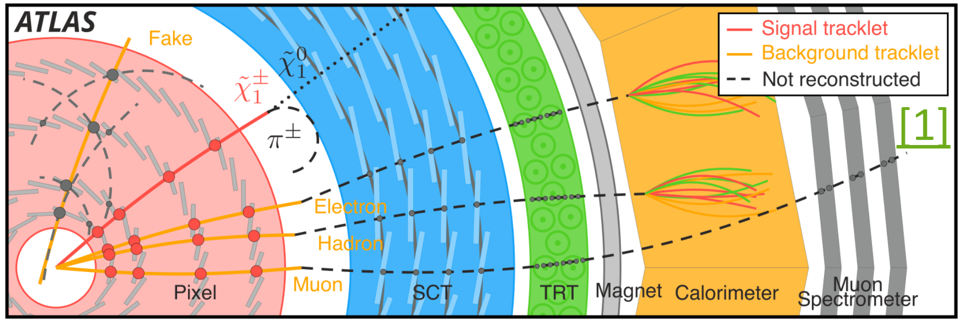
Event selection varies for EWK (Strong) cases:

- No leptons
- Pass missing $E_T$ trigger
- Missing $E_T$ > 200 (250) GeV
- At least 1 (3) jets with $p_T$ > 20 GeV
- Leading Jet $p_T$ > 100 GeV
- (2nd, 3rd Jet $p_T$ > 20 GeV)
- $\Delta\phi_{min}^{jets_{1\to4} - E_T^{miss}}$ > 1.0 (0.4)

Tracklet selection varies for EWK (Strong) cases:

- $p_T$ > 20 GeV
- 4 pixel hits, no SCT hits
- No spoilt hits, outliers
- $|d_0$ Significance$|$ < 1.5
- $|z_0 \sin(\theta)|$ < 0.5 mm
- Isolated (sum of track $p_T$ within $\Delta R$<0.4 / tracklet $p_T$ < 0.04)
- $\Delta R$(jets) > 0.4
- $\Delta R$(MSTracks) > 0.4
- Fit Quality > 0.1
- 0.1 < $|\eta|$ < 1.9
- Calorimeter Veto ($E_T^{topoclus20}$ < 5 GeV)

# Calorimeter Veto




Scattered electrons and hadrons will produce a calorimeter signal

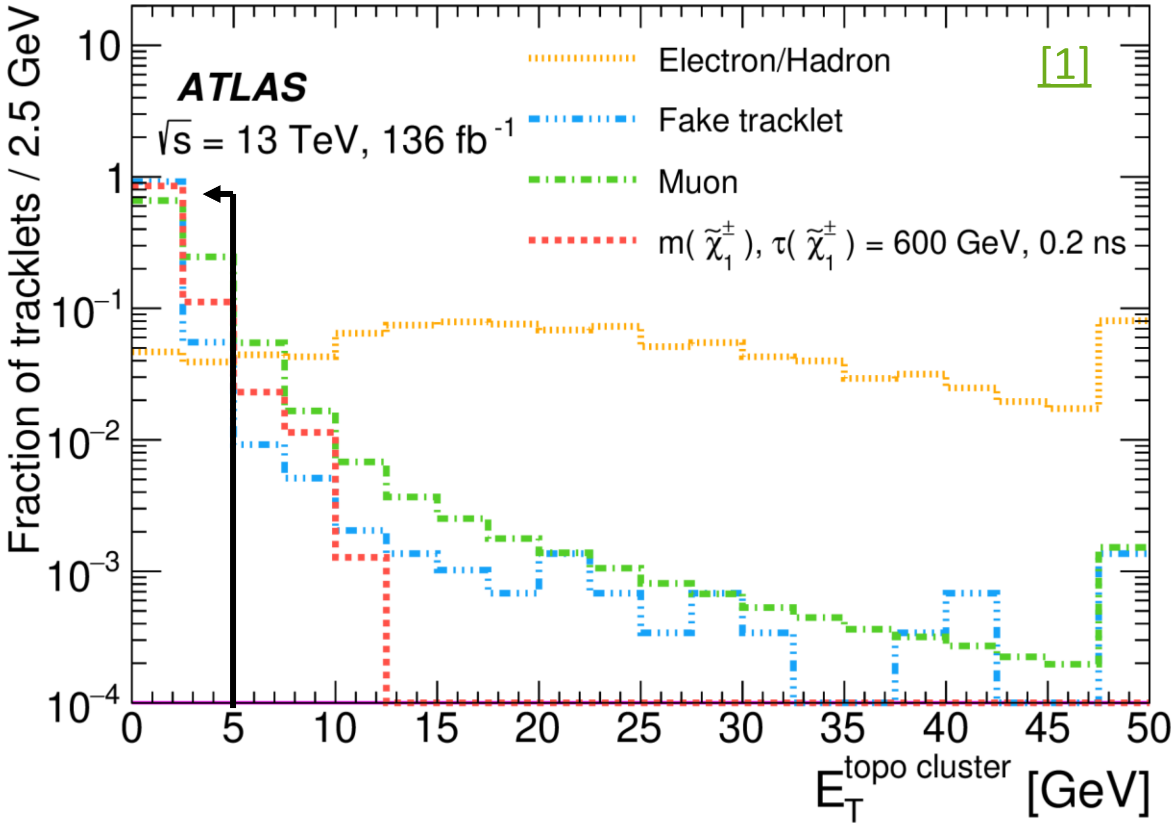
- Not always sufficient to be classified as a jet which could be used to reject a tracklet

Sum all topological energy clusters within $\Delta R<0.2$ of the tracklet

Require that this sum is less than 5 GeV

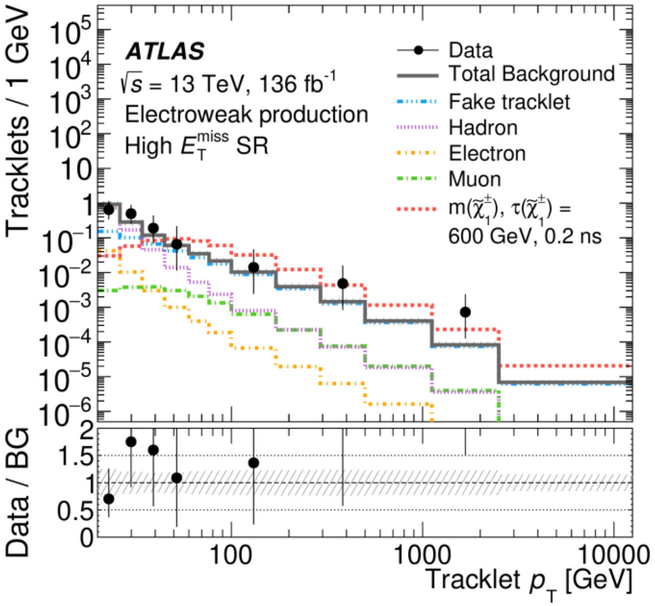
Significantly suppresses scattered backgrounds

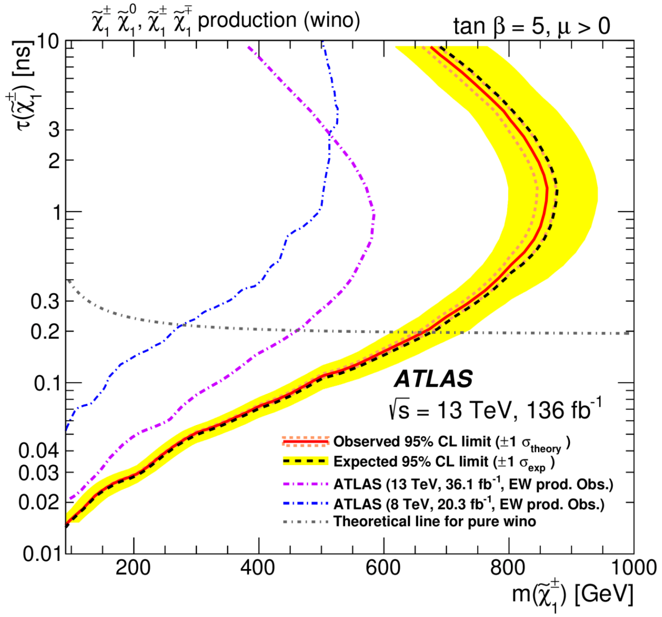
[1] [arxiv:2201.02472] [SUSY-2018-19]

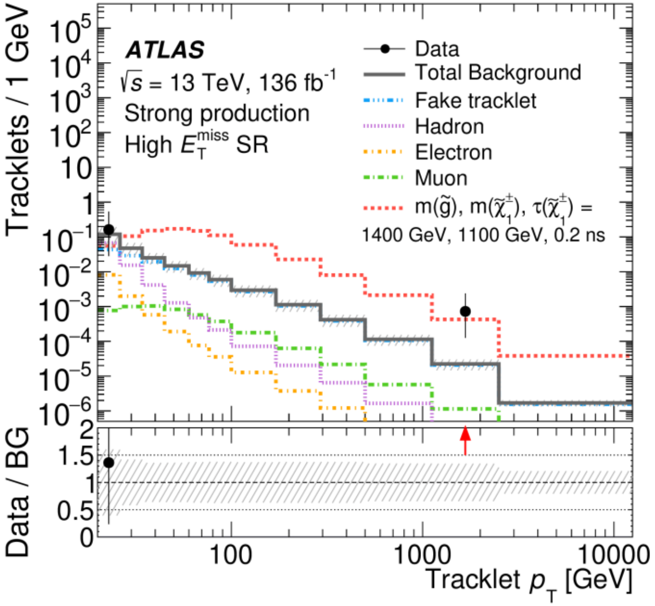


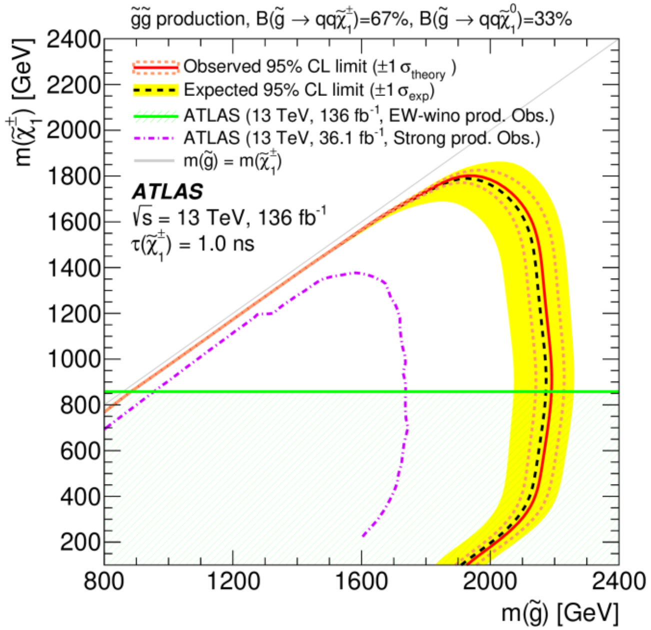
# New results

- No significant excesses identified
  - EWK: Observed **3**, Expected **3.0±0.7**
  - Strong: Observed **1**, Expected **0.84±0.33**
- Electroweak production excluded at 95% CL up to $m(\tilde{\chi}_1^{\pm})$ = 850 GeV
- Strong production excluded at up to $m(\tilde{g})$ = 2.1 TeV



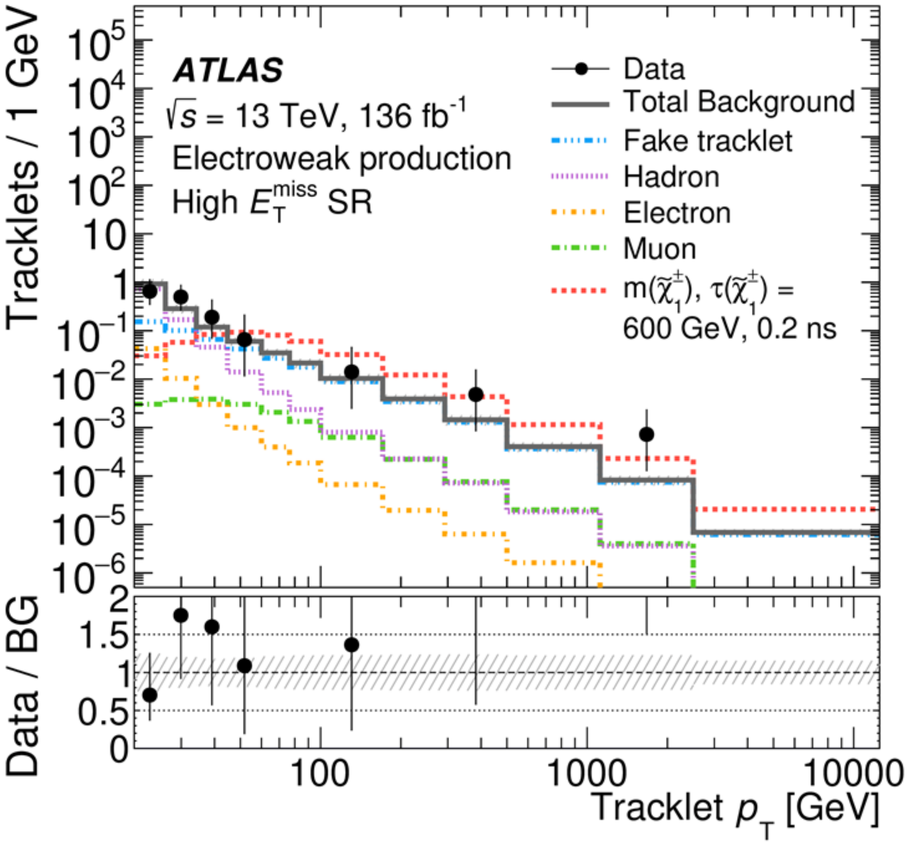



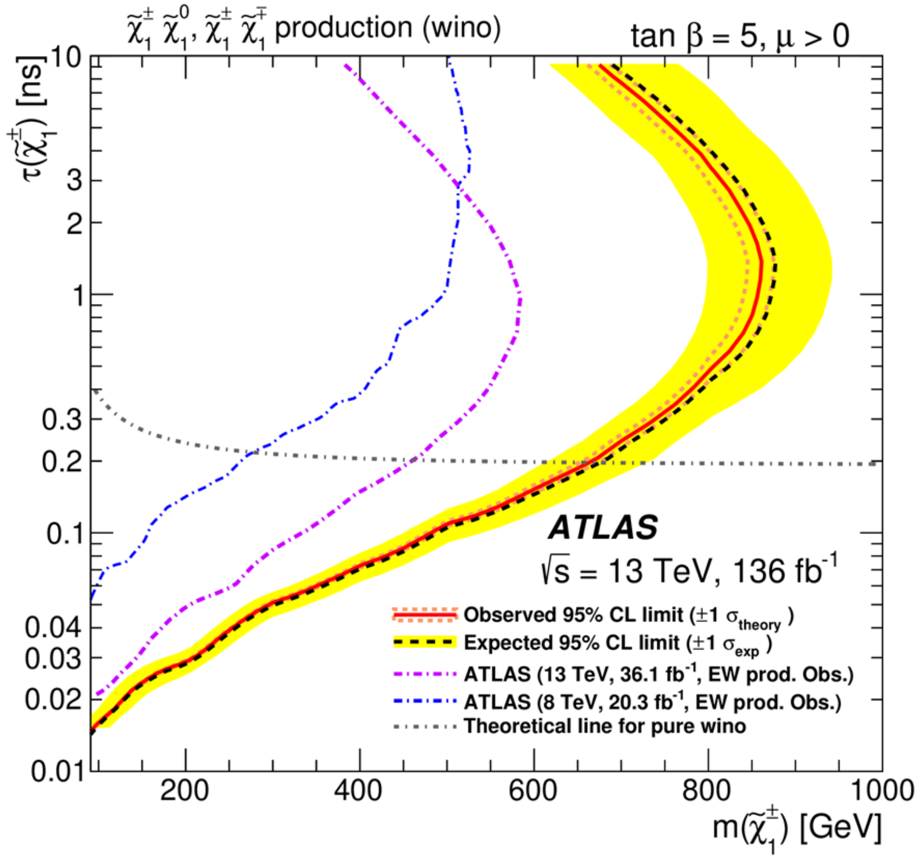



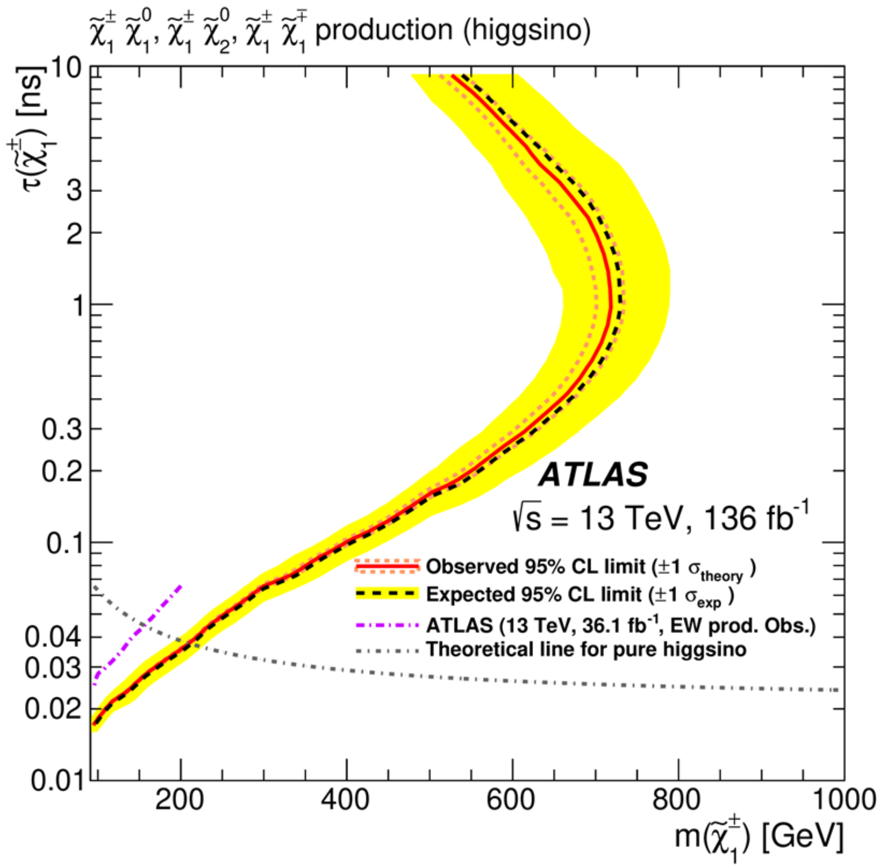

All Plots: [1] [arxiv:2201.02472] [SUSY-2018-19]

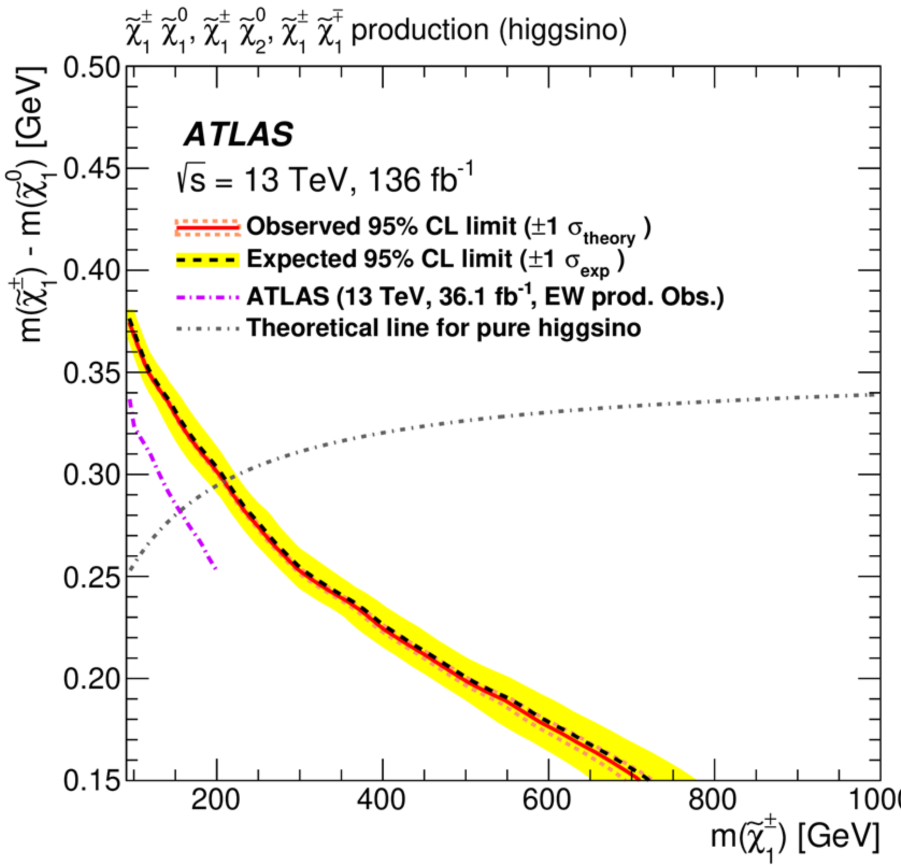
# Electroweak wino limits



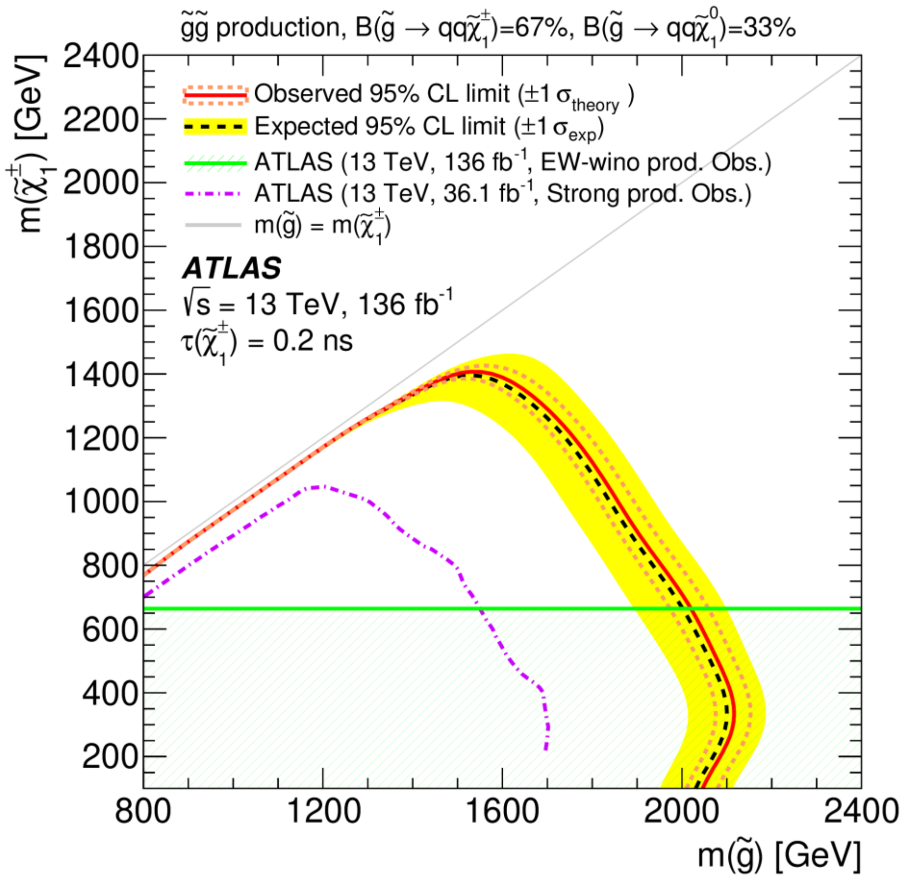



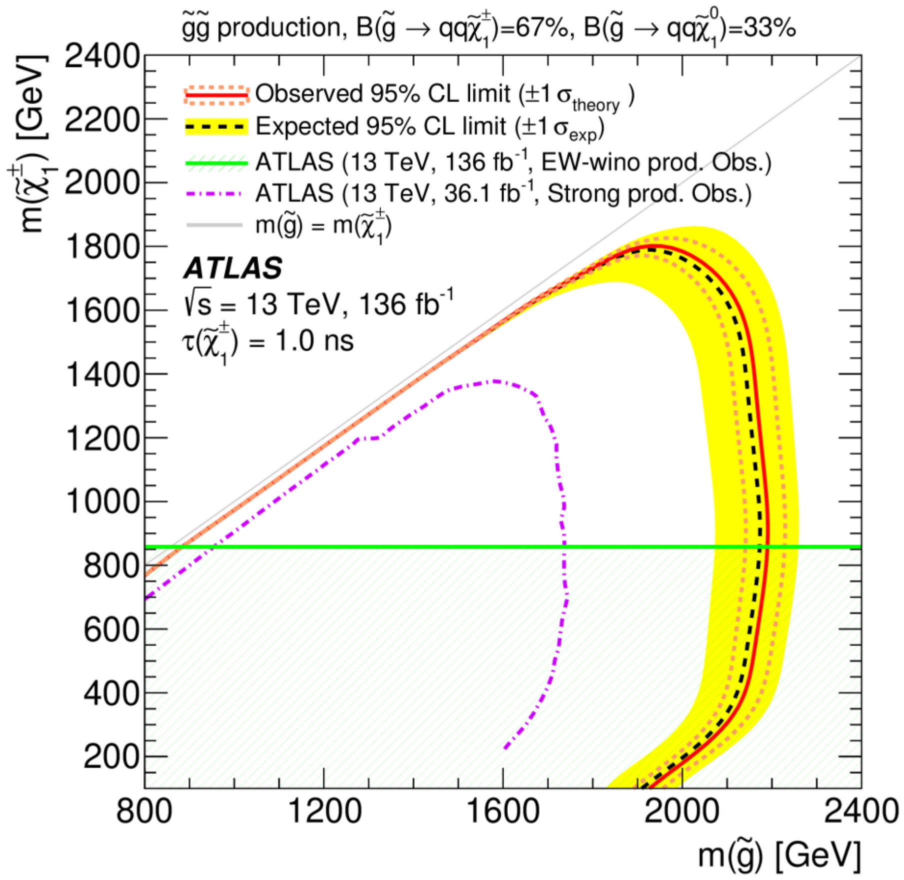
# Electroweak higgsino limits



# Strong limits

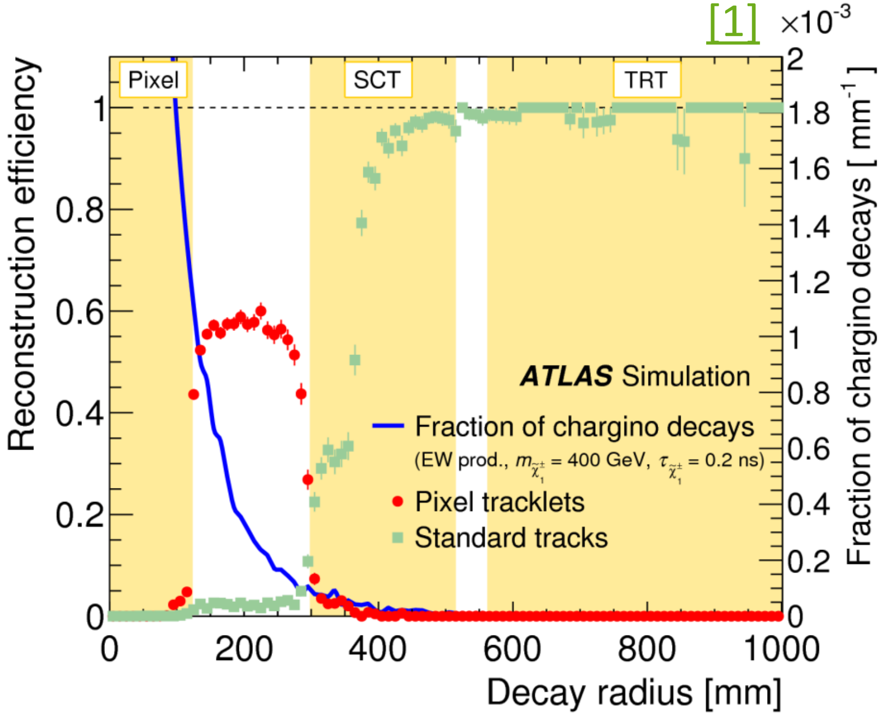


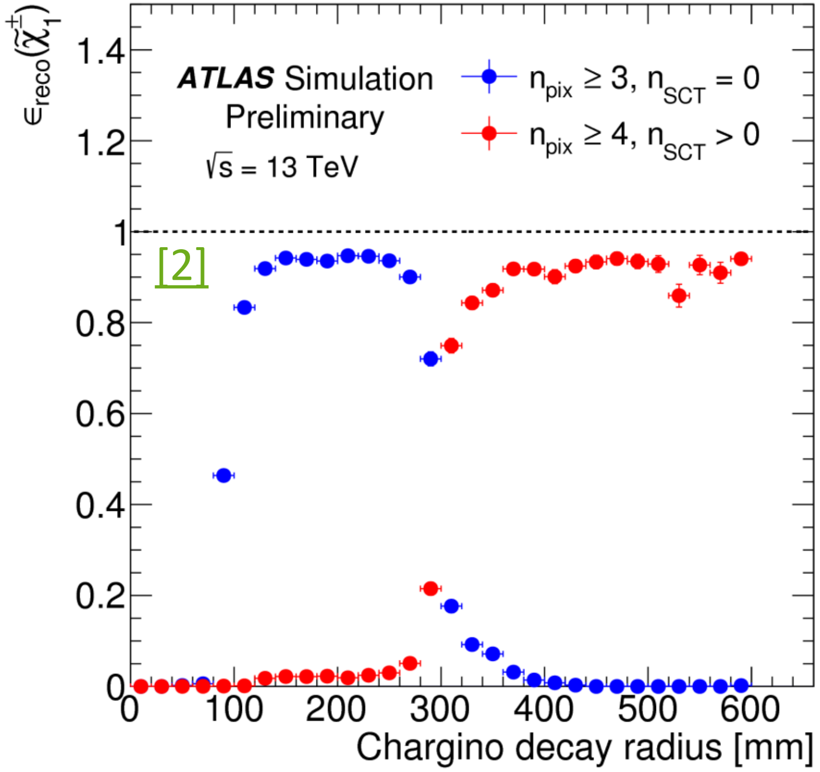



[1] [JHEP 06 (2018) 022] [arxiv:1712.02118] [SUSY-2016-06]
[2] [CDS] [ATL-PHYS-PUB-2019-011]

# Reconstruction Efficiency

[1]




[2]

# Low-$p_T$ Pions

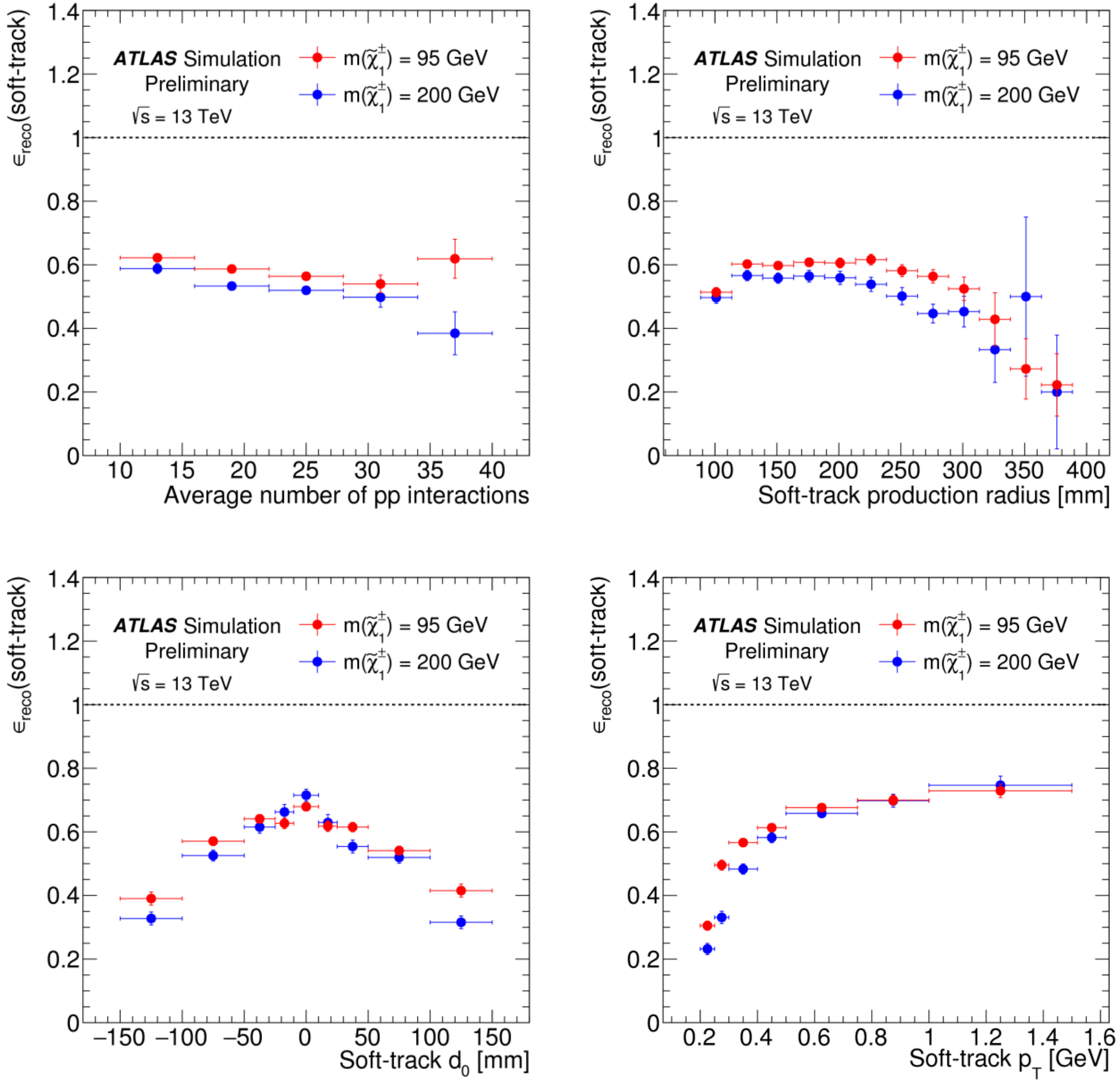
Track seeds (3 SCT hits) in region of interest:

- $\Delta R<0.8$ of tracklet
- $p_T>200$ MeV

Low-$p_T$ track with $d_0$ < 150mm and $z_0$ < 1000mm from tracklet's last pixel hit

At least 6 SCT hits

- no more than 2 shared with other tracks
- no more than 2 missing hits.



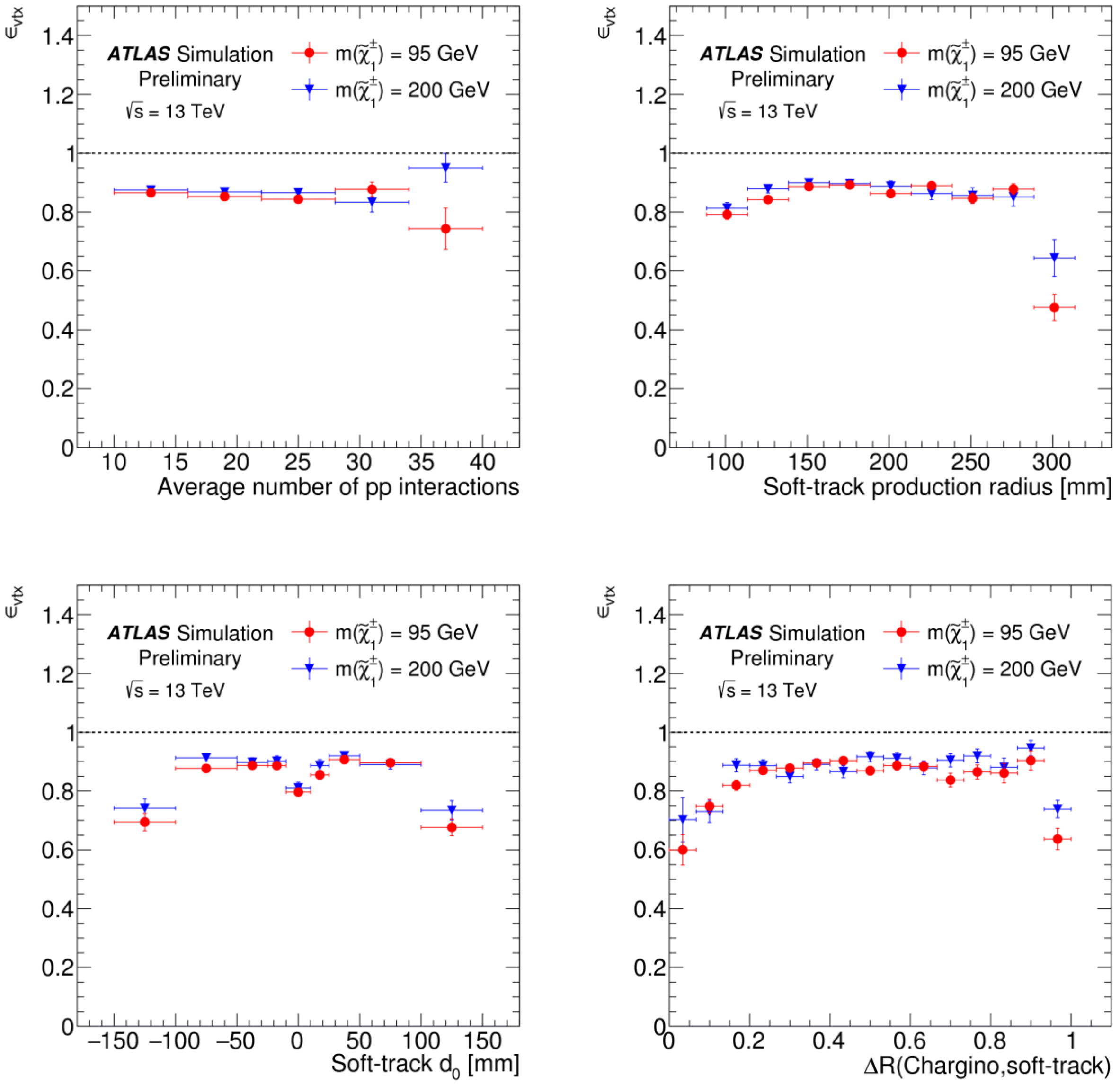

All Plots: [CDS] [ATL-PHYS-PUB-2019-011]

# Vertex Constraints

Fit tracklets and soft tracks together to estimate decay vertex

- Decay vertex can be used to improve tracklet pT resolution
- Also possible to veto areas with greater material density if scatter backgrounds are dominant

High efficiency with most cases, stable with respect to pileup



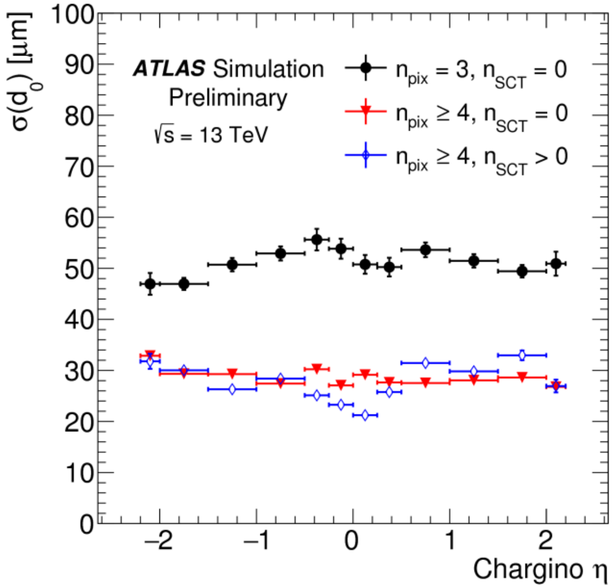

All Plots: [CDS] [ATL-PHYS-PUB-2019-011]

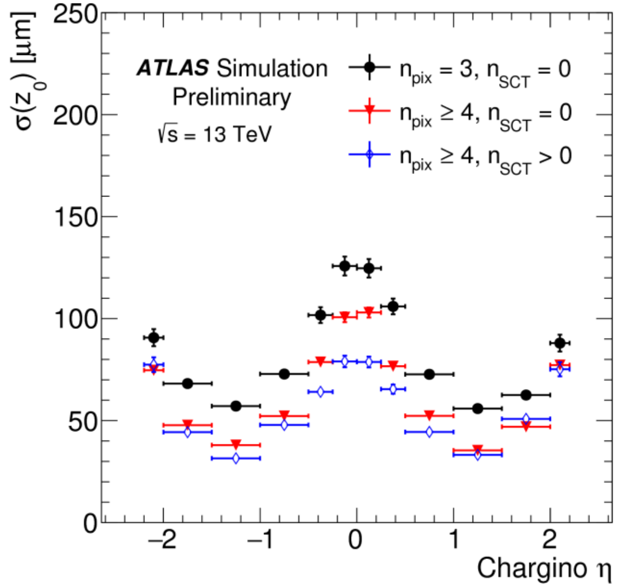
# Variable Impact Parameter cuts

Resolution of d0, z0 is dependent on d0, z0 respectively

Previously measured in 2019 [CDS]

Cuts at 2x resolution yield greatest significance vs fakes




All Plots: [CDS] [ATL-PHYS-PUB-2019-011]

# ABCD Background Estimations

Tracklet $p_T$ shape fits previously used were difficult to derive

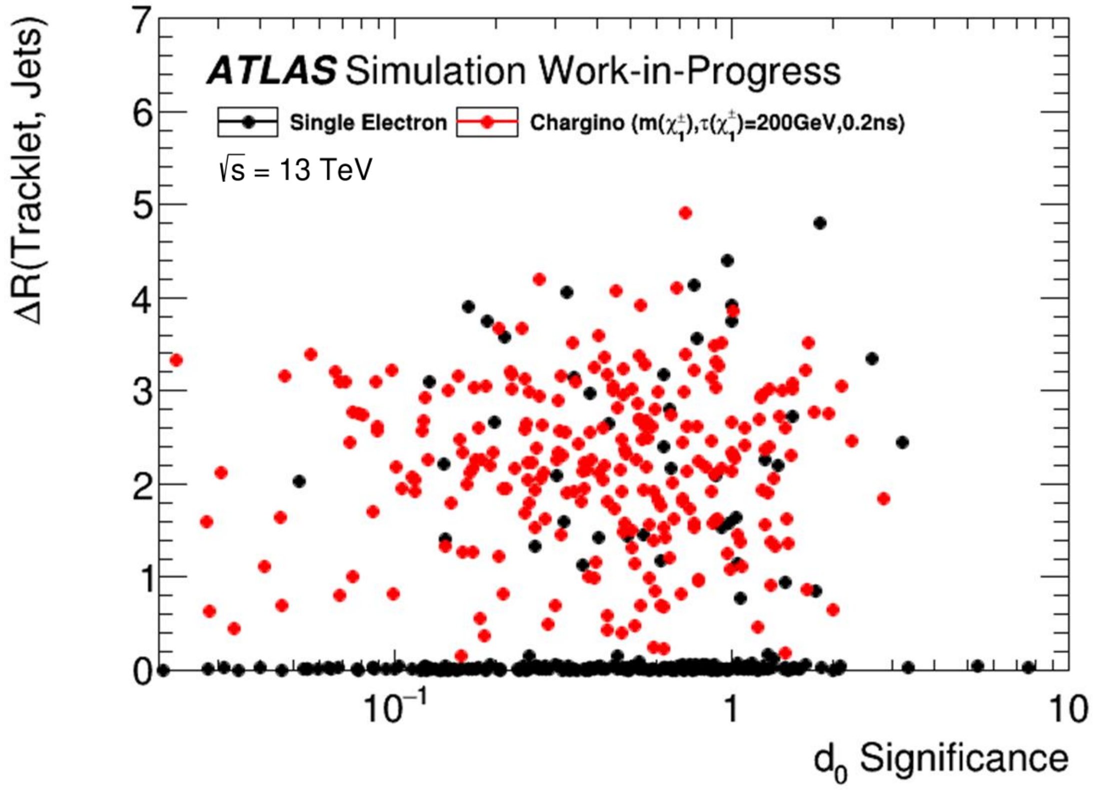
Fake control regions in data have contamination from scatters

Exploring ABCD methods for background estimation

- Not easy to cleanly separate signal and backgrounds

Exploring ML techniques with background estimation

- Improve signal significance
- Reduce signal contamination in control regions



# ABCDisCo

Use 1 or 2 NN classifiers to define ABCD plane

Use Distance Correlation (DisCo) between both classifiers in loss function as classifiers are trained to ensure they are uncorrelated

Improves signal significance

Reduces signal contamination in control regions, reducing background estimation uncertainty

[DOI: 10.1103/PhysRevD.103.035021]