Search for heavy long-lived multi-charged particles in the full Run-II pp collision data at $\sqrt{s} = 13$ TeV using the ATLAS detector

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Introduction

- This is a search for long-lived highly ionizing heavy muon-like particles with high electric charges based on their ionization loss measurements in several ATLAS detectors using the full Run-II dataset;

- “Blue-sky” search, but some models in fact predict new particles with charges greater than one:

    - Almost Commutative geometry model (AC-leptons) https://arxiv.org/abs/hep-th/0509213
    - Walking technicolor model (techni-leptons) https://arxiv.org/abs/hep-ph/0405209
    - Left-right symmetric model (doubly charged *H*) https://inspirehep.net/record/89314/

- **Any observation of multi-charged particles (MCPs) would be a striking evidence of physics beyond the Standard Model**;

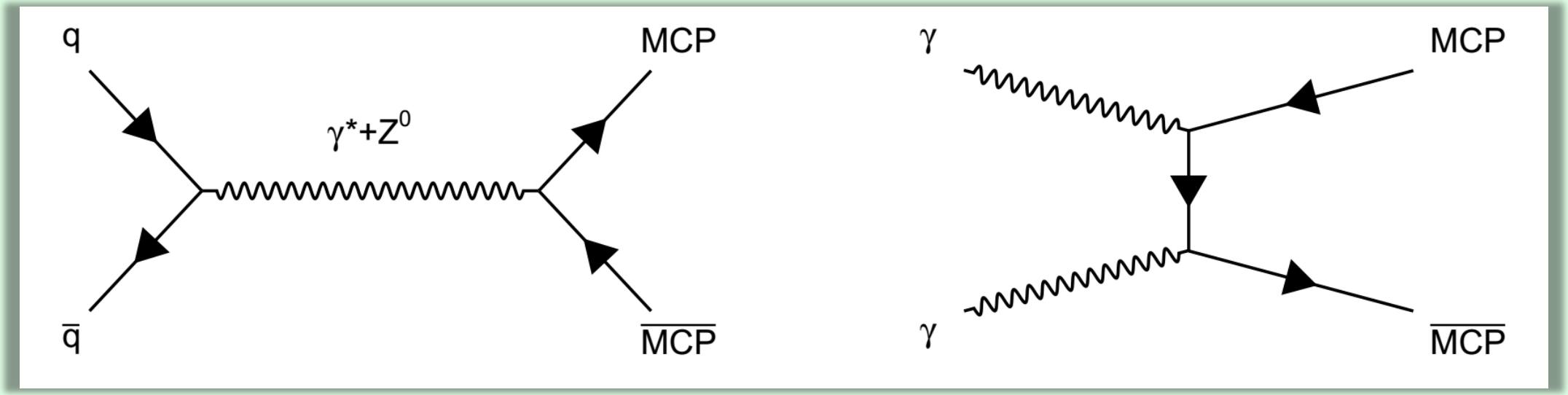
- Signal MC samples: particle pairs with masses of $500, 800, \ldots, 2000$ GeV and charges $z = {}^{|q|}/_{e} = 2, 3, \ldots$, and 7 produced via the Drell-Yan (DY) and photon-fusion (PF) mechanisms;

- CONF note: https://cds.cern.ch/record/2810156
- Plots and tables: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2022-034/

Production model

- DY and PF modes
- DY mode: exchange with both virtual Z^0 and γ^*

← only DY mode was used in previous MCP searches;
← exchange only with γ^* was used in previous MCP searches.



Derivation and trigger selections

- EXOT17 derivation keeps all events with at least one offline combined muon with $p_T > 50$ GeV;

- The trigger selection is an “OR” of the following unprescaled triggers:
  - single muon trigger ($p_T > 50$ GeV),
  - MET trigger ($E_T^{miss} > 70 - 110$ GeV),
  - “late-muon” trigger ($p_T > 10$ GeV) ← used for the MCP search for the first time

- Large E_T^{miss} originates from the ISR jets recoiling off of the MCP pair;

- The “late-muon” trigger (aka the “out-of-time muon trigger”):
  - fires in events with a $p_T > 50$ GeV jet in the current bunch crossing and a $p_T > 10$ GeV muon in the next one;
  - is unprescaled despite its low thresholds;
  - was brought into service in the C period of the 2017 data taking as one of the algorithms of the L1Topo trigger.

Preselection

- Selecting events with at least one combined muon with medium+ quality, $p_T^{\mu} > 50$ GeV (transverse momentum measured only by the MS, after the energy loss in the calorimeter), $p_T > 10$ GeV (transverse momentum measured by the combination of ID and MS, needed to reject fake muon tracks), $|\eta| < 2.0$ (TRT limitation), reliable dE/dx estimation in the MDT ($z = 2$ and $z > 2$), TRT ($z = 2$ and $z > 2$) and in the pixel ($z = 2$ only);

- Muon reconstruction has to provide the transverse momentum of a particle after it has lost its energy in the calorimeter → no `MuGirl` muons, no `MuGirlStau` algorithm;

- The corresponding ID-track segments should be isolated by at least $\Delta R = 0.01$ from other ID tracks to limit the background contribution from 2+ tracks firing the same TRT straws or MDTs.

Muons		ID tracks	
Variable	Value	Variable	Value
Type	combined	Quality	"LooseMuon" or higher
η, ϕ	$\|\eta\| < 2.0$ and not in BMG chambers	# TRT hits used for TRT dE/dx calculation	≥ 6
Transverse momentum	$p_{\mathrm{T}}^{\mathrm{MS}} > 50$ GeV and $p_{\mathrm{T}}^{\mathrm{ID+MS}} > 10$ GeV	Isolation	no other ID tracks within $\Delta R < 0.01$
Quality	"medium" or higher	# pixel hits used for pixel dE/dx calculation	≥ 2 ($z = 2$ case only)
Author	any but `MuGirl`	# pixel hits shared between at least two tracks	none ($z = 2$ case only)

dE/dx and dE/dx significance

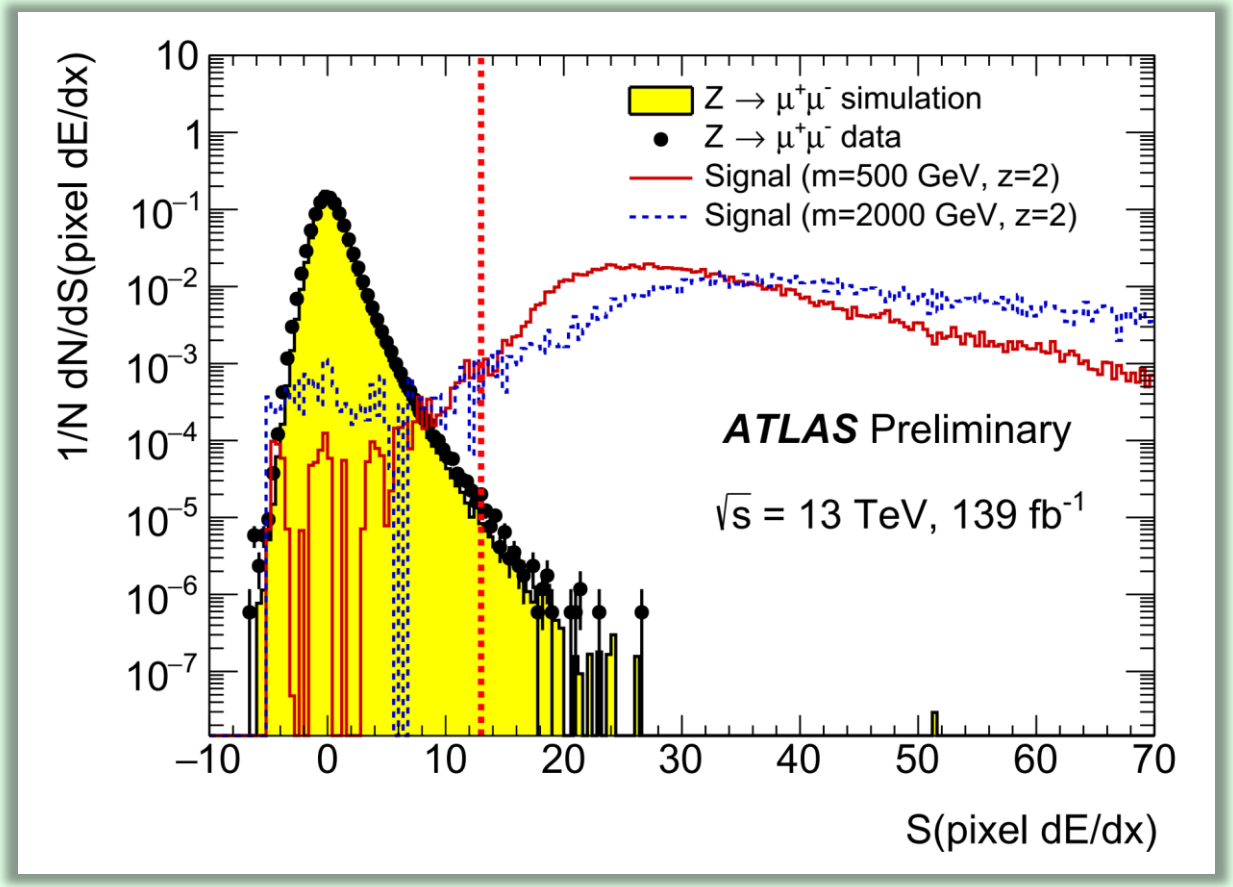
- **pixel dE/dx** is based on measurements of an output-signal width from the discriminator of every pixel;
- **TRT dE/dx** is based on measurements of a signal width exceeding the lower threshold (0.3 keV) divided by track-segment length in TRT;
- **TRT f^{HT}** is a fraction of high-threshold hits (with signal amplitude of at least 6 keV) on a track segment in TRT;
- **MDT dE/dx** is based on measurements of a time interval when the signal amplitude from the amplifier/shaper/discriminator exceeds a certain threshold within the first 18.5 ns of that signal;

- "Raw" dE/dx variables from different subdetectors have their own arbitrary units so we define "significance" as a difference between the observed dE/dx of a particle and the one expected from muons from $Z \to \mu^+\mu^-$ decays **in data** measured in units of the uncertainty of the measurement:

$$\text{significance} = \frac{{dE}/{dx} - \mu_{dE/dx\ of\ muons\ from\ Z^0\ decays}}{\sigma_{dE/dx\ of\ muons\ from\ Z^0\ decays}}$$

Tight selection

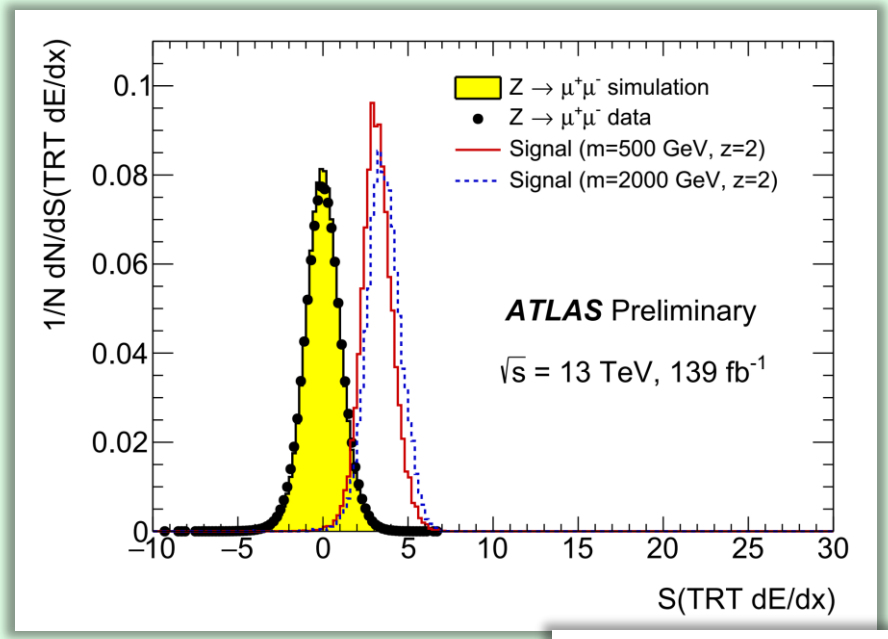
$z = 2$

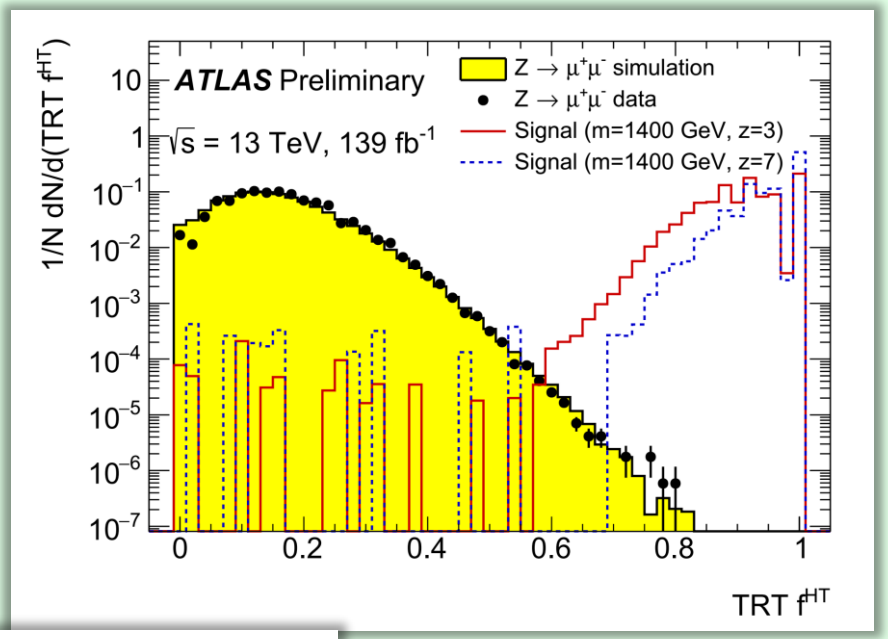


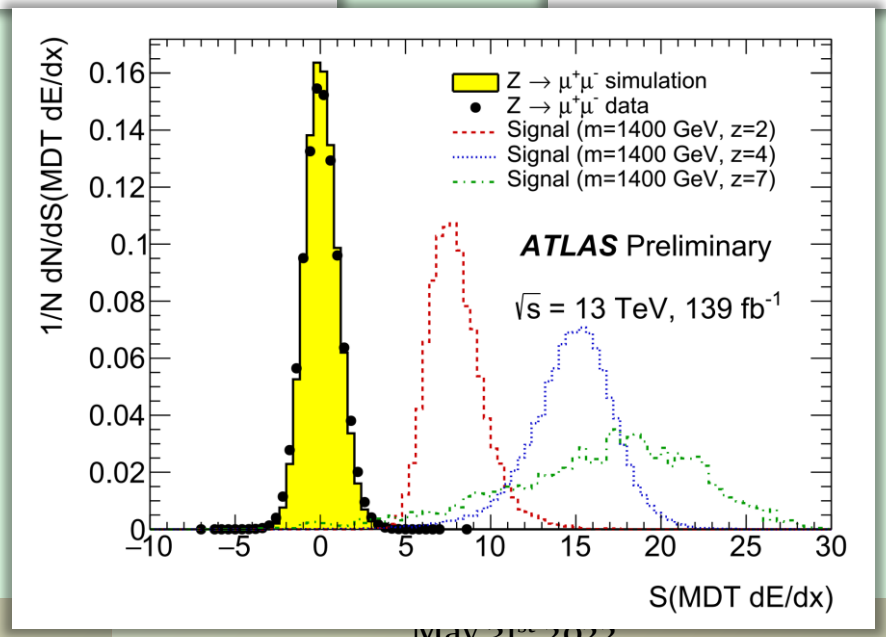
$z > 2$

none

Quantities used for the final selection

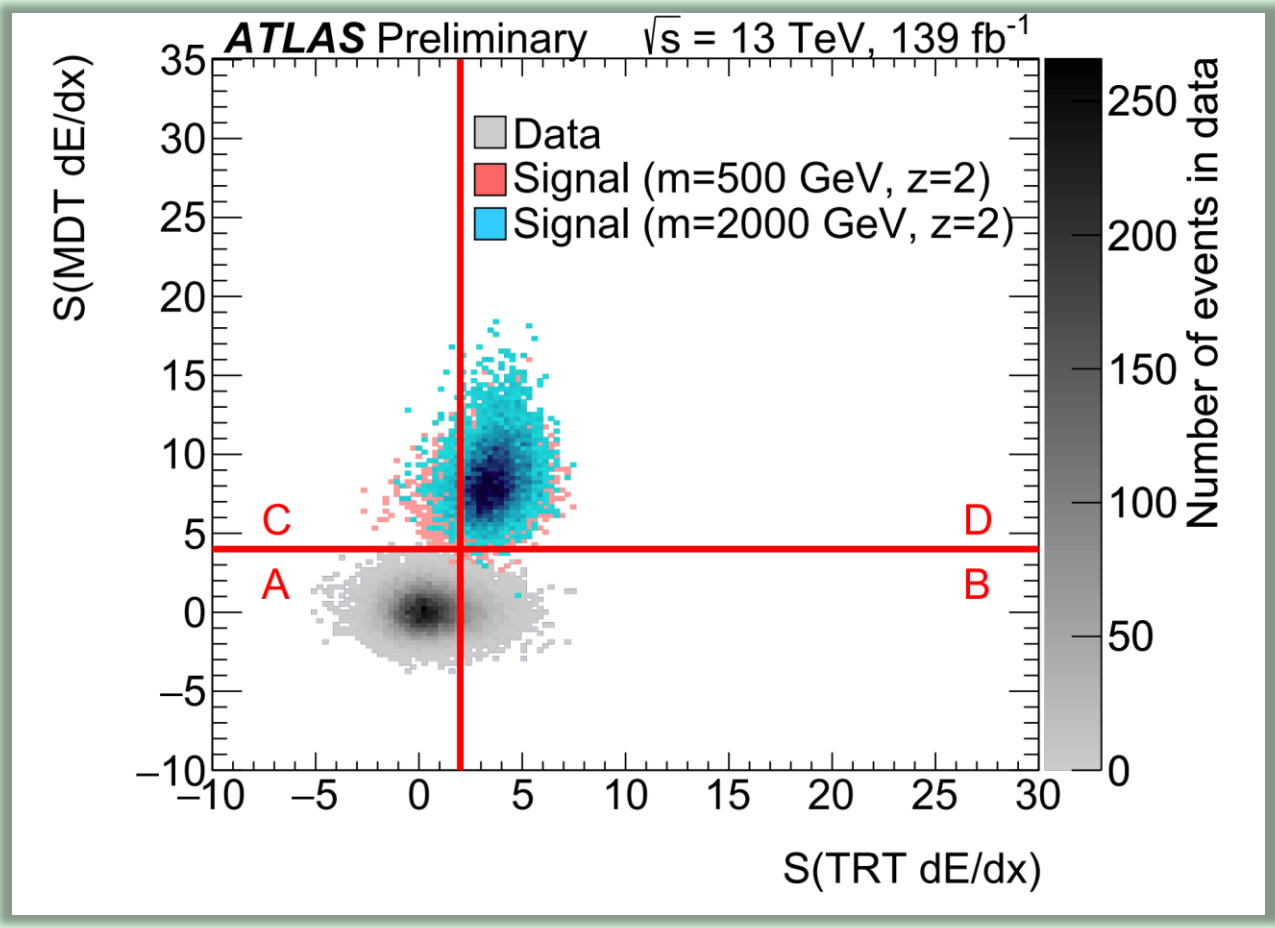




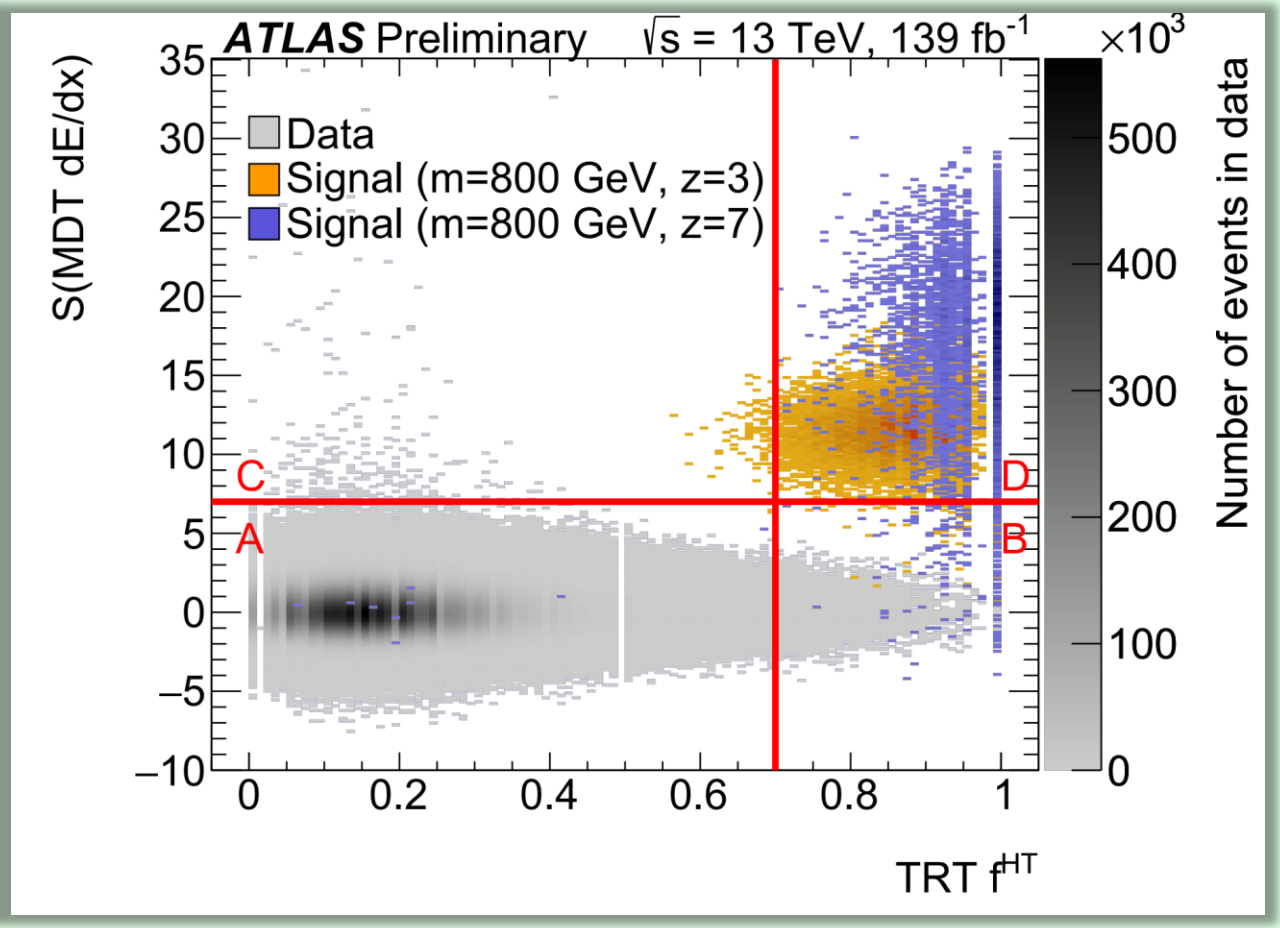


Final selection & bkg estimation

$z = 2$



$z > 2$

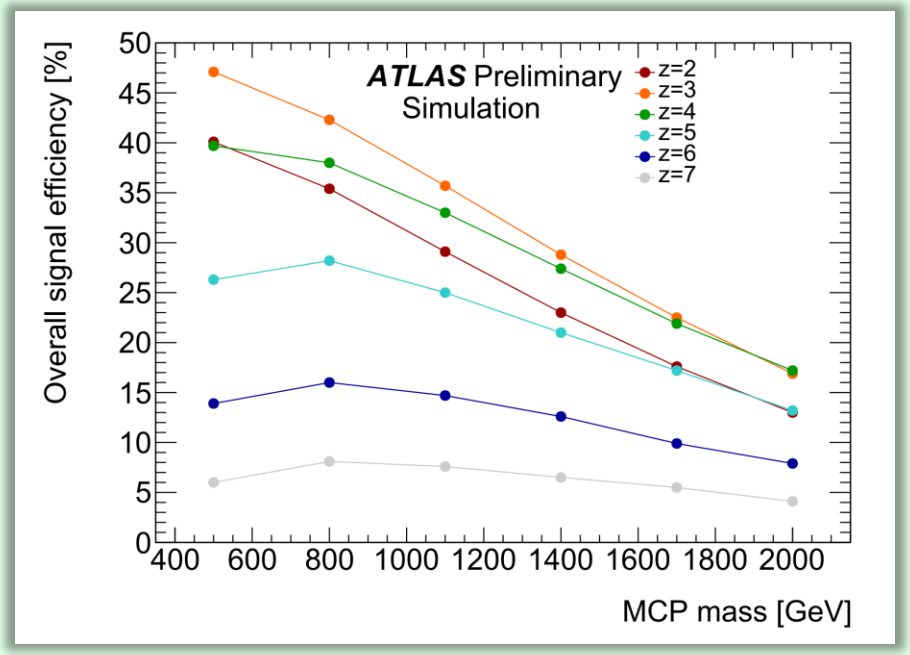


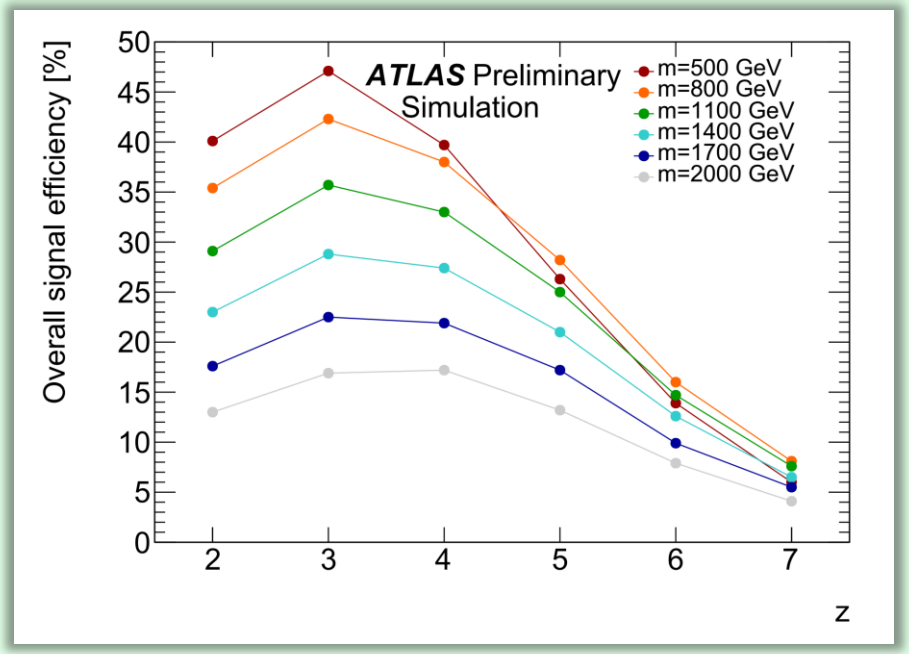
$D = \frac{B \times C}{A}$ gives:

$1.5 \pm 0.5\ (stat.)$ expected events

$0.034 \pm 0.002\ (stat.)$ expected events

Signal efficiency





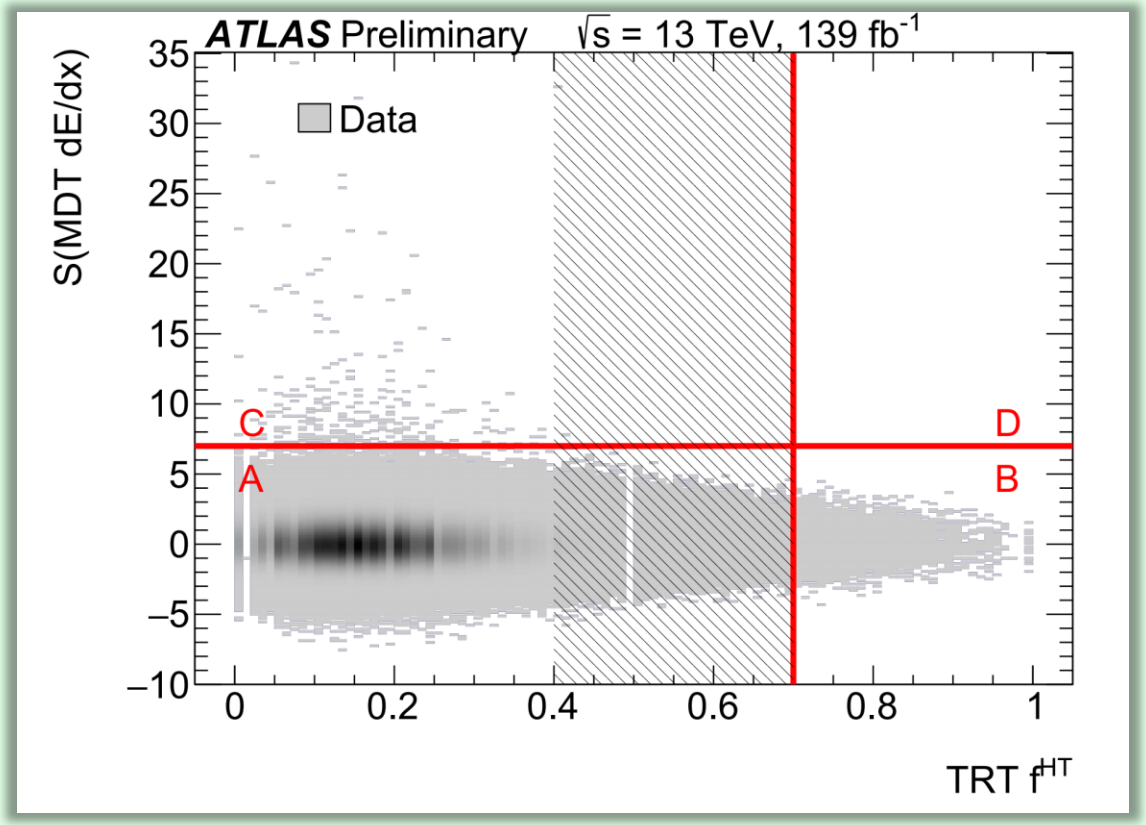
- Overall efficiency is a fraction of MC events with at least one MCP in the D region (i.e., after passing all selections) among all generated events;

- Reasons for relatively low efficiency:
  - **low masses**: η and especially p_T/z requirements;
  - **high masses**: reconstruction efficiency of muons;
  - **high charges**:
    - large ionization loss slows particles down – they may not make it into the timing window anymore and/or may lose all their kinetic energy before the MS;
    - stricter effective p_T/z requirement;
    - large δ-electron yield distorts timing parameters of MDT hits from MCPs leading to a smaller number of reconstructed combined muons.

Background-estimation systematics

A so-called “masked region” method is used to estimate this uncertainty:

- These “masked regions” were introduced between A+C and B+D (shown in figure) and between A+B and C+D (not shown), and the bkg estimation was recalculated without accounting for the entries inside these masked zones;
- The same method was already used in our 2015-2016 analysis;
- Systematic uncertainty is the relative difference between the nominal bkg estimation and the new one;
- Repeated for 20+ definitions of masked regions;
- Maximum relative differences are taken as final systematic uncertainties:

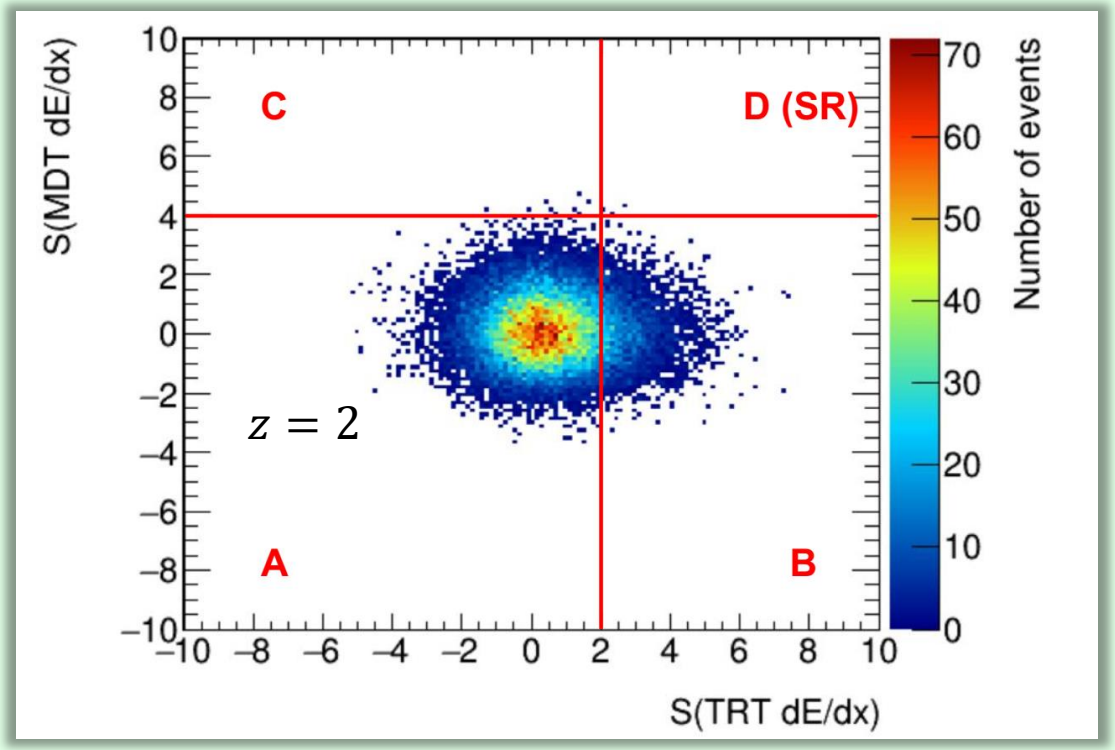


33% for the $z = 2$ case and 12% for the $z > 2$ case

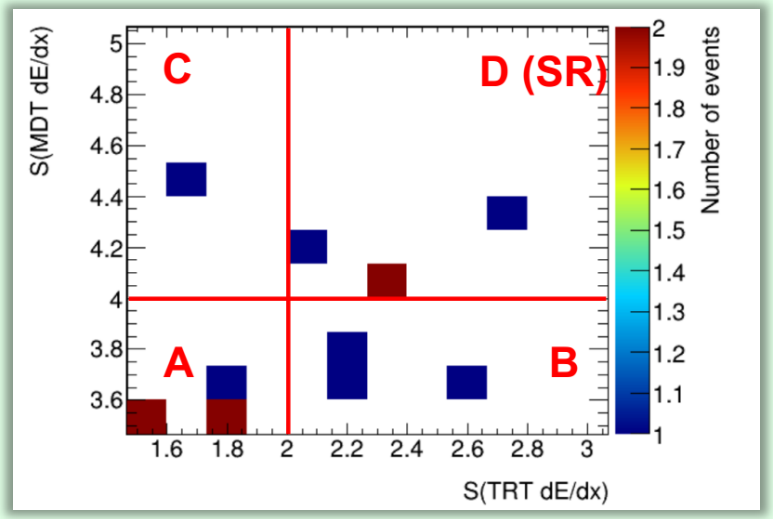
The results of the unblinding

Category	Expectation	Observation
$z = 2$	$1.5 \pm 0.5\ (stat.) \pm 0.5\ (syst.)$ events	4 events
$z > 2$	$0.034 \pm 0.002\ (stat.) \pm 0.004\ (syst.)$ events	0 events

1.5σ excess, p_0 value is 0.06



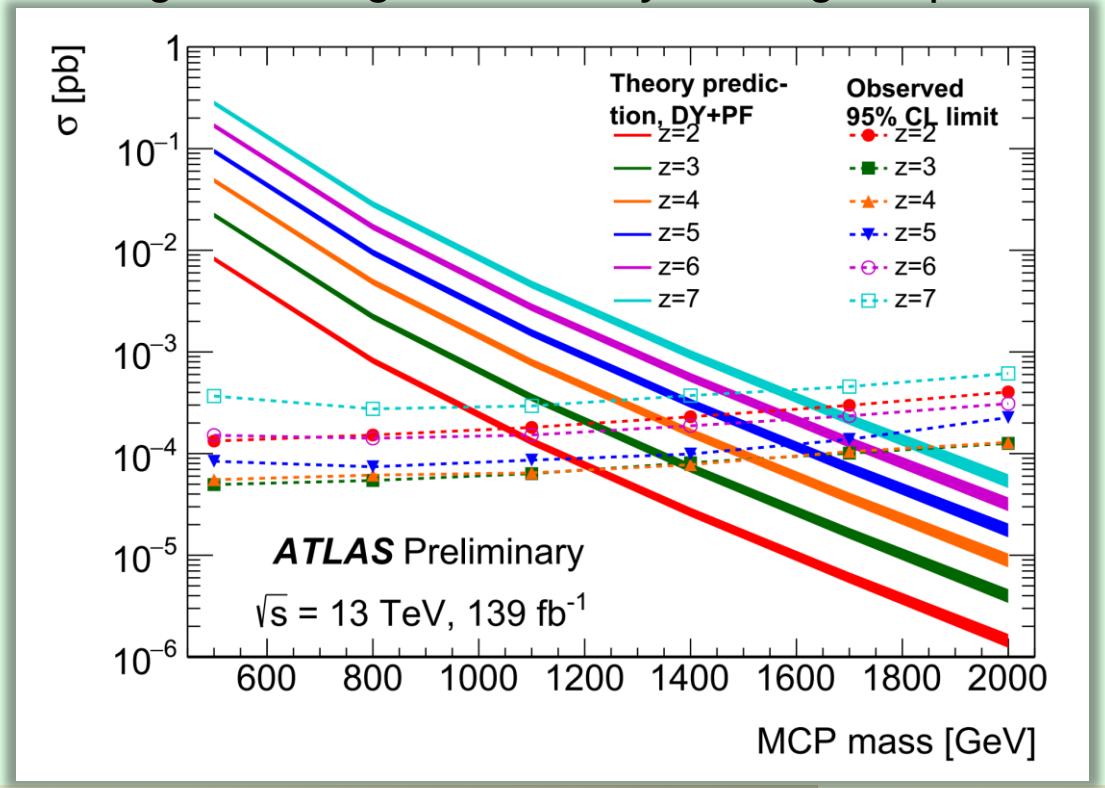
Zoomed in:

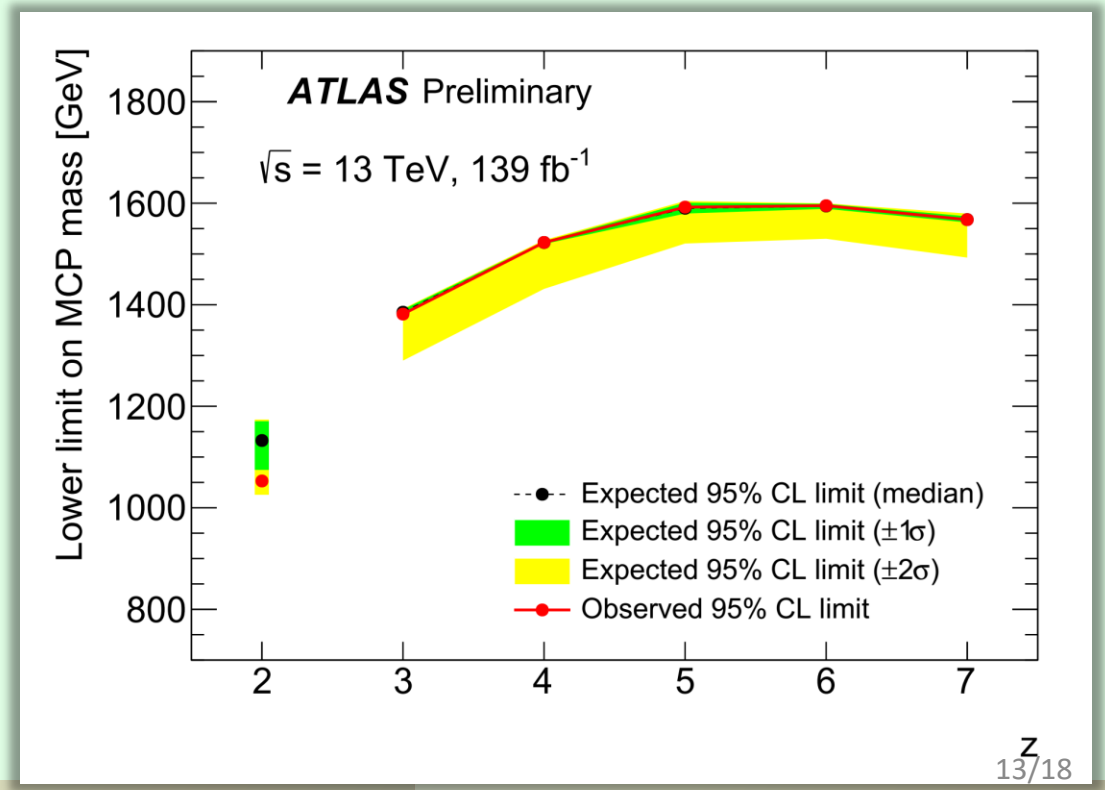


Limit setting

- The limit-setting framework makes use of the CL_s method and was used in our previous paper already;

- It takes the following as nuisance parameters:
  - luminosity uncertainty,
  - statistical and systematical uncertainties in the expected bkg estimation,
  - statistical and systematical uncertainties in the signal efficiency,
  - signal leakages into every non-signal quadrant.





7 candidates observed in the SR-Inclusive_High bin in the 1100<m<2800 GeV window of the SUSY-pixel-dE/dx analysis

N	Run #	Event #	Is a CB muon?	p_T^{ID} [TeV]	p_T^{MS} [TeV]	p_T^{ID+MS} [TeV]	η	φ	Pixel dE/dx $[MeV \times cm^2/g]$	pixel dE/dx significance	Passes our S(pixel dE/dx) cut?	TRT dE/dx significance	Passes our S(TRT dE/dx) cut?	MDT dE/dx significance	Passes our S(MDT dE/dx) cut?	TRT f^{HT}
1	309674	1638836577	✓	1.40	1.10	1.14	-0.318	-0.384	3.72	17.15	✓	-1.87	✗	-1.85	✗	0.09
2	337404	801851726	✓	0.69	0.43	0.68	0.148	2.617	3.52	15.85	✓	0.16	✗	0.21	✗	0.23
3	338767	1420590010	✗	1.34	-	-	-0.168	-0.194	2.94	12.11	✗	2.71	✓	-	-	0.29
4	363400	1316463910	✗	0.36	-	-	-1.464	2.876	3.16	13.56	✓	2.55	✓	-	-	0.39
5	304008	634260425	✓	1.35	0.60	0.65	0.443	0.947	2.59	9.90	✗	-1.25	✗	2.67	✗	0.36
6	355599	598445927	✓	1.12	0.41	0.79	-0.216	-2.911	2.88	11.73	✗	0.89	✗	1.30	✗	0.22
7	339387	617314844	✓	0.84	0.50	0.61	-0.411	-2.646	2.48	9.19	✗	-0.67	✗	0.02	✗	0.24

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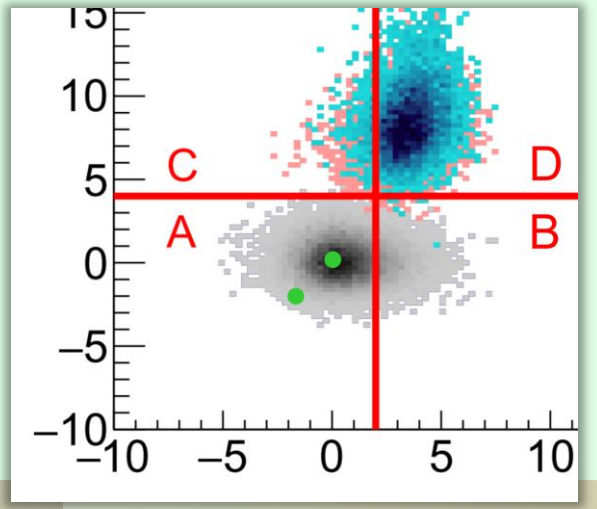
- The first two candidates are combined muons with high pixel-dE/dx values but low TRT dE/dx and MDT dE/dx;



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- The next two candidates are not muons; these feature high TRT dE/dx (and f^{HT}) values and fairly high pixel dE/dx;

7 candidates observed in the SR-Inclusive_High bin in the 1100<m<2800 GeV window of the SUSY-pixel-dE/dx analysis

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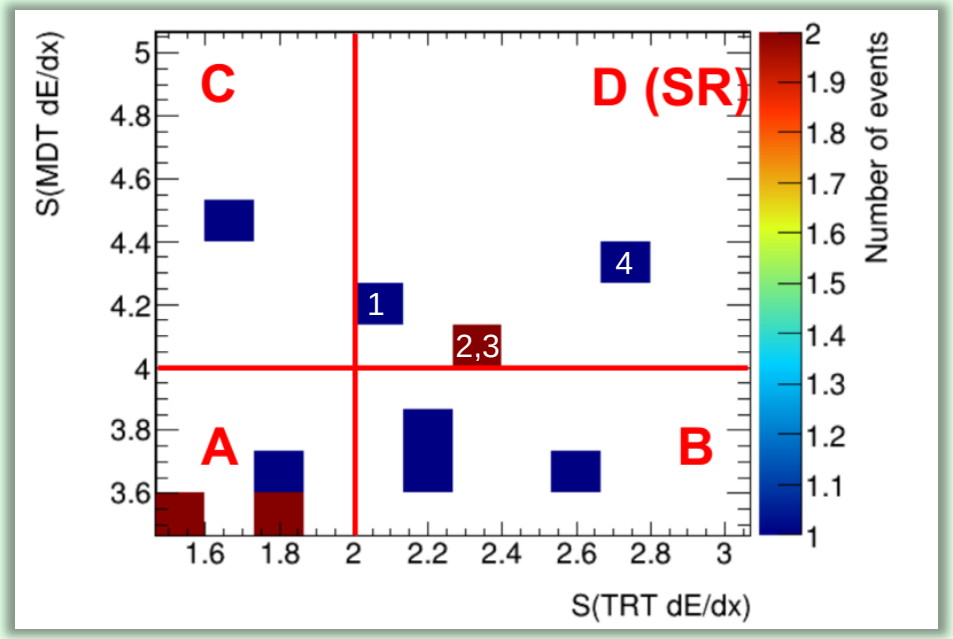
- The last three candidates are combined muons, but neither of pixel dE/dx, TRT dE/dx, or MDT dE/dx of all three candidates satisfy our selection criteria.

Conclusion

- We performed a search for long-lived multi-charged particles in the full Run 2 data;
- The changes wrt the previous search are related to the improvements in the production model and to the usage of an additional trigger, increasing the signal efficiency in the $0.4 < \beta < 0.8$ range;
- Four ionization estimators from three ATLAS subsystems are used to separate signal and background;
- Signal efficiencies are up to 47% ($m = 500$ GeV, $z = 3$);
- Background expectation and observation:
  - $z = 2$ category: $1.5 \pm 0.5\ (stat.) \pm 0.5\ (syst.)$ events expected, 4 observed;
  - $z > 2$ category: $0.034 \pm 0.002\ (stat.) \pm 0.004\ (syst.)$ events expected, 0 observed;
- All four observed events are very close to the boundaries between the signal and non-signal regions; this observation is within two standard deviations from the expectation → no discovery;
- Observed mass limits range from 500 GeV up to $(1050 - 1600)$ GeV depending on the charge;
- The largest increase in the observed mass limits wrt the previous search is 450 GeV (1120 GeV → 1570 GeV, $z = 7$);
- A manual check of the 7 candidates observed in the SUSY-pixel-dE/dx analysis explains the exact reasons for their absence in the $z = 2$ SR of this analysis.

THANKS!

Details of the particles observed in the $z = 2$ SR



Candidate	Run number	Event number	η	φ	S(pixel dE/dx)	S(TRT dE/dx)	S(MDT dE/dx)
1	338480	833131394	-0.36	$+1.76$	13.75	2.05	4.22
2	298633	204751183	-0.26	-0.49	14.40	2.27	4.08
3	328263	2234090061	$+1.88$	$+2.06$	16.57	2.28	4.08
4	361862	977582700	-0.97	$+1.00$	13.50	2.80	4.35

Analysis features

- Ionization losses are highly sensitive to the electric charge of a particle; $dE/dx \sim z^2$
- Long-lived particles → expected response in the muon chambers;
- High mass → low β → muon-trigger-timing window can be too short for these particles;
- Track reconstruction always assumes particles with charge $\pm 1e$ → momentum misreconstruction by a factor of z;
- Timing mismodeling of the RPC trigger for particles with low β → requires corrections of the MC trigger efficiency.