Searches for unusual signatures in leptonic and missing energy channels with the ATLAS detector

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On Behalf of the ATLAS Collaboration

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Long-lived Particles in ATLAS

- Beyond Standard Model (BSM) models may yield “long-lived” particles (LLPs), due to weak couplings, small mass splittings, or off-shell decays
  - Supersymmetry (SUSY), Dark Sectors, Axion-like Particles (ALPs), Heavy Neutral Leptons (HNLs)…
- LLPs leave unusual signatures, requiring **new triggers** + **analysis and reconstruction techniques**:
  - Displaced electron and muon triggers
  - Displaced tracks, displaced vertices, high specific ionization tracks, delayed signatures…
- This talk → final states with leptons and missing energy (MET)
  - For ATLAS LLP searches with hadronic final states → see previous talk by P. Scholer

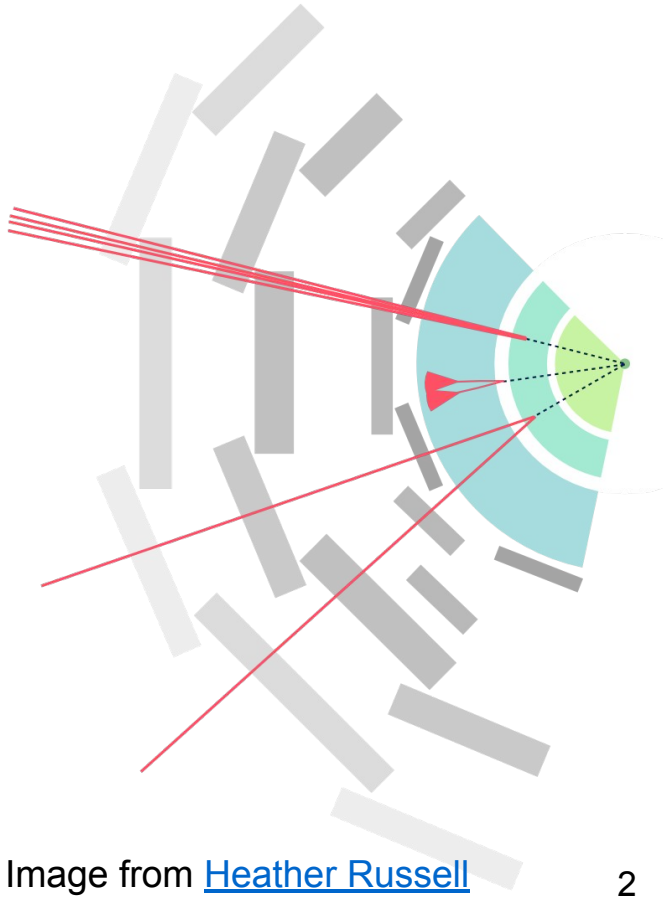
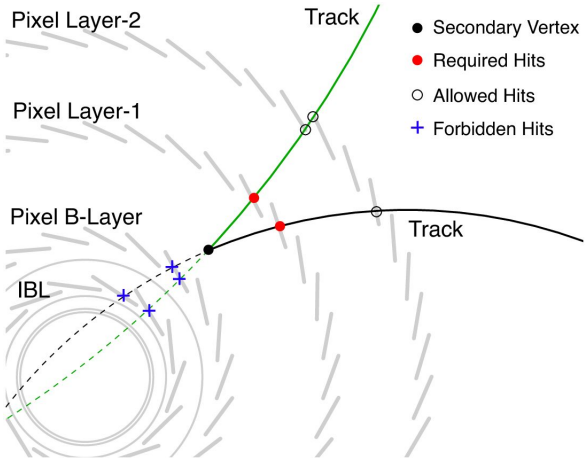


Image from Heather Russell

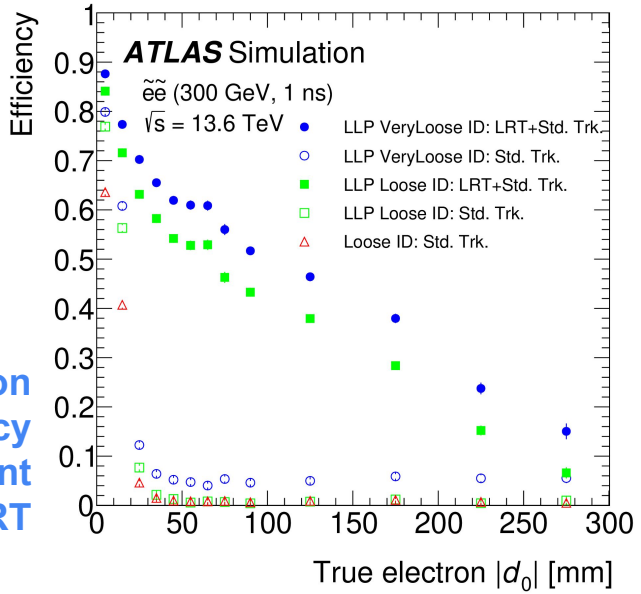
Displaced Track and Vertex Reconstruction

Large Radius Tracking (LRT) Improvements

- Standard track reconstruction in ATLAS: v. limited efficiency for displaced trajectories (cut at $|d_0| < 5$ mm)
- Secondary (LRT) tracking: uses leftover hits to reconstruct tracks for $3 < |d_0| < 300$ mm
- Since Run 2, LRT algorithm sped up and fake rate reduced → included in trigger for Run 3 (allows lower pT thresholds) + run on all offline events



Electron Efficiency Improvement with LRT



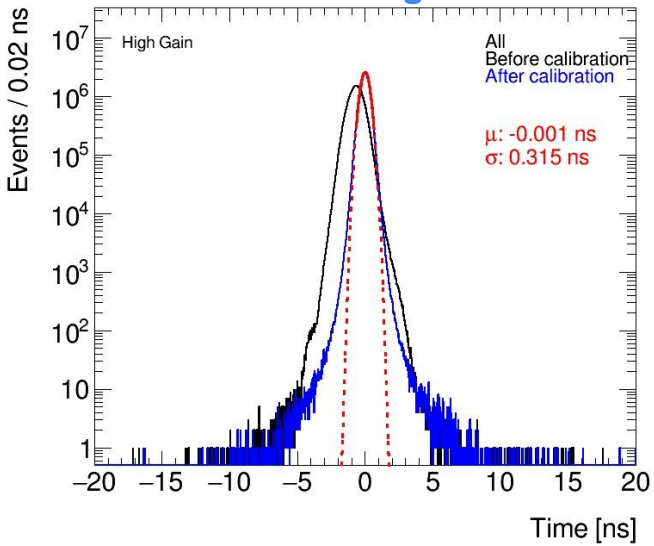
Displaced Vertexing

- Displaced tracks originating from potential LLP decays vertexed through dedicated secondary vertexing algorithms
- Optimized vertexing for displaced leptonic vertices → increased signal acceptance

Details on Large Radius Tracking, Displaced Vertexing Performance

Calorimeter Timing

LAr Calorimeter Timing Calibration



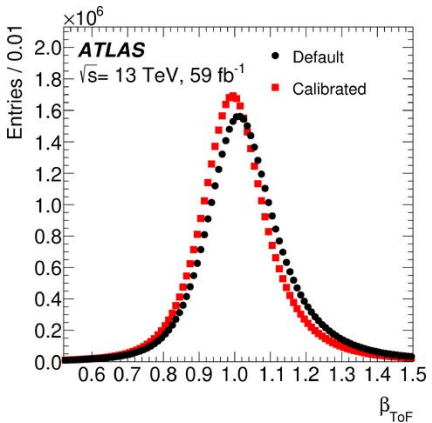
Electromagnetic (EM) Calorimeter Timing

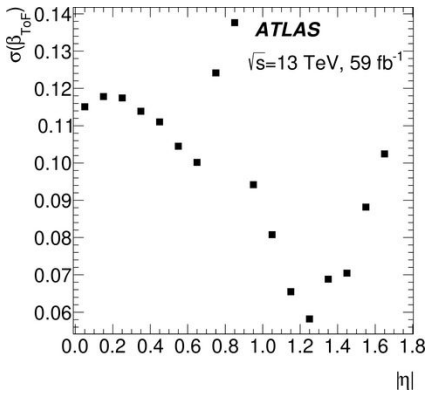
- Calibrated timing measurements from Liquid Argon (LAr) calorimeter w/ O(200 ps) resolution for EM-objects (dominated by beamspread)
  - Potential discrimination from prompt background for LLP signals with delays >~O(ns)
- Timing calibration: centers distribution of prompt objects at t=0

Hadronic Calorimeter Timing

- Meta-/stable- LLPs not expected to shower in EM calorimeter: tile calorimeter timing signal with resolution ~O(1 ns)
- Used to estimate β from particle time-of-flight

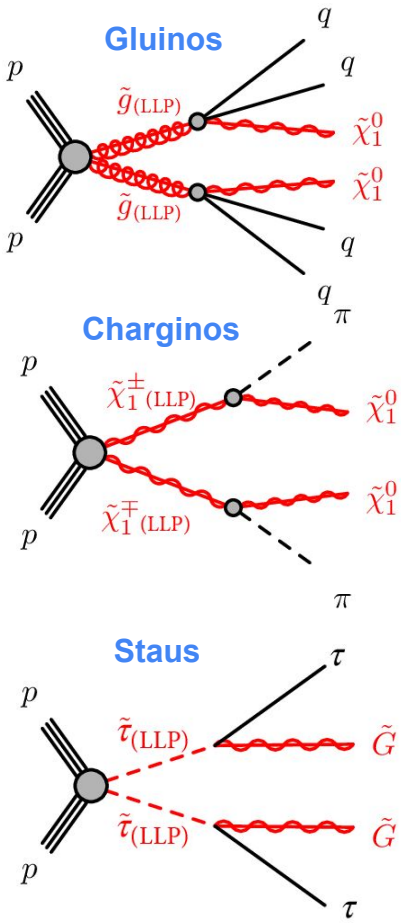
ATLAS Tile Calorimeter β_{TOF} Calibration



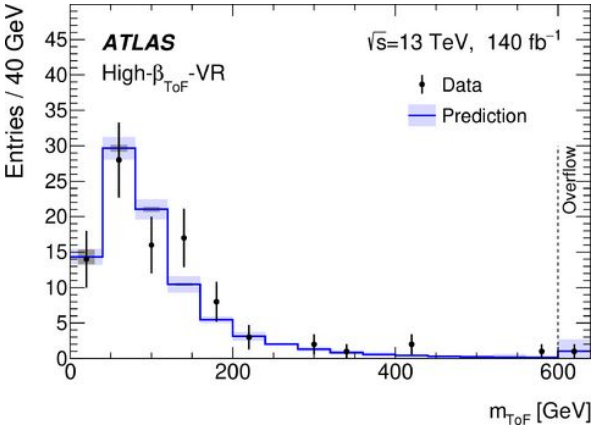


Pixel dE/dX + β-calo

arXiv: 2502.06694
140 fb^{-1}, s=√13 TeV

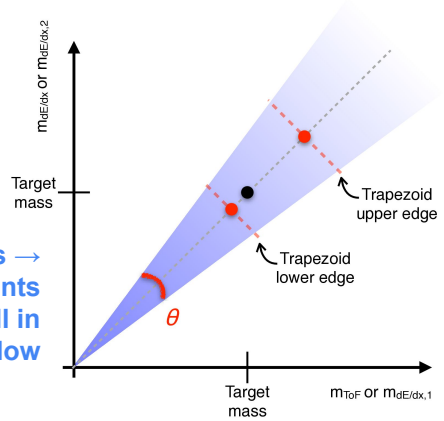


- Search for (meta)stable (τ > 3 ns) massive (2 GeV < m < 3 TeV) charged particles predicted in various SUSY scenarios
  - Leave high specific ionization (dE/dx) tracks in Pixel detector (agnostic to decay mode)
  - Follow-up of prev. search [JHEP 06 158]) which saw 3.3σ excess at m_{LLP}=1.4 TeV
- Two independent searches:
  - **β-search**: require >=1 high dE/dx track with β measured from pixel dE/dX and Tile calorimeter time-of-flight (TOF)
  - **Di-track search**: require >=2 opposite-sign high dE/dx tracks
- Both searches: mass of LLP from β and pT measurements as analysis variable



← **Mass templates extracted from pseudo-data in signal-depleted VRs**

Both mass → measurements required to fall in compatibility window



Pixel dE/dX + β-calo

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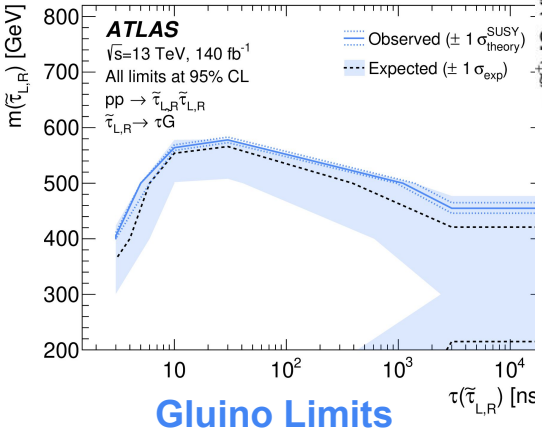
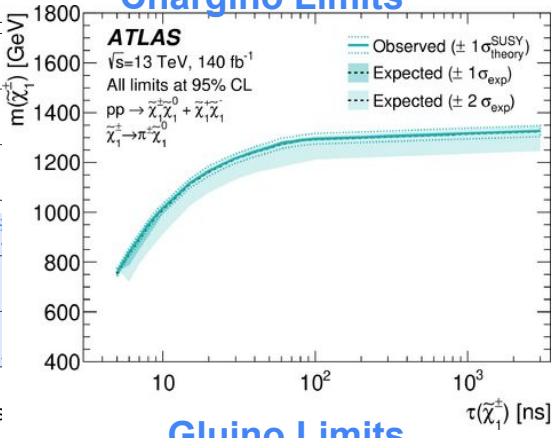
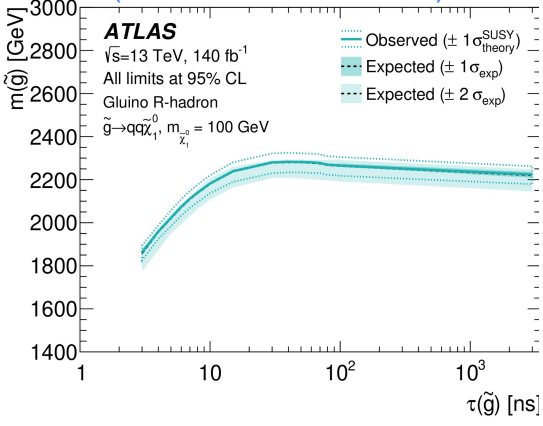
Stau Limits



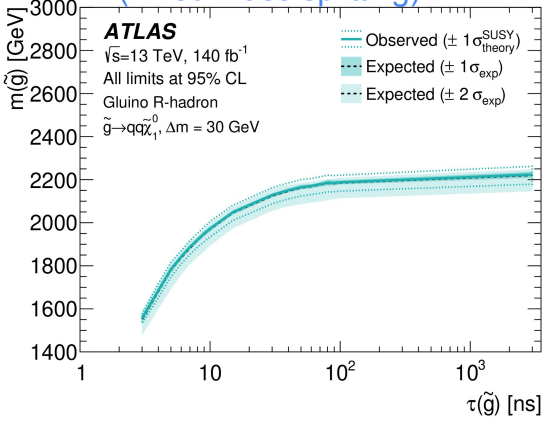
Chargino Limits



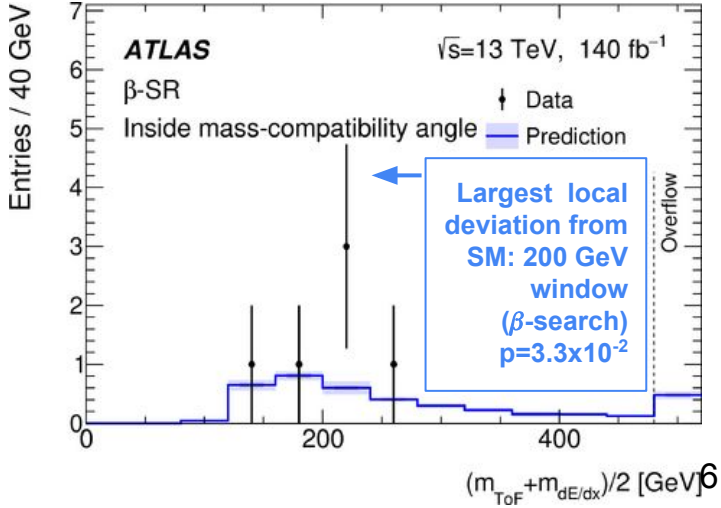
Gluino Limits (Fixed neutralino mass)



Gluino Limits (Fixed mass splitting)



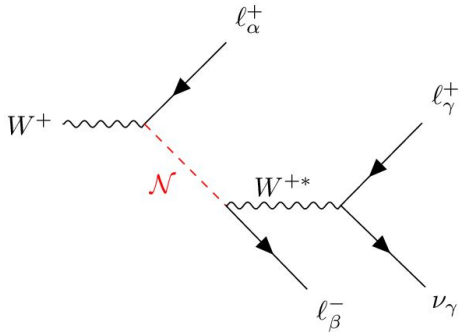
- Agreement with SM observed
- Most stringent limits to date for detector-unstable LLP with τ > 10ns !
  - Di-track: stau limits
  - β-search: chargino and gluino limits
- 7 events comprising excess in previous search → all excluded by β_{TOF} selection



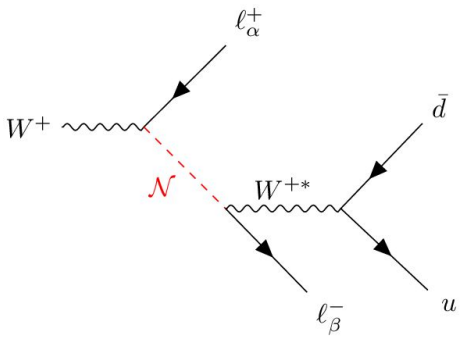
Displaced Heavy Neutral Leptons

arXiv:2503.16213
140 fb^{-1}, s=√13 TeV

Leptonic Decay Mode

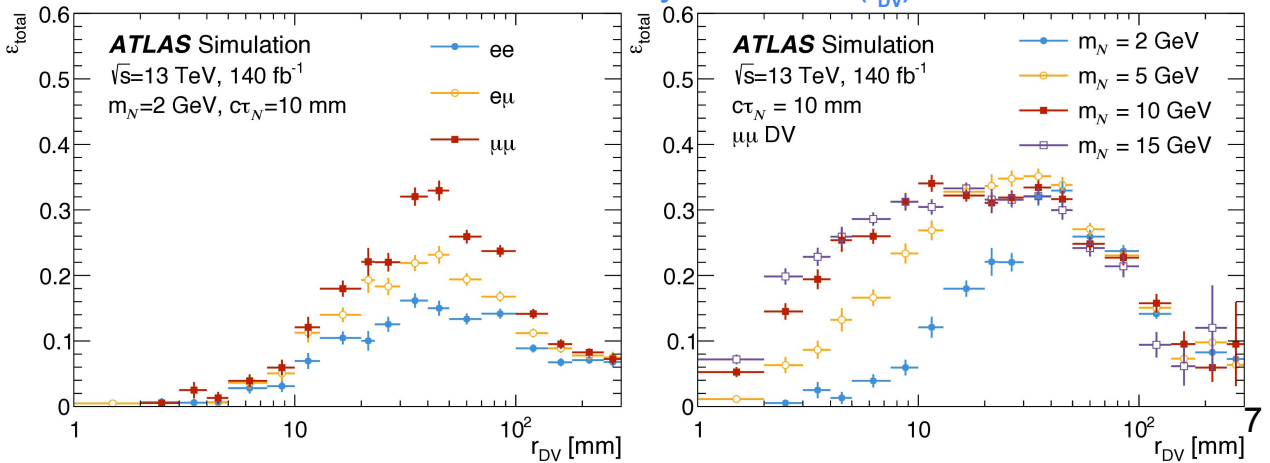


Semi-leptonic Decay Mode



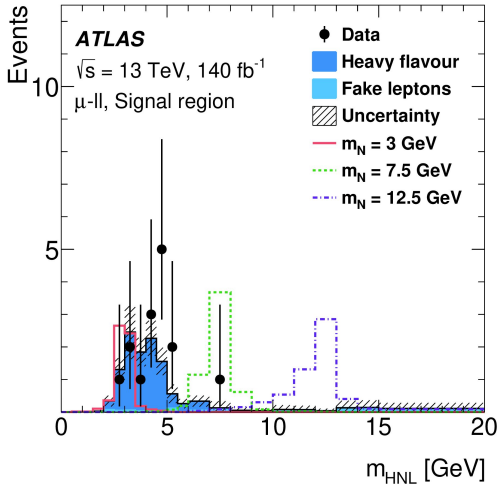
- Heavy Neutral Leptons (HNLs) predicted in BSM theories of neutrino (Dirac or Majorana) mass including Type-I Seesaw Mechanism (prompt or long-lived)
- Search for long-lived HNLs from decay of W boson, with HNL decaying leptonically or semi-leptonically – mass 1-20 GeV (1-3 GeV semi-leptonic), cτ 0.1 mm - 1 m
  - Require >=1 displaced vertex (DV) with >=1 matched lepton tracks offline
  - SR: W mass window of $m_{lll} \in$[40-90 GeV]/$m_{ll\pi} \in$ [70-90] GeV + 0 tagged b-jets in DV
- Follow up of previous analysis [PRL 131 (2023) 061803] using same dataset
- Backgrounds: SM heavy flavor hadron decays (est. from MC in CR with inverted b-jet veto) + mis-reconstructed leptons (est. from data in W-mass sideband regions)

Vertex Reco Efficiency vs. DV radius (r_{DV})



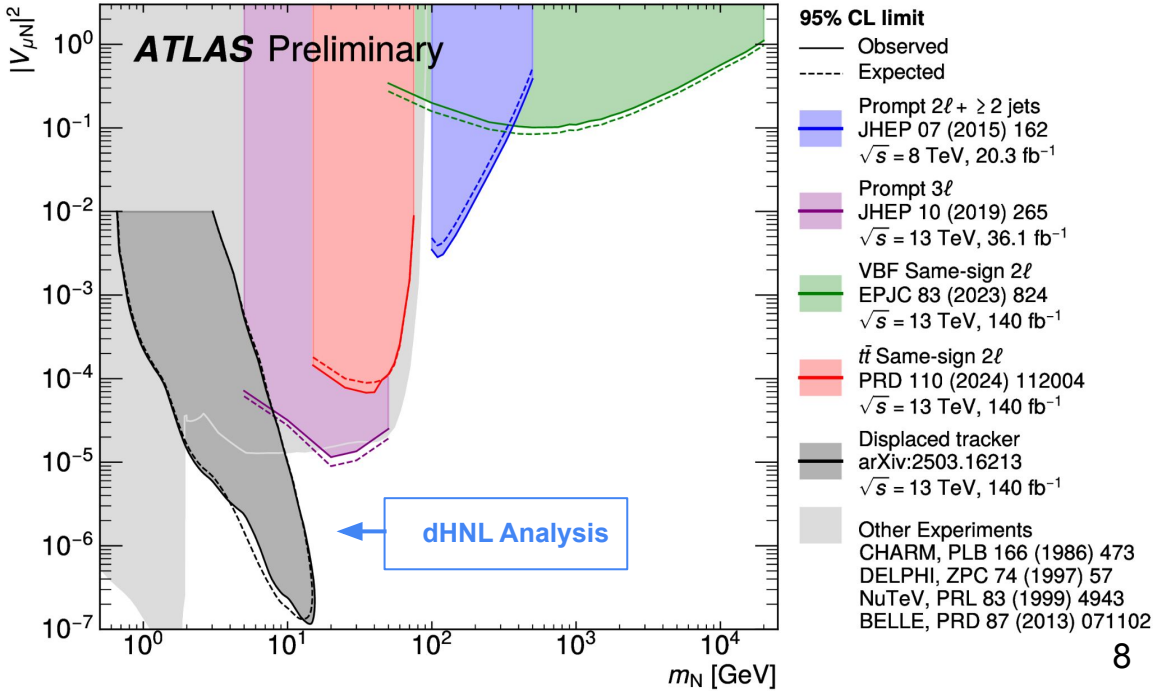
Displaced Heavy Neutral Leptons

arXiv:2503.16213
140 fb^{-1}, s=√13 TeV



← Small signal-like excess observed in μ-ll channel, with local significance of 3.σ (global <2.1σ)

- No significant deviation from SM
- Limits placed on HNL mass and coupling to SM in both Single Lepton Flavor and Quasi-Degenerate HNL models (Dirac and Majorana scenarios) for $0.5 < m_N < 16$ GeV



- Higher masses and lower couplings excluded with respect to previous analysis using same dataset, due to inclusion of semi-leptonic channel and improvements to LRT algorithm !

Summary of HNL limits from ATLAS search program → vs. mass and lifetime (from ATL-PHYS-PUB-2025-008)

Displaced Leptons

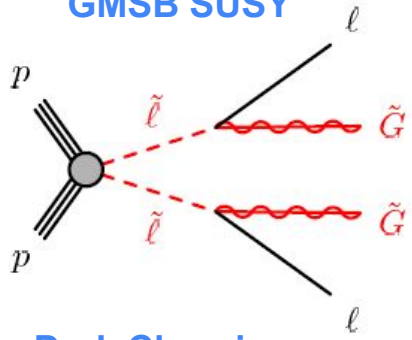
arXiv:2410.16835

140 fb^{-1} @ s=√13 TeV + 56.3 fb^{-1} @ s=√13.6

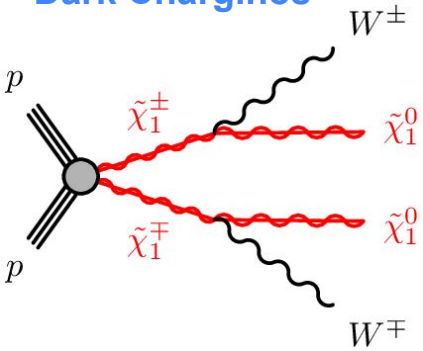
First ATLAS search using Run 3 data!

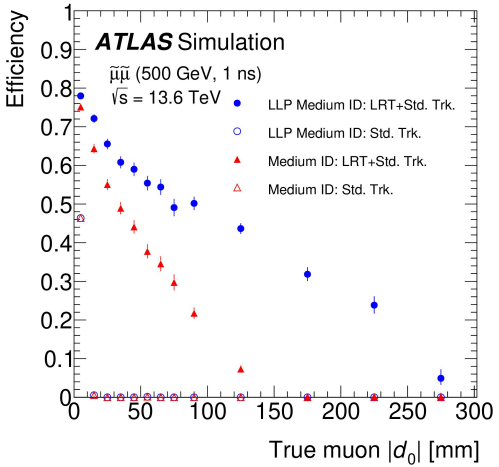
- Search for pair-produced displaced leptons in Run 2 **+ partial Run 3**
- Final states: ee, eμ, μμ + additional reco. states – displaced e reconstructed as ɣ, and single-EM objects
  - **ABCD Region (ee, eμ, μμ)**: uses new Run 3 Large Radius Tracking (LRT) triggers to extend to lower pT
  - **EM-BDT Region (>=1 e or >=2e/ɣ)**: uses BDT (including calorimeter (LAr) precision timing) to isolate signal
- Data-driven background estimation in fake-enriched/negative timing CRs

GMSB SUSY

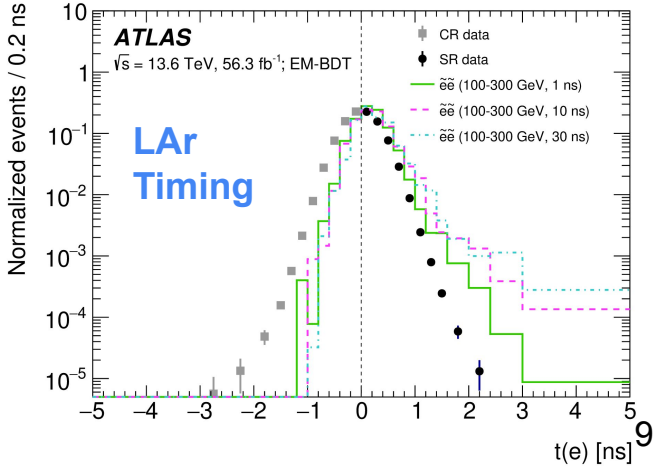


Dark Charginos





← LRT Efficiency

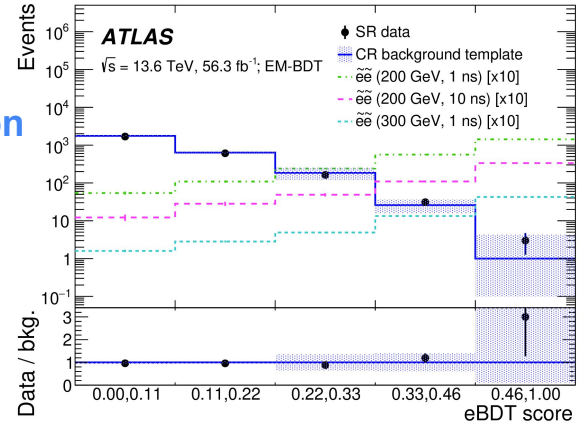


Displaced Leptons

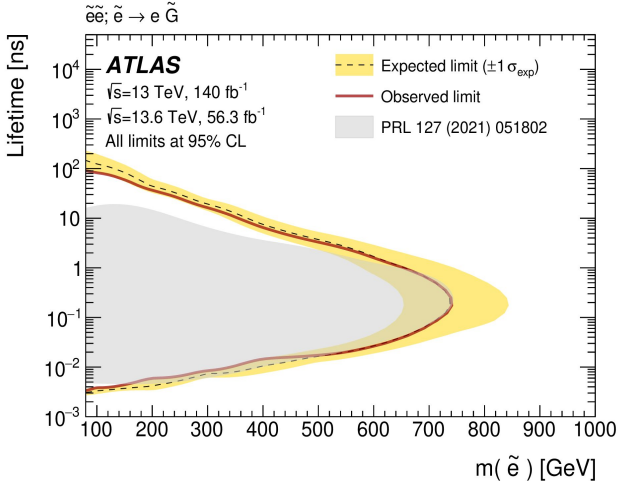
arXiv:2410.16835
140 fb^{-1} @ s=√13.6 TeV + 56.3 fb^{-1} @ s=√13.6

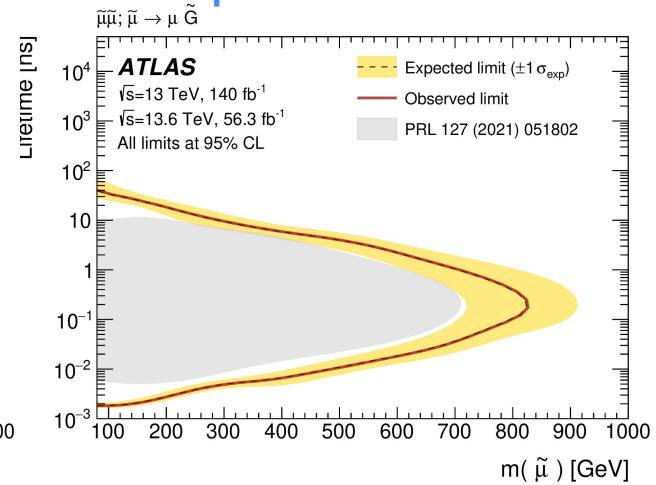
- No deviation from SM observed → exclusion of GMSB selectrons, smuons, and staus improved with respect to previous Run 2 only analysis [PRL127051802]
- Increased sensitivity to higher lifetimes from single-electron regions and to lower pT final states from LRT triggers
- Limits also set on dark chargino model: masses, lifetimes and mass splitting of chargino

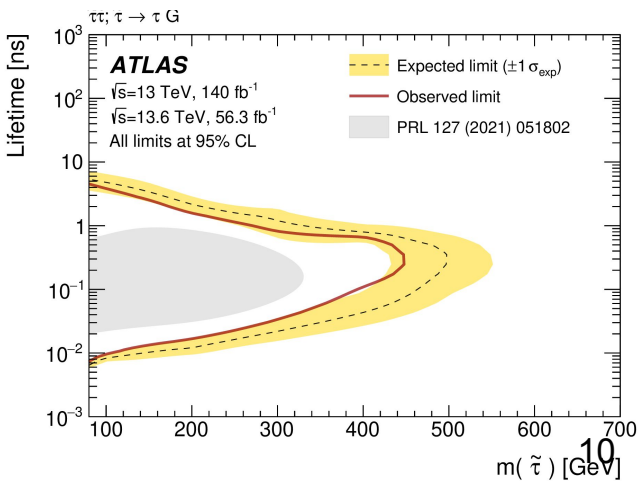
EM-BDT Distribution



Limits on Slepton Masses and Lifetimes



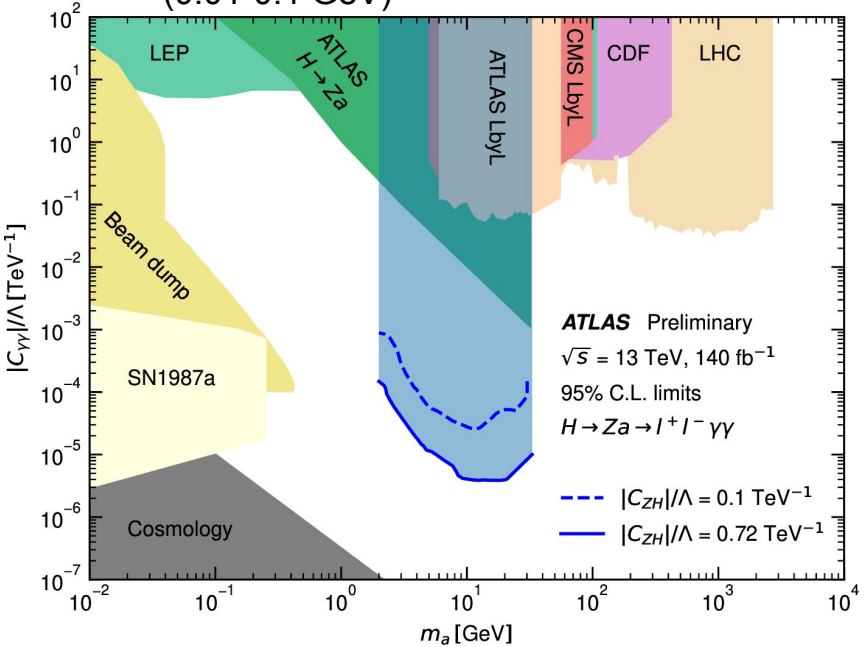


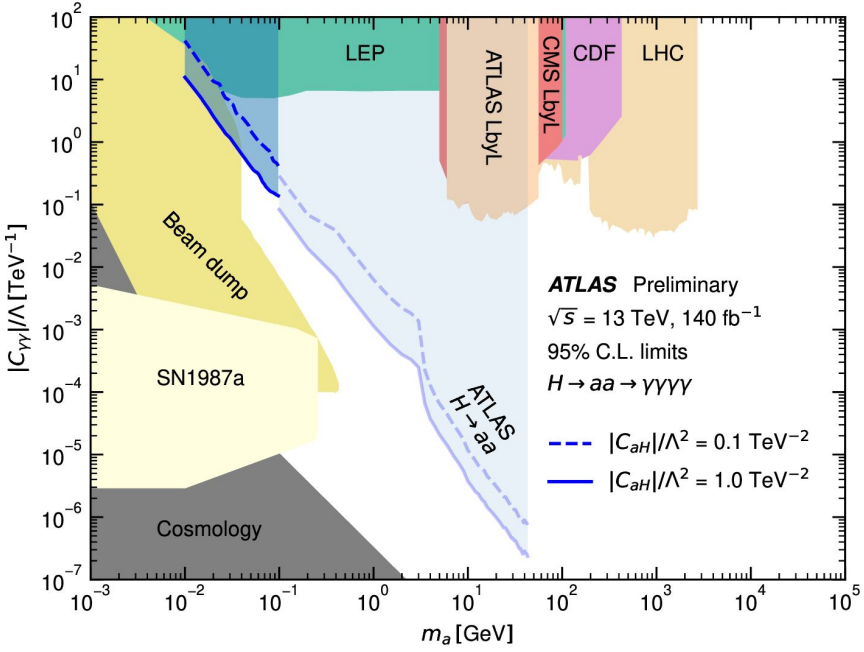


Long-Lived ALPs Interpretation

ATL-PHYS-PUB-2025-007
140 fb^{-1}, s=√13.6 TeV

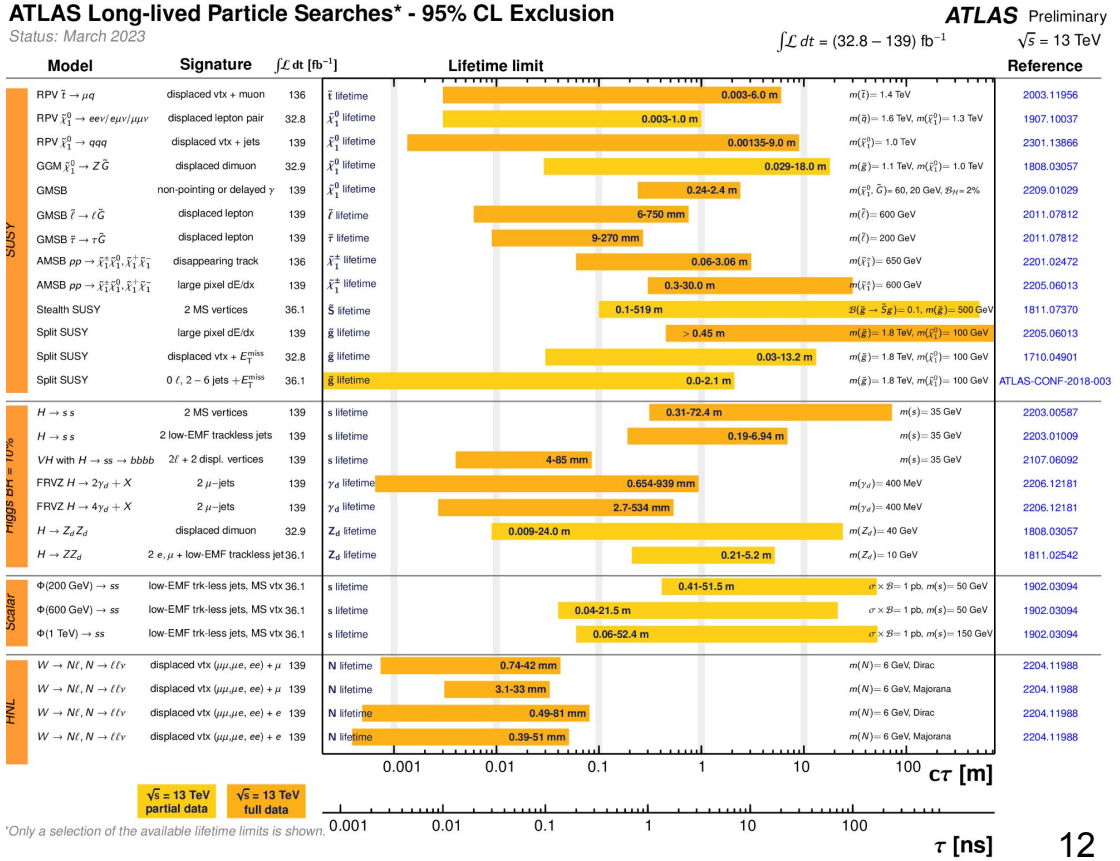
- Re-interpretation of two searches for axion-like particles (ALPs) produced in the decay of the SM Higgs and decaying to photons in extended regimes
  - H→Za→l$^+$l$^-$γγ search [PLB 850 (2024) 138536] for prompt ALPs (a) → lifetime reweighting of MC samples + additional displacement-based uncertainty used to exclude to longer lifetimes (cτ > 3 mm)/lower couplings
  - H→aa→γγγγ search [EPJC 76 (2016) 210] for long-lived ALPs (a) → reinterpreted to extend to lower masses (0.01-0.1 GeV)





Summary and Conclusion

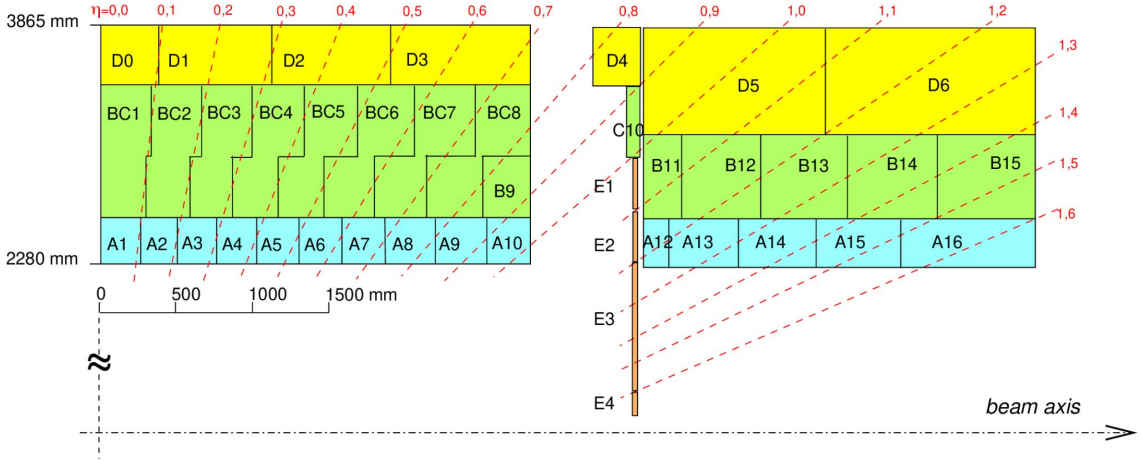
- Many new Run 2/Run 3 results searching for long-lived signatures in final states with leptons and MET
- Sophisticated reconstruction and analysis techniques for these challenging signatures have been and are being developed in ATLAS
- See P. Scholer's talk (hadronic final states) and ATLAS Search Results (latest summaries)
- Many scenarios have been ruled out, but **more phase space left to explore**
  - Run 3 is ongoing (~350 fb^{-1} expected)
  - **Only ~10% of full LHC expected luminosity (3000-4000 fb^{-1}) collected so far !**



BACKUP

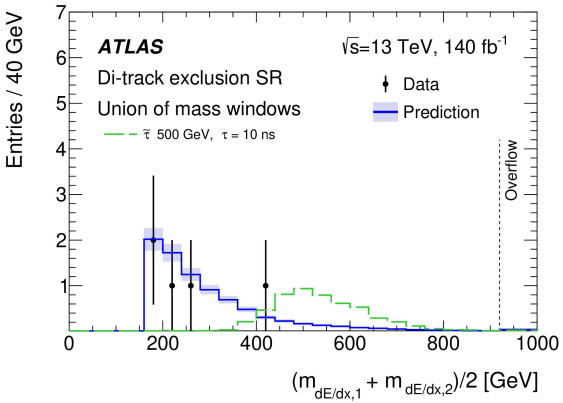
Pixel dE/dX + β-calo

arXiv: 2502.06694
140 fb^{-1}, s=√13 TeV



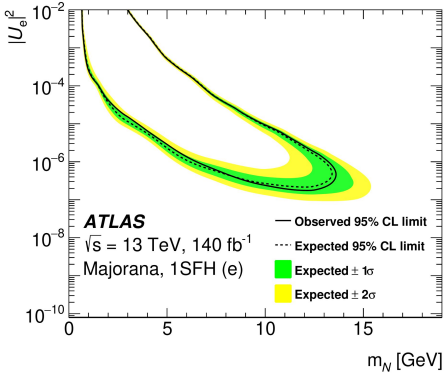
- Schematic of Tile calorimeter with values of pseudorapidity overlaid
- β_{TOF} measurements extracted from resolution-weighted average of timing measurements of Tile cells

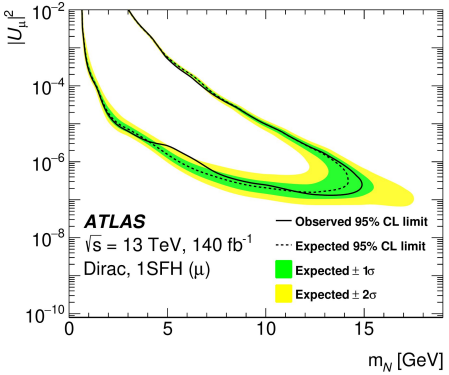
- Distribution of events in di-track signal region
- Only events in mass compatibility window included

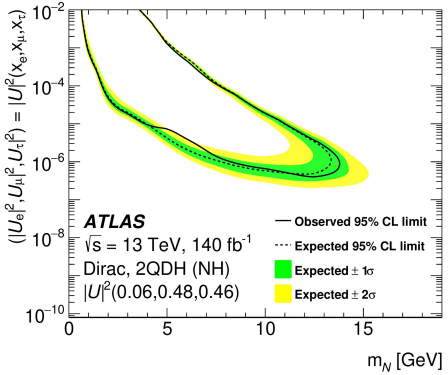


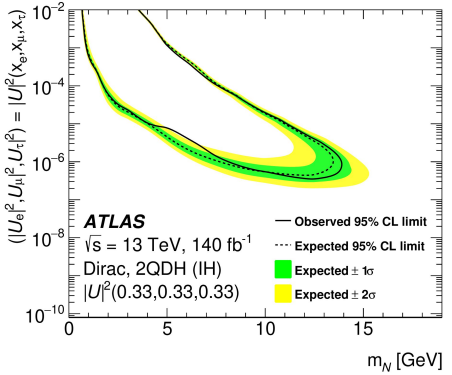
Displaced Heavy Neutral Leptons: Limits

Limits on Dirac Mass Scenarios

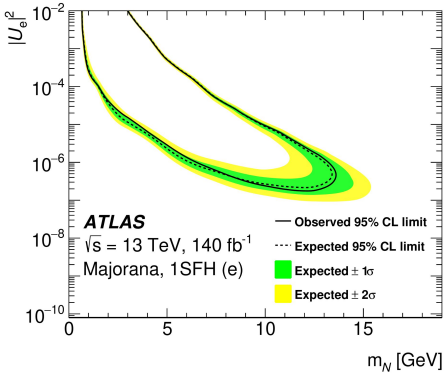


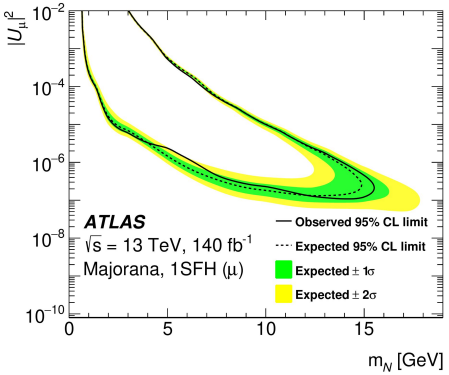


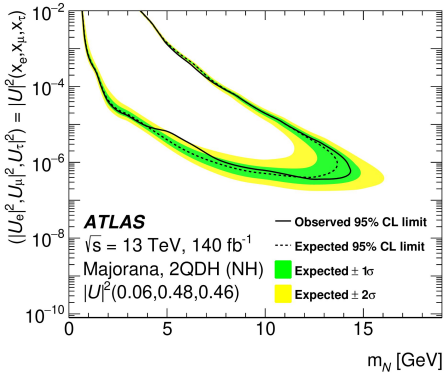


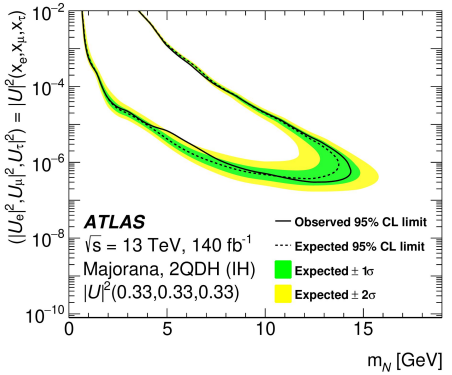


Limits on Majorana Mass Scenarios









Displaced Leptons

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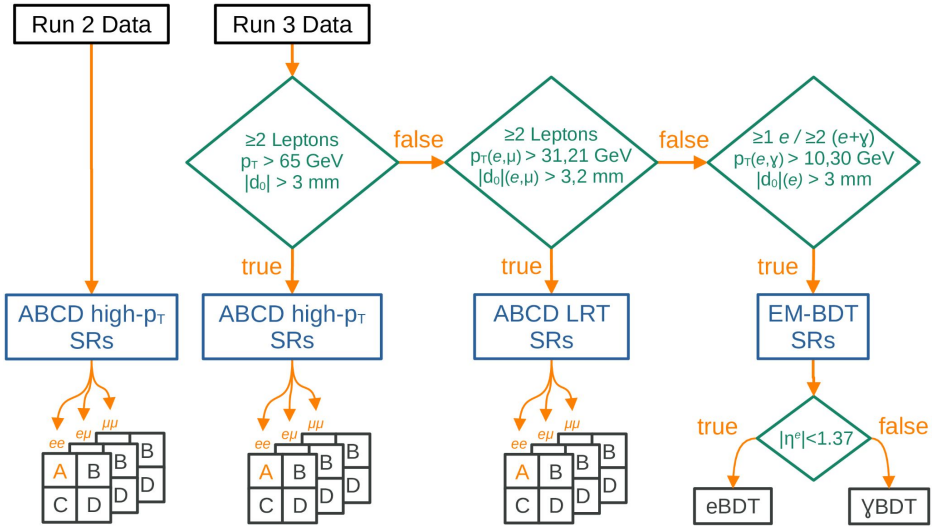

^ Analysis Region flow chart: orthogonal regions defined by reconstructed lepton type, number, and pT

Exclusion of → selectron and stau models split by analysis region