

Searches for displaced vertices and unconventional signatures

J. Anders (ATLAS)
On behalf of ATLAS and CMS

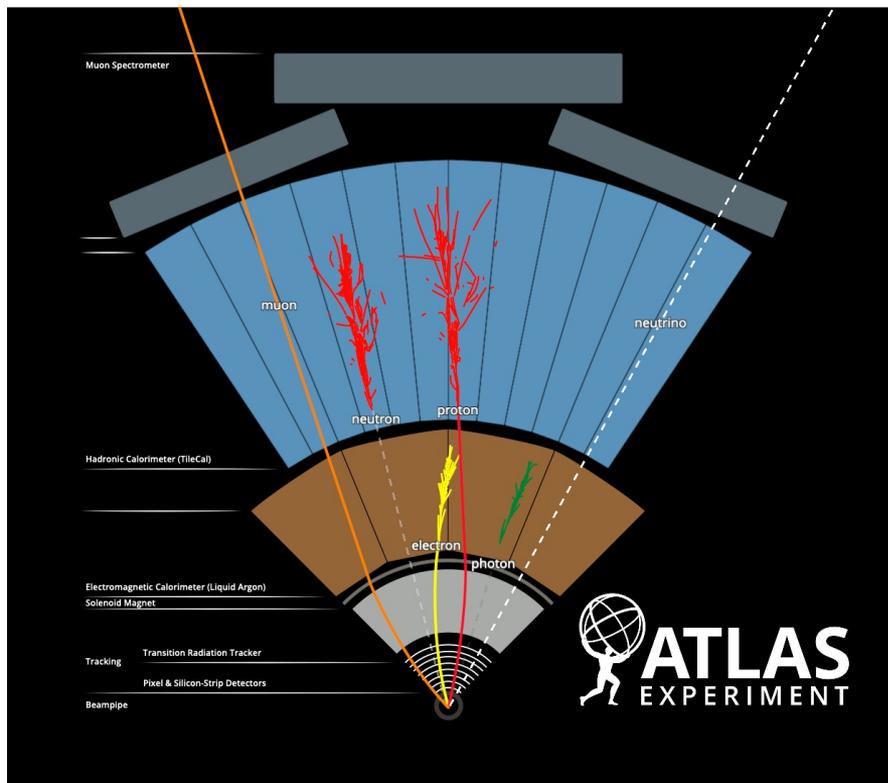
[Moriond EW 2026](#)

Usually, searches performed by ATLAS and CMS assume that any new physics particles would decay immediately into SM particles that we then detect

These particles satisfy "standard" reconstruction requirements, and leave conventional signatures within our detector:

- Electrons, muons, hadrons, and photons

We then select events using these standard particles, to target our Beyond the Standard Model (BSM) scenario and search



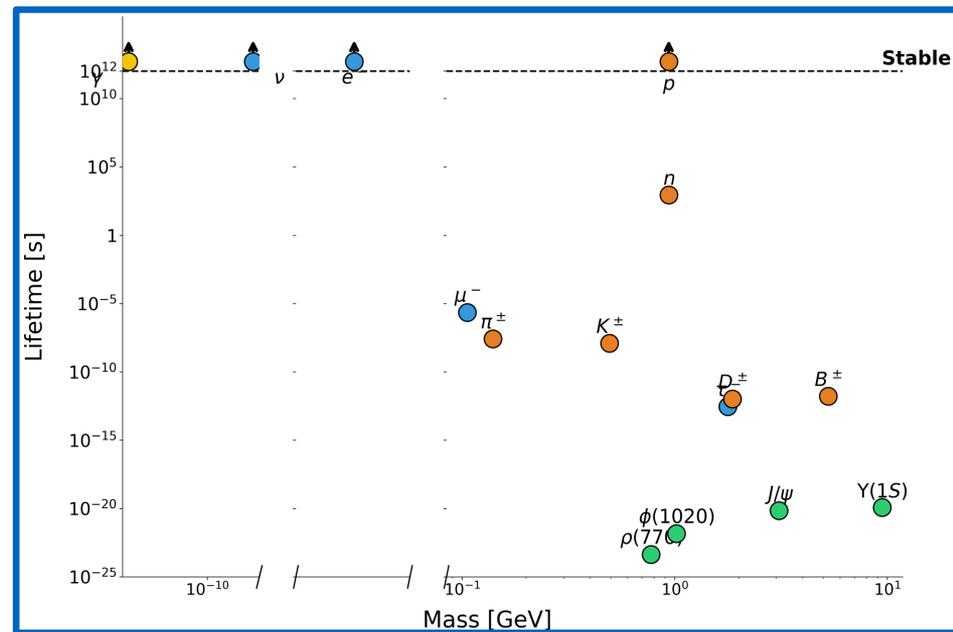
Promptly decaying BSM is a perfectly valid assumption, but it is not the only scenario possible!

Most particles we know do not decay immediately and are relatively long lived!

In restricting ourselves to only prompt decays we could be missing obvious new physics

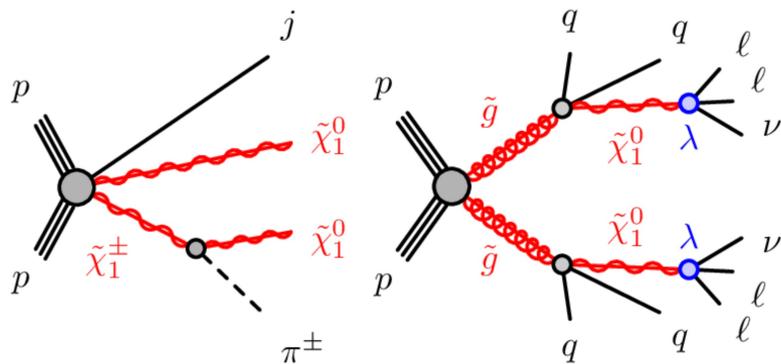
Motivating searches for "unconventional signatures":

- Displaced vertices
- Non-standard charged tracks
- Dramatic event topologies

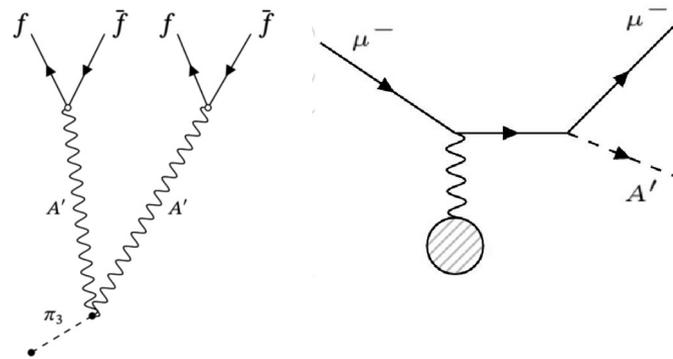


A plethora of BSM physics scenarios motivate searches for unconventional signatures

Non-standard tracks/energy deposits left behind by long-lived particles (LLPs) or displaced vertices with large associated masses
(Long-lived or R-parity violating (RPV) SUSY models)



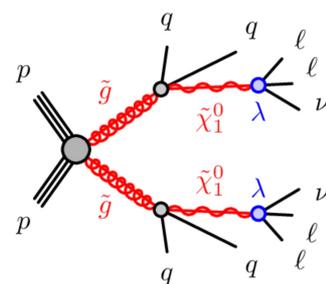
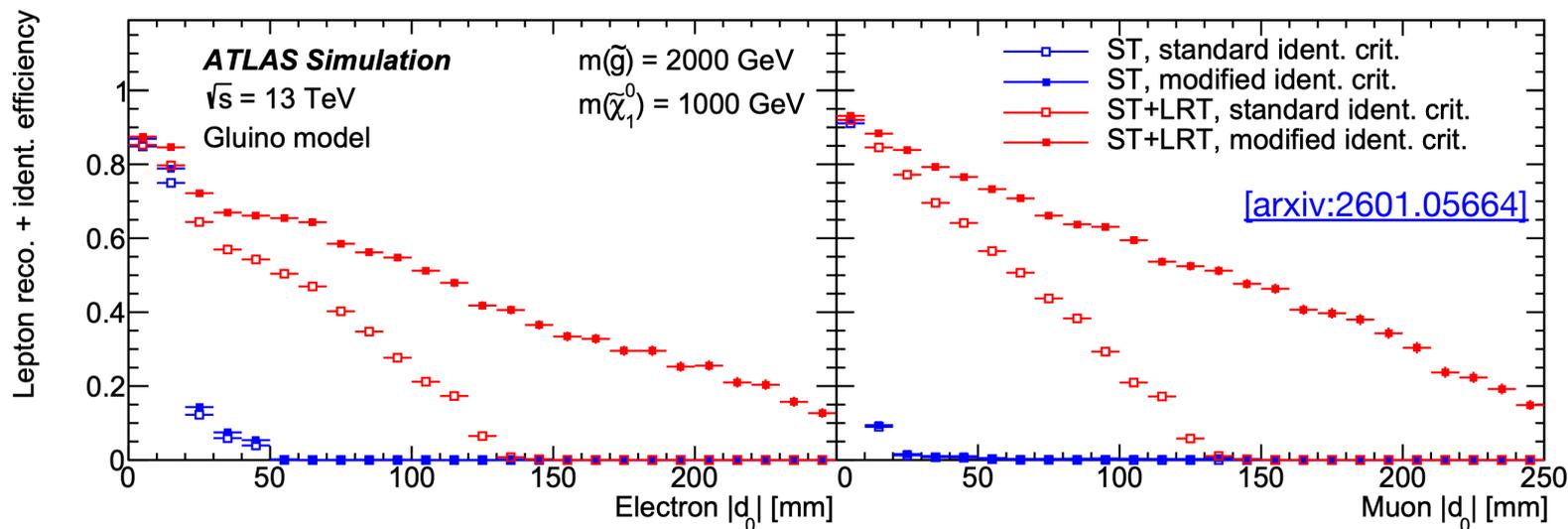
Unexplained energy loss in standard particles/jets
(Dark sector models)



Investigating these scenarios requires considerable effort in developing non-standard reconstruction techniques

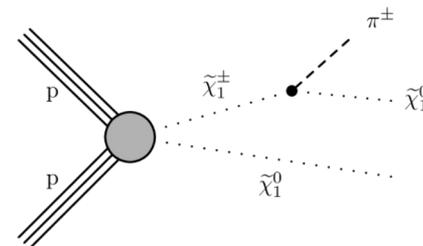
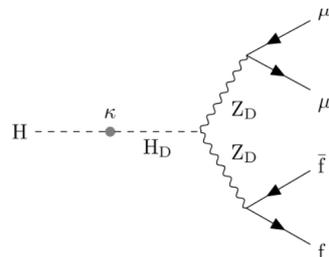
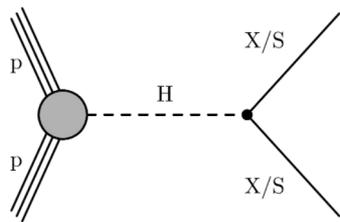
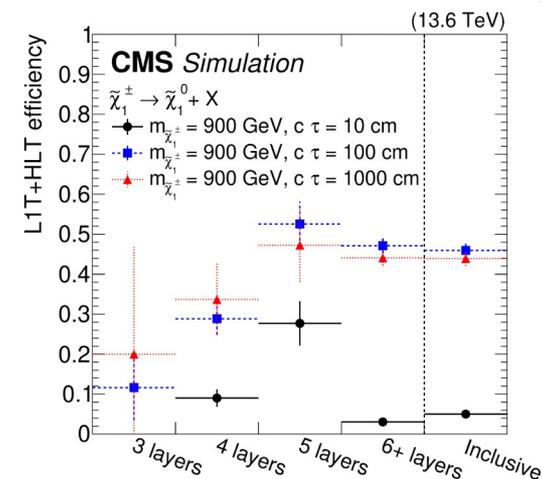
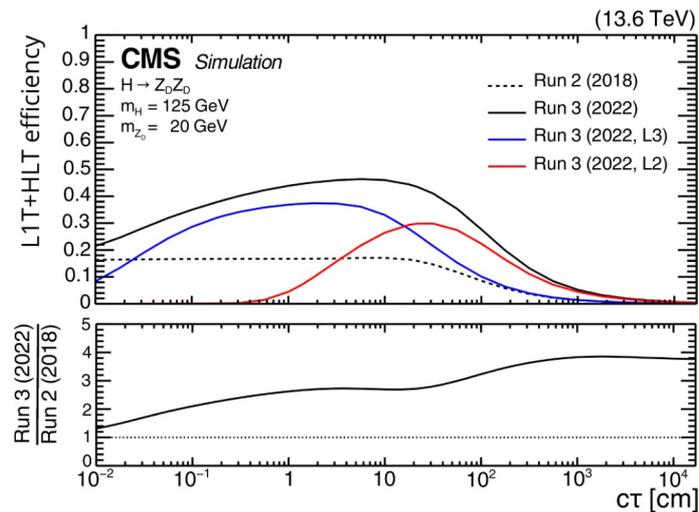
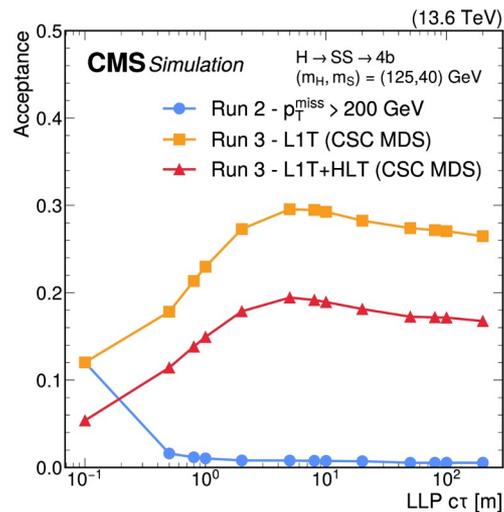
Example: Applying standard tracking algorithms to identify displaced leptons from LLP decays:

- **Standard tracking** - very low efficiency for LLP decays
- **Augmented tracking** by including "Large Radius Tracking" (LRT) - recovers the lost efficiency



It's also very unlikely that unconventional signatures satisfy standard trigger requirements.

New triggers installed during LS2 by CMS to greatly enhance LLP sensitivity

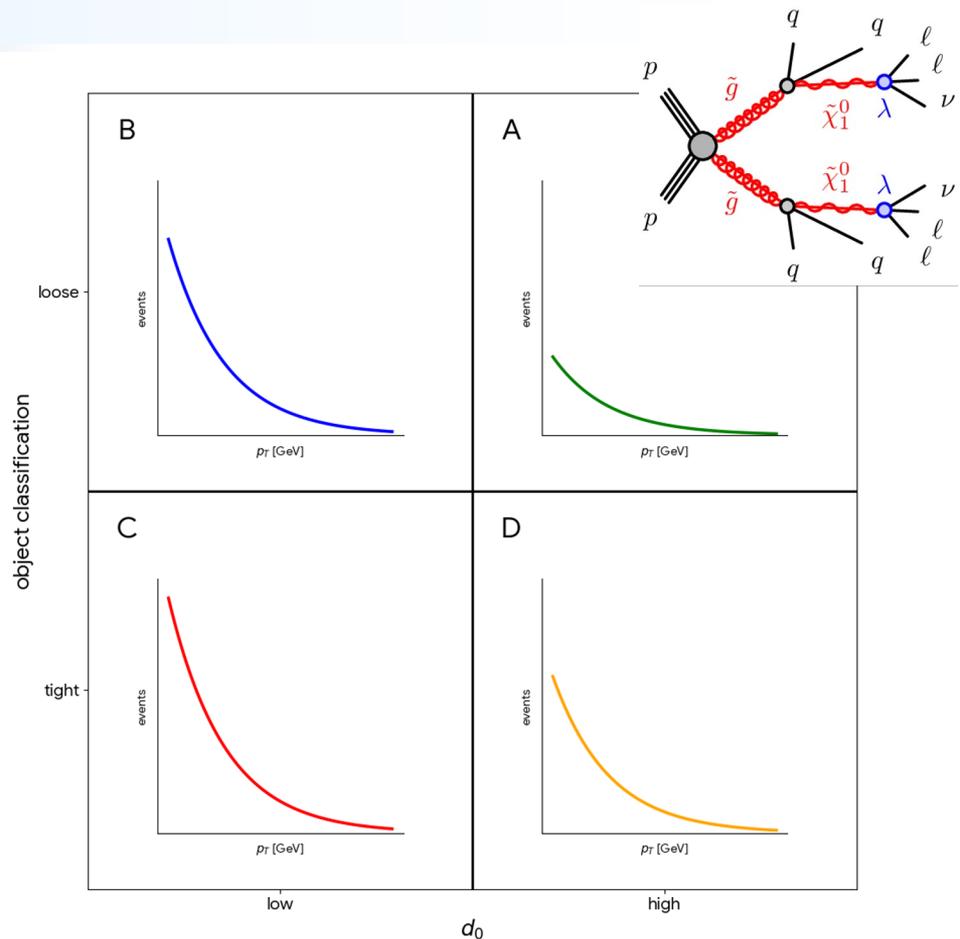


Generally, backgrounds are due to standard objects which fail standard reconstruction.

Data-driven methods are used, for example ABCD methods

Eg, for a "displaced lepton" search:

- Background arises due to a mis-ID'd standard lepton
- Take a standard lepton p_T distribution (C)
- Use "tag and probe" events to calculate transfer factors to estimate cases where the probe lepton is mis-ID'd as loose (B) or where it has a high displacement (D)
- Apply both transfer factors to the original distribution, to get the estimate in (A) the Signal Region (SR)



Unconventional Overview

Nine new results showing the power of unconventional signatures!

Run 3:

CMS	- Search for LLPs decaying into Muons	CMS-PAS-EXO-24-016
ATLAS	- Displaced Vertices and Displaced Muons	[2603.01991]
CMS	- Search for Heavy LLPs with L1 Trigger scouting data	[2601.20063]
ATLAS	- Search for Quantum black holes with leptons and jets	ATLAS-EXOT-2024-32

Run 2

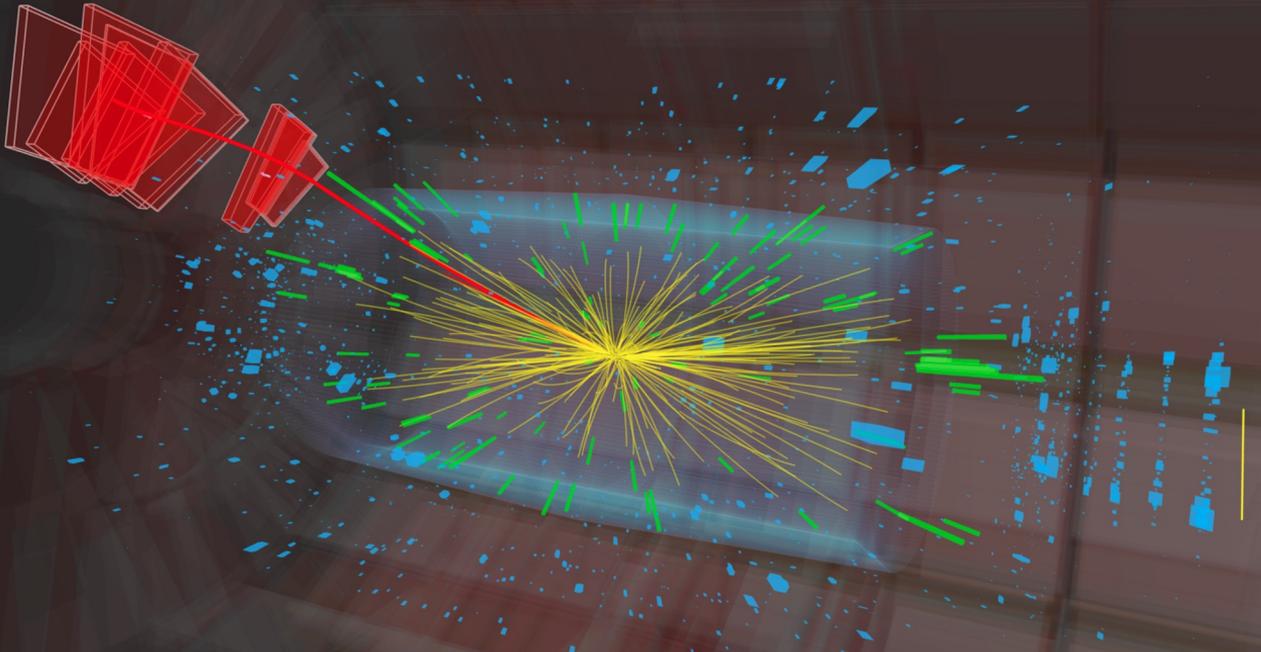
CMS	- Search for microscopic black holes and sphalerons	CMS-PAS-EXO-24-028
CMS	- Search for dark photon bremsstrahlung by muons	CMS-PAS-EXO-23-008
ATLAS	- Missing mass in forward proton-tagged dilepton events	ATLAS-EXOT-2023-13
ATLAS	- Search for LLPs using displaced vertices with OS Leptons	[2601.05664]
ATLAS	- Disappearing Track Search	[2603.08315]



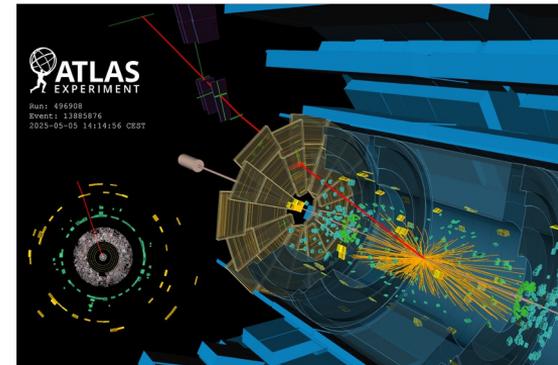
CMS Experiment at the LHC, CERN

Data recorded: 2026-Mar-07 15:14:08.834048 GMT

Run / Event / LS: 401623 / 10112375 / 45

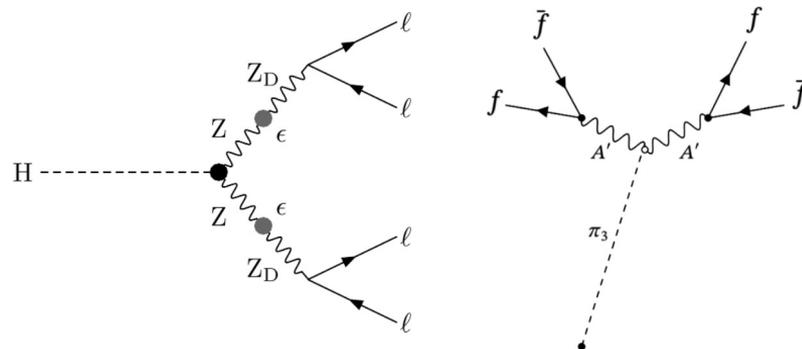


Run 3 Searches



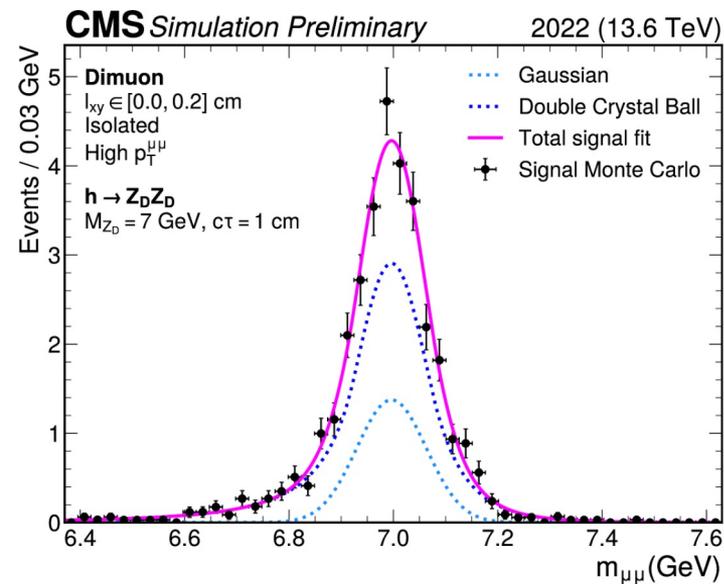
Data-scouting datasets investigating long lived dark sector particles decaying to muons at a secondary vertex

- Allows for lower p_T thresholds (below 10 GeV in di-muon mass) but reduced event information



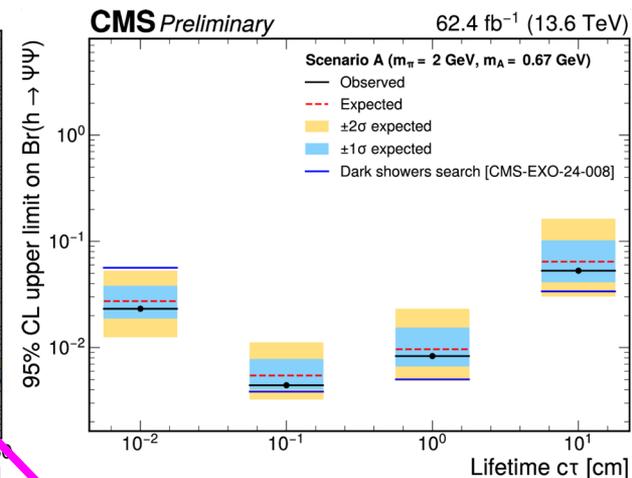
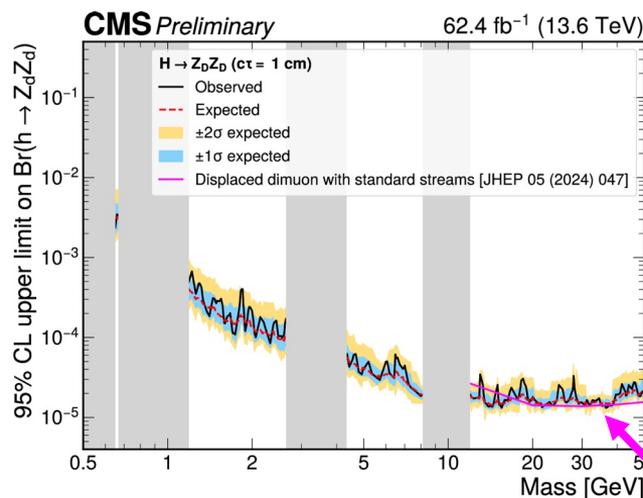
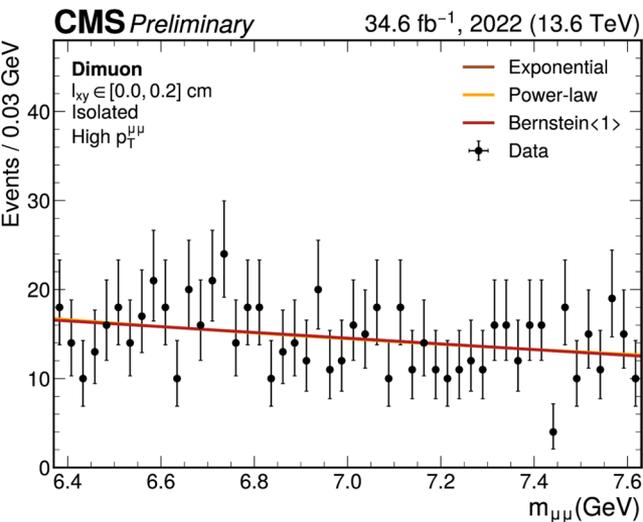
Search Regions with displaced vertices:

- $\mu^+\mu^-$ pair(s), with displacement up to 70cm, three categories
 - 1 $\mu^+\mu^-$ pair
 - 2 $\mu^+\mu^-$ pairs with resolved secondary vertices
 - 2 $\mu^+\mu^-$ pairs with one overlapping secondary vertex
- Fit is performed in different vertex displacement categories across the dimuon mass spectrum



Background is taken directly from data

- Fitting analytic functions (Bernstein polynomials, power law and exponential functions) to the $\mu^+\mu^-$ mass spectra



No significant deviations from the background predictions

- Data scouting allows for significantly lower masses to be probed than previously possible!
- Limits placed in dark photon and dark shower dimuon models

Focuses on neutral LLP decays within the ATLAS innermost detector layers

- One displaced vertex and at least one muon with large transverse impact parameter

Unconventional trigger and tracking

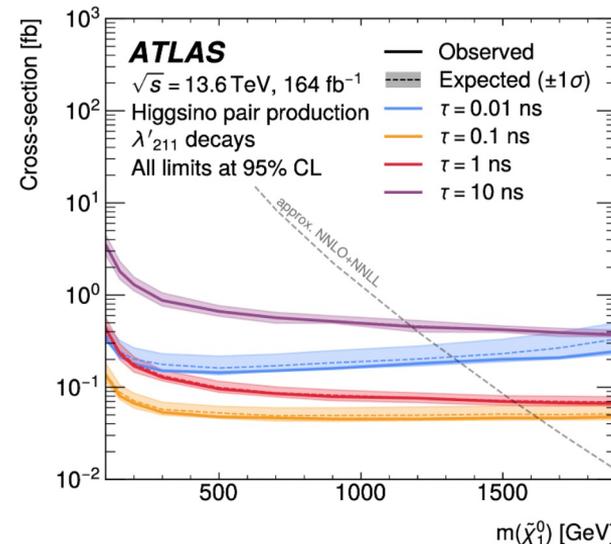
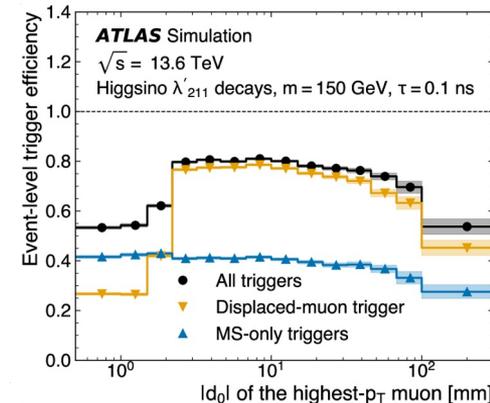
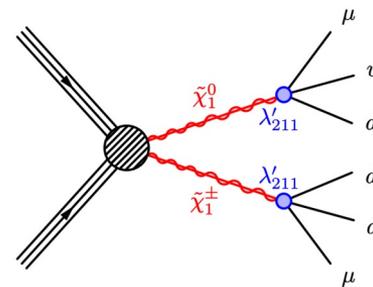
- Trigger uses Muon Spectrometer (MS) information only
- LRT identifies large impact parameter muons

ABCD Method to estimate background

- Mainly arises from tracks reconstructed from coincidental/unrelated hits
- Invert muon-requirements and impact parameter

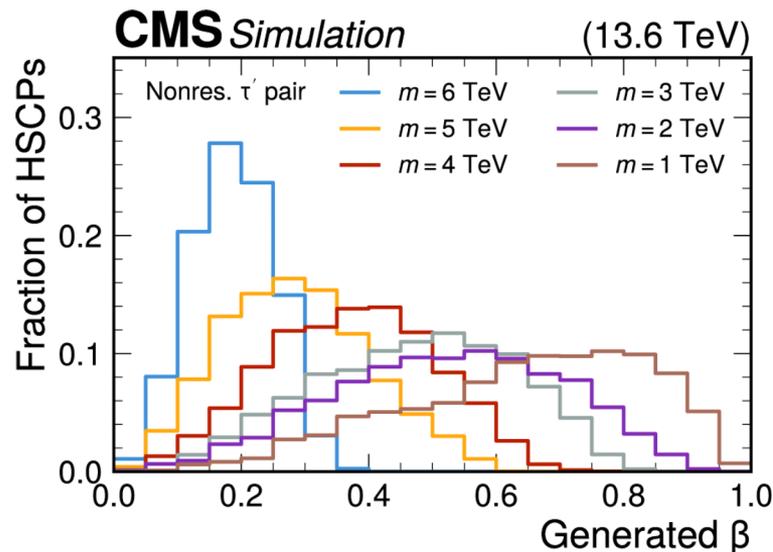
No significant excess

- Model independent limits and
- Interpretations in multiple RPV SUSY models



More in [David Rousso's talk](#)

Generically investigating heavy long-lived charged particles (such as a τ' -lepton) travelling through the detector at various β



Unconventional trigger:

- First time the analysis has been performed without requiring any trigger selection, allowing events between bunch-crosses to be analysed, L1 system operating at 40MHz to collect data
- Allows "stub" tracks (short tracks built from drift tube and RPC info) to be reconstructed between bunch crossings

Analysis selection requires:

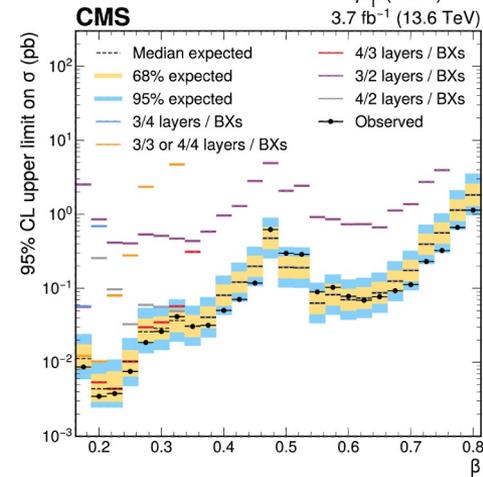
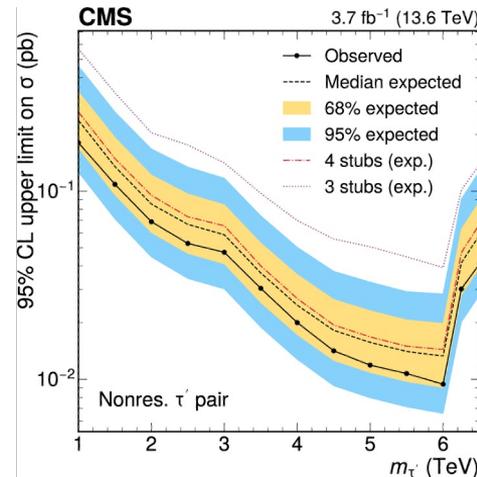
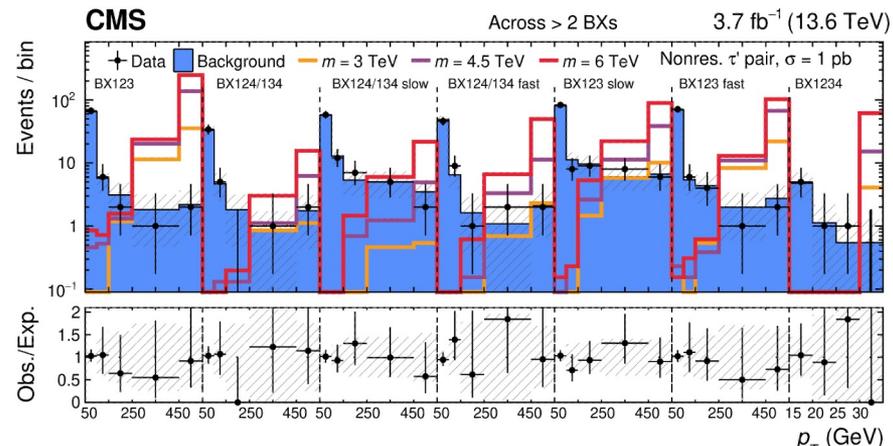
- At least one track with 3 or 4 stubs, reconstructed across a minimum (maximum) of 2 (4) bunch crossings

Backgrounds arise due to:

- Misidentification of highly relativistic particles and combinations of unrelated stubs
- The track p_T distribution is estimated using tracks with "asynchronous" time ordering of the stubs

No significant excesses seen:

- Limits placed on heavy charged LLPs (such as τ') and upper limits on cross-section (in β)
- Proof of concept L1 data scouting system complementing searches by extending the sensitivity to lower β values.



Investigating QBH production in very energetic events

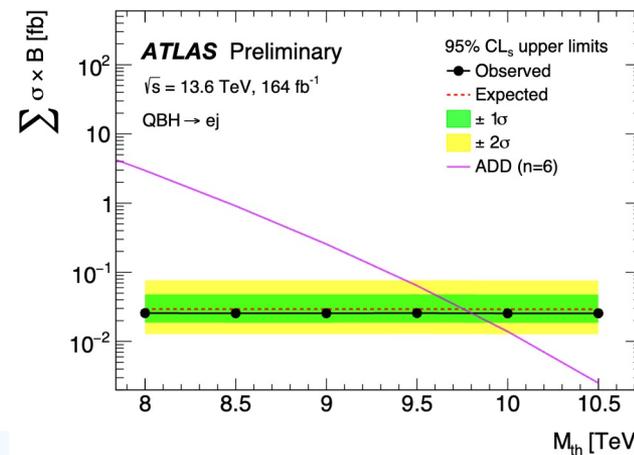
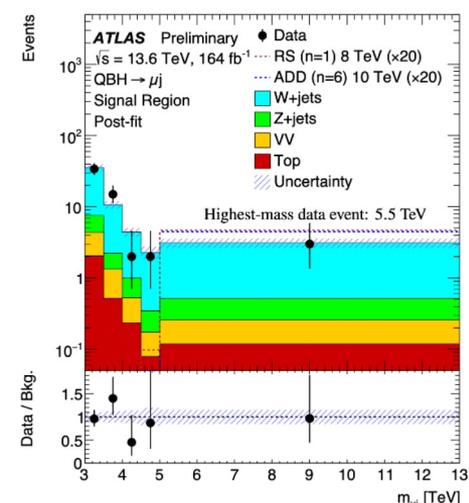
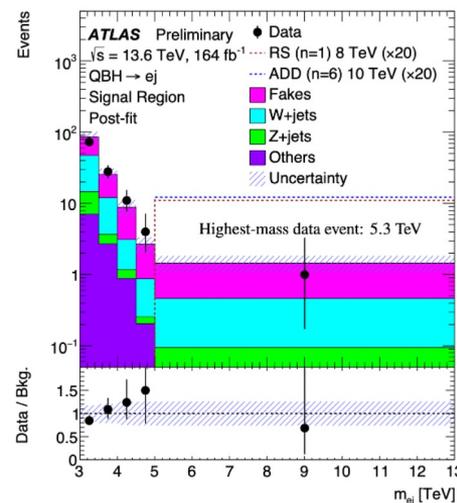
- Increased cross section for highest masses due to increase in \sqrt{s}
- Requires at one lepton (e, μ) and at least one jet, produced back-to-back with high invariant mass

Backgrounds due to :

- e-channel - fakes, estimated with ABCD method
- μ -channel - W+jets, extrapolated from orthogonal Control Region

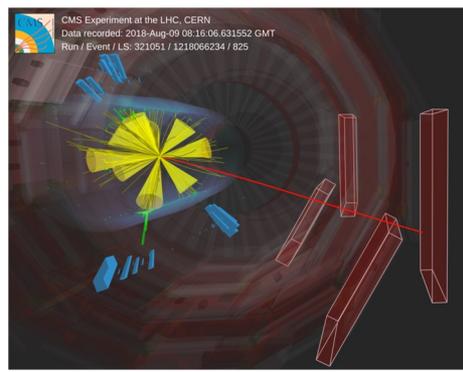
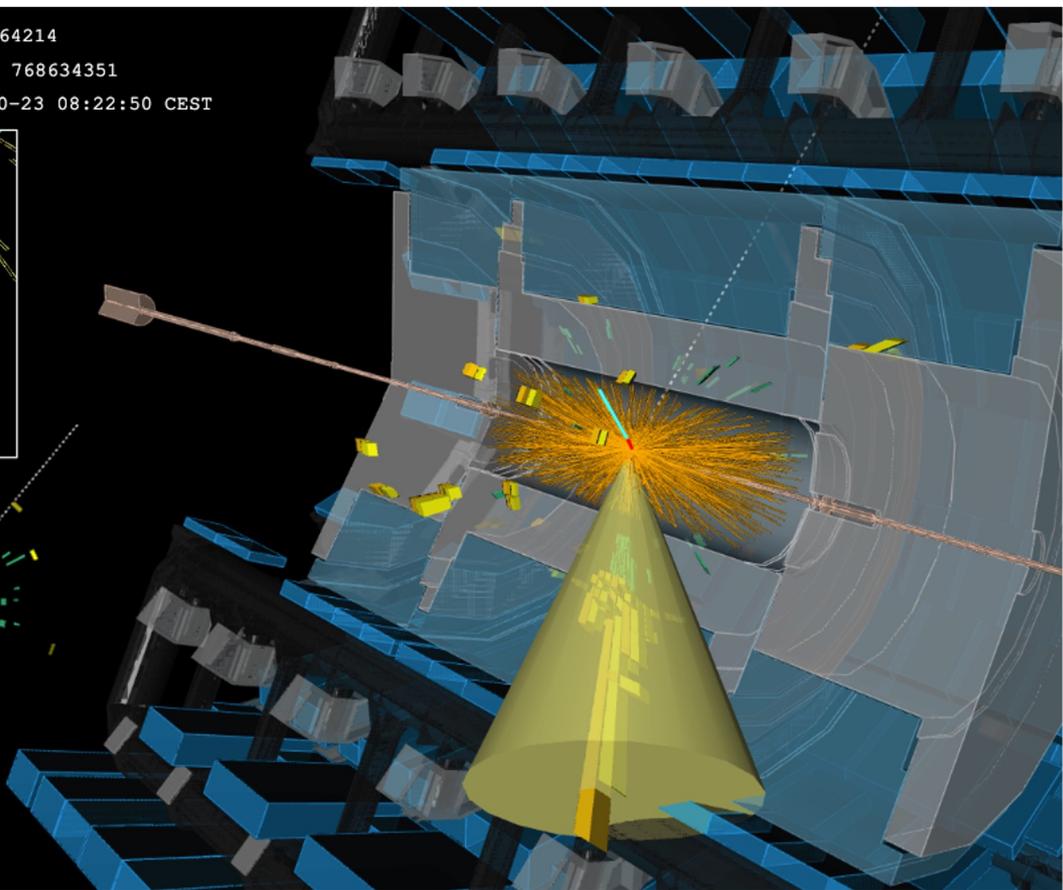
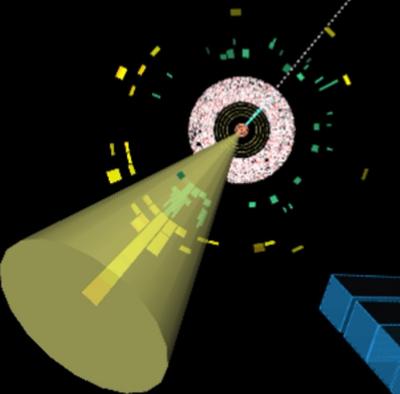
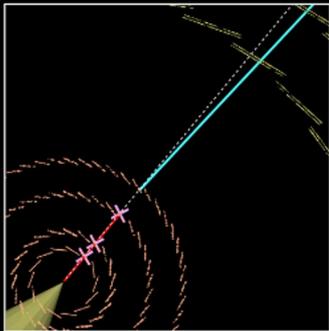
Excellent agreement with SM predictions:

- Very high energy events of 5.3 and 5.5TeV observed
- Limits placed up to 9.8TeV in ADD and 7.7TeV in QBH models



 **ATLAS**
EXPERIMENT

Run: 364214
Event: 768634351
2018-10-23 08:22:50 CEST



Run 2 Searches

Spectacular events with final states with very high object multiplicities

Model independent approach:

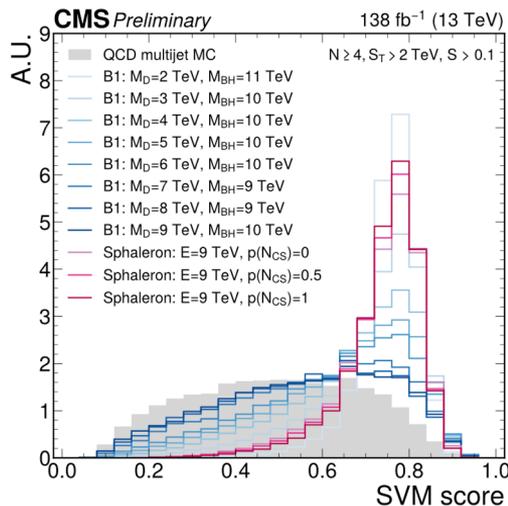
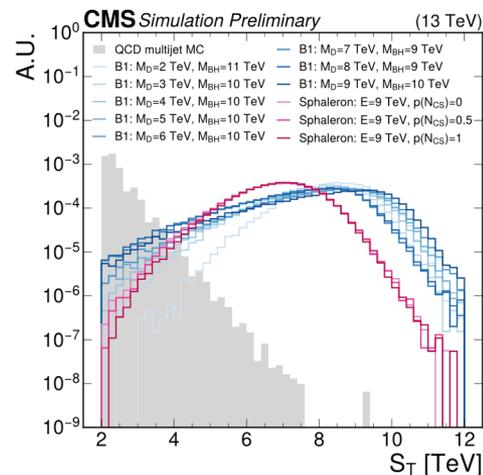
- Focus on shape invariance of S_T (scalar sum of all objects in the event) across multiplicities

Model dependent approach:

- "Phase space" distance between two events on a $(N-1)$ simplex and $(2N-3)$ hypersphere:

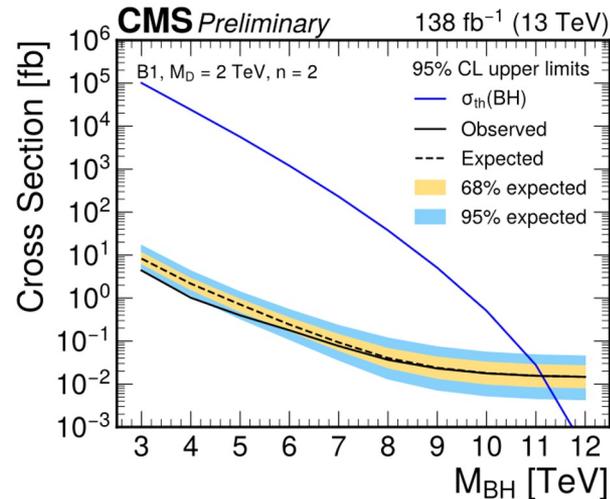
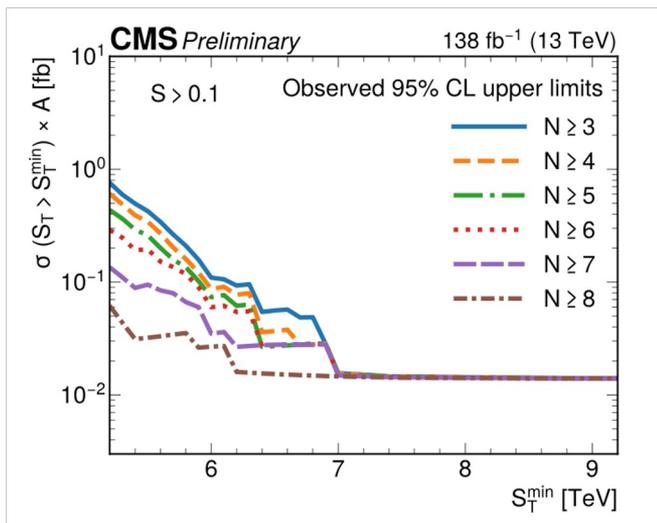
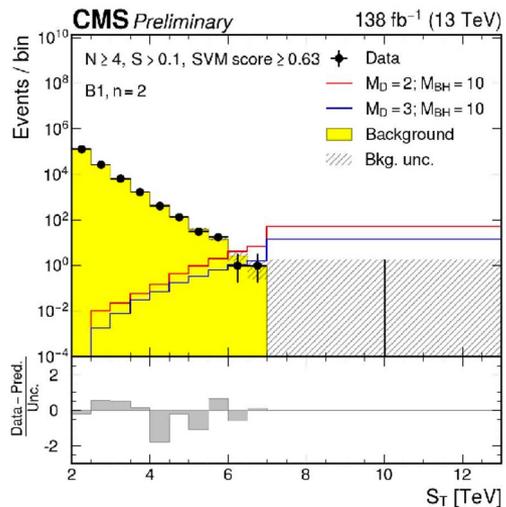
$$d_{\Pi}(\vec{\rho}_A, \vec{v}'_A; \vec{\rho}_B, \vec{v}'_B) = \sqrt{\frac{1}{16\pi^2} \left(\frac{c}{4}\right)^{\frac{3-2N}{3N-4}} d_{\Delta}^2(\vec{\rho}_A, \vec{\rho}_B) + \frac{1}{4\pi^2} \left(\frac{c}{4}\right)^{\frac{N-1}{3N-4}} d_S^2(\vec{v}'_A, \vec{v}'_B)}$$

- Support Vector Machine (SVM) used as a ML classifier trained on background (multi-jets MC) and signal (black hole MC), using a radial basis function to maximise the phase space distance



Data driven background estimation strategies:

- Shape invariance - fit analytic functions to S_T to higher object multiplicities
- Phase Space Distance - ABCD method extrapolate events from low SVM score to high score by multiplying by a S_T dependent transfer factor

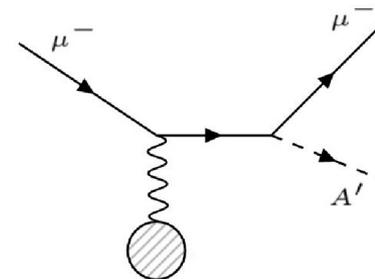


No significance excesses above background prediction in any region

- Model independent limits placed in bins of S_T (shape invariance method)
- Model dependent limits in a set of black hole models

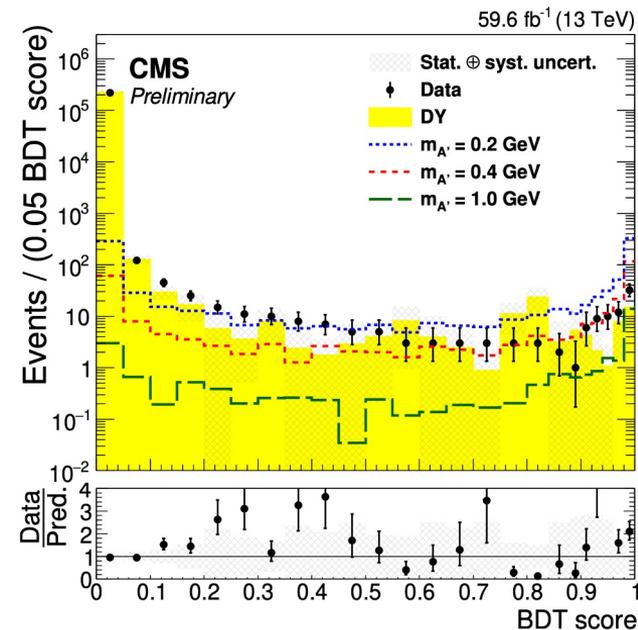
First search of this type at an LHC experiment, searching for muons interacting in the end-cap calorimeters

- Requires $\mu^+\mu^-$ consistent with a Z-boson decay
one standard μ and one "track" μ



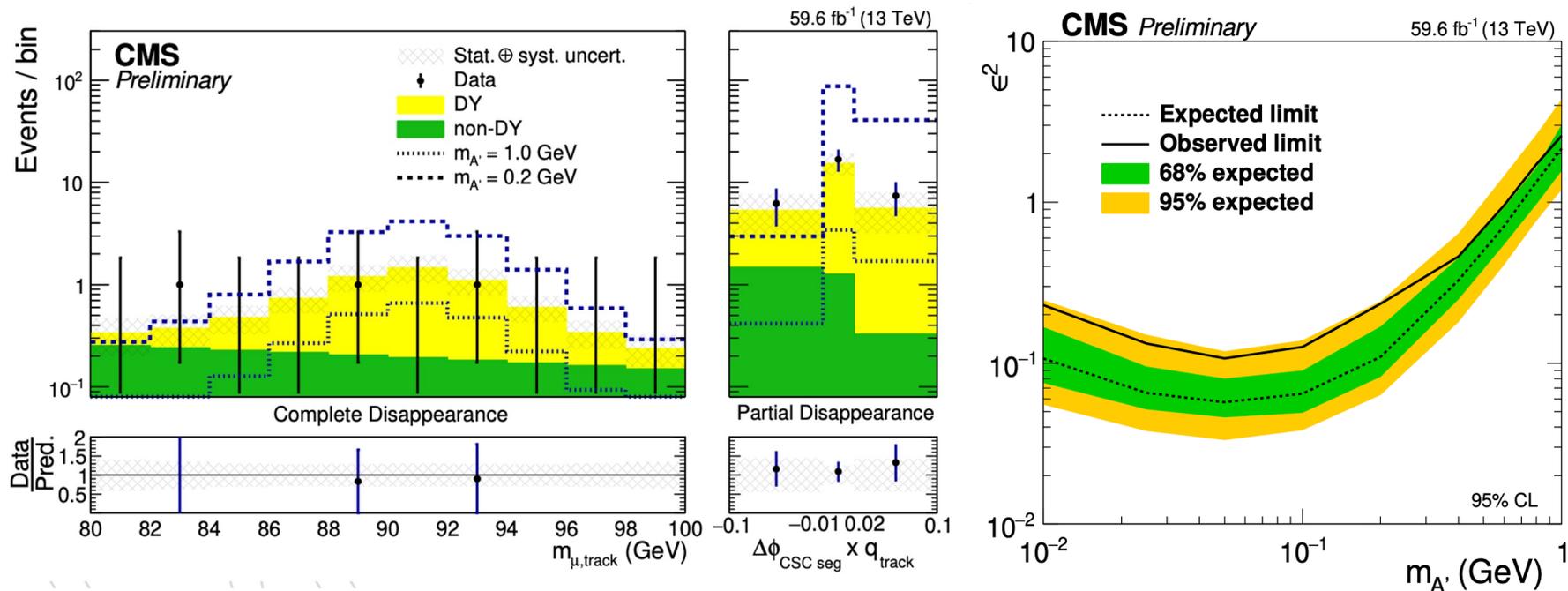
Unconventional muon interaction with end-cap calorimeter

- Track μ loses energy in the end-cap calorimeters due to dark bremsstrahlung
- Complete disappearance - absence of the μ in the muon chambers
- 'Partial' disappearance - μ can be associated with deposits in the muon chambers (loss of energy)
 - Uses a BDT to distinguish between Drell-Yan (DY) background



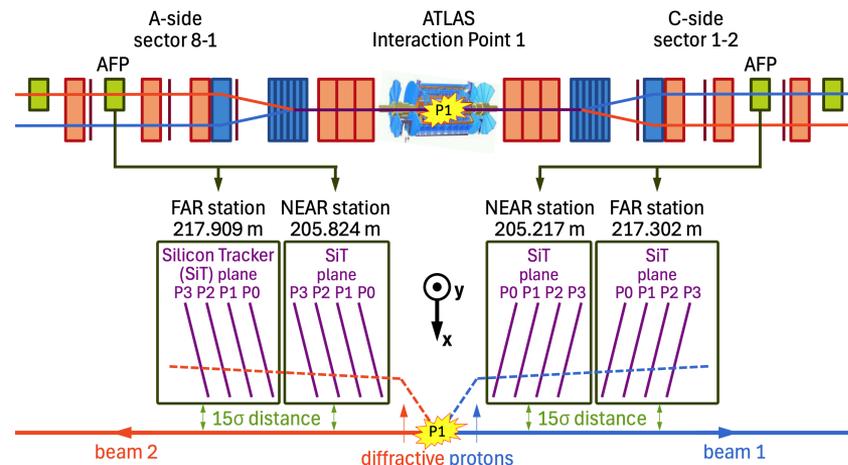
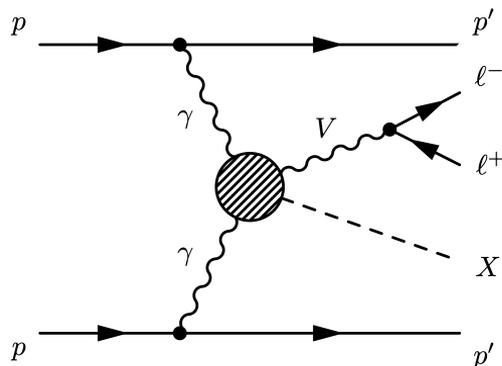
Main backgrounds due to DY interactions with "missed" muons

- DY taken from MC, non-DY taken from data in both categories, fitting function to the data in orthogonal CRs



No significant excesses in either set of SRs with limits placed on low-mass dark photons

Investigation into diffractive processes initiated by photon interactions



What's unconventional?

- Uses the ATLAS Forward Proton (AFP) spectrometer to identify forward protons
- Simple calculations allow for the 3D "missing mass" to be calculated based upon the deflection from the beamline

"Tagging" forward protons allows a model agnostic search to be performed

- Investigate a generic "narrow" resonance in the missing-mass spectrum from 100-900 GeV

Event selection containing:

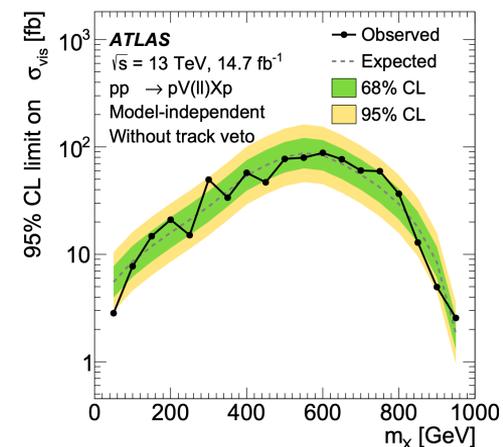
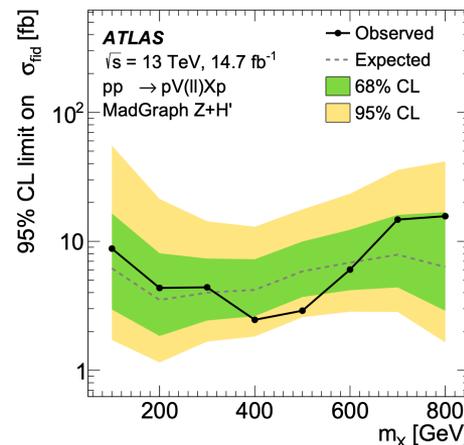
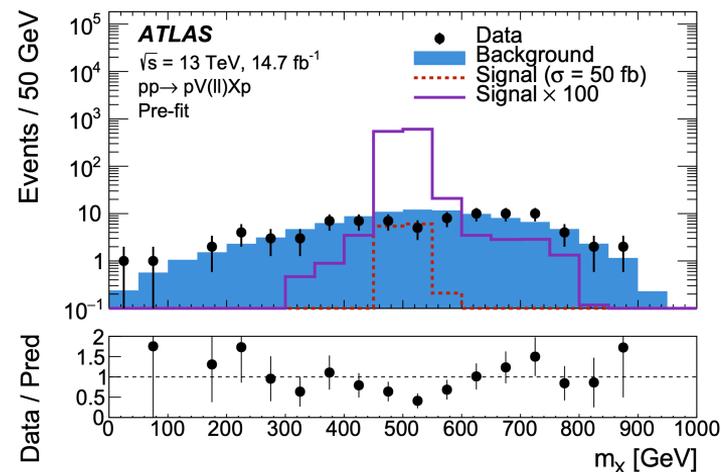
- e^+e^- or $\mu^+\mu^-$, no additional tracks
- Two "tight" identified protons in the AFP detector with fractional energy loss < 0.12

Main backgrounds due to inclusive SM processes being combined with protons from pile-up events

- Uses an event mixing procedure, mixing central dilepton events with proton information from a different event

No significant excess

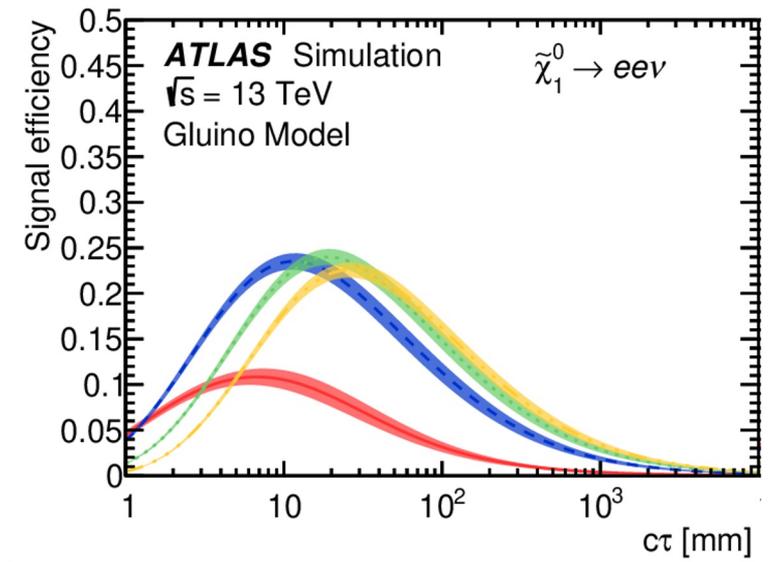
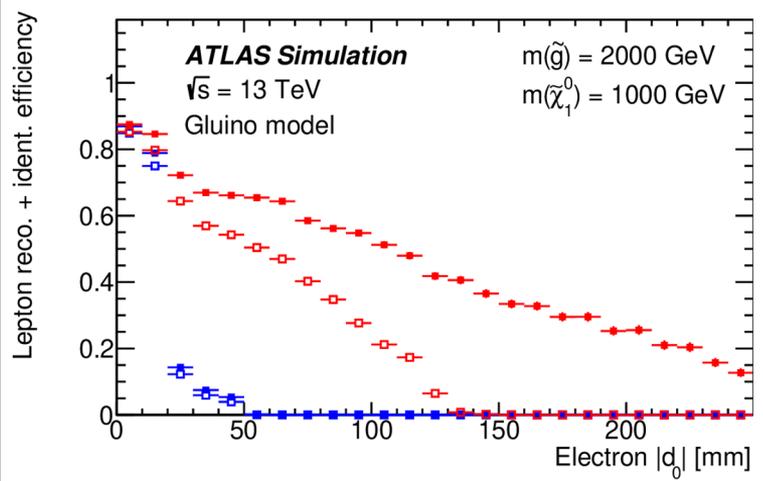
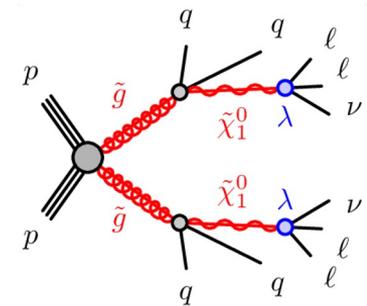
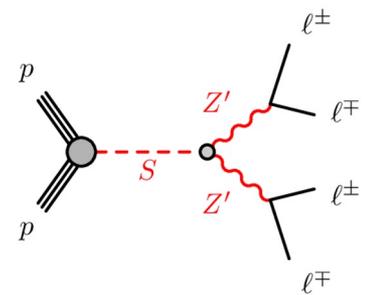
- Model independent σ_{inv} limits down to 100fb
- Interpretations in multiple dark sector models



Investigating models with long lived scalars, and RPV SUSY scenarios

Unconventional signature requiring displaced vertices:

- No ID tracking information is used to trigger, only MS (for μ) and calorimeter (for e)
- LRT used to recover sensitivity

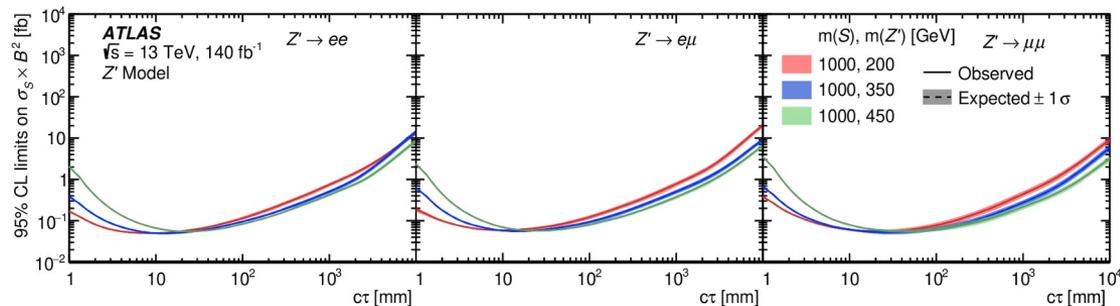
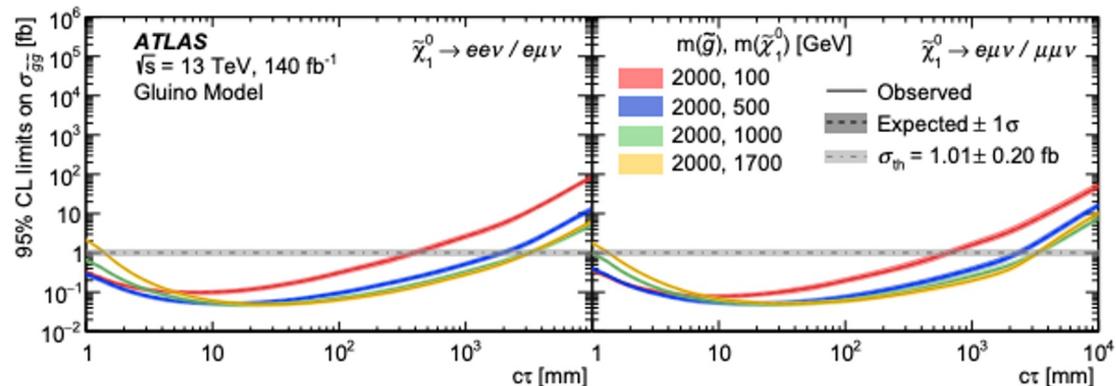


SR Selection requiring:

- At least one displaced vertex associated with e^+e^- , $e^\pm\mu^\mp$, $\mu^+\mu^-$
- Background mainly due to randomly crossing lepton tracks, estimated using "event mixing"

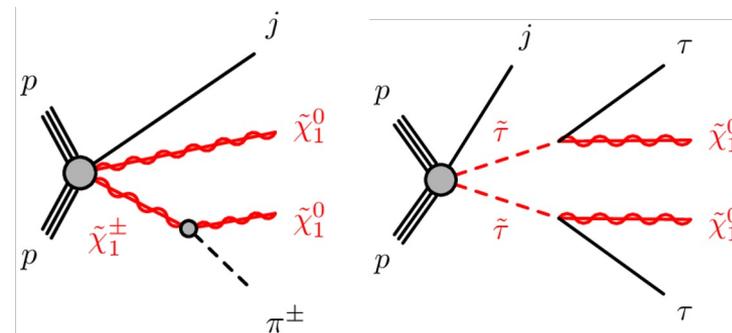
Zero events observed in SR (consistent with background expectation):

- Cross-section upper limits placed in Gluino, Z' and electroweakino models



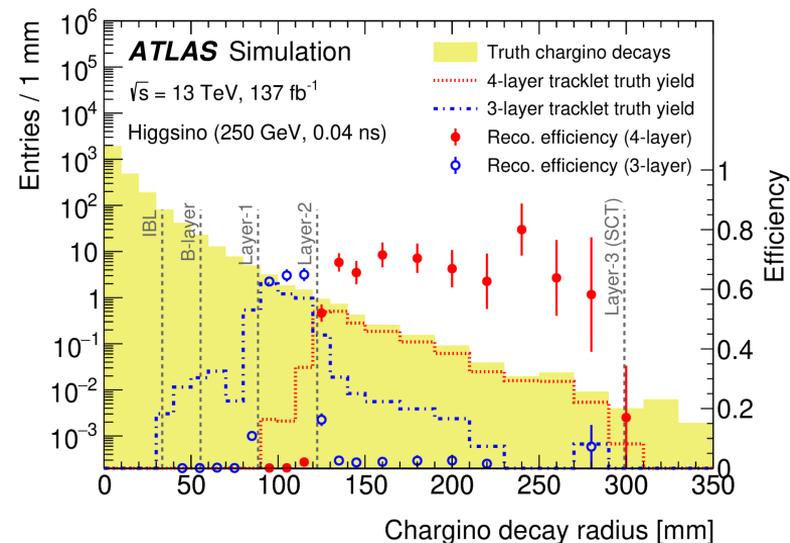
Search for SUSY scenarios with light electroweakinos

- Long-lived chargino decaying within the innermost layers of ATLAS
 - Reconstructed as a "tracklet" (short track) using additional tracking from 3- or 4-hits
- Also sensitive to stau production with long-lived decays (GMSB, CMSSM)
- Follow-up to previous Run 2 analysis



Four Signal Regions defined with an ISR selection and require the presence of a tracklet

- Improvements from previous analysis:
 - Two SRs with hits in only three-layers (very short tracklets)
 - BDT to reconstruct low-energy charged pions

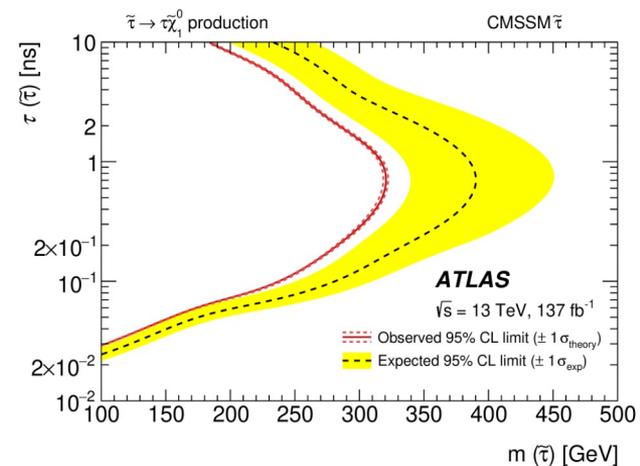
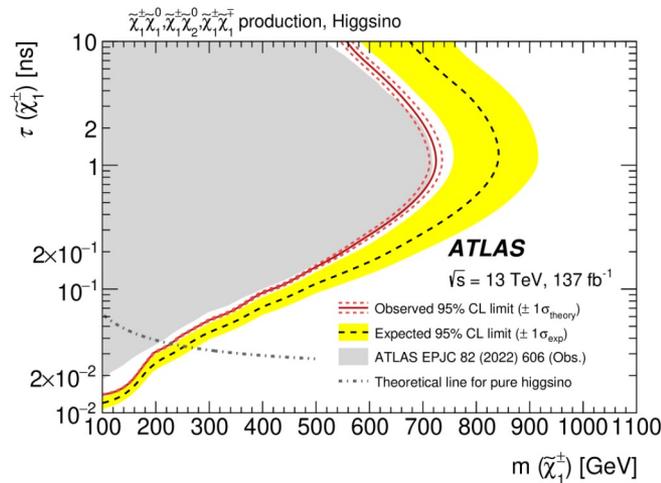
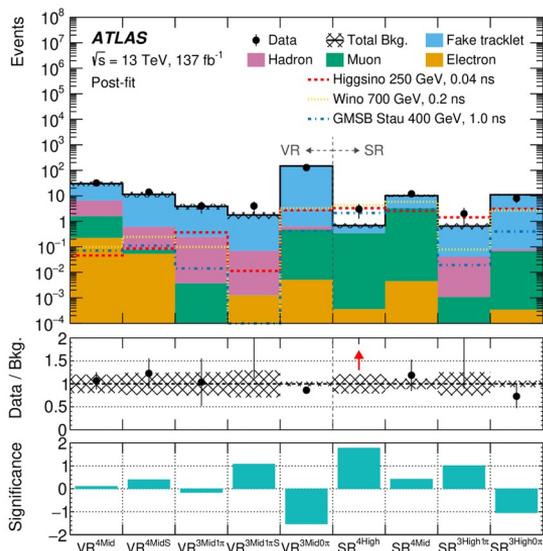


Data-driven (ABCD-style) method to estimate all backgrounds

- Arises from "fake" (coincidental hits forming a tracklet) and mis-identification of standard objects

Slight excesses ($< 2\sigma$) in two SRs

- One SR event consistent with that of the previous analysis
- Events in the three-hit tracklet soft-pion SR consistent with material interaction in ID



A Conventional Conclusion

Remarkable effort from both collaborations to target unconventional signatures that would otherwise evade us!

Considerable analysis efforts pushing experimental capabilities

- Non-standard reconstruction
- New triggers
- Robust background estimation

Exciting prospects ahead for the final Run 2 results and Run 3 analyses!

