Searches for Long-Lived Particles and Other Exotica at the LHC

Windows on the Universe 2023

Evan M. Carlson

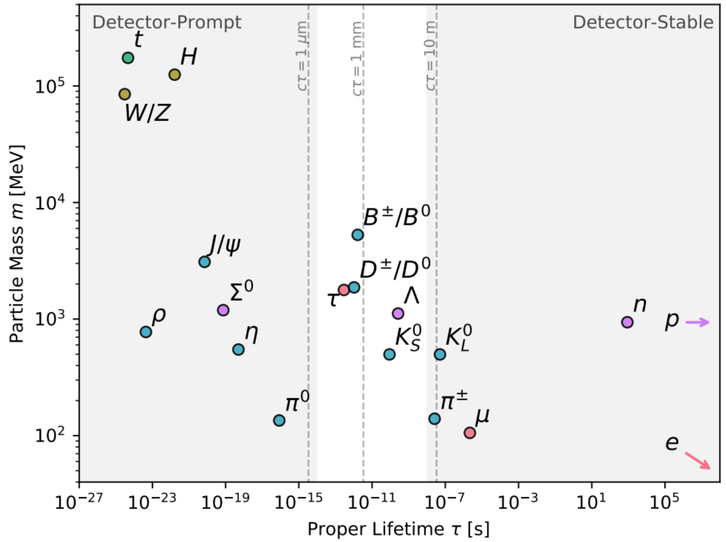
University of Victoria / TRIUMF

On behalf of the ATLAS and CMS Collaborations

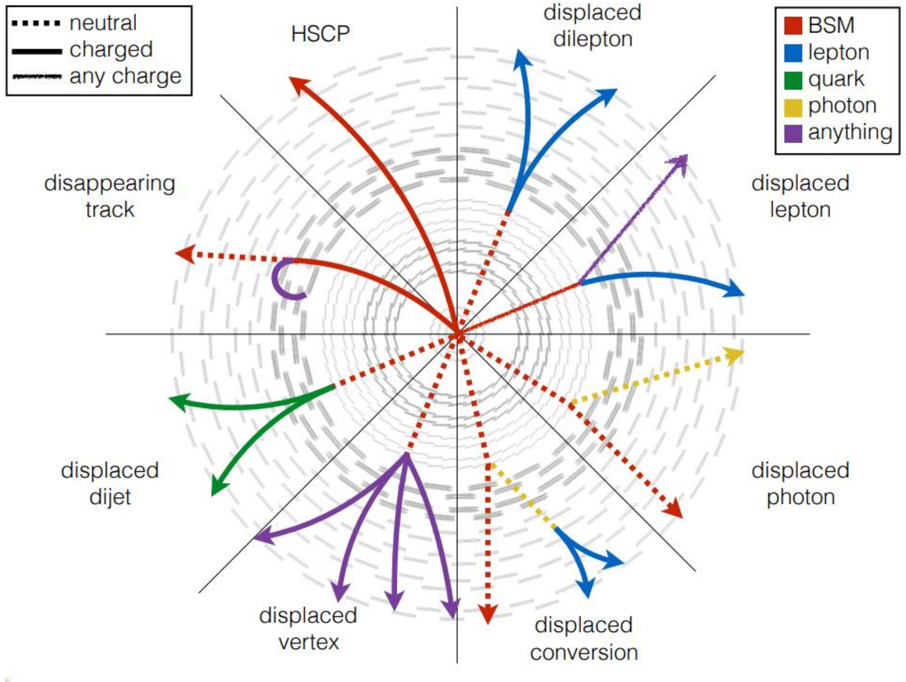
August 8th, 2023

Why Search for LLPs and Exotic Particles?

- Standard Model (SM) leaves many questions unanswered
  - Dark matter (DM), neutrino masses, matter-antimatter asymmetry…
- Questions could be answered by existence of long-lived particles (LLPs) or other exotic particles that have remained undetected
  - Define an LLP as any Beyond-SM (BSM) particle that travels a macroscopic distance (relative to the detector resolution)
  - Can decay inside the detector or escape undetected
- LLP lifetime can come from massive mediators of decays, small phase space or small couplings
- Direct detection
  - Electric charge, large ionization, lifetime…
- Indirect detection
  - Displaced tracks, displaced vertices, displaced calorimeter deposits
- Many challenging and unique signatures to explore



[1]

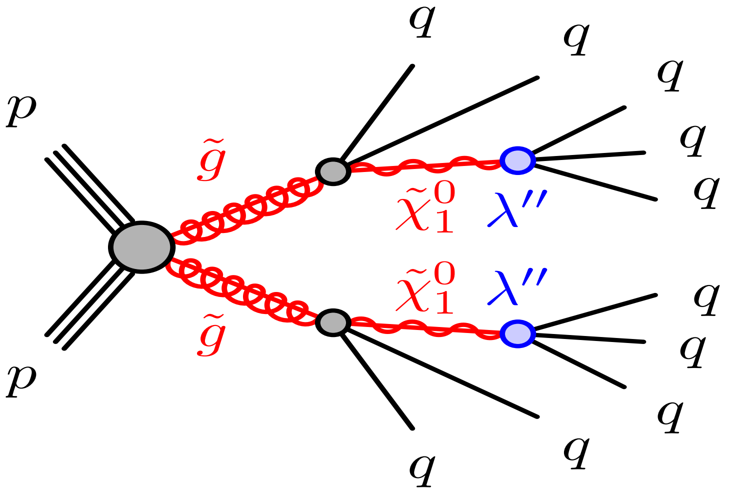


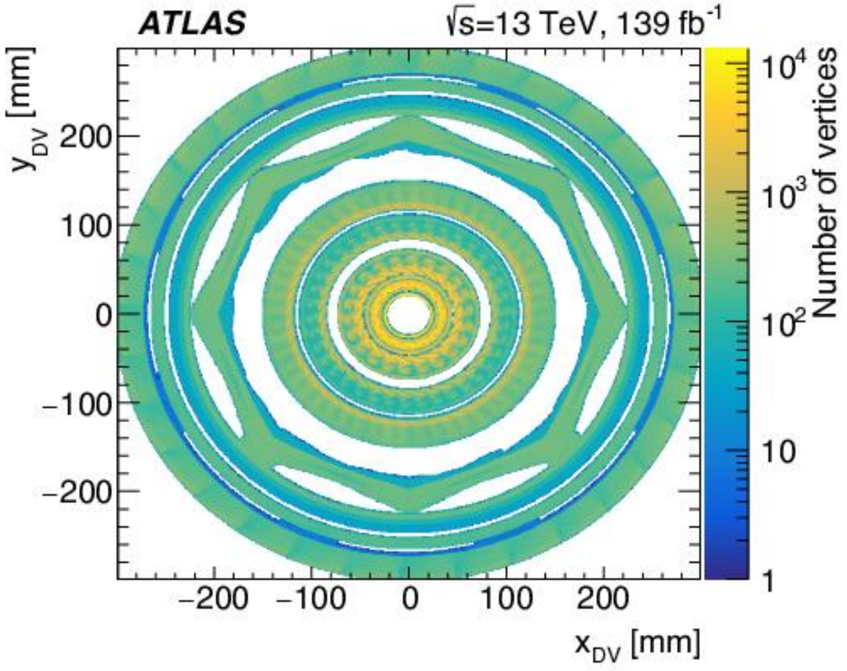
[2]

ATLAS – Displaced Vertices in Multijet Events

arXiv:2301.13866

- R-parity violating (RPV) SUSY models can produce long-lived massive particles in multijet events
  - LLP lifetime from small RPV coupling, λ”
  - $\tilde{\chi}_1^0$ LLP decays to SM quarks, producing a displaced vertex (DV) in inner detector
- Trigger on high jet-multiplicity events
  - High p_T Jet and Trackless Jet signal regions
- No SM particles produce high-mass DVs
  - Background from material interactions, random crossing of tracks, and merged vertices
- Estimate background using correlation of DVs with prompt jets in data
  - Derive probability that a jet with a given p_T and number of tracks produces a DV in photon triggered CR
  - Apply the probability to jets passing the multijet trigger to estimate background DVs in SR



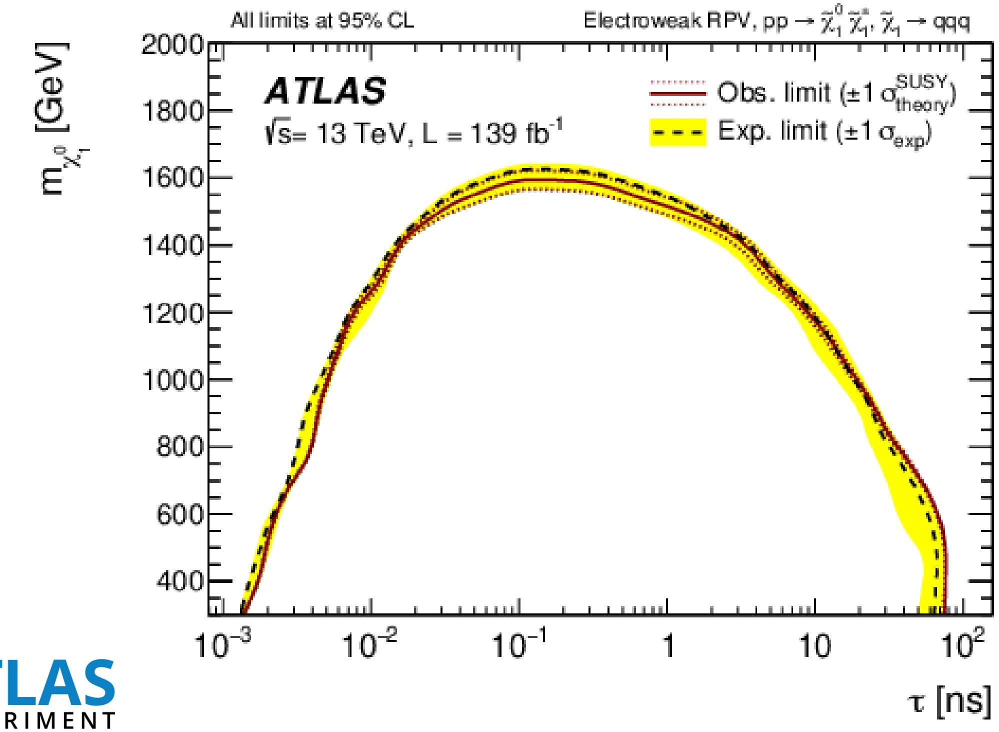


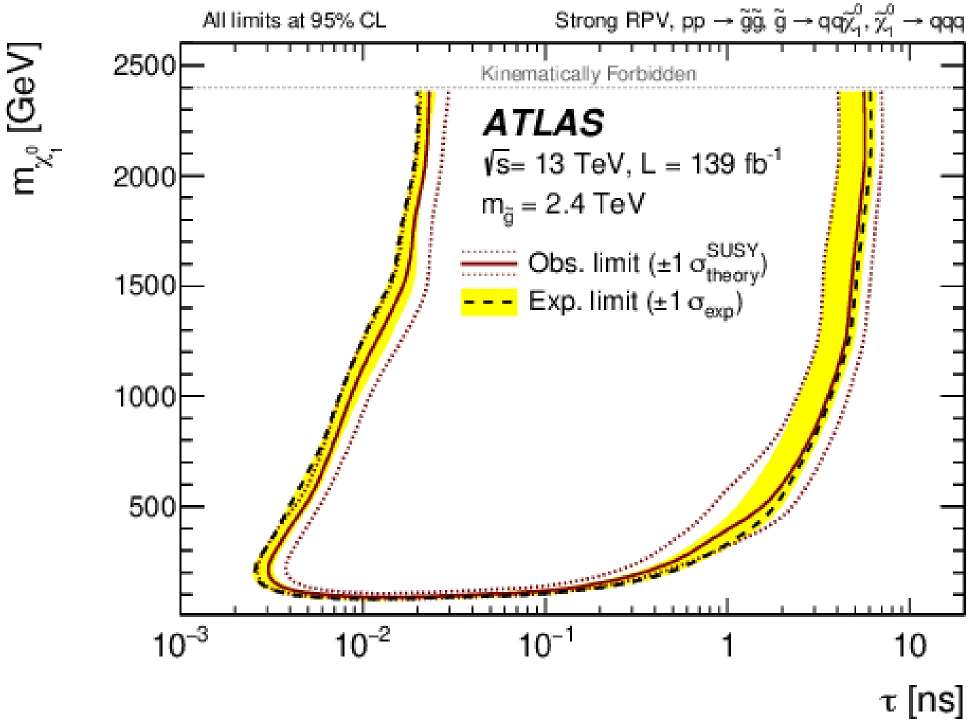
ATLAS EXPERIMENT

ATLAS – Displaced Vertices in Multijet Events

arXiv:2301.13866

- Observed 1 event in signal region – consistent with expected background
- Set limits on cross sections of electroweakinos decaying via a small RPV coupling
  - Pair-production of electroweakinos with $m(\tilde{\chi}_1)$ < 1.5 TeV excluded for 0.03 ns < τ < 1 ns (left)
  - When produced via the decay of a 2.4 TeV gluino, electroweakinos with $m(\tilde{\chi}_1)$ < 1.5 TeV are excluded for lifetime in the range for 0.02 ns < τ < 4 ns (right)

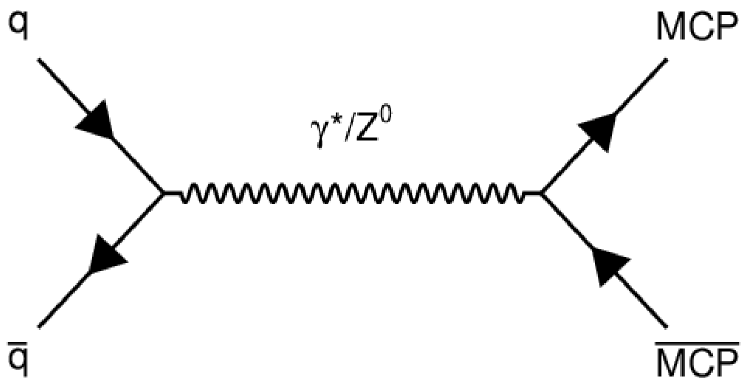


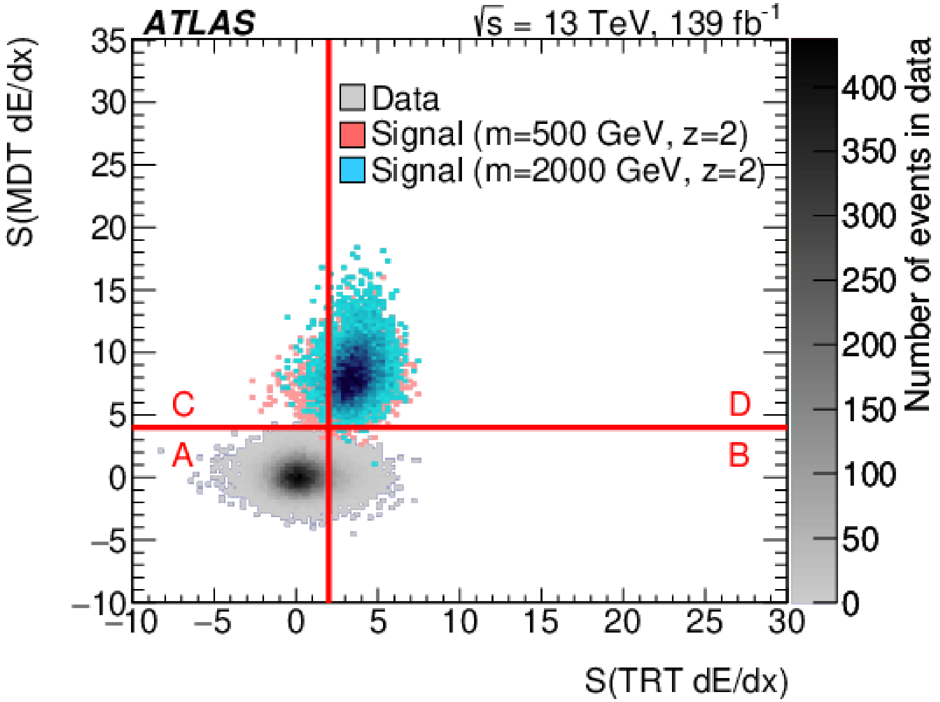


ATLAS – Multi-Charged Particles

arXiv:2303.13613

- Long-lived particles w/ high electric charge can produce anomalously high ionization in the detector
- Targets multi-charged particles (MCP) with charge 2e ≤ $|z * e|$ ≤ 7e
  - $z = 2$ and $2 < z \leq 7$ signal regions
- Highly charged LLPs leave a muon-like track in inner detector and muon systems
  - Require track to have segments in tracker and muon spectrometer
  - Use single muon trigger, missing energy trigger, and late-muon trigger (muon in bunch-crossing after high-p_T jet)
- Use significance of ionization energy loss (*dE/dx*) with respect to average muon to discriminate from background
  - $S\left(\frac{dE}{dx}\right) = \left(\frac{dE}{dx} - \left\langle\frac{dE}{dx}\right\rangle_\mu\right)/\sigma\left(\frac{dE}{dx}\right)_\mu$ must be above threshold

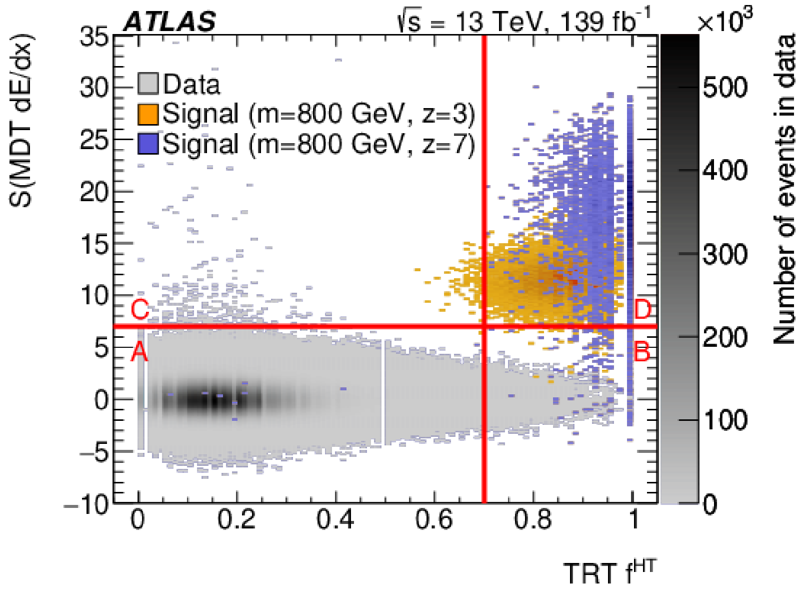


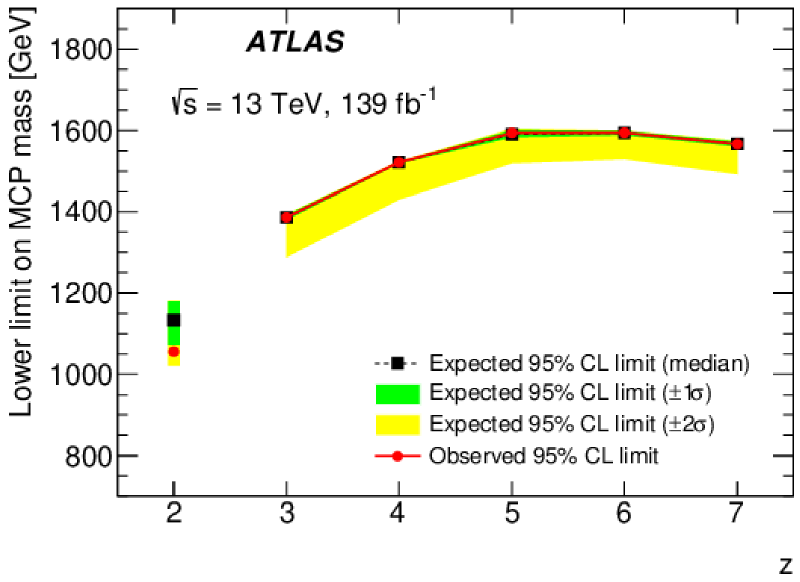


ATLAS – Multi-Charged Particles

arXiv:2303.13613

- Require fraction of transition radiation tracker (TRT) hits over high threshold (f^{HT}) be greater than 0.7 for $z > 2$ SR
- Estimate background w/ data-driven ABCD method
  - $z = 2$: S(TRT dE/dx) > 2 and S(MDT dE/dx) > 4
  - $z > 2$: $f^{HT} > 0.7$ and S(MDT dE/dx) > 7
- No significant excess observed
- Set upper limits on cross section for a Drell-Yan plus photon-fusion production mode
  - Exclude $m_{MCP} < 1060$ GeV for $|q| = 2e$
  - Exclude $m_{MCP} < 1600$ GeV for $|q| = 6e$
- Previous ATLAS analysis based on pixel dE/dx measurements observed an excess of events
  - JHEP06(2023)158
  - Same events from previous pixel dE/dx analysis excess passed $z = 2$ baseline selection but did not pass signal region selections



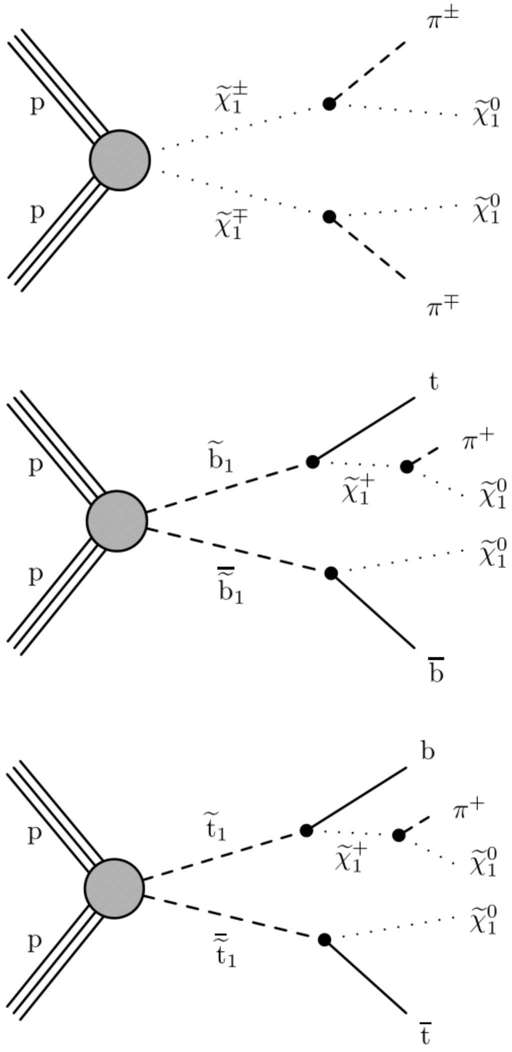


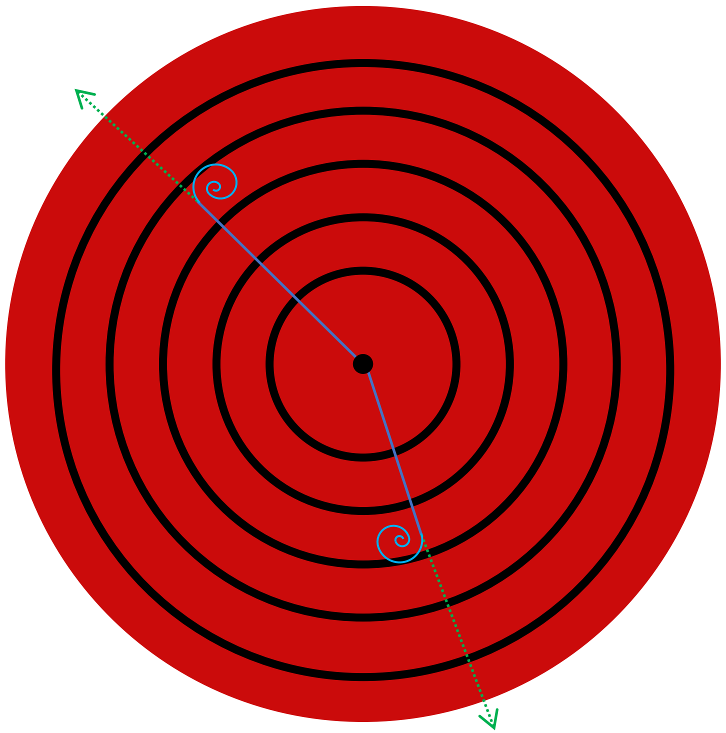
ATLAS EXPERIMENT

CMS – Disappearing Tracks

CMS-PAS-SUS-21-006

- Some SUSY models predict charginos and neutralinos that are nearly degenerate in mass
  - $m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^{0})$ is O(100 MeV)
- Long-lived charginos can provide a disappearing track (DTk) signature
  - $\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^{0} + \pi^{\pm}$ results in a pion with momentum too low to be reconstructed
  - $\tilde{\chi}_1^{\pm}$ leaves hits until it decays, resulting in a track coming from the interaction point that ends abruptly inside the tracking volume
- Four channels
  - Hadronic DTk (missing momentum trigger)
  - Muon DTk (single muon trigger)
  - Electron DTk (single electron trigger)
  - Two DTks
- Search regions for each channel further categorized by $N_{B\ Jets}$, N_{Jets}, $N_{short\ DTk}$, $N_{long\ DTk}$, and the DTk dE/dx

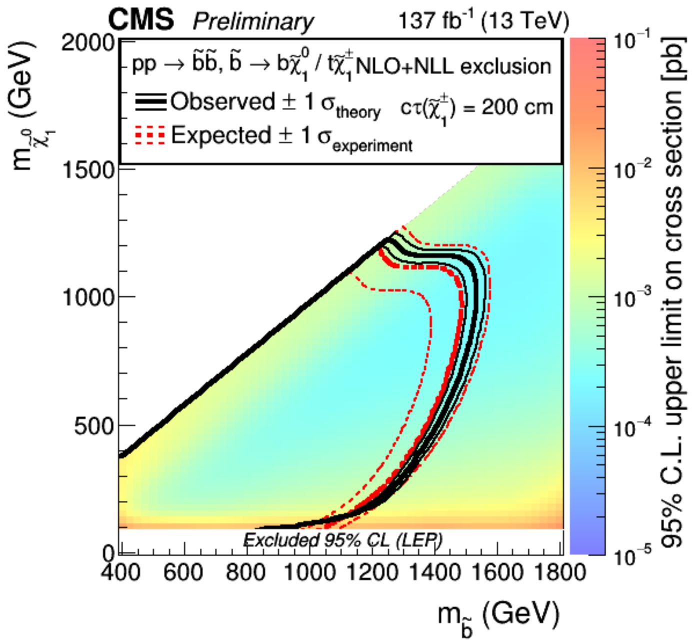


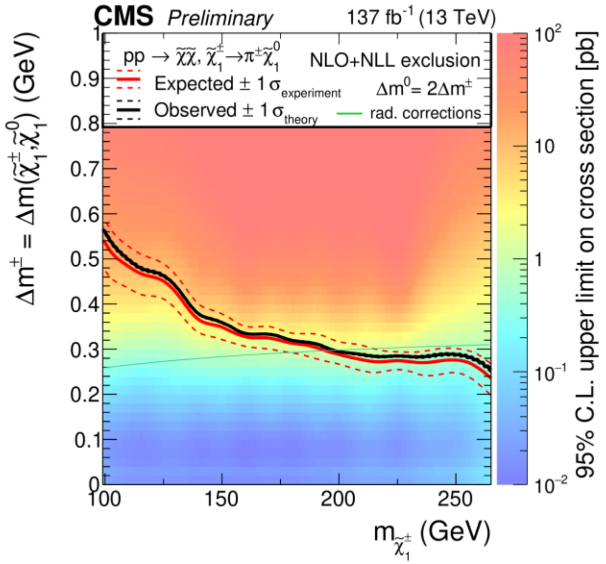


CMS – Disappearing Tracks

CMS-PAS-SUS-21-006

- BDT classifier used to improve purity of DTk candidates
  - Signal training uses chargino-matched tracks from simulated SUSY events
  - Background training uses tracks from all SM processes
- Background comes from misreconstruction of charged particle or coincidental misalignment of hits
  - Particle could shower in a crack between calorimeter crystals
- Background evaluated in sideband region based on BDT output and energy deposited in calorimeter near the track candidate
- No significant excess observed
  - Set limits on the pair production cross section of gluinos, squarks, and electroweakinos

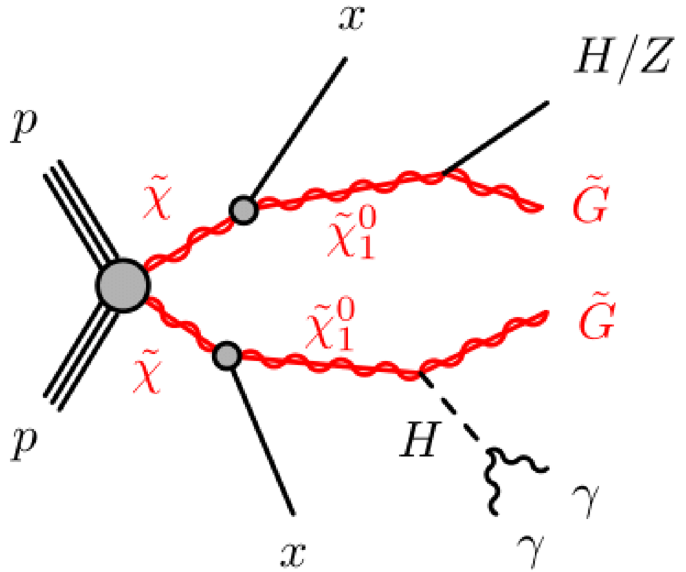


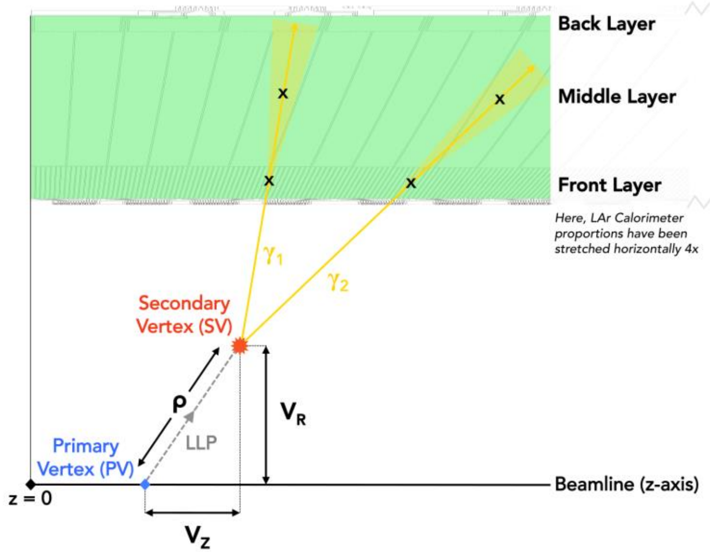


ATLAS – Displaced Diphoton Vertex

arXiv:2304.12885

- GMSB models with $\tilde{G}$ LSP and weak coupling to the $\tilde{\chi}_1^0$ NLSP can give NLSP non-negligible lifetime
- If $\tilde{\chi}_1^0$ is mostly higgsino, most likely decay modes will be $\tilde{\chi}_1^0 \rightarrow H/Z + \tilde{G}$
  - Search targets vertex from displaced decay of $H \rightarrow \gamma\gamma$ or $Z \rightarrow ee$
  - Use diphoton trigger
  - Objects are reconstructed w/ ***only*** EM calorimeter information, so no distinction between γ and e
- Use liquid argon (LAr) calorimeter to measure trajectories and arrival times of γ and e
  - EM objects arrive delayed to calorimeter compared to prompt objects in same final state
- Calo-vertexing method uses pointing to localize displaced diphoton vertex (DDV) in two dimensions – R and z
  - DDV position denoted with V_R and V_Z
  - Displaced photons will have correlated V_R and V_Z, can use $\rho = \sqrt{V_R^2 + V_Z^2}$ to discriminate from background

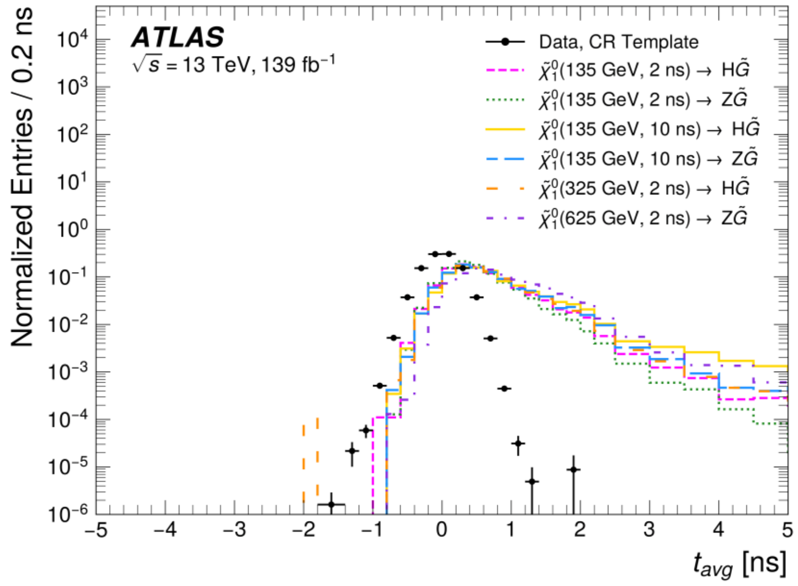


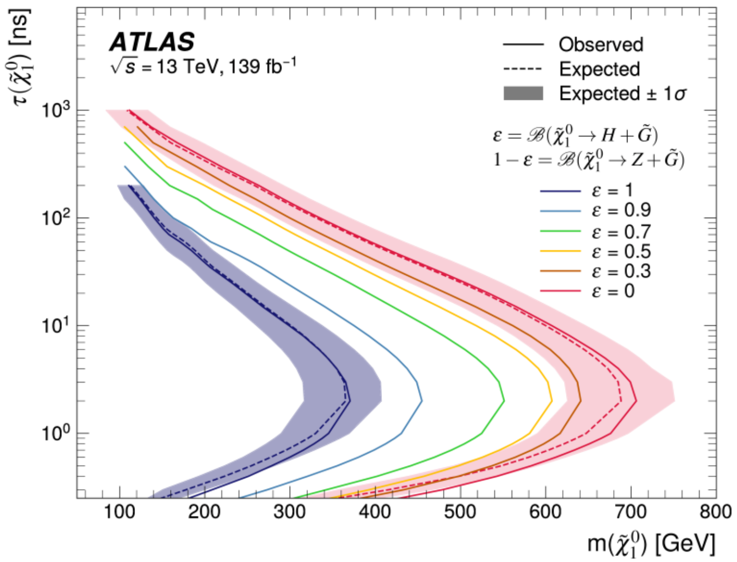


ATLAS – Displaced Diphoton Vertex

arXiv:2304.12885

- Require > 30 GeV of E_T^{miss} from $\tilde{G}$
- No SM processes produce DDV w/ significant mass
  - Background from misreconstructed photon (such as those from satellite collisions) or fake photons
- Can use timing information of two photons, $t_{avg} = \frac{t_1 + t_2}{2}$, to discriminate from background
- Data-driven background estimate
  - Use low E_T^{miss} CR to extract t_{avg} templates from data for fake and real photons
  - Mix templates to match high E_T^{miss} SR purity to estimate background
- No significant excess observed
  - Set limits on GMSB models with nearly degenerate triplet $\tilde{\chi}_1^0, \tilde{\chi}_1^{\pm}$

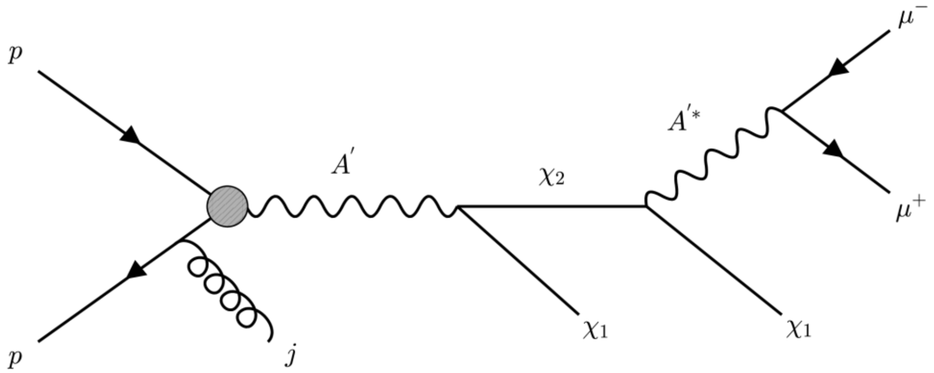


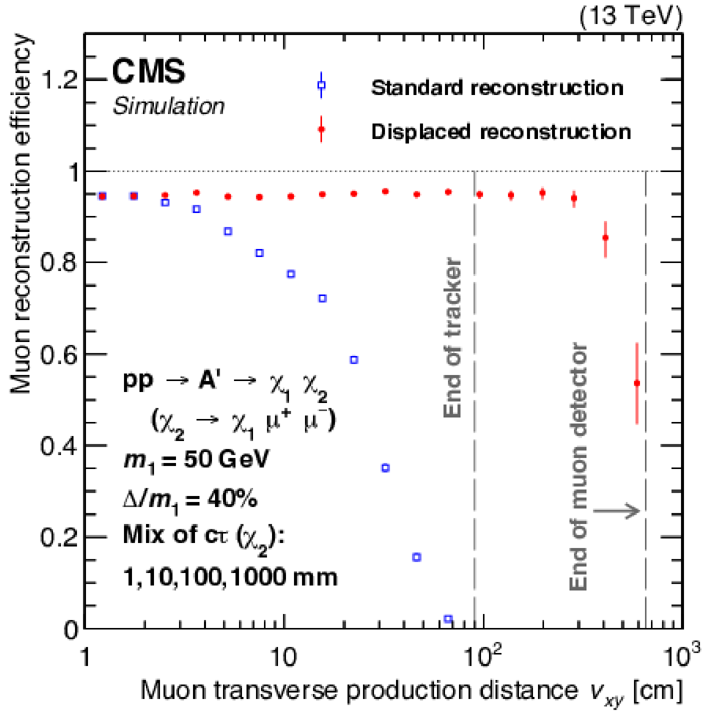


CMS – Inelastic DM w/ Displaced Muons

arXiv:2305.11649

- Inelastic DM model w/ ≥ 2 DM states alongside a dark photon A' which mixes with SM hypercharge
  - Small mass splitting leads to lifetime for χ_2
- Final state w/ soft, displaced muon pair, ≥ 1 energetic jet (ISR) and p_T^{miss}
  - Use p_T^{miss} trigger due to low p_T of muons
- Reconstruct muons w/ displaced standalone algorithm (DSA) for increased efficiency
  - Uses only information from muon system and does not require muons originate from IP
  - Can match muons w/ small displacement to standard reco. muons to recover resolution
  - Categorize events by number of DSA matches
- Second ISR jet w/ p_T > 30 GeV allowed
  - Suppresses background from QCD events
- Require dimuon system to be collimated with p_T^{miss}

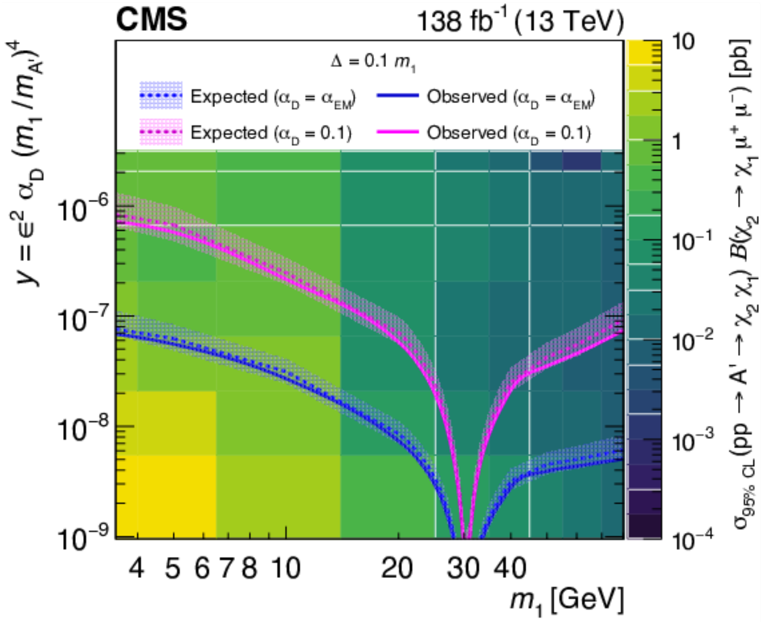


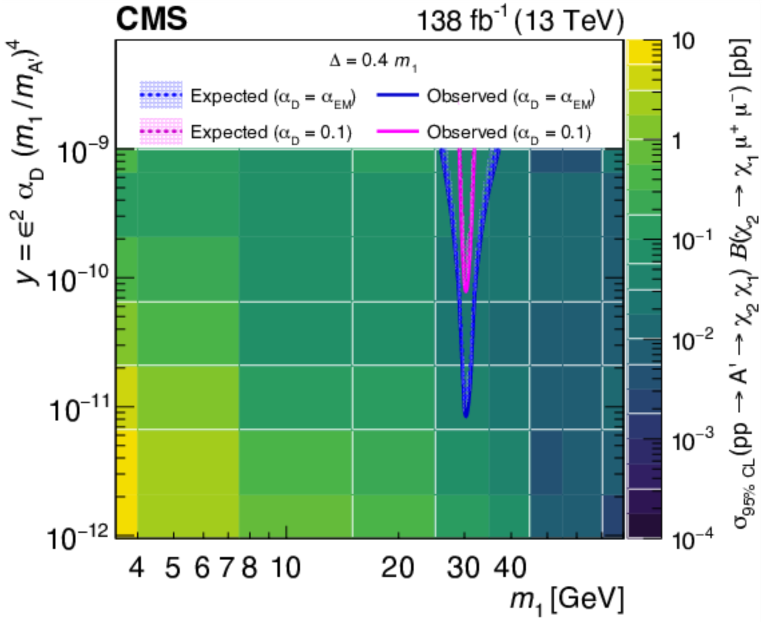


CMS – Inelastic DM w/ Displaced Muons

arXiv:2305.11649

- Backgrounds mainly from 3 event types
  - QCD events w/ genuine or misidentified muons
  - $W \rightarrow \mu\,\nu$ + Jets events w/ an additional misidentified muon (contributes to 1 DSA match region)
  - $Z \rightarrow \nu\,\nu$ + Jets w/ two misidentified muons (contributes to 1 and 0 DSA match regions)
- Use modified ABCD method to estimate background
  - All three categories use minimum d_{xy} of two muons
  - 1 and 2 match region uses relative PF isolation of min-d_{xy} muon
  - 0 match category uses $\Delta\varphi^{miss}_{\mu\,\mu} = \varphi^{miss} - \varphi^{\mu\,\mu}$
- No significant excess observed
  - Set limits on product of DM production cross section and branching fraction
  - Limits set as a function of DM mass m_1 and interaction strength

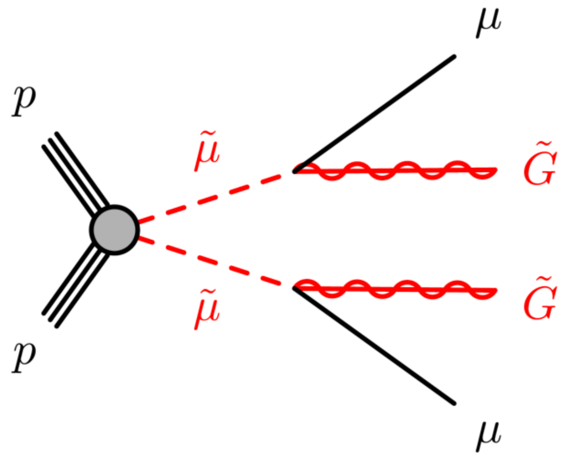


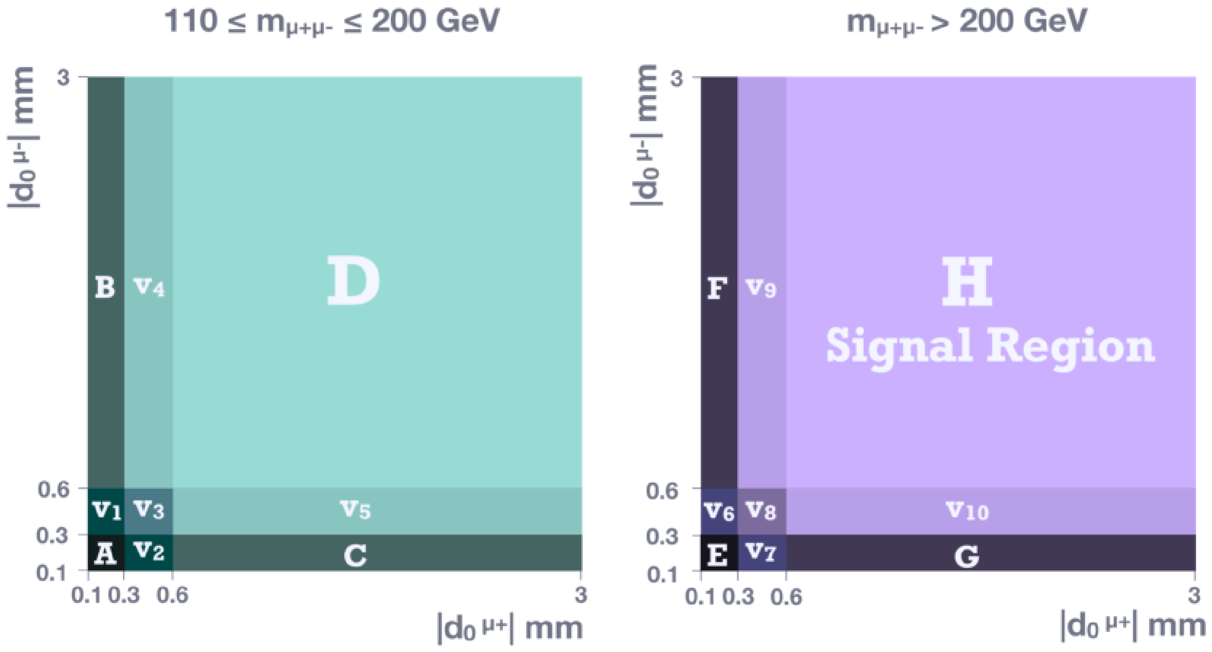


ATLAS – Micro-Displaced Muons

arXiv:2305.00205

- GMSB SUSY models w/ a $\tilde{G}$ LSP can have $\tilde{e}$, $\tilde{\mu}$ and $\tilde{\tau}$ as degenerate co-NLSPs
  - Pair-produced sleptons decay to $\tilde{G}$ and a charged lepton w/ same flavour as parent
- Search for $\tilde{\mu}$ with a lifetime of O(1-10) ps
  - Lifetime comes from small coupling to $\tilde{G}$
  - Aim to fill a gap in coverage between prompt and displaced slepton searches
- Use dimuon trigger w/o explicit cuts on d_0
- Require $|d_0|$ > 0.1 mm and $m_{\mu\mu}$ ≥ 100 GeV to reduce background from prompt SM processes
- Use extended ABCD method w/ three variables - $\left|d_0^{\mu^+}\right|$, $\left|d_0^{\mu^-}\right|$ and $m_{\mu^+\mu^-}$
- Simplified cuts make analysis model-independent



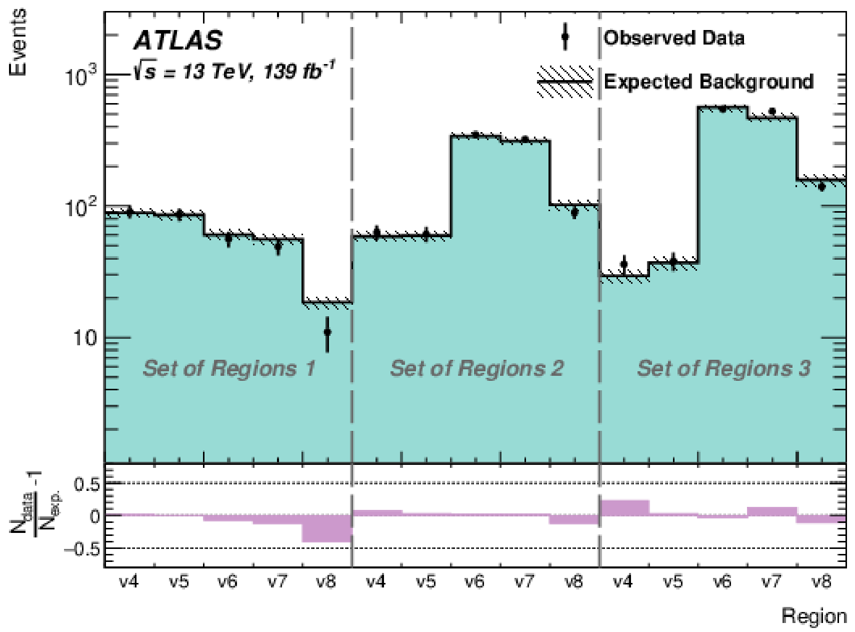


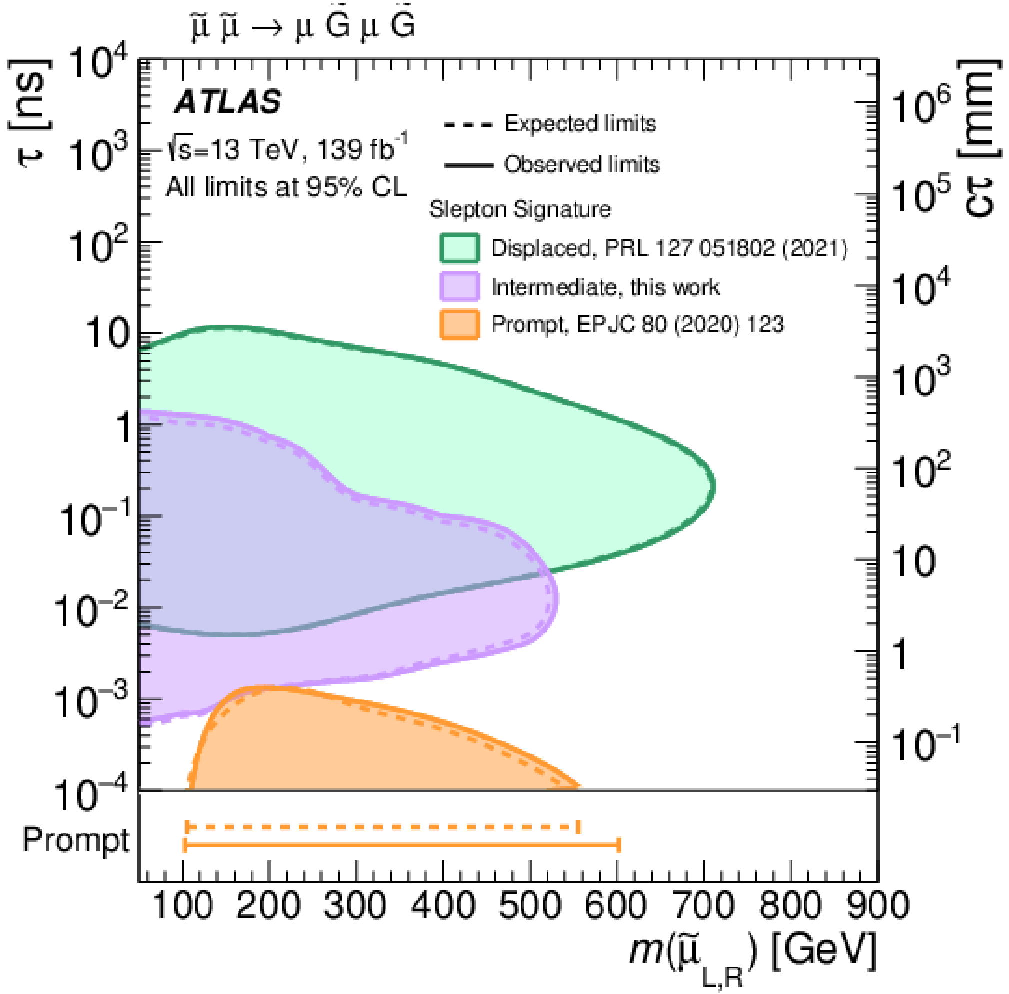
Evan M. Carlson (UVic / TRIUMF)

ATLAS – Micro-Displaced Muons

arXiv:2305.00205

- Main SM background from semileptonic B-hadron decays and V + Jets
- Predicted background agrees with observed data in all validation regions
- $\tilde{\mu}$ w/ lifetimes down to 1 ps are excluded for $m_{\tilde{\mu}}$ < 200 GeV
- $\tilde{\mu}$ w/ a lifetime of 10 ps are excluded for $m_{\tilde{\mu}}$ < 520 GeV

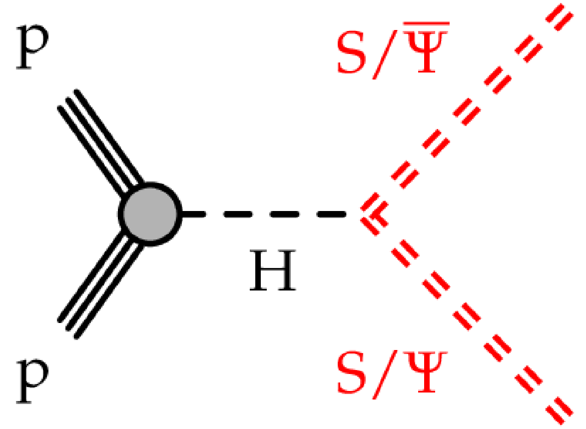


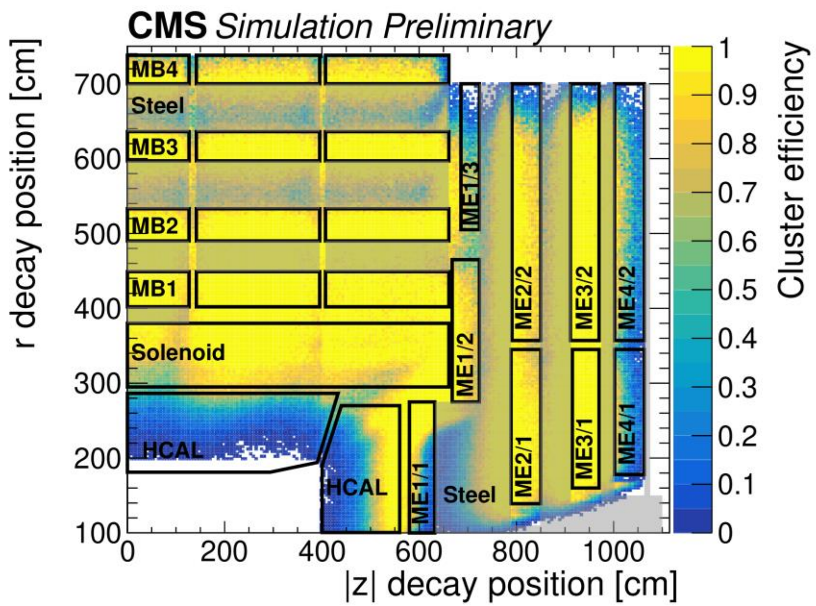


CMS – LLPs Decaying in the Muon System

CMS-PAS-EXO-21-008

- Many BSM models predict LLPs w/ lifetimes that would lead to decays inside muon detectors
  - Benchmark twin Higgs model has SM Higgs decaying to a pair of LL scalars, S, which can decay hadronically or electromagnetically
- LLP decays inside muon detectors lead to clusters w/ large hit multiplicity in localized region
  - Require 50 hits in detectors to separate from muon clusters
  - Use p_T^{miss} trigger and offline p_T^{miss} cut to select events
- Dense detector material strongly suppresses particle showers from punch-through jets
- Barrel region composed of drift tubes (DT) and endcap region composed of cathode strip chambers (CSC)
- Divide search into 3 categories – events w/ 2 clusters, events w/ exactly 1 DT cluster and events w/ exactly 1 CSC cluster

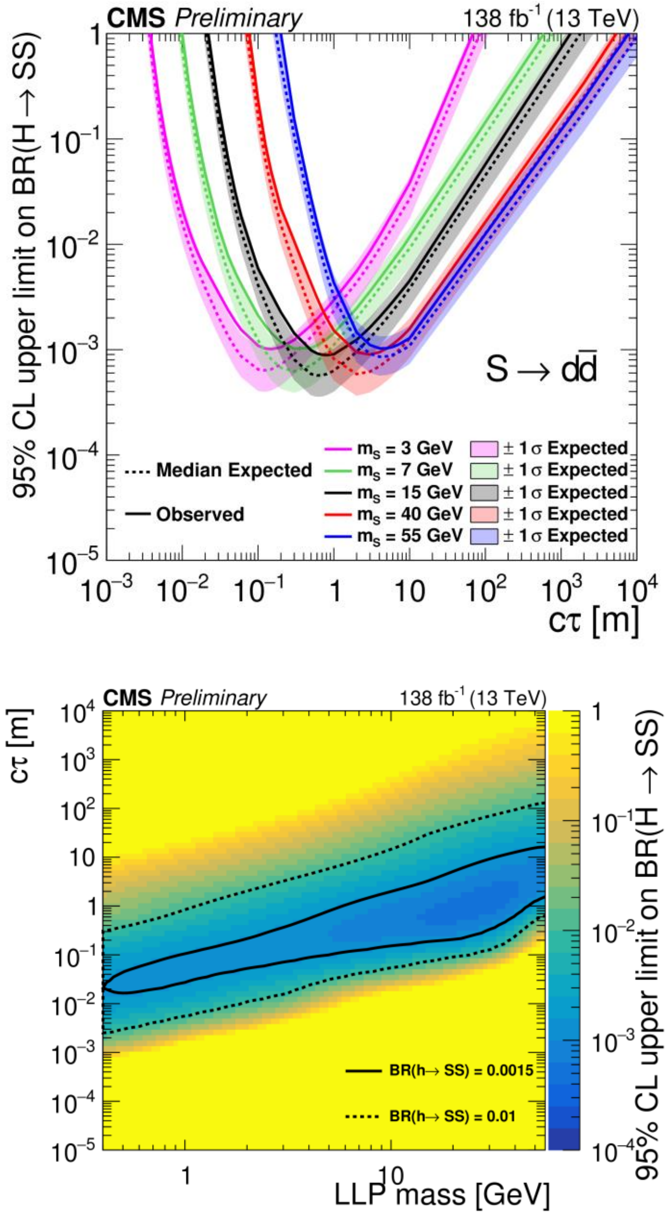




CMS – LLPs Decaying in the Muon System

CMS-PAS-EXO-21-008

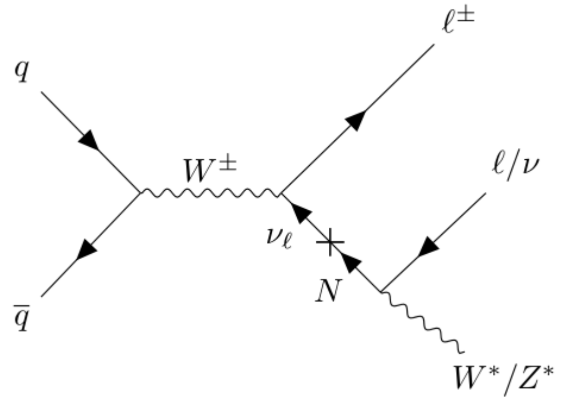
- Primary SM backgrounds are punch-through jets, muon bremsstrahlung and isolated hadrons from pileup and recoils
- Suppress jet and muon background with isolation cuts
- Use ABCD method to estimate background
  - For double cluster events: use N_{Hits} for each cluster
    - Validate estimate in inverted regions of N_{Hits} and isolation between p_T^{miss} and cluster
  - For single cluster events: use N_{Hits} and isolation between p_T^{miss} and cluster
    - Validate estimates in out-of-time events and regions with cluster ID criteria inverted
- No significant excess observed
  - Set upper limits on branching ratio of $H \rightarrow S\,S$ as a function of $c\tau$ for different scalar masses and decay modes

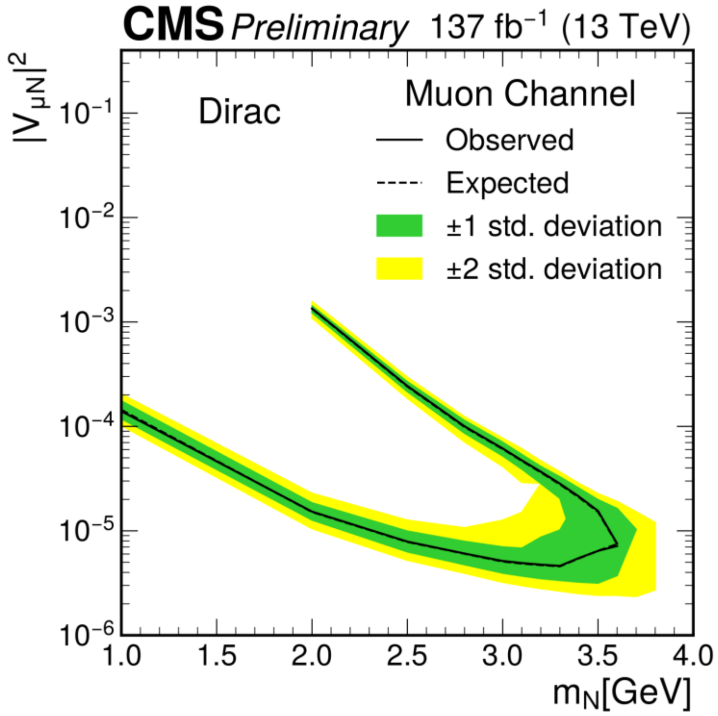


CMS – HNLs Decaying in the Muon System

CMS-PAS-EXO-22-007

- Muon detector clusters can also be used to search for heavy neutral leptons (HNLs) with m_N < 10 GeV and $c\tau$ between 0.1-10m
  - HNL can be Dirac or Majorana
- HNL decay via virtual W boson leads to final state w/ two charged leptons and neutrino or one charged lepton and two quarks
- Trigger on prompt lepton from HNL production
- Require p_T^{miss} > 30 GeV and isolation from jets and muons to suppress SM background
- Dominant background is W + Jets producing prompt lepton and pileup or recoil providing cluster
- Estimate background w/ ABCD method
  - Use N_{Hits} and $\Delta\varphi(lepton\ , cluster)$ as discriminating variables
- No significant excess observed
  - Set limits on HNL coupling strengths as a function of m_N for Dirac and Majorana HNLs





Conclusions

- Both ATLAS and CMS are pursuing a robust LLP and exotics search program
  - Variety of signatures utilizing all detector components have been explored
    - Displaced vertices, disappearing tracks, highly ionizing particles and more
  - Probing many models and regions of phase space
    - No significant excesses detected yet
    - New limits on Higgs portal models, SUSY, multi-charged particle models…
- Run-3 of the LHC has begun and numerous improvements for BSM searches are being implemented
  - Dedicated triggers, special reconstruction, improved background estimation techniques…
  - More data!
- More results are on the way, so stay tuned!
  - CMS Public Results
  - ATLAS Public Results

Thank you!

References

1. Diagram of SM Particle Lifetimes: https://arxiv.org/abs/1810.12602
2. Diagram of LLP Signatures: https://indico.cern.ch/event/517268/contributions/2041293/
3. ATLAS DV + Jets: http://arxiv.org/abs/arXiv:2301.13866
4. ATLAS Multi-Charged Particle: http://arxiv.org/abs/arXiv:2303.13613
5. ATLAS Pixel dE/dx: https://link.springer.com/article/10.1007/JHEP06(2023)158
6. CMS Disappearing Tracks: https://cds.cern.ch/record/2859611/
7. ATLAS Displaced Diphoton Vertex: https://arxiv.org/abs/2304.12885
8. CMS Inelastic Dark Matter with Displaced Muons: http://arxiv.org/abs/arXiv:2305.11649
9. ATLAS Micro-Displaced Muons: http://arxiv.org/abs/arXiv:2305.02005
10. CMS LLPs Decaying Inside Muon Detectors: https://cds.cern.ch/record/2864874/
11. CMS HNLs Decaying Inside Muon Detectors: https://cds.cern.ch/record/2865227/