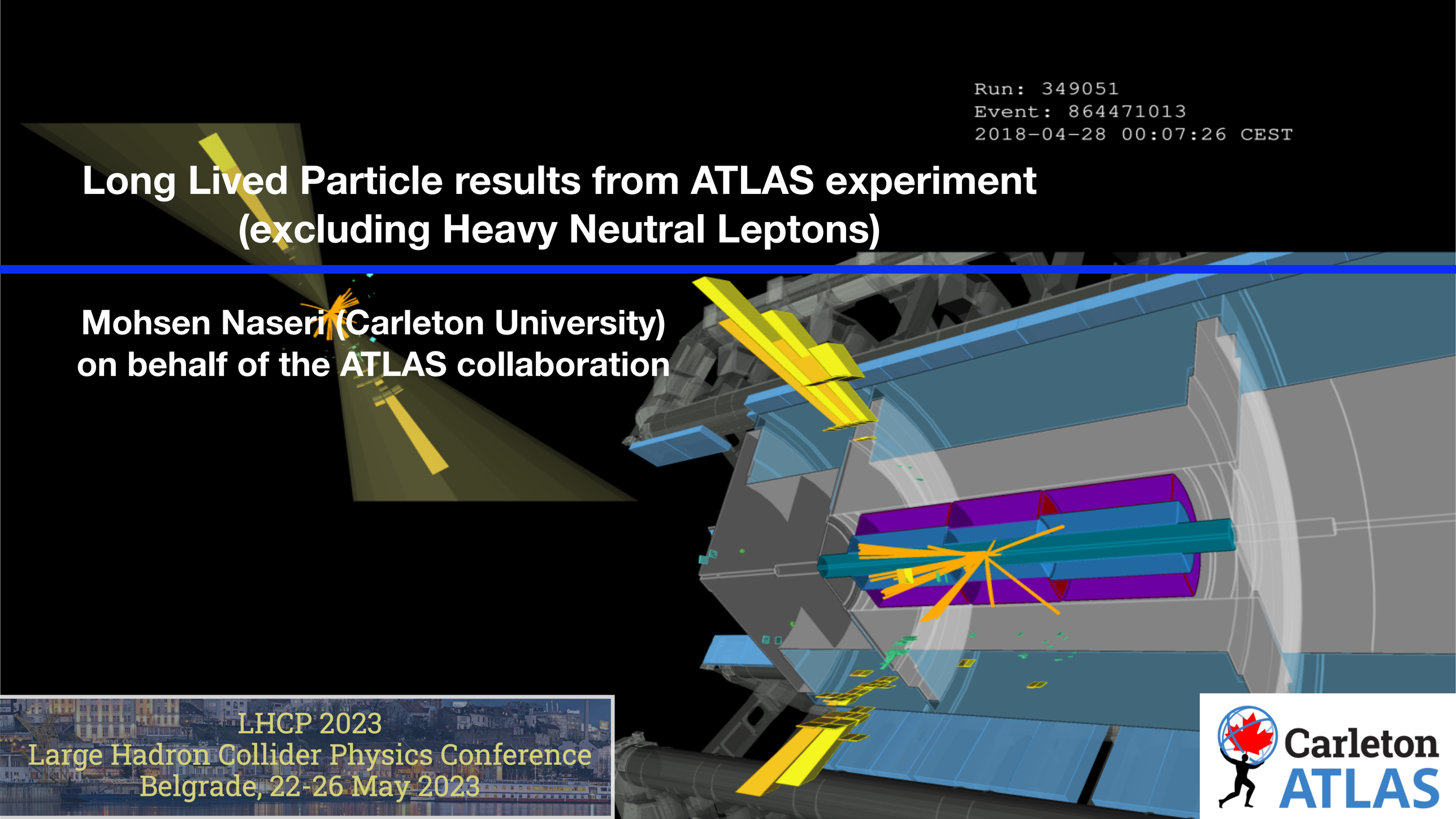


Long Lived Particle results from ATLAS experiment (excluding Heavy Neutral Leptons)

Mohsen Naseri (Carleton University)
on behalf of the ATLAS collaboration

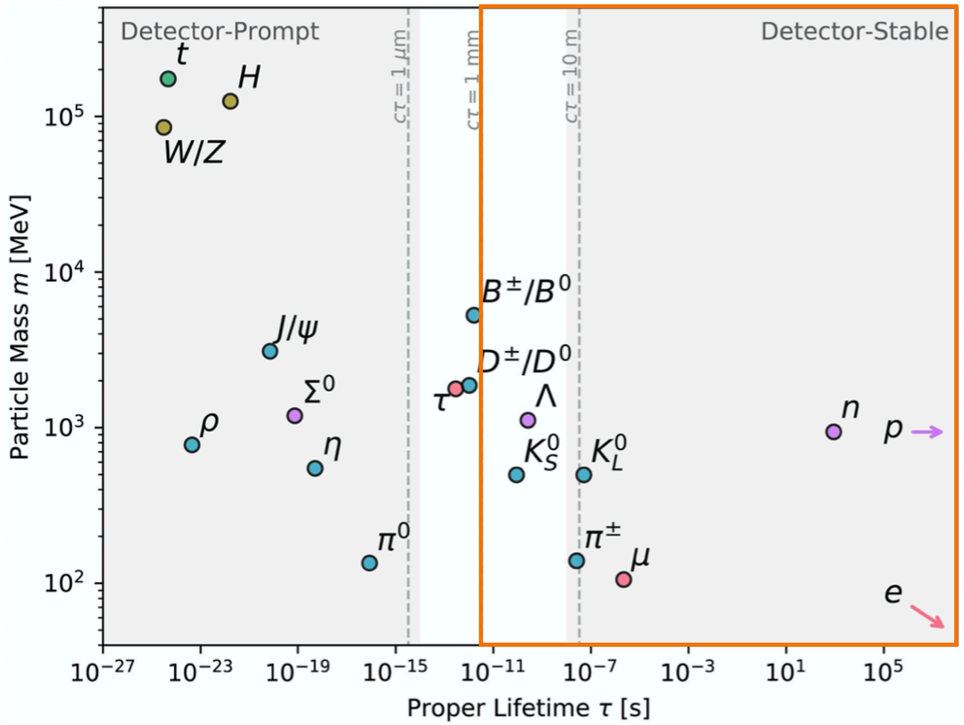
LHCP 2023
Large Hadron Collider Physics Conference
Belgrade, 22-26 May 2023

Carleton ATLAS

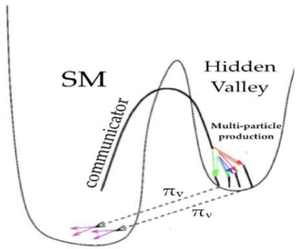
INTRODUCTION

- We know BSM extensions are needed to account for unexplained phenomena, in particular **dark matter**
- Many of the BSM models (e.g. SUSY) produce invisible particles → large missing energy!
  - no such missing energy signatures have been observed
- Another possibility is that BSM particles produced at LHC are moderately long lived, **LLP**
  - no or only little missing energy expected - compatible with observation
  - more challenging final states - wide range of compelling models exists

Many SM particles are long-lived!

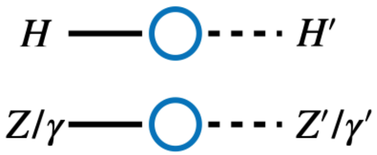


Hidden Valleys

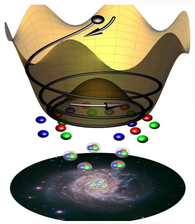


SUSY

Portal models



Axion-like particles



THEORETICAL MOTIVATION

Long-lived particles with macroscopic lifetime(even in SM) can arise when:

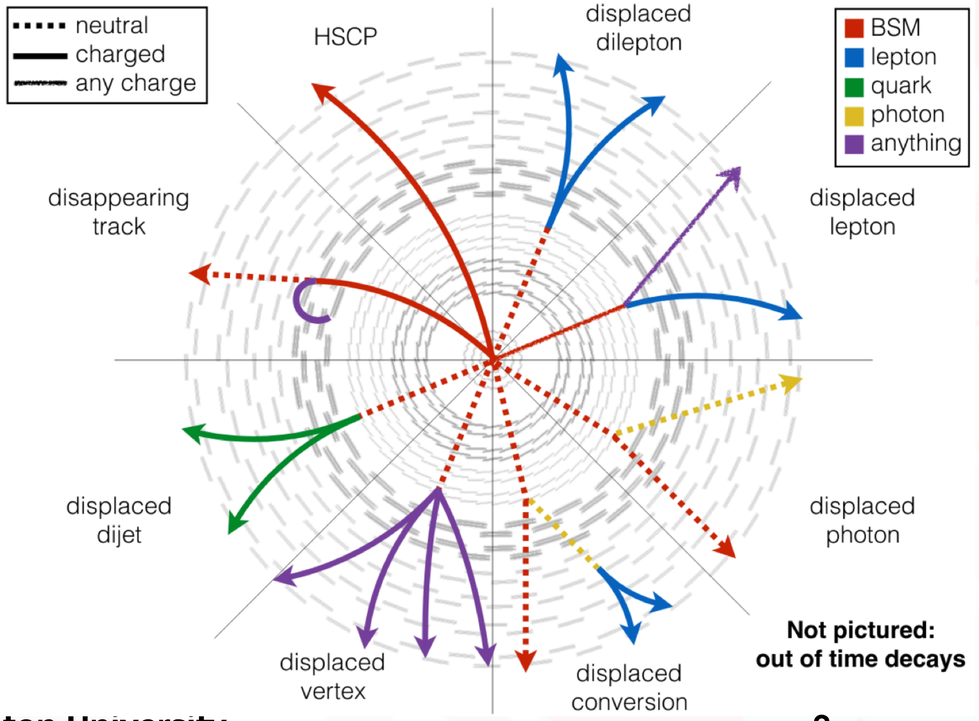
- small phase space (suppression, small mass-splitting)
- small couplings
- small matrix element (off-shell mediator)

$$\frac{1}{\tau} = \Gamma \propto g^2 |\mathscr{M}|^2 \Phi$$

Searches for long-lived particles are signature driven → depends on mass, charge, and decay position in detector

- multiple search scenarios are possible:
  - they can decay to quarks, gluons, leptons, invisible particles leaving missing energy

Graphic credit: J. Antonelli



LLP signatures are experimentally challenging:

- MC simulations may not accurately model backgrounds
- require innovative and dedicated trigger algorithms
- custom reconstruction
- ML tools for background elimination
- fully data-driven background estimation techniques

LLP SEARCHES @ ATLAS EXPERIMENT

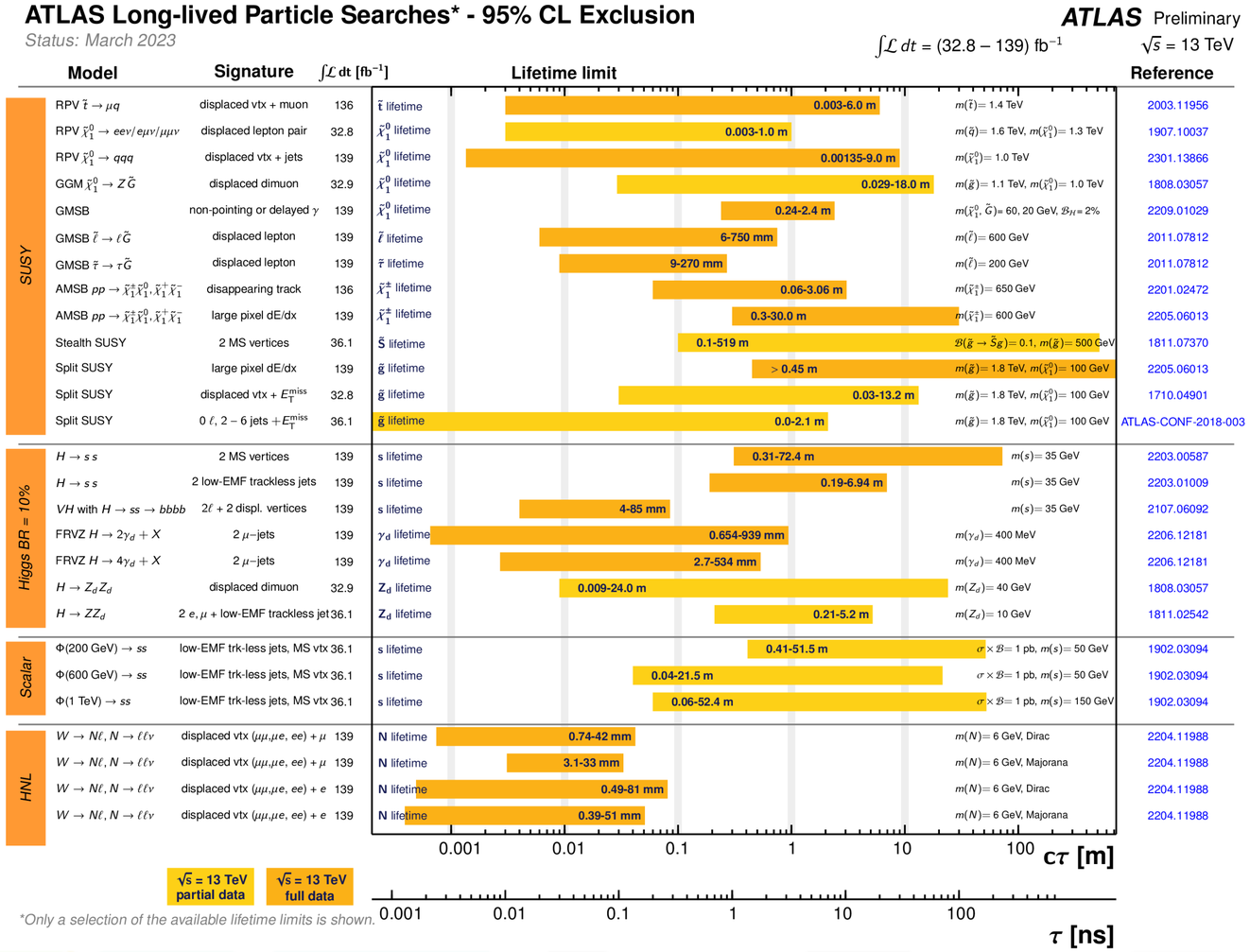
Specific theories can suggest new signatures to explore:

- ability to re-interpret results in a different model to ensure full exploration

A lot of searches in this sector!

- in the following few examples based on signatures.
- all results use full Run-2 dataset: 139 fb^{-1} at $\sqrt{s}$ = 13 TeV

ATLAS Search	Signature	arXiv	Paper release
Multicharge particles	Track with large dE/dx	arXiv:2303.13613	23 March 2023
Heavy charged particles	Track with large dE/dx	arXiv:2205.06013	12 May 2022
Displaced photonics vertex	Di-photon or di-e DV + MET	arXiv:2304.12885	25 April 2023
Displaced photons	1, >= 2 photon + lepton + MET	arXiv:2209.01029	2 Sep. 2022
Displaced Hadronic vertices	DV + jets	arXiv:2301.13866	1 Feb 2023



The summary plots are not up to date, but do show nicely the breadth of the searches and their reach

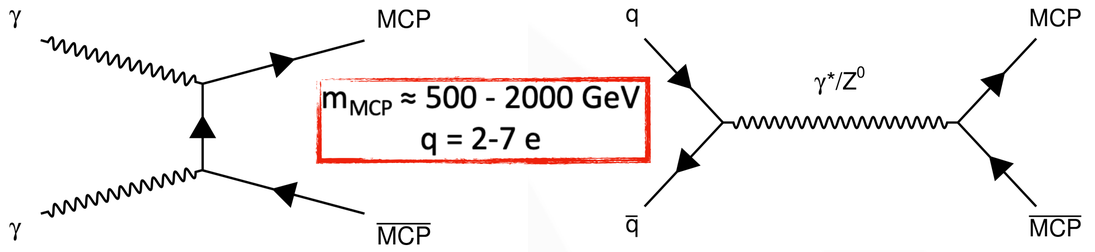
MULTI-CHARGED PARTICLES (MCPs)

arXiv:2303.13613

Many theories predict multi-charge particles

Benchmark model: MCP produced in pairs via Drell-Yan or photon-fusion mode

Motivation: multi-charged particles deposit more energy in trackers than SM particle

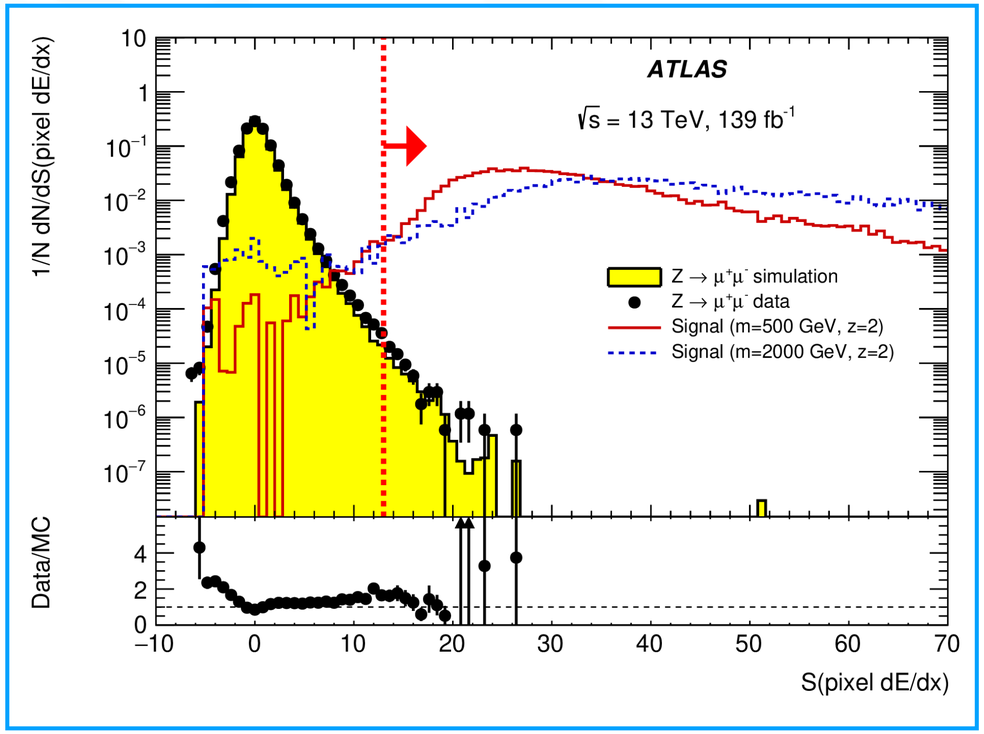


$$\frac{\mathrm{d}E}{\mathrm{d}x} \propto \frac{z^2}{\beta^2}$$

$\frac{\mathrm{d}E}{\mathrm{d}x}$: charge / e⁻; β^2: velocity

Signature: muon-like tracks with anomalously large dE/dx significance in the inner-tracking (Pixel/TRT) and muon (MDT) detectors and/or fraction of high-threshold TRT hits.

$$S(dE/dx) = \frac{dE/dx - \langle dE/dx \rangle_\mu}{\sigma(dE/dx)_\mu}$$



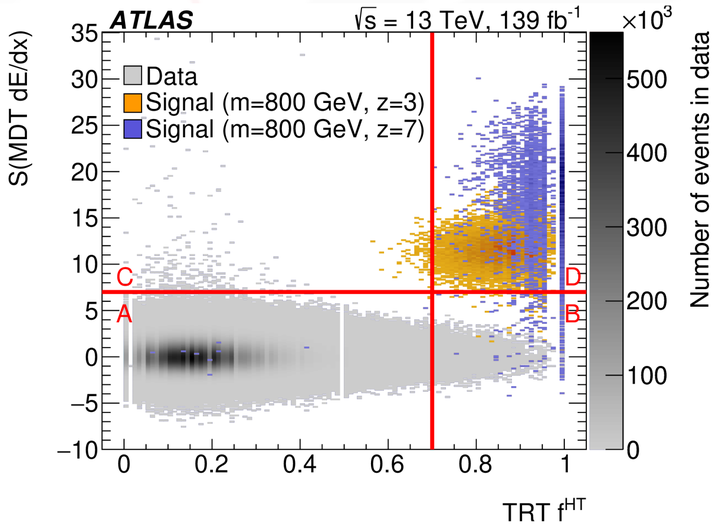
Strategy:

- trigger on prompt muons (β > 0.65), missing energy, and late muons (0.4 < β < 0.8)
- at least one muon reconstructed in both the tracker and the muon spectrometer

MULTI-CHARGED PARTICLES (MCPs)

arXiv:2303.13613

Background: instrumental effects and δ-rays, estimated using data driven ABCD method



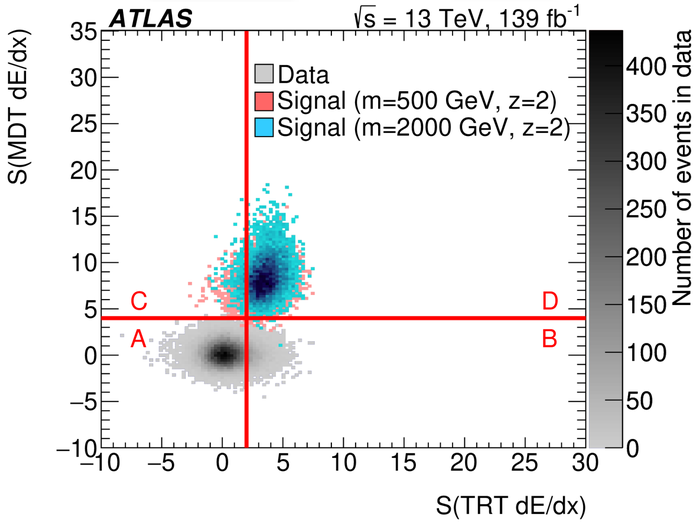
ABCD parameters

q = 2e

1. S > 13 σ in Pixel
2. S > 2 σ in TRT
3. S > 4 σ in MDT

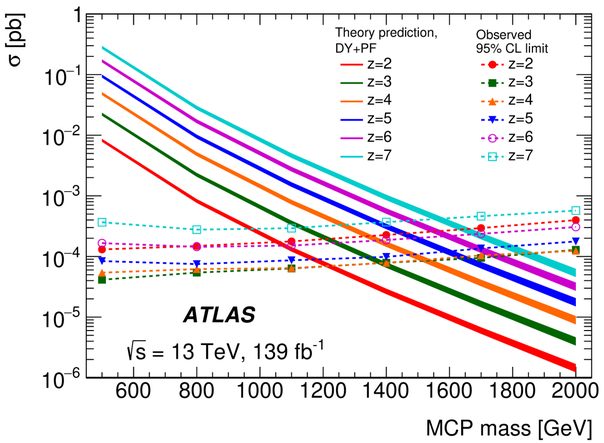
q = [3, 7] e

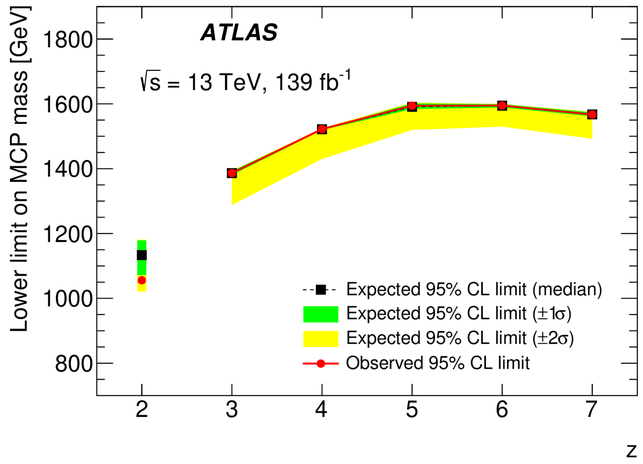
1. Saturated TRT signal (70%)
2. S > 7 σ in MDT



No excess observed → exclusion limits on σ vs m_{MCP} and Z_{MCP}: $m_{MCP} > 1.05$ TeV (z=2) and $m_{MCP} > 1.57$ TeV (z=7)

Search category	$N^{A\ observed}_{data}$	$N^{B\ observed}_{data}$	$N^{C\ observed}_{data}$	$N^{D\ expected}_{data}$	$N^{D\ observed}_{data}$
$z = 2$	41 674	5024	13	1.6 ± 0.4 (stat.) ± 0.5 (syst.)	4
$z > 2$	192 036 934	15 004	441	0.034 ± 0.002 (stat.) ± 0.004 (syst.)	0





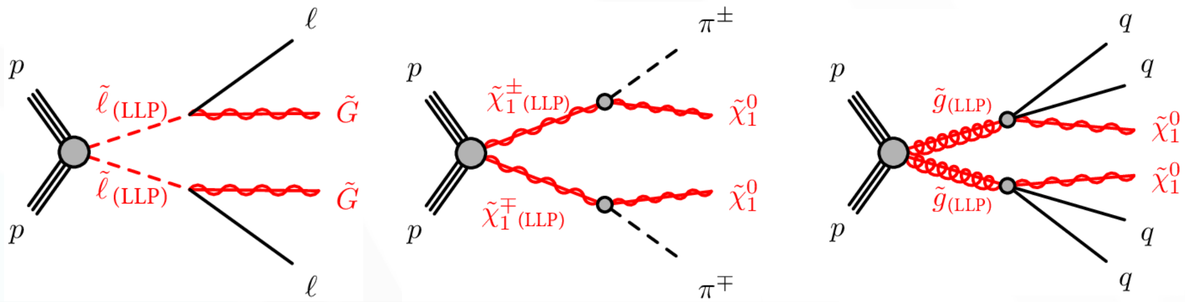
CHARGED LLPs WITH LARGE IONIZATION LOSS

Motivation: slow, massive charged particles deposit more energy in trackers than SM particles

Signature: missing energy and well-isolated track or muon with large p_T and with large dE/dx

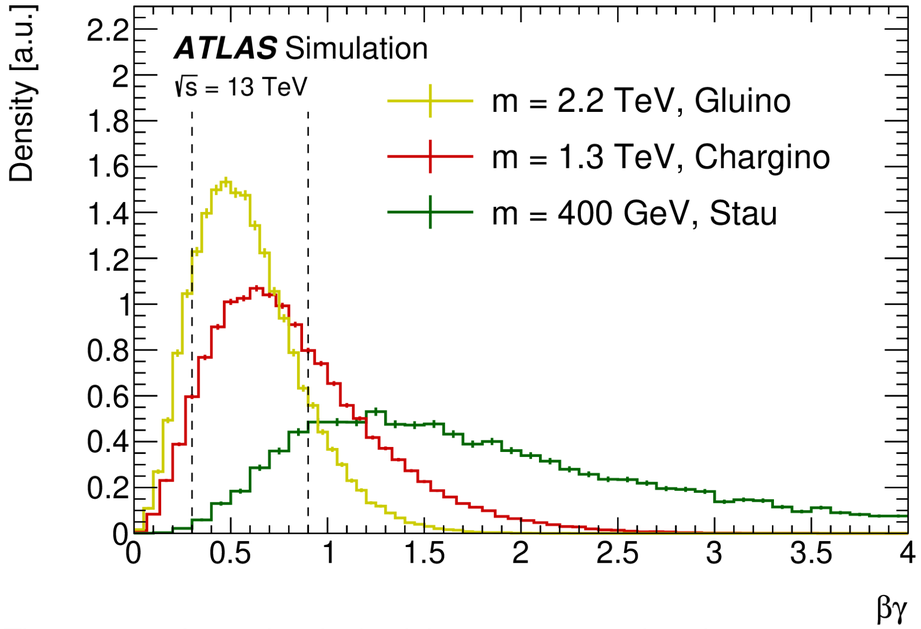
arXiv:2205.06013

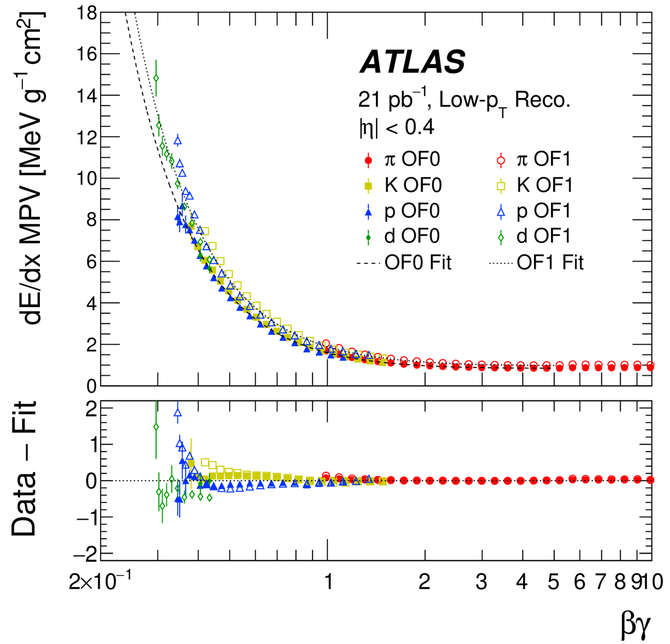
SUSY benchmark models



Measure <dE/dx> in pixel tracker ⟶ Convert to $\beta\gamma$ using Bethe-Bloch relation ⟶ Calculate mass = p / $\beta\gamma$

Strategy: select events with E_T^{Miss}> 170 GeV, track with p_T > 120 GeV and dE/dx > 1.8 MeV g^{-1} cm^2





The ranges shown by dashed lines correspond to the acceptance of the search from the dE/dx

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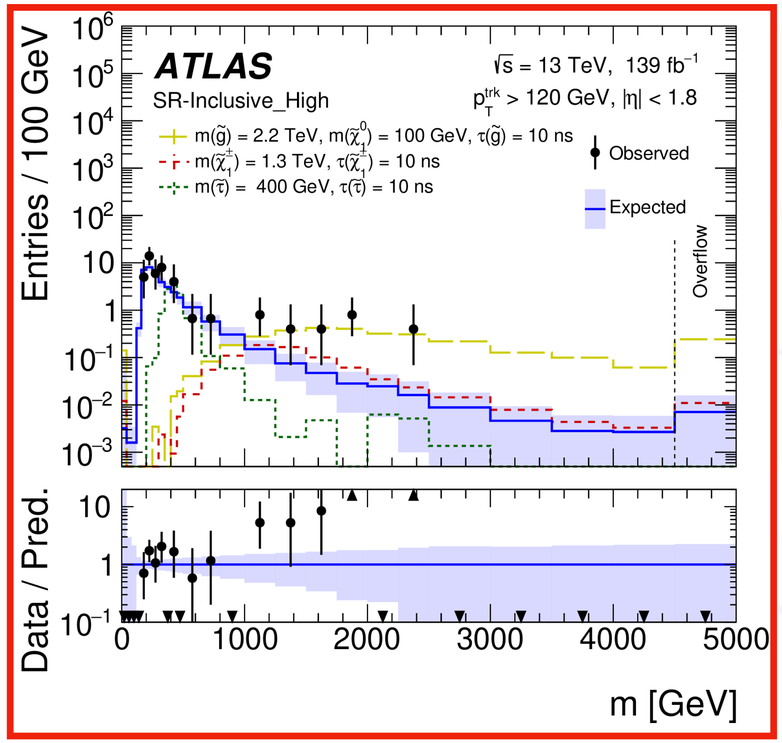
CHARGED LLPs WITH LARGE IONIZATION LOSS

Background: random large dE/dx from Landau tail, fully data-driven

- for most of the SR, the observed data agrees well with the predicted background.
  - significance of 3.6σ observed for a mass window [1.1, 2.8] TeV in high-dE/dx SR.
  - global significance: 3.3σ
    - no obvious pathologies were identified in the measurement of these events
      - cross-check with calorimeter/muon system find all tracks to have β consistent with 1.

arXiv:2205.06013



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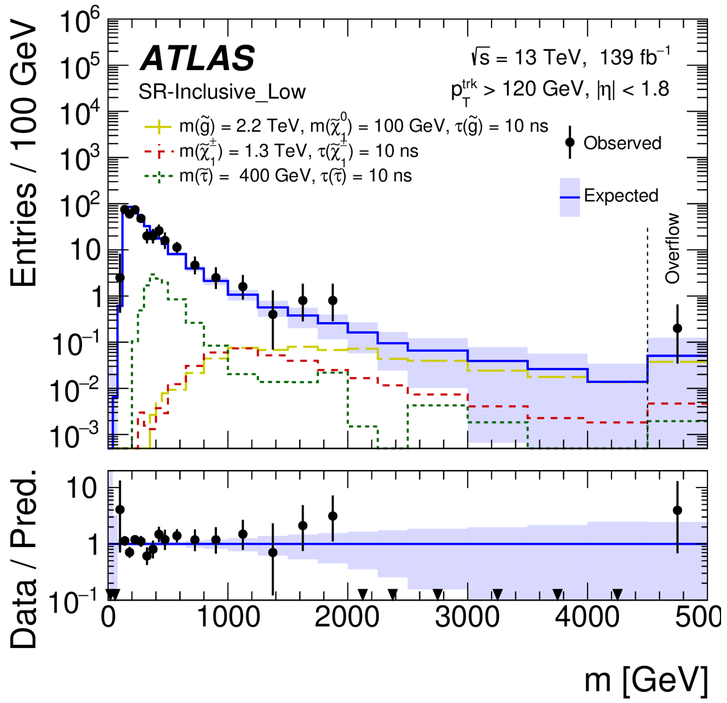
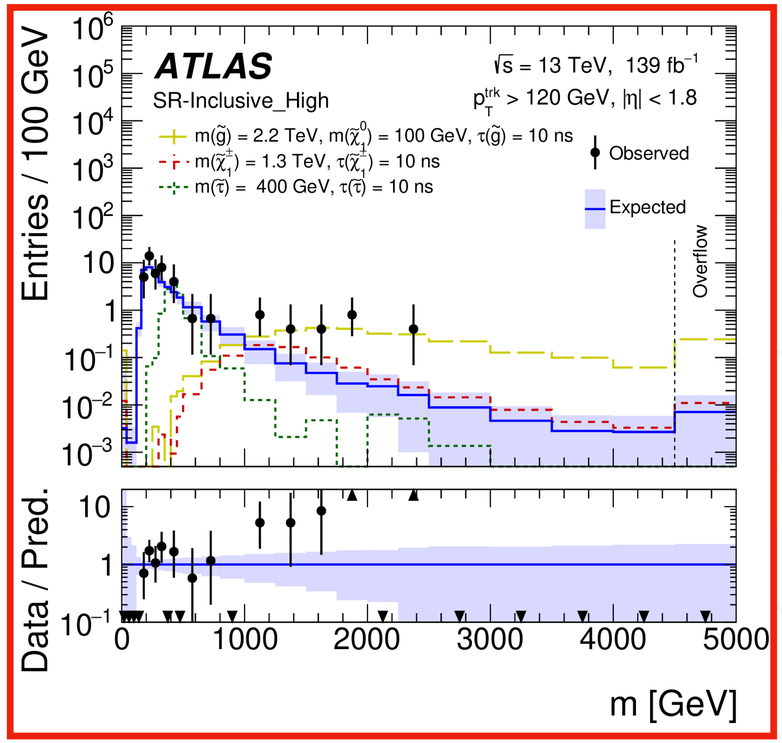
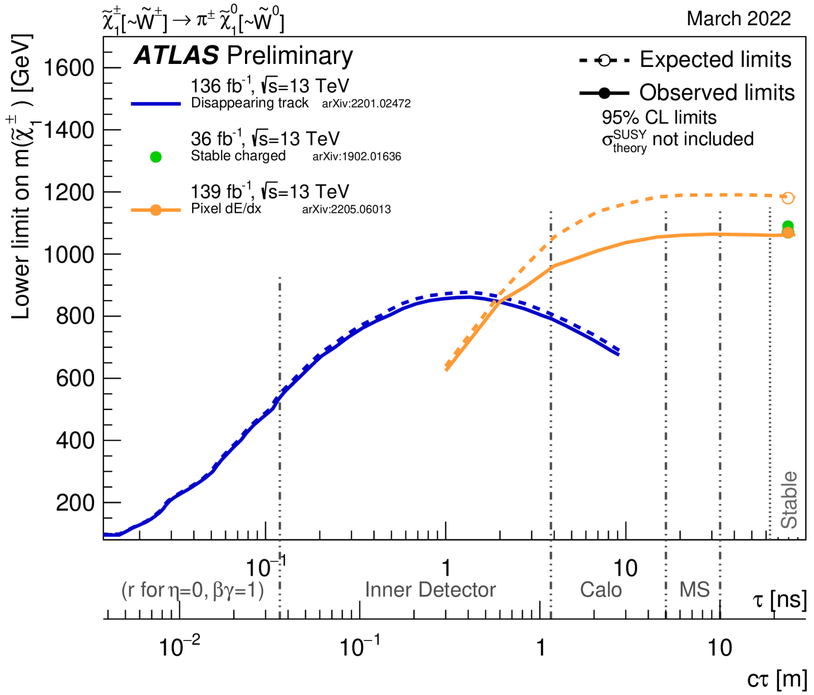






DISPLACED PHOTONS

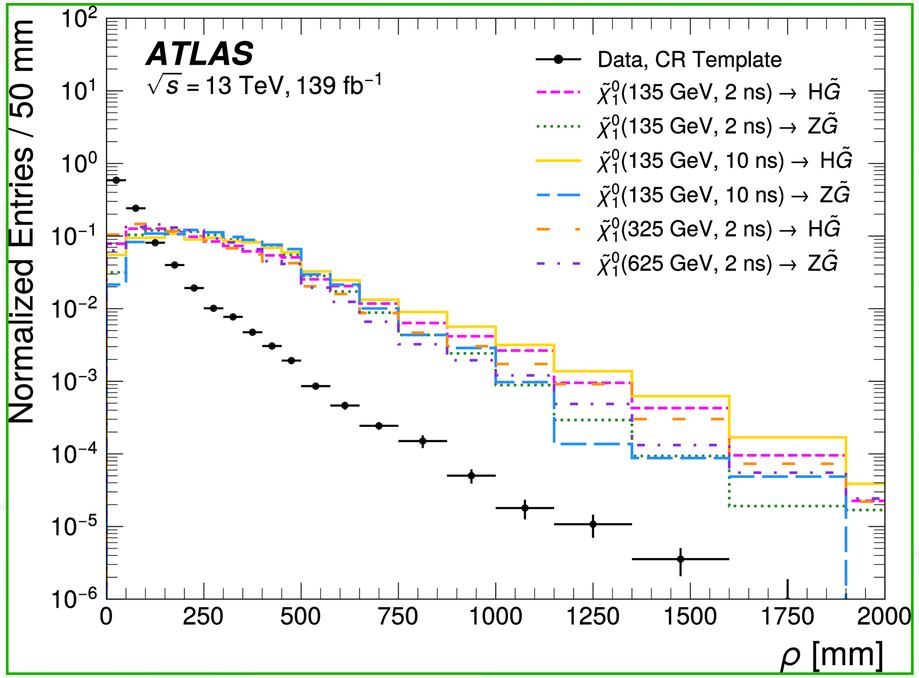
Non-prompt photons from BSM decays before EM Calo

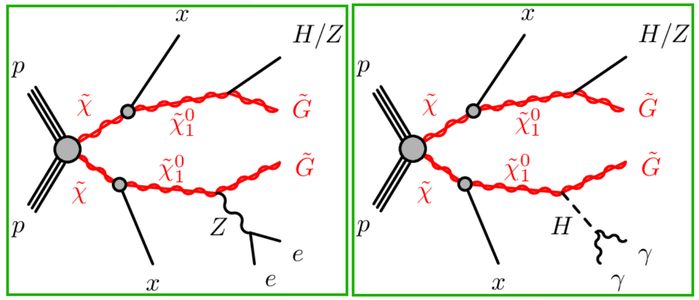
arXiv:2304.12885

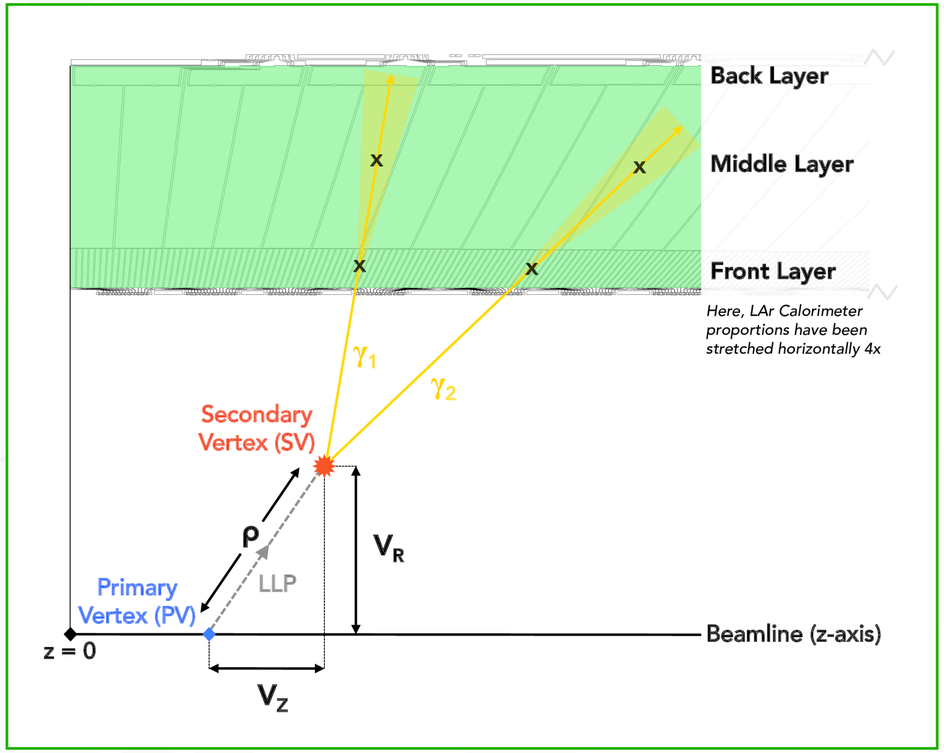
1. Photons from same decays

- LLP particles, originating displaced H→γγ or Z→ee decays
- two photons produced in decay of same LLP → Di-photon trigger
- trajectory based on shower shape
- signal region for high missing energy and at least 2 trigger matched photons
- exploit LAr arrival time (t_{avg}) as well as the mass and 2D position (ρ) of the displaced vertex → average timing in calo $t_{avg} = (t_{\gamma 1} + t_{\gamma 2})/2$

displacement $\rho = \sqrt{V_R^2 + V_Z^2}$







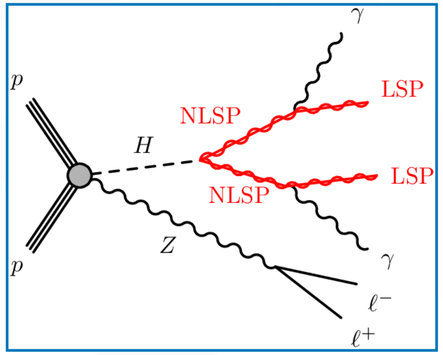
DISPLACED PHOTONS

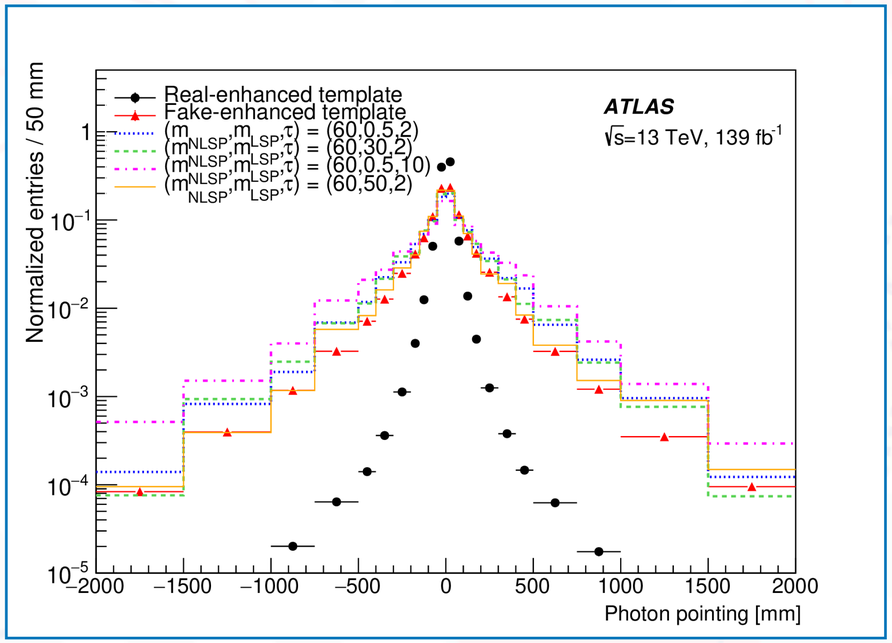
Non-prompt photons from BSM decays before EM Calo

arXiv:2209.01029

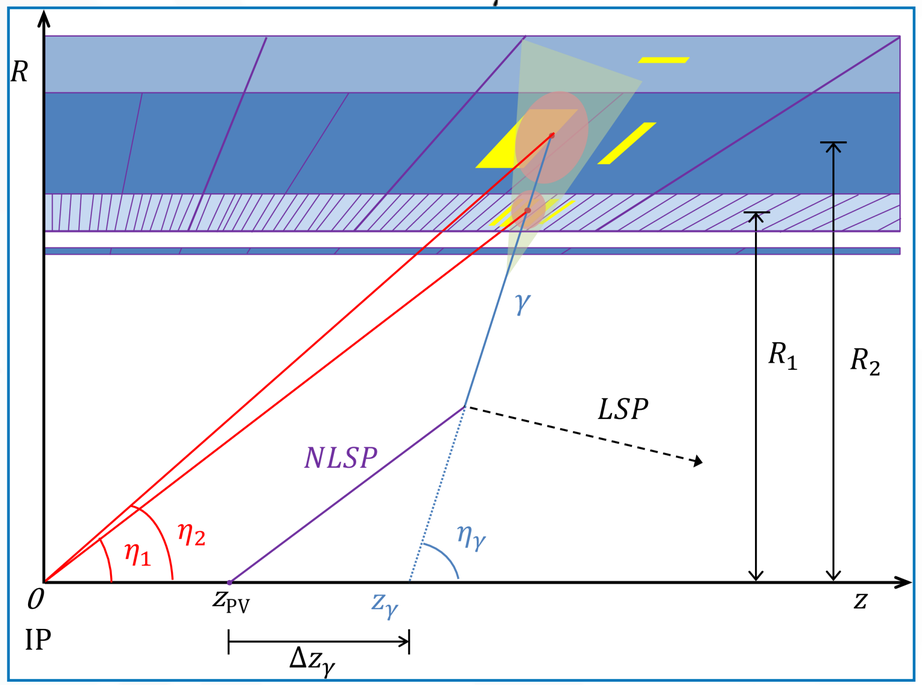
2. Photons from different decays

- two non pointing photons coming from different of LLPs in association with leptons
  - → per photon timing in calo tγ, single lepton trigger
- exploited EM calorimeter info for precise pointing and timing measurements
- signal region for 1 and ≥ 2 photons
- isolated photons, ≥1 lepton and high missing energy





pointing $\Delta z_\gamma = |z_\gamma - z_{PV}|$



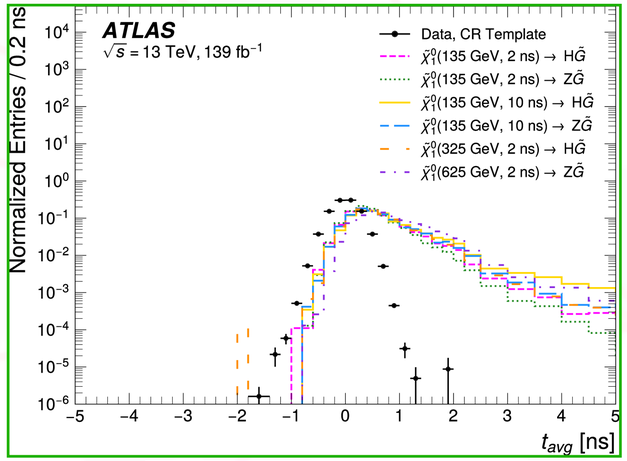
DISPLACED PHOTONS

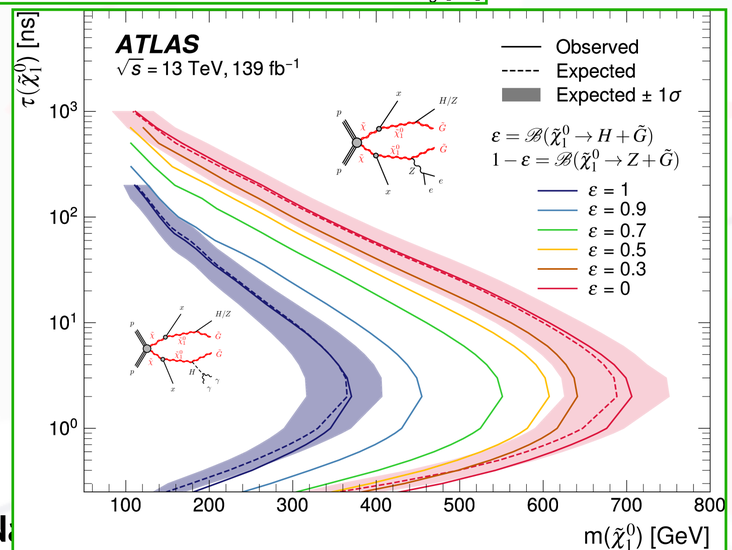
Background: - real prompt photons - fake photons (electrons or jets faking photons)

1. Photons from same decays

- likelihood fit over t_{avg} spectrum in non-overlapping bins of ρ,
- background estimated from t_{avg} templates from CR

arXiv:2304.12885



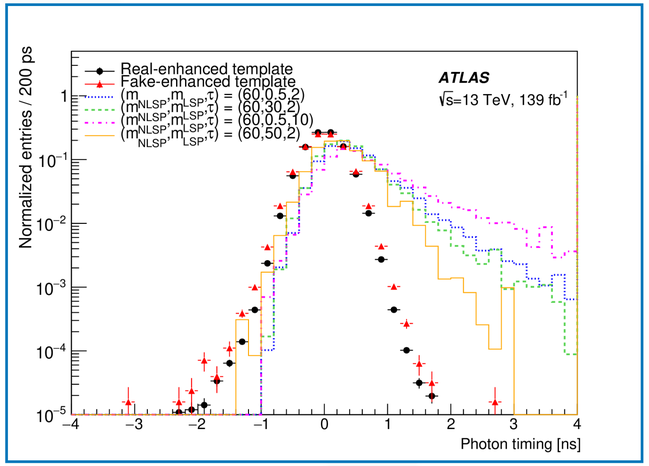


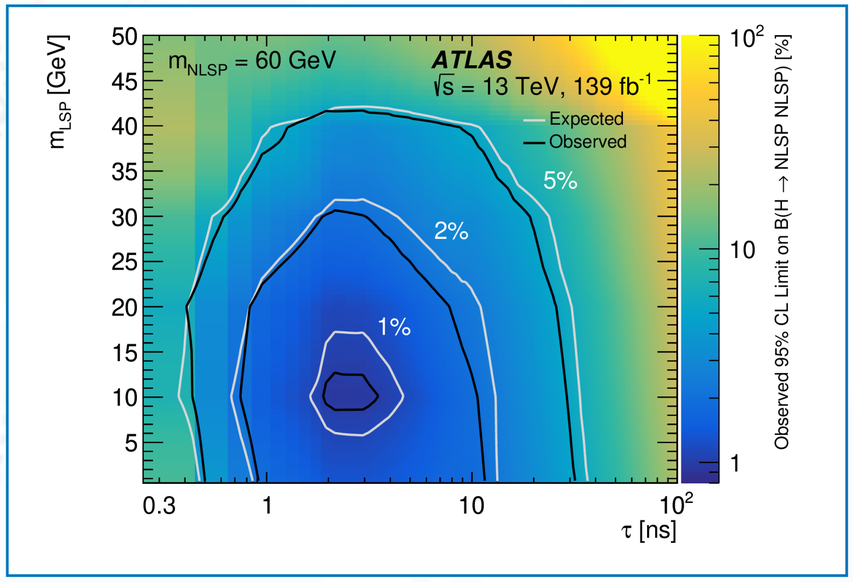
No excess observed and limits set as a function of mass

2. Photons from different decays

- likelihood fit performed over timing distribution in non-overlapping bins of |Δz |

arXiv:2209.01029





Carleton ATLAS

DISPLACED VERTEX + JETS

arXiv:2301.13866

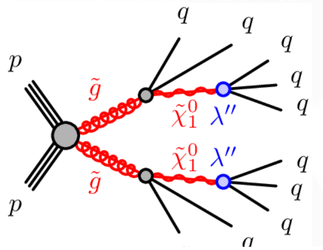
- search for massive LLPs decaying in the Inner Detector into hadrons
- benchmark models are SUSY scenarios:
  - neutralino decaying via small RPV coupling to three SM quarks
  - production via gluinos that each promptly decay to two SM quarks and neutralino

Signature: looking for an excess in multi-jet events with displaced vertices (large mass, multiple tracks)

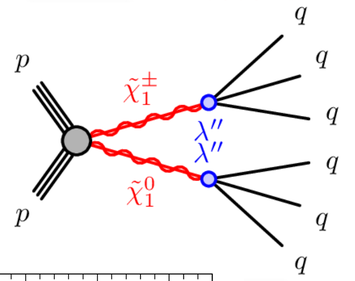
→ **displaced vertices (DVs) and multi-jets → jet triggers**

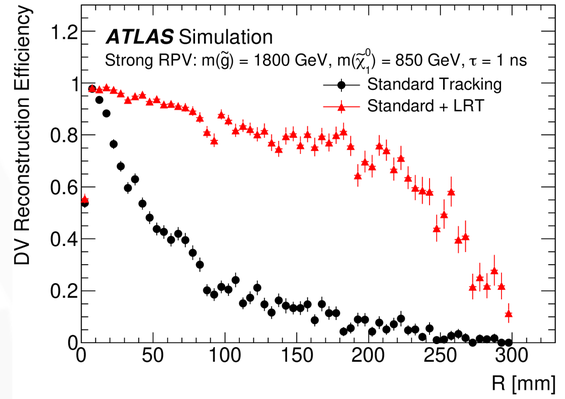
algorithm: Displaced Vertex reconstruction possible up to 300 mm (Large Radius Tracking) →

RPV STRONG SUSY



RPV EWK SUSY





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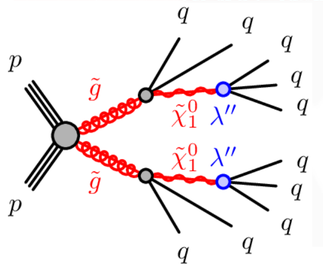

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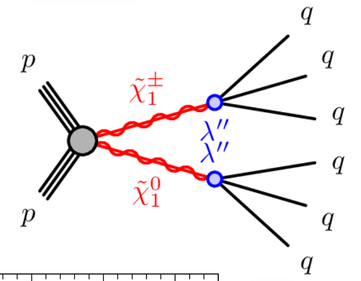
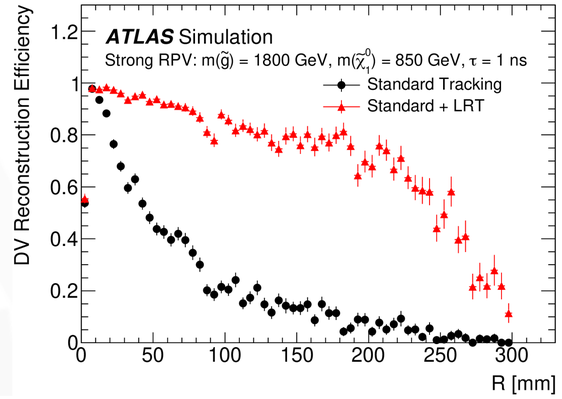


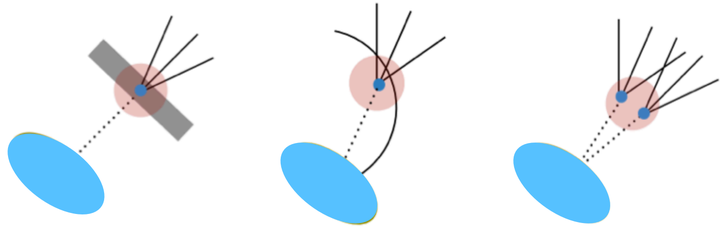


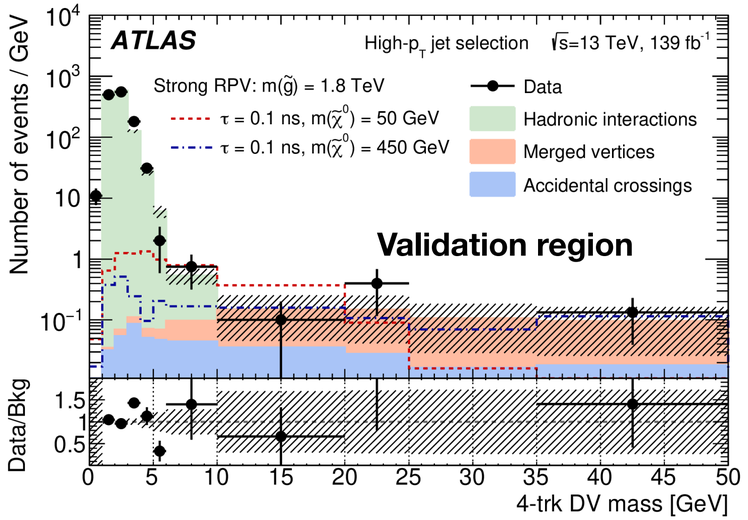
Strategy:

- ≥ 1 displaced vertex with high-mass (m_{DV} > 10 GeV) and high track multiplicity ($n_{Trk} \geq 5$)
- 2SRs targeting RPV EWK or RPV Strong SUSY
  - ≥ 4 - 7 high-p_T jets and trackless jets (p_T > 55 - 250 GeV)

Background sources:

- hadronic interactions with detector material
- accidental track-crossings
- merged vertices





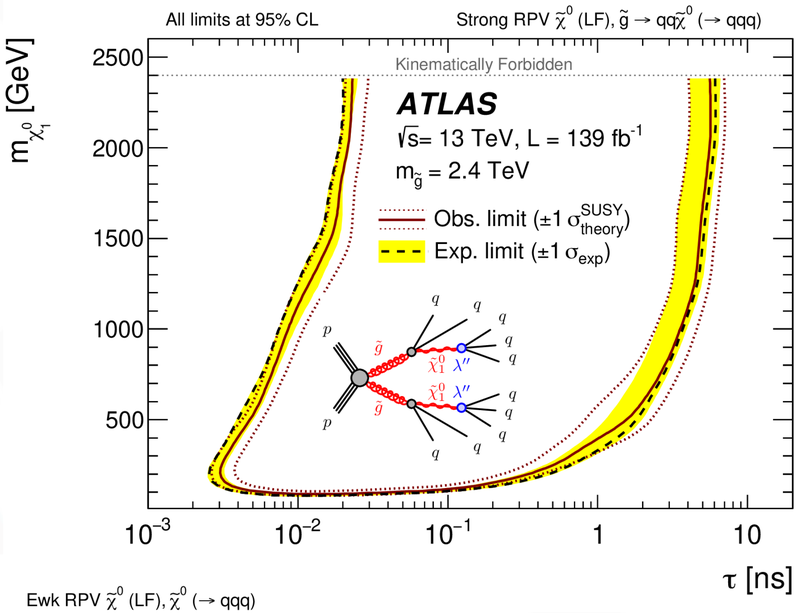
DISPLACED VERTEX + JETS

arXiv:2301.13866

Fully data driven background estimate, performed in two steps:

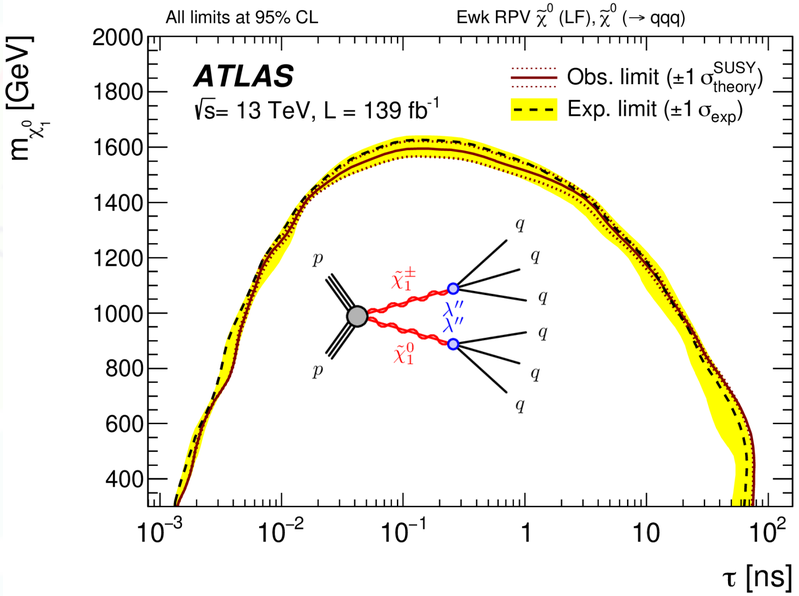
1. calculate probability of finding a SR-like DV produced in proximity to a jet using track jets in CRs
2. apply probability to track jets in events passing event-level SR selection
   - estimate nevents with a DV in the SR

$$p^{SR}_{\mathrm{DV-jet}} = p^{CR}_{\mathrm{DV}\leftrightarrow\mathrm{track-jet}} f^{CR\to SR}$$



- observed event yields consistent with the background-only hypothesis
  → limits are set on the SUSY benchmark models.

Signal Region	Expected	Observed
High-p_{T} jet SR	$0.46^{+0.27}_{-0.30}$	1
Trackless jet SR	$0.83^{+0.51}_{-0.53}$	0



- The pair-production of electroweakinos with masses below 1.5 TeV is excluded for mean proper lifetimes in the range from 0.03 ns to 1 ns.

SUMMARY AND CONCLUSION

- In the last few years, ATLAS have produced a large variety of searches for long-lived particles
- No obvious sign of new physics observed (yet)
- We have a very exciting LLP plan for Run-3

ATLAS Search	Signature	arXiv	Paper release
Multicharge particles	Track with large dE/dx	arXiv:2303.13613	23 March 2023
Heavy charged particles	Track with large dE/dx	arXiv:2205.06013	12 May 2022
Displaced photonics vertex	Di-photon or di-e DV + MET	arXiv:2304.12885	25 April 2023
Displaced photons	1, >= 2 photon + lepton + MET	arXiv:2209.01029	2 Sep. 2022
Displaced Hadronic vertices	DV + jets	arXiv:2301.13866	1 Feb 2023

Run3 is here!

- More statistics for rare decays
- Lots of exciting developments that will enhance the discovery potential of the Run 3 dataset:
  - many dedicated LLP triggers
  - ability to reconstruct displaced tracks for all the events recorded
  - ..
  - .
- Already 36 fb^{-1} of 13.6 TeV data collected

Looking forward to new results with run 3!

BACKUP

MULTI-CHARGED PARTICLES (MCPs)

arXiv:2303.13613

Search category	Preselection	Tight selection	Final selection
$z = 2$	Combined muon with: 'medium' identification criteria, $p_{\mathrm{T}}^{\mu}/z > 50\,\mathrm{GeV}$, $p_{\mathrm{T}}/z > 10\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.0$, no other particles with $p_{\mathrm{T}}/z > 0.5\,\mathrm{GeV}$ within $\Delta R = 0.01$	Preselected candidate with $S(\text{pixel } dE/dx) > 13$	Tightly selected candidate with: $S(\text{TRT } dE/dx) > 2$, $S(\text{MDT } dE/dx) > 4$
$z > 2$		–	Preselected candidate with: TRT $f^{\text{HT}} > 0.7$, $S(\text{MDT } dE/dx) > 7$

CHARGED LLPs WITH LARGE IONIZATION LOSS

arXiv:2205.06013

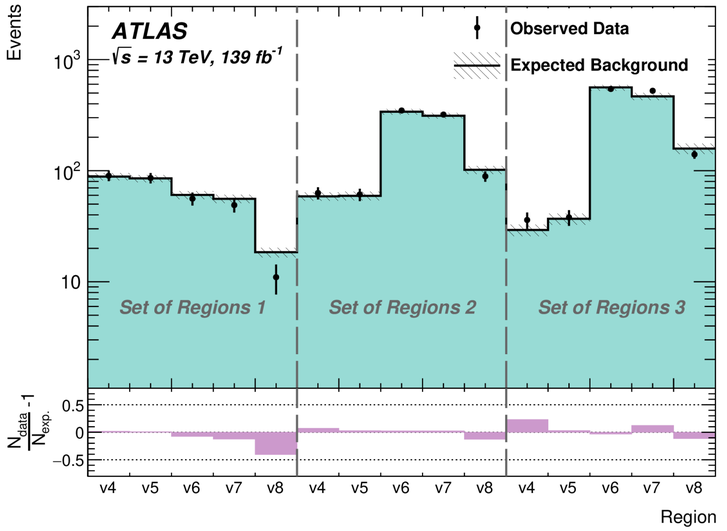
Category	Item	Description
Event topology	Trigger	Unprescaled lowest-threshold $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
	$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 170$ GeV
	Primary vertex	The hard-scatter vertex must have at least two tracks
Events are required to have at least one track fulfilling *all* criteria listed below; tracks sorted in p_{T} descending order		
Track kinematics	Momentum	$p_{\mathrm{T}} > 120$ GeV
	Pseudorapidity	$\lvert\eta\rvert < 1.8$
	$W^{\pm} \to \ell^{\pm}\nu$ veto	$m_{\mathrm{T}}(\mathrm{track}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}) > 130$ GeV
Track quality	Impact parameters	Track matched to the hard-scatter vertex; $\lvert d_0\rvert < 2$ mm and $\lvert\Delta z_0 \sin\theta\rvert < 3$ mm
	Rel. momentum resolution	$\sigma_p < \max\left(10\%, -1\% + 90\% \times \frac{\lvert p\rvert}{\mathrm{TeV}}\right)$ and $\sigma_p < 200\%$
	Cluster requirement (1)	At least two clusters used for the $\langle \mathrm{d}E/\mathrm{d}x\rangle_{\mathrm{trunc}}$ calculation
	Cluster requirement (2)	Must have a cluster in the IBL (if this is expected), or a cluster in the next-to-innermost pixel layer (if this is expected while a cluster is not expected in IBL)
	Cluster requirement (3)	No shared pixel clusters and no split pixel clusters
	Cluster requirement (4)	Number of SCT clusters > 5
Vetoes	Isolation	$\left(\sum_{\mathrm{trk}} p_{\mathrm{T}}\right) < 5$ GeV (cone size $\Delta R = 0.3$)
	Electron veto	EM fraction < 0.95
	Hadron and τ-lepton veto	$E_{\mathrm{jet}}/p_{\mathrm{track}} < 1$
	Muon requirement	`SR-Mu`: MS track matched to ID track; `SR-Trk`: otherwise
Pixel $\mathrm{d}E/\mathrm{d}x$	`Inclusive`	`Low`: $\mathrm{d}E/\mathrm{d}x \in [1.8, 2.4]$ MeV g^{-1}cm^2 `High`: $\mathrm{d}E/\mathrm{d}x > 2.4$ MeV g^{-1}cm^2
	Binned	`IBL0_Low`: $\mathrm{d}E/\mathrm{d}x \in [1.8, 2.4]$ MeV g^{-1}cm^2 and $\mathrm{OF}_{\mathrm{IBL}} = 0$ `IBL0_High`: $\mathrm{d}E/\mathrm{d}x > 2.4$ MeV g^{-1}cm^2 and $\mathrm{OF}_{\mathrm{IBL}} = 0$ `IBL1`: $\mathrm{d}E/\mathrm{d}x > 1.8$ MeV g^{-1}cm^2 and $\mathrm{OF}_{\mathrm{IBL}} = 1$

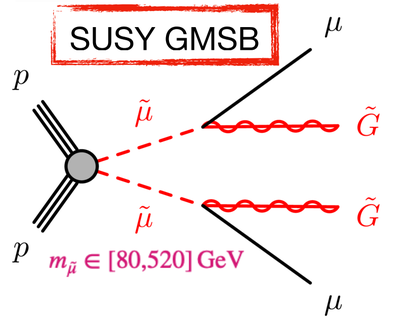
MUON PAIRS WITH SMALL DISPLACEMENTS

arXiv:2305.02005

Signature: LLPs decaying slightly displaced in the Inner Detector (ID) with a lifetime of $O(1 - 10\ ps)$, filling a gap between prompt and displaced searches:

- a pair of opposite-charged muons
- large impact parameter



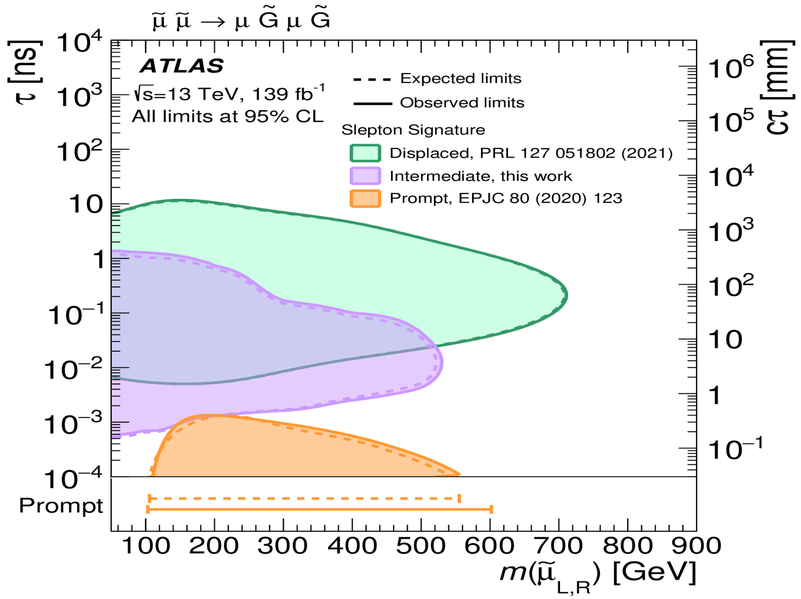


Set of Regions	Lower displacement region	Higher displacement region	Threshold $m_{\mu^+\mu^-}$	Additional cut
1	$0.1 \leq \lvert d_0 \rvert < 0.3$	$0.6 \leq \lvert d_0 \rvert < 3$ mm	200 GeV	-
2	$0.1 \leq \lvert d_0 \rvert < 0.3$	$0.6 \leq \lvert d_0 \rvert < 3$ mm	140 GeV	-
3	$0.1 \leq \lvert d_0 \rvert < 0.3$	$0.6 \leq \lvert d_0 \rvert < 1.3$ mm	125 GeV	$\Delta R_{\mu^+\mu^-} > 3$ rad.

Background: B-hadron decays

→ ABCD data driven method using dμ+ and dμ– impact parameters as discriminating variables

- no excess observed over expected background in the SRs
- smuon mass up to 520 GeV and lifetime down to 1 ps excluded at 95% confidence interval
- a model-dependent 2D exclusion limit for GMSB SUSY is extracted
  - bridges a gap between the displaced leptons and prompt analyses



DISPLACED VERTEX + JETS

arXiv:2301.13866

Signal Region	High-p_{T} jet SR	Trackless jet SR
Jet selection	$n_{\mathrm{jet}}^{250} \geq 4$ or $n_{\mathrm{jet}}^{195} \geq 5$ or $n_{\mathrm{jet}}^{116} \geq 6$ or $n_{\mathrm{jet}}^{90} \geq 7$	Fail High-p_{T} jet selection, $n_{\mathrm{jet}}^{137} \geq 4$ or $n_{\mathrm{jet}}^{101} \geq 5$ or $n_{\mathrm{jet}}^{83} \geq 6$ or $n_{\mathrm{jet}}^{55} \geq 7$, $n_{\text{Trackless jet}}^{70} \geq 1$ or $n_{\text{Trackless jet}}^{50} \geq 2$
DV preselection	$R_{\mathrm{DV}} < 300$ mm, $\lvert z_{\mathrm{DV}}\rvert < 300$ mm, $\min(\lvert\vec{R}_{\mathrm{DV}} - \vec{R}_{\mathrm{CV}}\rvert) > 4$ mm, $\chi^2/n_{\mathrm{DoF}} < 5$, $n_{\text{Selected tracks}}^{\mathrm{DV}} \geq 2$, satisfy material map veto	
$n_{\mathrm{Tracks}}^{\mathrm{DV}}$	≥ 5	
m_{DV}	>10 GeV	

Carleton ATLAS