Searches for BSM physics using challenging and long-lived signatures with the ATLAS detector

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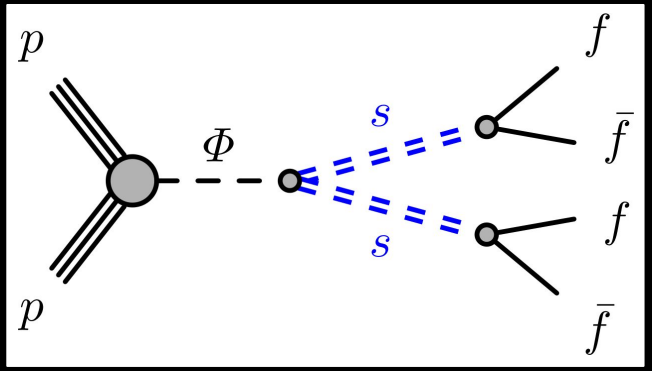
Long-lived particles

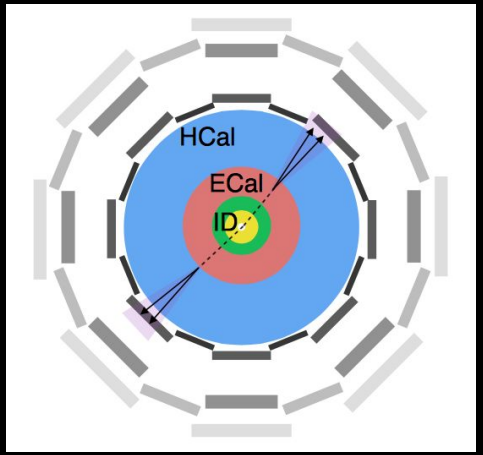
- Standard Model particles span a wide range of lifetimes
- Various BSM theories predict new long-lived particles (LLPs)
  - Unstable but with macroscopic decay length
  - Can help explain some of the big unresolved mysteries[1]: dark matter, baryogenesis, neutrino masses, naturalness
- Unique signatures, difficult to reconstruct, challenging backgrounds
- Adds a whole new dimension to analyses!
- In this talk, some of the most recent LLP results from ATLAS:
  - Displaced jets in the calorimeter
  - Dark photons
  - Displaced heavy neutral leptons
  - Displaced photons in exotic Higgs decays
  - Heavy charged LLPs

[1] arXiv:1806.07396

Displaced jets in the calorimeter (arXiv:2203.01009)

- Model:
  - Hidden sector mediator → two scalar LLPs
  - Mediator can be 125 GeV Higgs boson
- Signature: Two jets with very little associated activity in the tracking layers and inner calorimeter layers
  - Occurs when LLPs decay within the calorimeter
- Trigger: Narrow jet with an unusually large ratio of hadronic calorimeter energy to electromagnetic calorimeter energy (CalRatio)





Displaced jets in the calorimeter (arXiv:2203.01009)

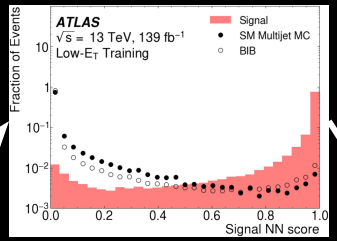
Low-level information from:

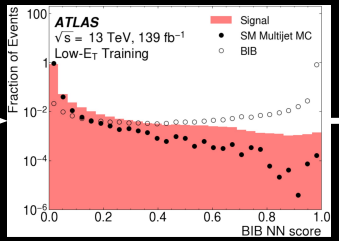
Jets

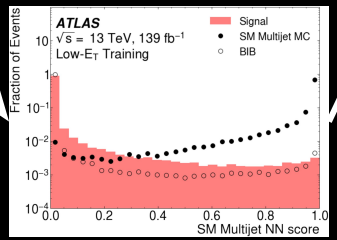
Tracks

Muons

Per-jet neural network

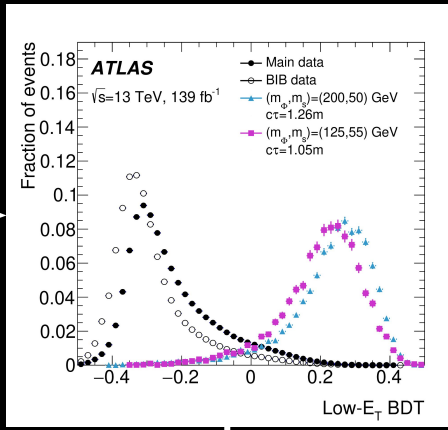






Event-level information

Per-event boosted decision tree



Background estimation by ABCD method

Displaced jets in the calorimeter (arXiv:2203.01009)

Low-level information from:

Jets

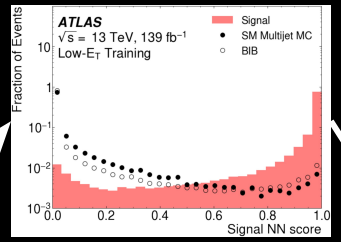
Tracks

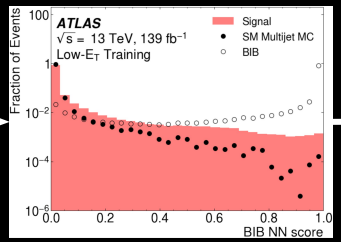
Muons

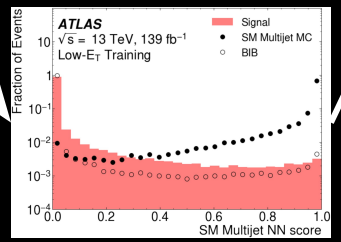
Per-jet neural network

Adversarial training to minimize impact of MC mismodeling

First use of an adversarial network for this purpose in ATLAS



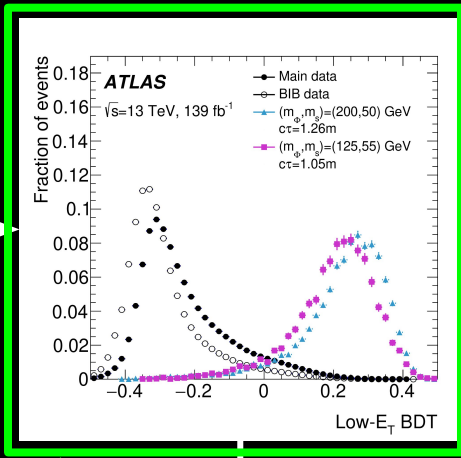




Event-level information

"How much is each *jet* like signal, QCD, or beam-induced background (BIB)?"

Per-event boosted decision tree



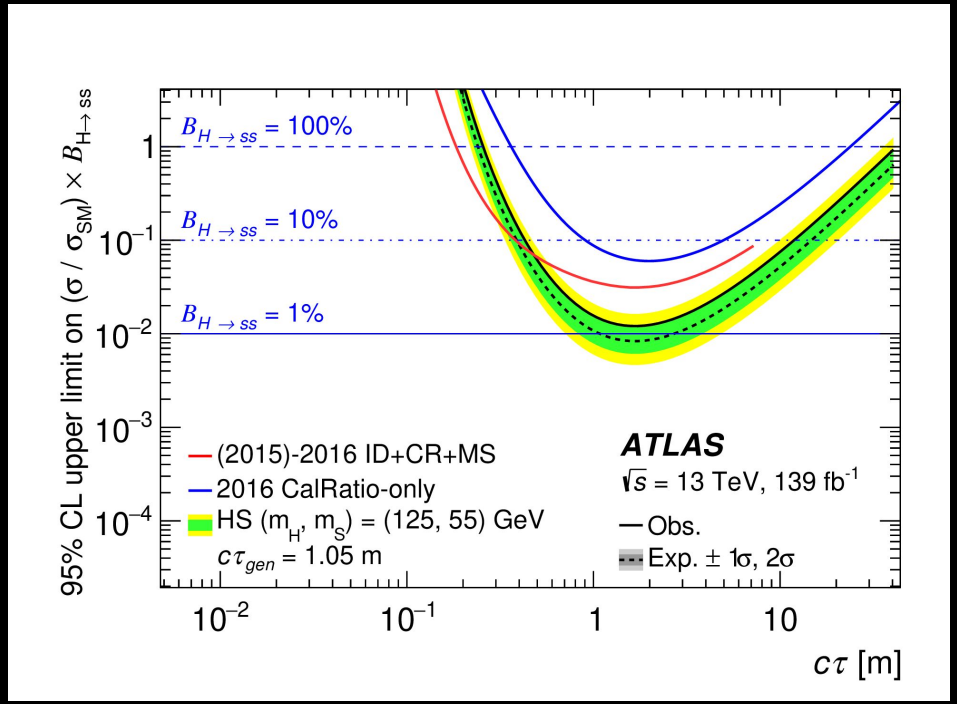
"How signal-like is each *event*?"

Background estimation by ABCD method

Displaced jets in the calorimeter (arXiv:2203.01009)

- Slight excess in signal region, but not statistically significant

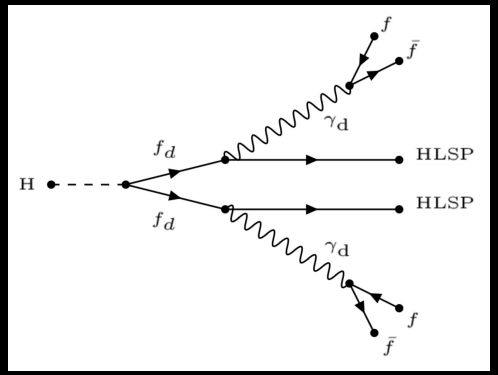
High-E_T selection	A	B	C	D
Observed data	22	7	233	131
a priori				
Estimated background	12.4 ± 4.7	7 ± 2.6	233 ± 15	131 ± 11
a posteriori (background-only fit)				
Fitted background	18.8 ± 3.5	10.2 ± 3.2	236 ± 15	128 ± 11
a posteriori (signal-plus-background fit)				
Fitted background	10.0 ± 6.0	5.7 ± 2.4	230 ± 15	131 ± 11
Fitted signal $((m_\Phi, m_s) = (600, 150) GeV)$	12.2 ± 8.7	1.4 ± 1.0	3.4 ± 2.5	< 1
Low-E_T selection	**A**	**B**	**C**	**D**
Observed data	23	3	220	61
a priori				
Estimated background	10.8 ± 6.6	3 ± 1.7	220 ± 15	61 ± 7.8
a posteriori (background-only fit)				
Fitted background	20.6 ± 4.0	5.4 ± 2.3	222 ± 15	59 ± 7.7
a posteriori (signal-plus-background fit)				
Fitted background	8.4 ± 7.7	2.4 ± 1.5	217 ± 15	61 ± 7.8
Fitted signal $((m_\Phi, m_s) = (125, 55) GeV)$	14.6 ± 9.9	< 1	3.2 ± 2.2	< 1



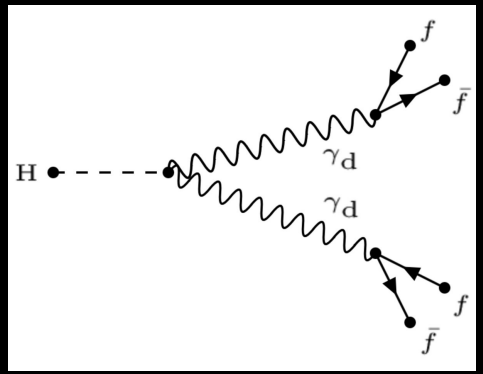
Dark photons (ATLAS-CONF-2022-001)

- Models:
  - Falkowski-Ruderman-Volansky-Zupan (FRVZ)
  - Hidden Abelian Higgs Model (HAHM)
- Signatures:
  - Displaced collimated muon pairs
  - Displaced jets
- Trigger:
  - ggF production:
    - Multi-muon triggers
    - CalRatio trigger
  - WH production:
    - Single lepton triggers

FRVZ model

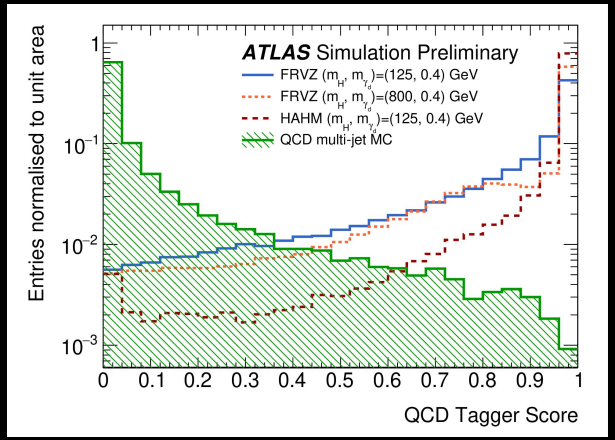


HAHM model



Dark photons (ATLAS-CONF-2022-001)

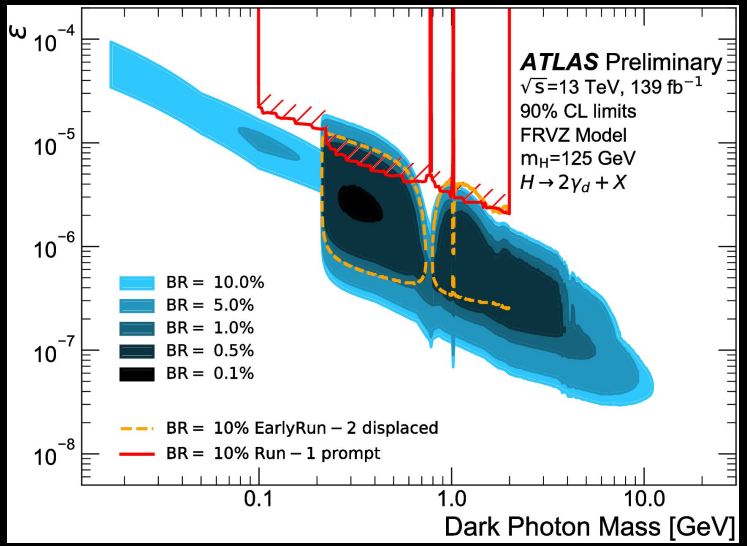
- Muonic dark photon jet candidates (μDPJs)
  - Formed by muon tracks not matched to inner detector tracks
  - Cosmic ray tagger
    - Deep neural network trained to reject cosmic ray muons
- Calorimeter dark photon jet candidates (caloDPJs)
  - Formed by jets with a high CalRatio
  - QCD tagger
    - Convolutional neural network utilizing 3D spatial convolutions of calorimeter energy deposits
    - Trained to reject QCD multijet events
  - BIB tagger
    - Same neural network architecture as QCD tagger, but trained to reject beam-induced background (BIB)
- Channels requiring varying numbers of μDPJs and caloDPJs
- ABCD method used to estimate background

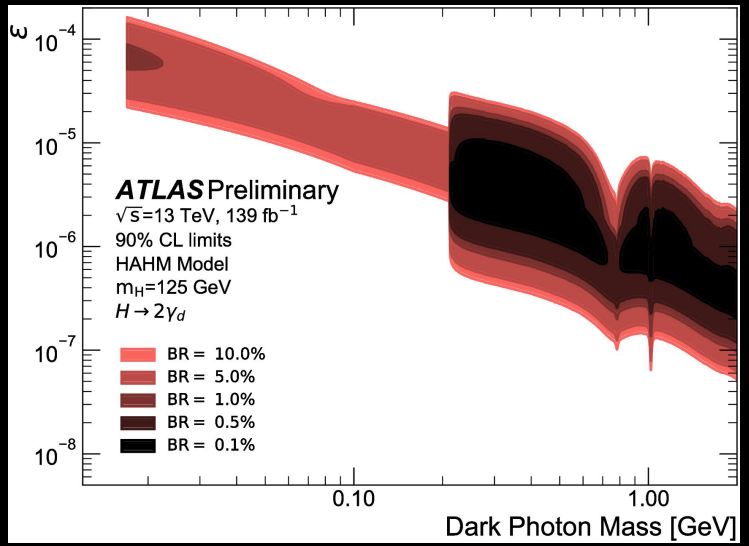


Dark photons (ATLAS-CONF-2022-001)

- First ATLAS limits set for HAHM dark photons

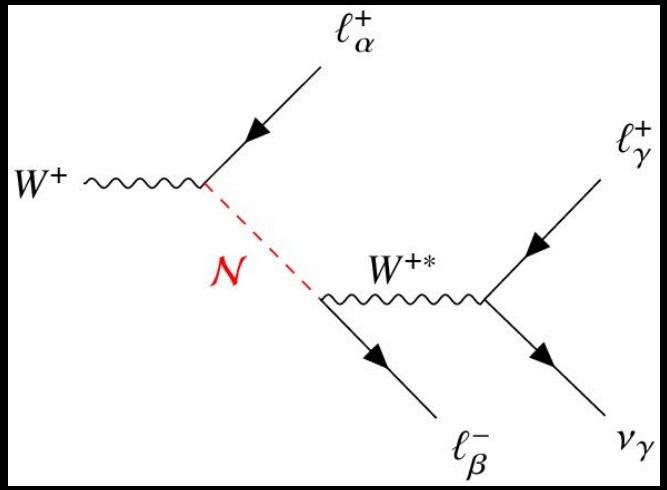
Selection	Search channel	CRB	CRC	CRD	SR expected	SR observed
ggF	2μ	55	61	389	317 ± 47	269
	c+μ	169	471	301	108 ± 13	110
	2c	97	1113	12146	1055 ± 82	1045
WH	c	1850	3011	155	93 ± 12	103
	c+μ	30	49	31	19 ± 8	20
	2c	79	155	27	14 ± 5	15

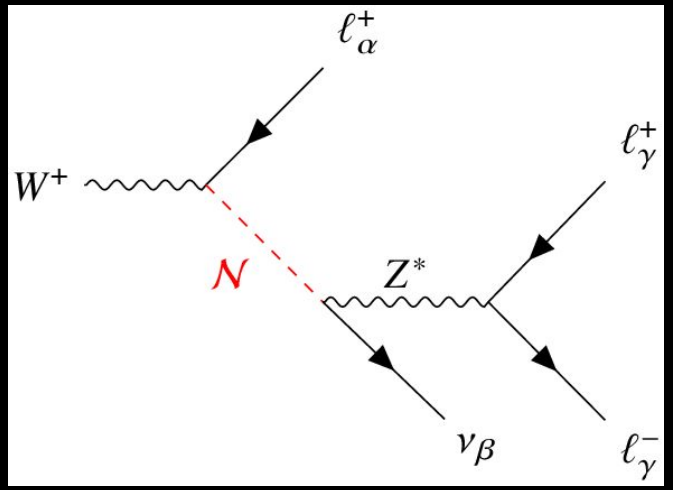




Displaced heavy neutral leptons (arXiv:2204.11988)

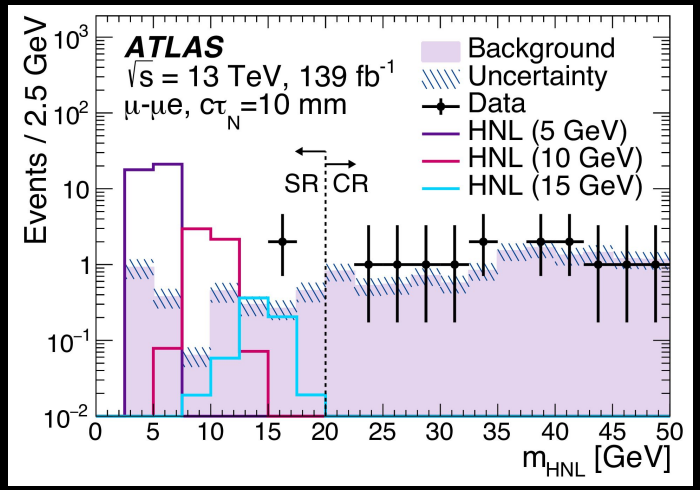
- Heavy neutral lepton (HNL) models:
  - One HNL, single-flavor mixing (1SFH) with either ν_e or ν_μ
  - Two quasi-degenerate HNLs (2QDH), normal hierarchy (NH) or inverted hierarchy (IH)
- Signature: Prompt lepton + two-lepton displaced vertex (DV)
- Trigger: Single lepton triggers

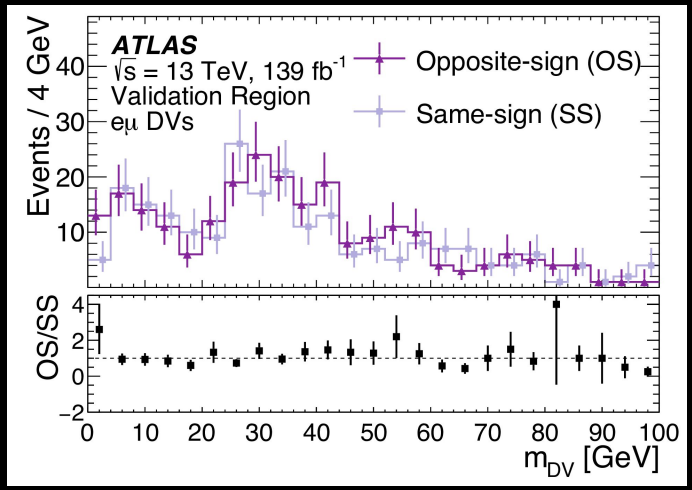




Displaced heavy neutral leptons (arXiv:2204.11988)

- HNL candidate four-momentum reconstructed by observable kinematics, DV position, and the measured *W* mass
- Signal region (SR) defined by invariant mass of HNL candidate: $m_{HNL} < 20$ GeV
  - Higher masses lead to lifetimes too short (via relationship to mixing parameters) for sensitivity by this search
- Irreducible background from random lepton track crossings
  - Shape estimated by “event shuffling”: combining prompt leptons from same-sign DV events and opposite sign DVs from events without prompt leptons

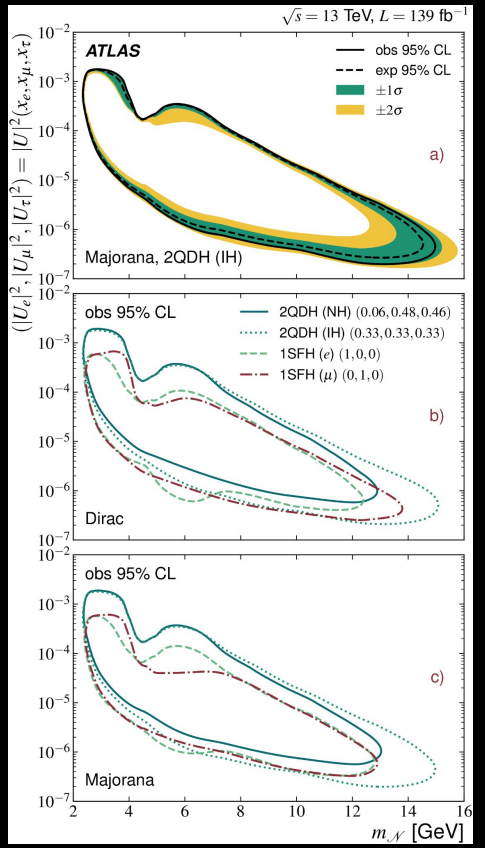




Displaced heavy neutral leptons (arXiv:2204.11988)

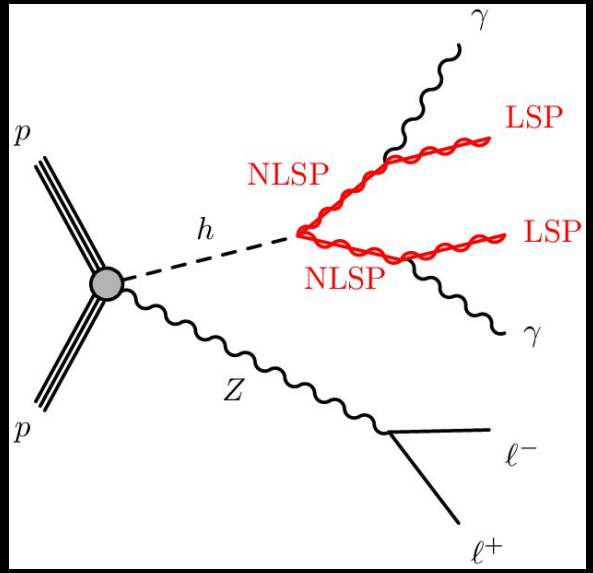
- First limits set on a multi-flavor mixing model (2QDH)
  - Simplest HNL model compatible with neutrino oscillation measurements

Channel	Signal region		Control region	
	Background	Observed	Background	Observed
$e{-}ee$	0.4 ± 0.3	2	3.6 ± 1.8	2
$\mu{-}ee$	0.2 ± 0.1	1	1.8 ± 1.3	1
$e{-}e\mu$	0.9 ± 0.4	0	4.1 ± 1.9	5
$\mu{-}\mu e$	2.8 ± 0.8	2	12.2 ± 3.2	13
$e{-}\mu\mu$	1.2 ± 0.9	1	2.8 ± 1.6	3
$\mu{-}\mu\mu$	2.2 ± 1.4	2	8.7 ± 2.9	9
$e^{\pm}{-}e^{\mp}\mu^{\pm}$	0.6 ± 0.3	0	2.4 ± 1.4	3
$\mu^{\pm}{-}\mu^{\mp}e^{\pm}$	1.9 ± 0.6	0	8.1 ± 2.6	10



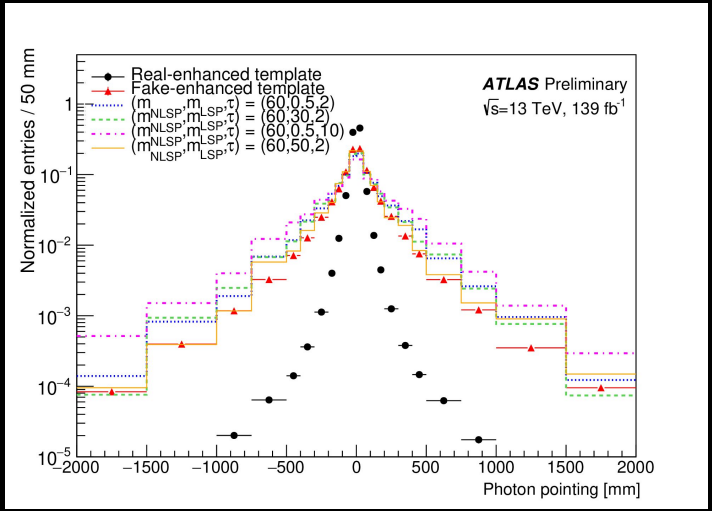
Displaced photons (ATLAS-CONF-2022-017)

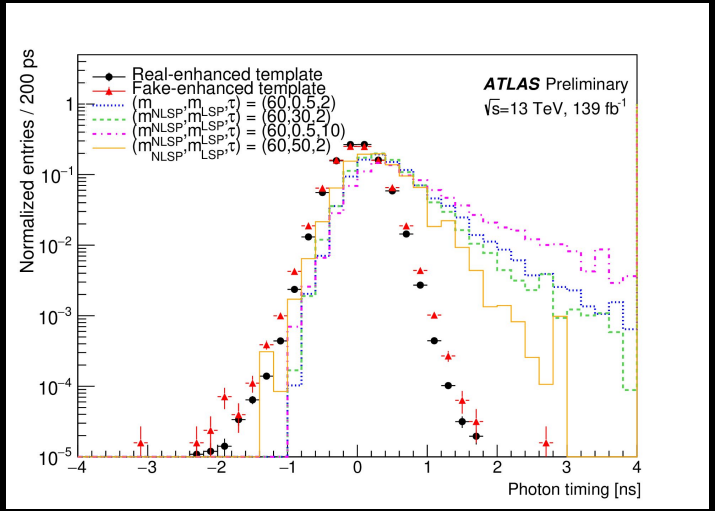
- Models: Gauge-mediated SUSY Breaking
  - Exotic Higgs decay to two next-to-lightest SUSY particles (NLSPs), which each in turn decays to a SM photon and the lightest SUSY particle (LSP)
- Signature: $Z/W/t\bar{t}$ + displaced photons + missing transverse momentum
- Trigger: Single lepton triggers



Displaced photons (ATLAS-CONF-2022-017)

- Displacement of photons determined by timing and pointing measurements
  - These measurements are unique capabilities of the ATLAS liquid argon calorimeter
- Genuine-photon enriched and fake enriched samples produced in control region by tighter identification requirements
- Template timing distributions from these samples used in simultaneous fit in signal region to estimate background, in categories of photon pointing and multiplicity

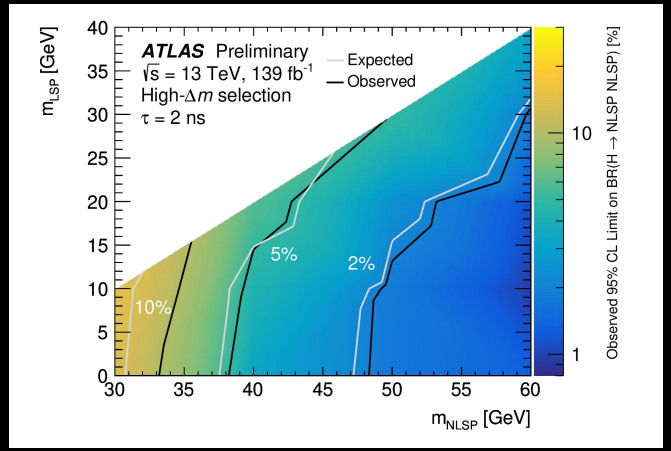


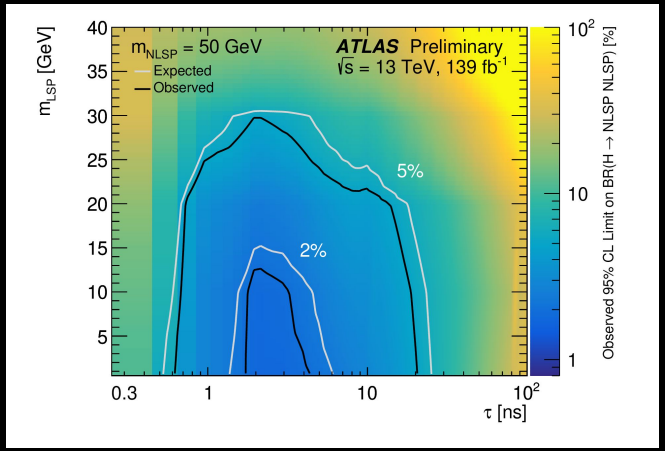


Displaced photons (ATLAS-CONF-2022-017)

- First limits set for displaced photons arising from Higgs boson decays

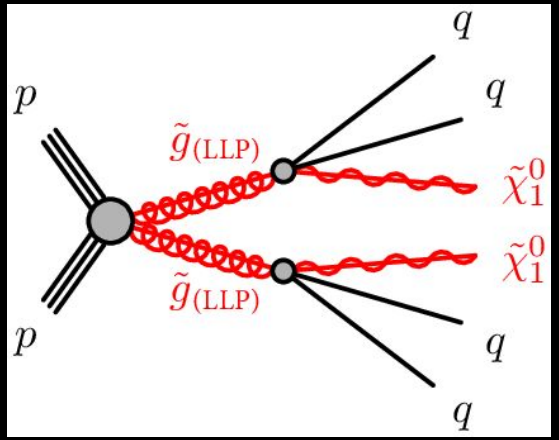
Region	Requirements	Expected	Observed	σ_{vis}^{95} [fb]
1γ	$1.5 < t_\gamma < 12$ ns, $\lvert\Delta z_\gamma\rvert > 300$ mm	3.8 ± 1.6	4	0.042
$\geq 2\gamma$	$1.0 < t_\gamma < 12$ ns, $\lvert\Delta z_\gamma\rvert > 300$ mm	0.28 ± 0.04	0	0.022
$\geq 1\gamma$		4.1 ± 1.7	4	0.041

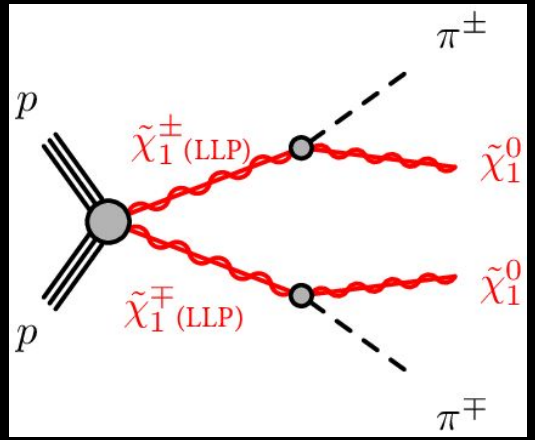


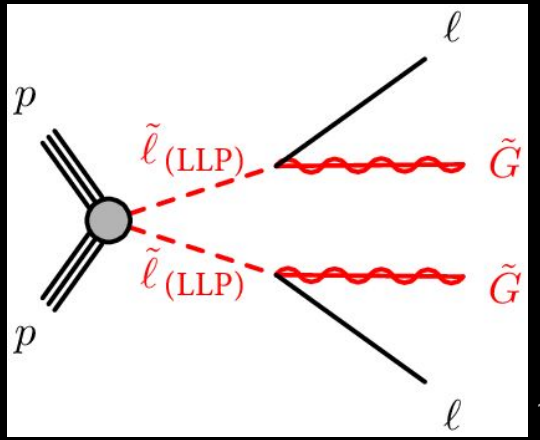


Heavy charged LLPs (SUSY-2018-42)

- Models:
  - Split SUSY (long-lived gluinos that can form electrically charged *R*-hadrons)
  - Anomaly-mediated SUSY breaking (long-lived charginos)
  - Gauge-mediated SUSY breaking (long-lived sleptons)
- Signature: Tracks with large ionization energy loss (dE/dx) + missing transverse momentum
  - High mass ($\gtrsim$ 100 GeV) → low β → significantly higher dE/dx than minimum ionizing particles
- Trigger: Missing transverse momentum

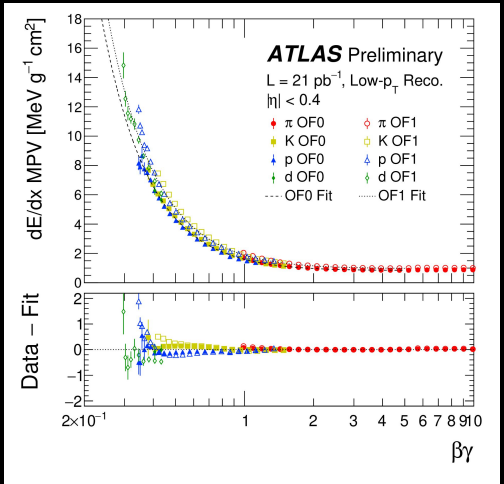


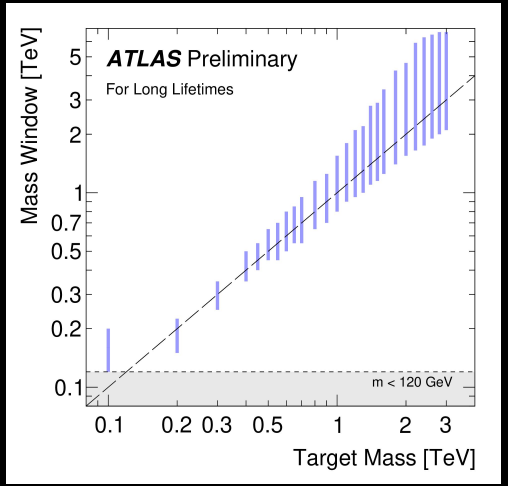




Heavy charged LLPs (SUSY-2018-42)

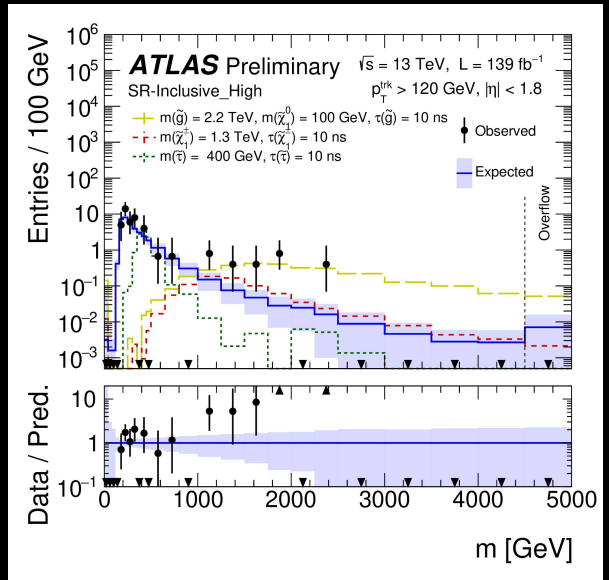
- dE/dx is averaged across clusters of pixel detector hits in a track
  - Signal regions require dE/dx > 1.8 MeV g^{-1} cm^2
- Low-momentum tracks were used to create a mapping from dE/dx to $\beta\gamma$
- With momentum of track and $\beta\gamma$, can calculate mass
- Hypothesis testing is done in mass windows for each target mass
- Data-driven background estimation based on control regions defined by inverting selections of either dE/dx or missing transverse momentum

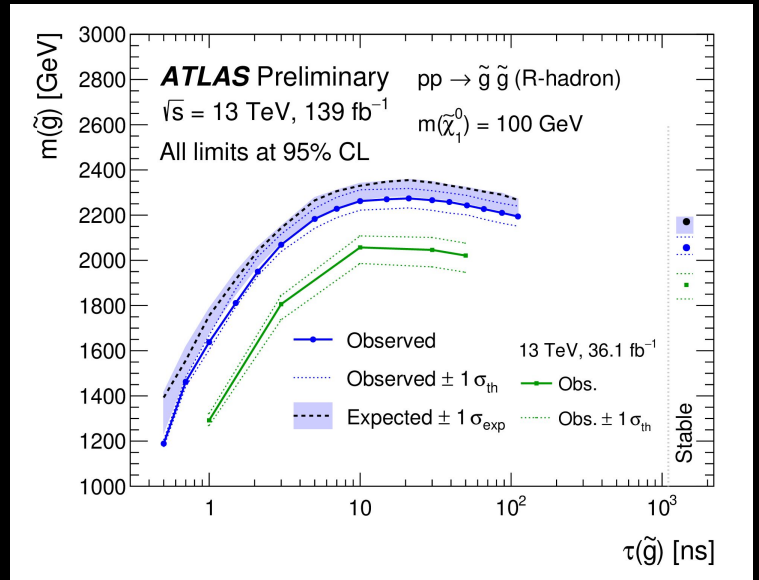




Heavy charged LLPs (SUSY-2018-42)

- Excess observed in highest dE/dx signal region for masses > 1 TeV
  - No obvious abnormalities detected in these events
  - But: all still compatible with $\beta = 1$ based on time-of-flight measurements
- Most stringent limits to date set for all models considered





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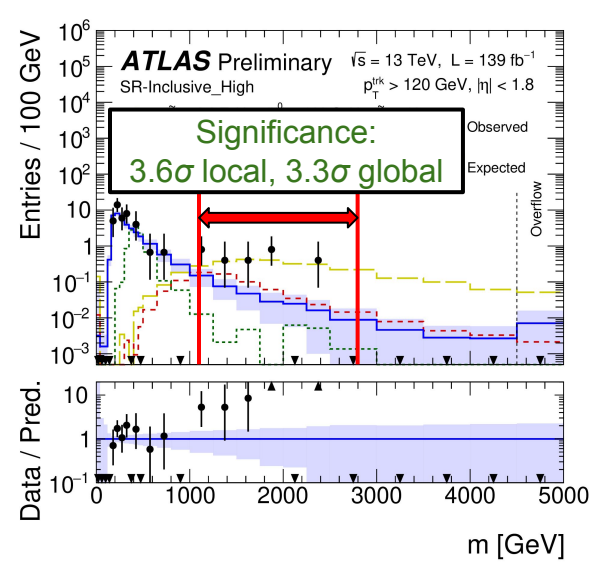
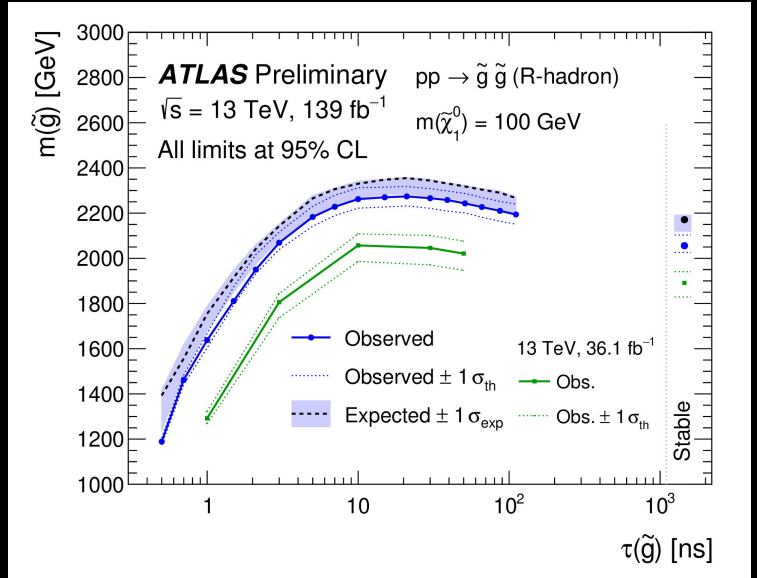
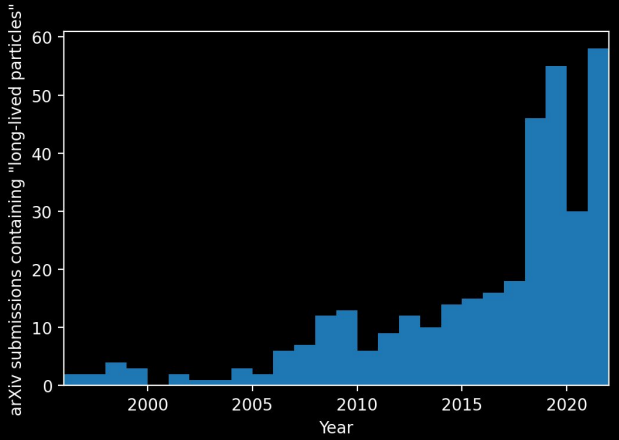


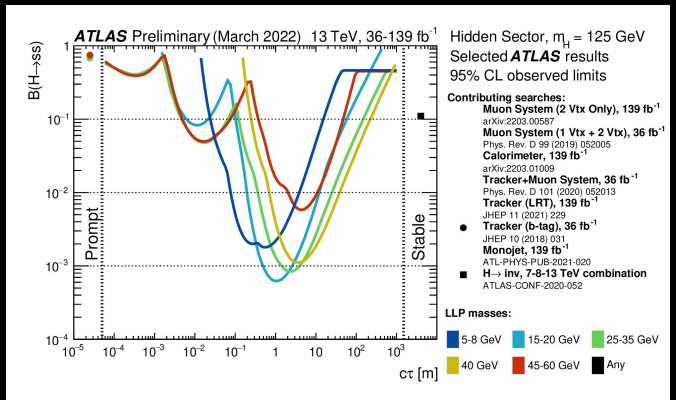


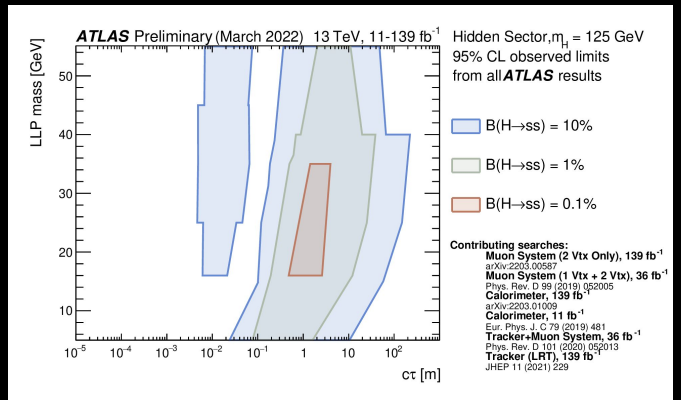
Summary (and some summary plots)

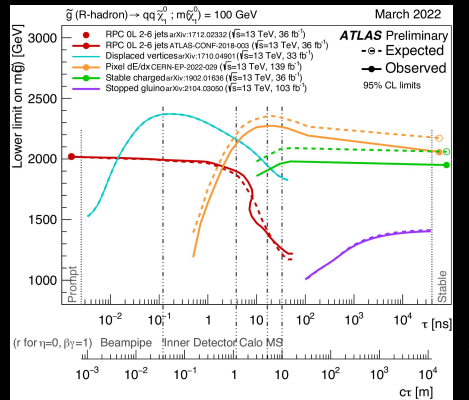
- New LLPs beyond the Standard Model are well motivated and interest in them has surged in the past few years
- The challenges of these unusual signatures have motivated new triggers, customized reconstruction, and innovative use of machine learning algorithms
- Plenty more ATLAS LLP analyses still in progress
- With Run 3 of the LHC started now, new data is just around the corner…



The current state of ATLAS hidden sector (ATL-PHYS-PUB-2022-007) and long-lived gluino searches (ATL-PHYS-PUB-2022-013):

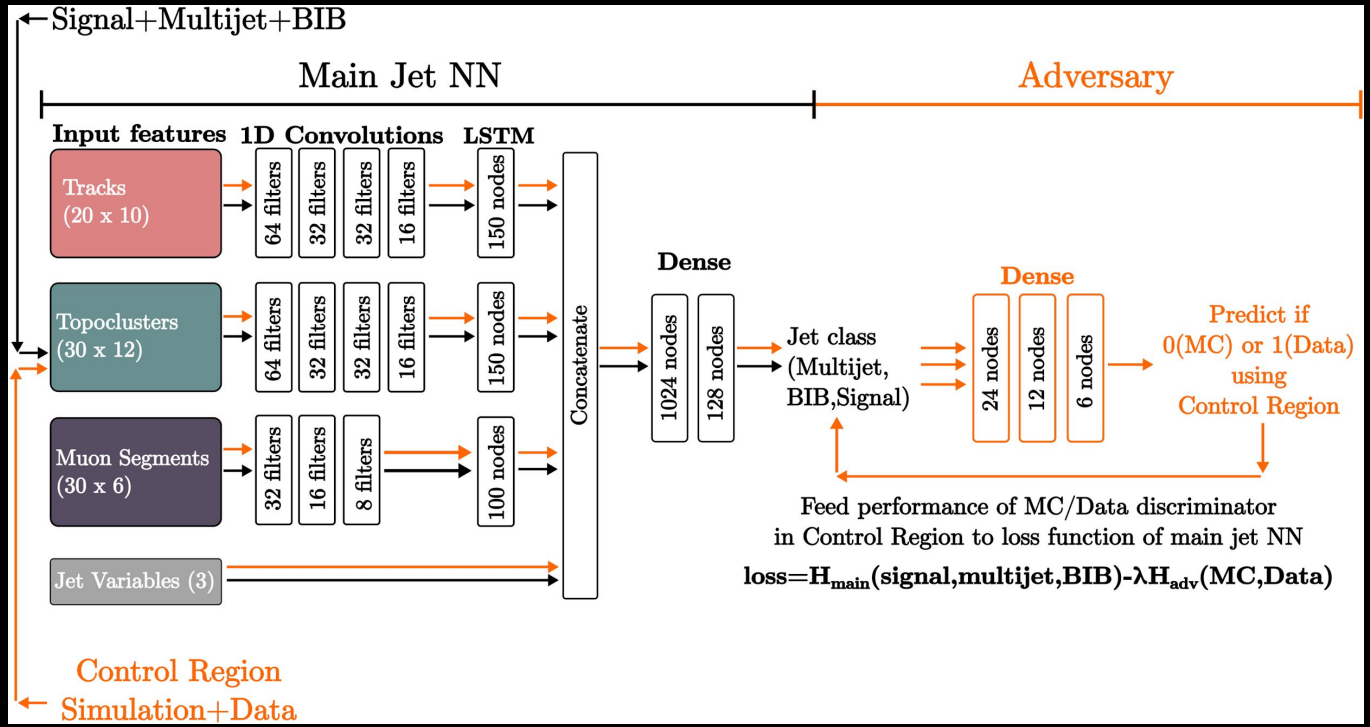




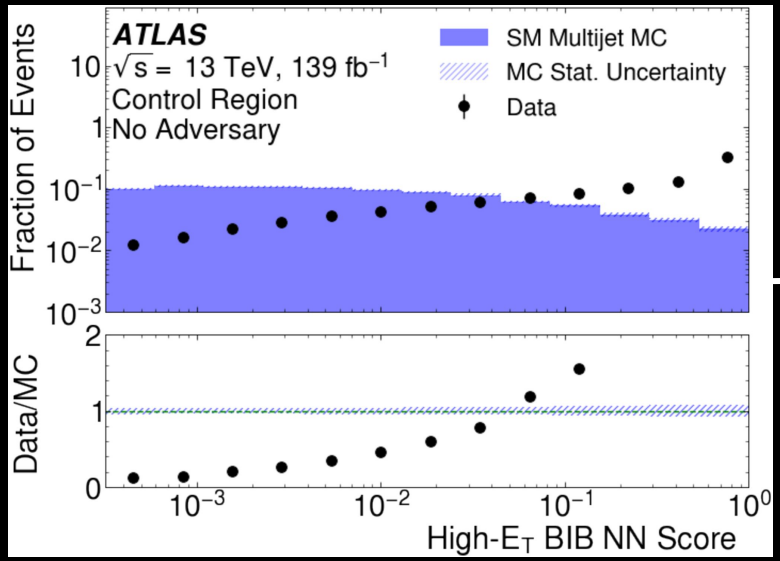


Backup

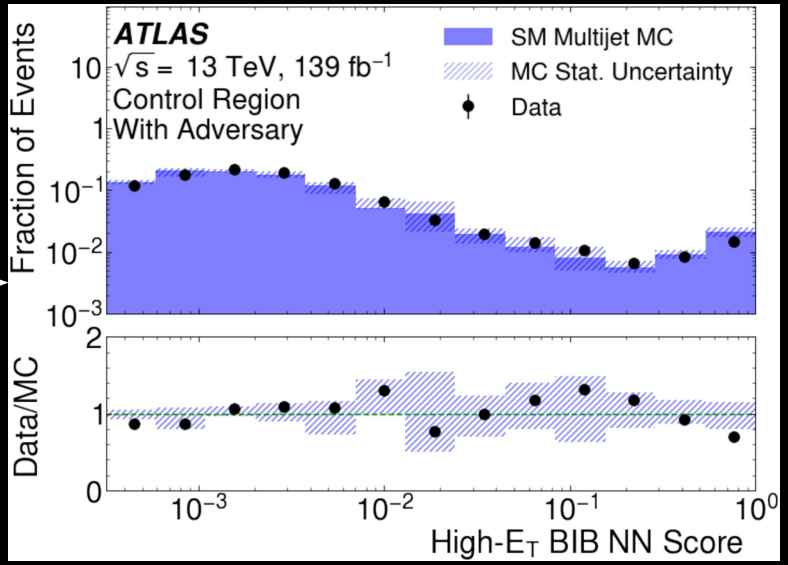
Displaced jets in the calorimeter (arXiv:2203.01009)



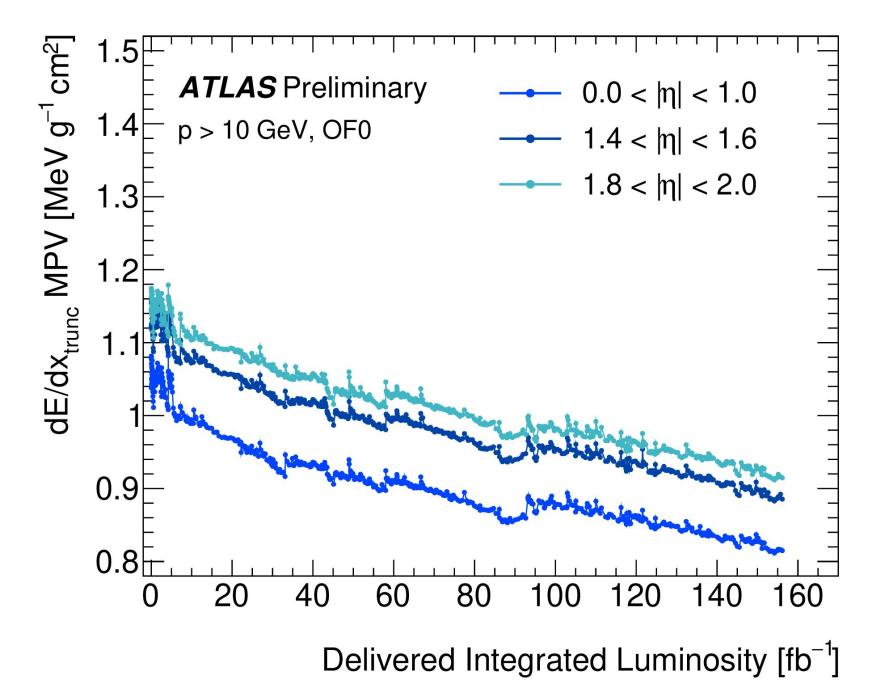
Displaced jets in the calorimeter (arXiv:2203.01009)

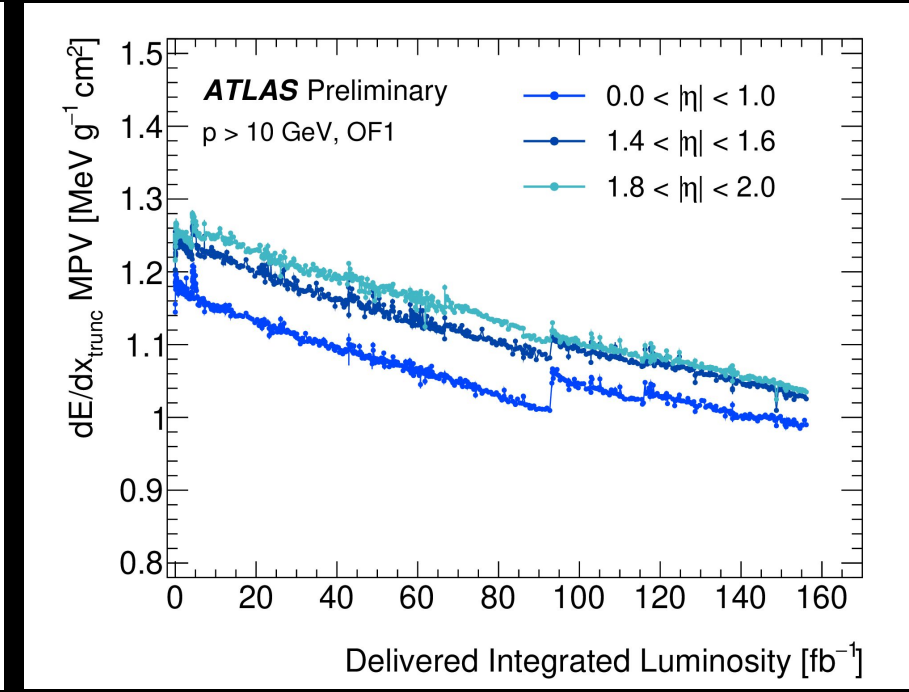


Adversarial training

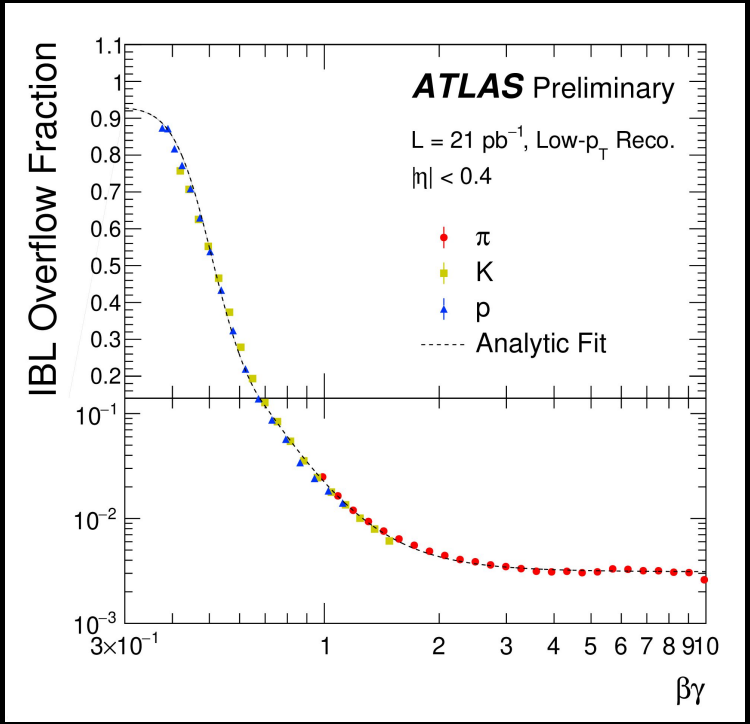


Heavy charged LLPs (SUSY-2018-42)

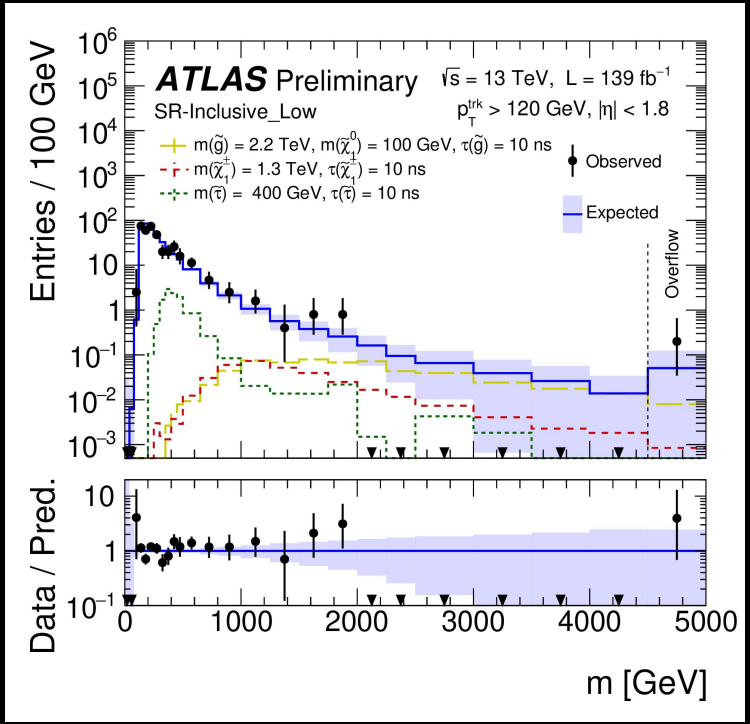




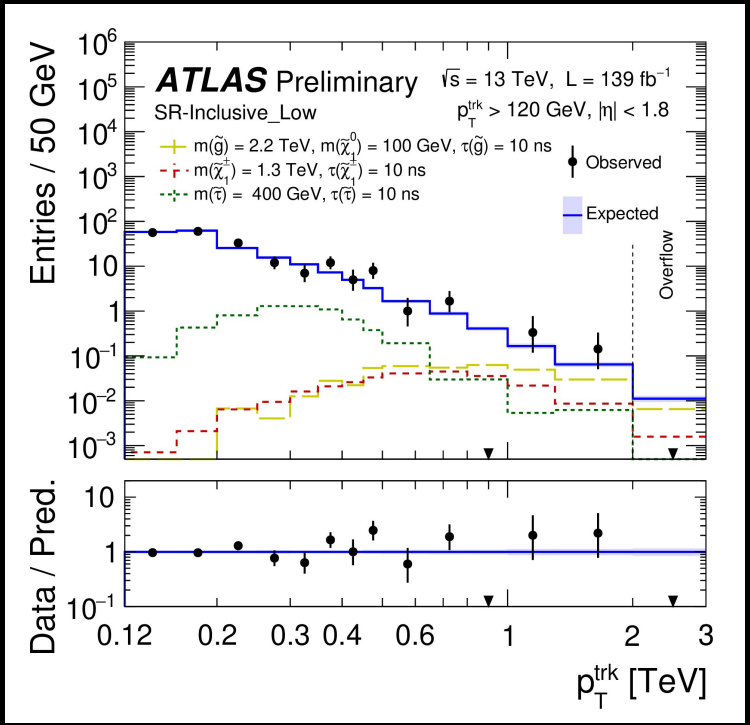
Heavy charged LLPs (SUSY-2018-42)

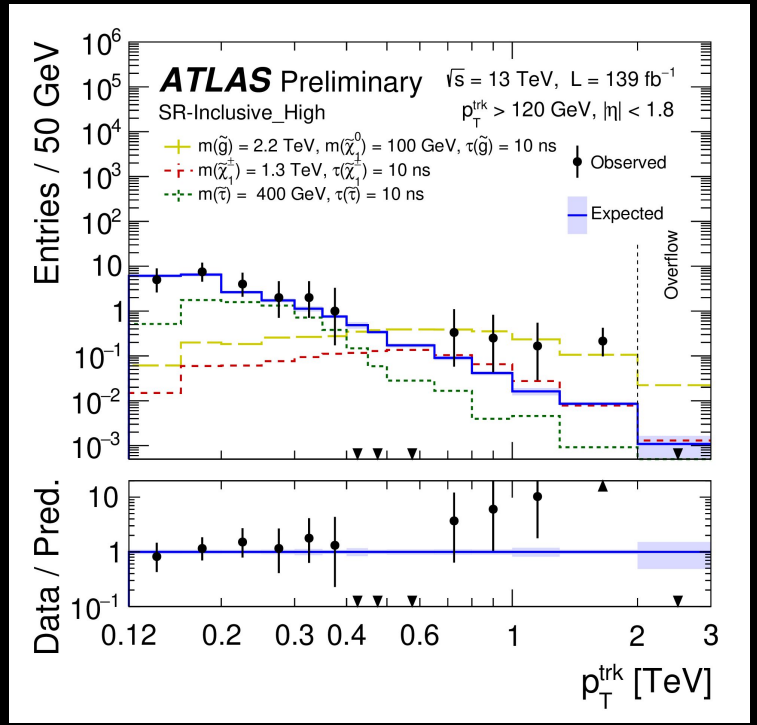


Heavy charged LLPs (SUSY-2018-42)

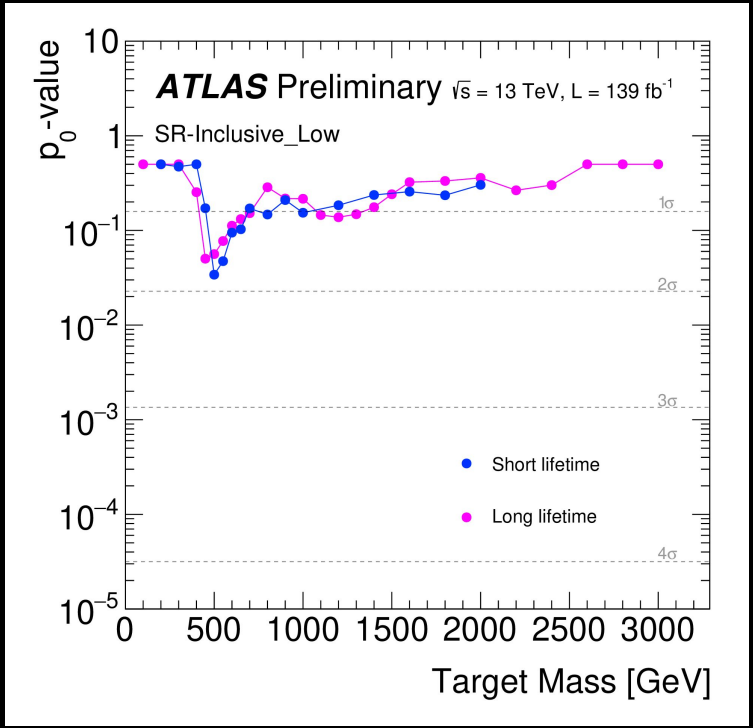


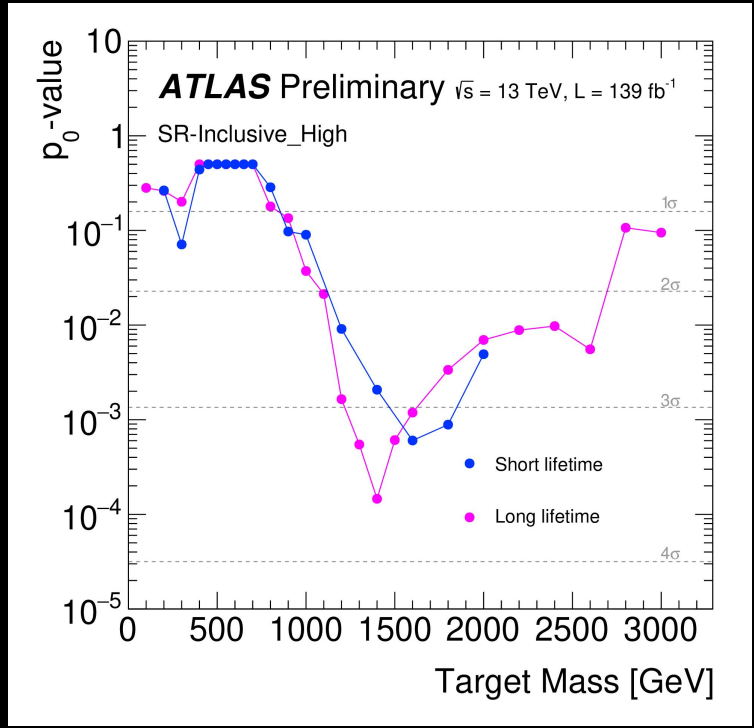
Heavy charged LLPs (SUSY-2018-42)



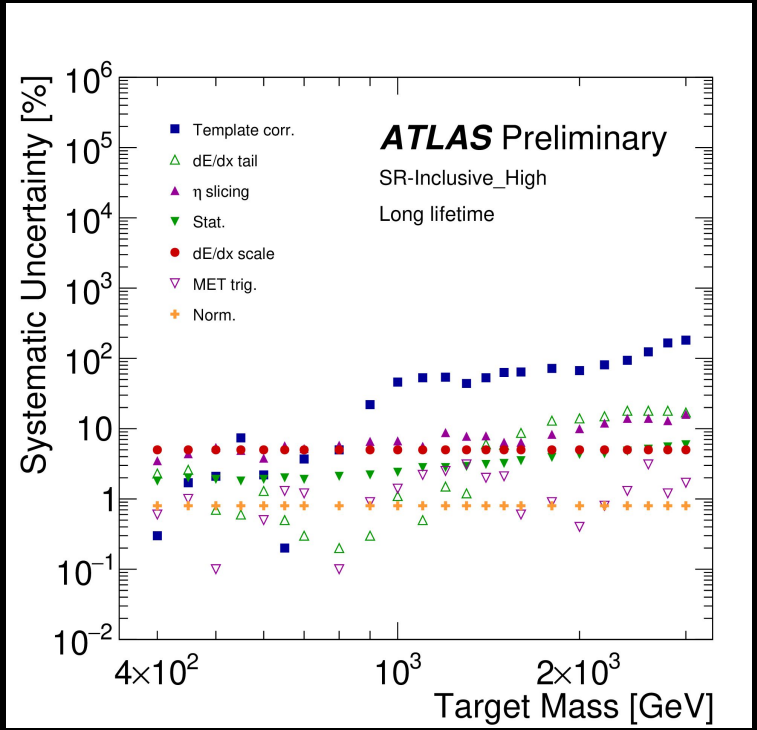


Heavy charged LLPs (SUSY-2018-42)





Heavy charged LLPs (SUSY-2018-42)



Heavy charged LLPs (SUSY-2018-42)