ATLAS search for long-lived particles with large ionisation energy loss

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on behalf of the ATLAS collaboration

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ATLAS EXPERIMENT

INFN GENOVA

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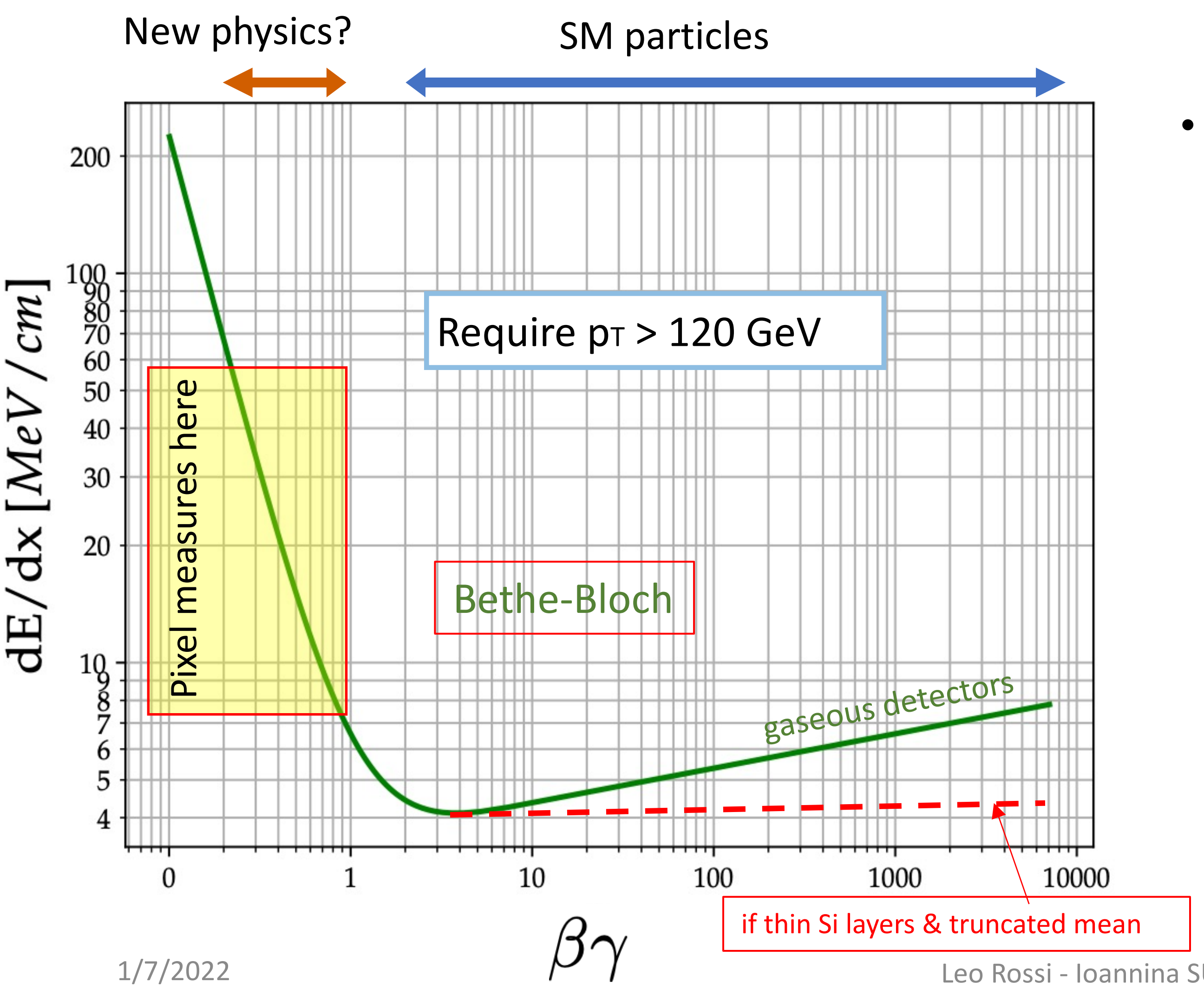
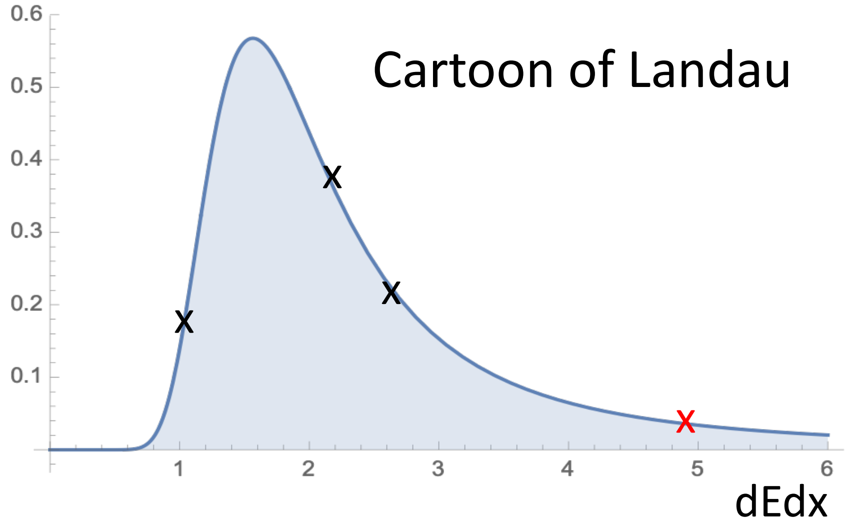
1) Search for heavy Long Lived Charged Particles using Pixel ionization measurement in pp collisions at √s=13 TeV using the ATLAS experiment and the full Run 2 dataset:

(arXiv:2205.06013, submitted to JHEP) Measurement assumption: Ionisation losses follow Bethe-Bloch distribution
➔high-dEdx is indicator of low-βγ and therefore of high-mass if the particle momentum is high (m=p/βγ) and z=1.



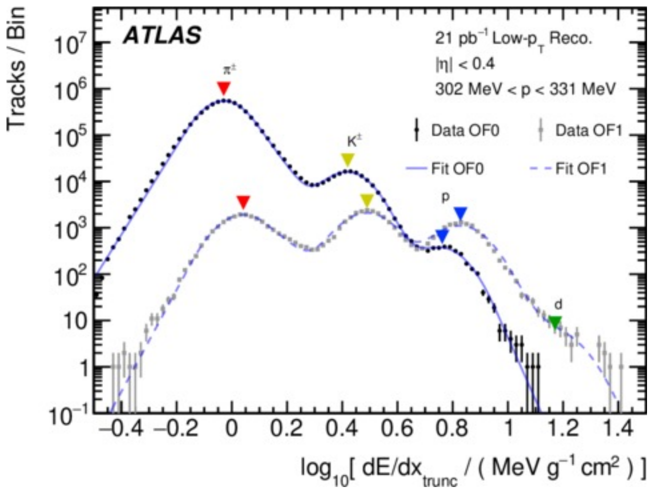
The experimental method

- ATLAS pixel detector provides (typ.) 4 ionization measurements along each track (and within r<13 cm from the p-p interaction). Each measurement follows a Landau distribution

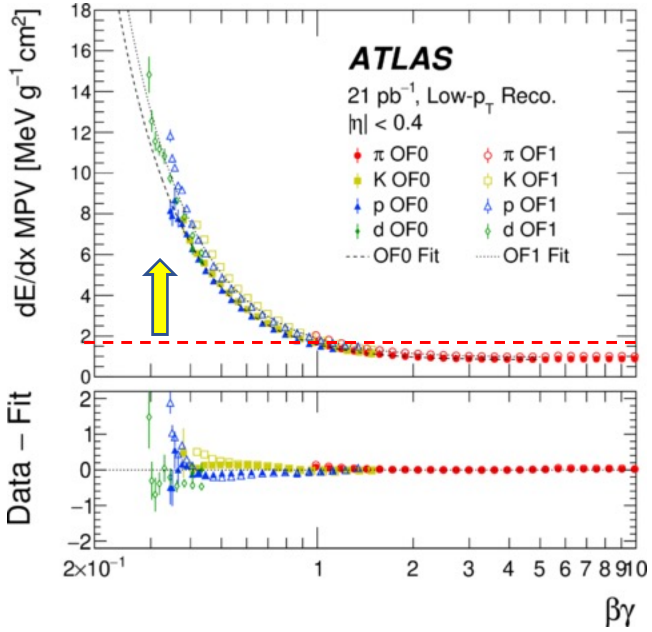


- Averaging dEdx after rejection of the highest dEdx gets rid of the Landau tails and provides σ_{dEdx}~12%

- Peculiar to this measurement is the calibration capability using low-$\beta\gamma$ SM particles (abundant at Pixel radii)

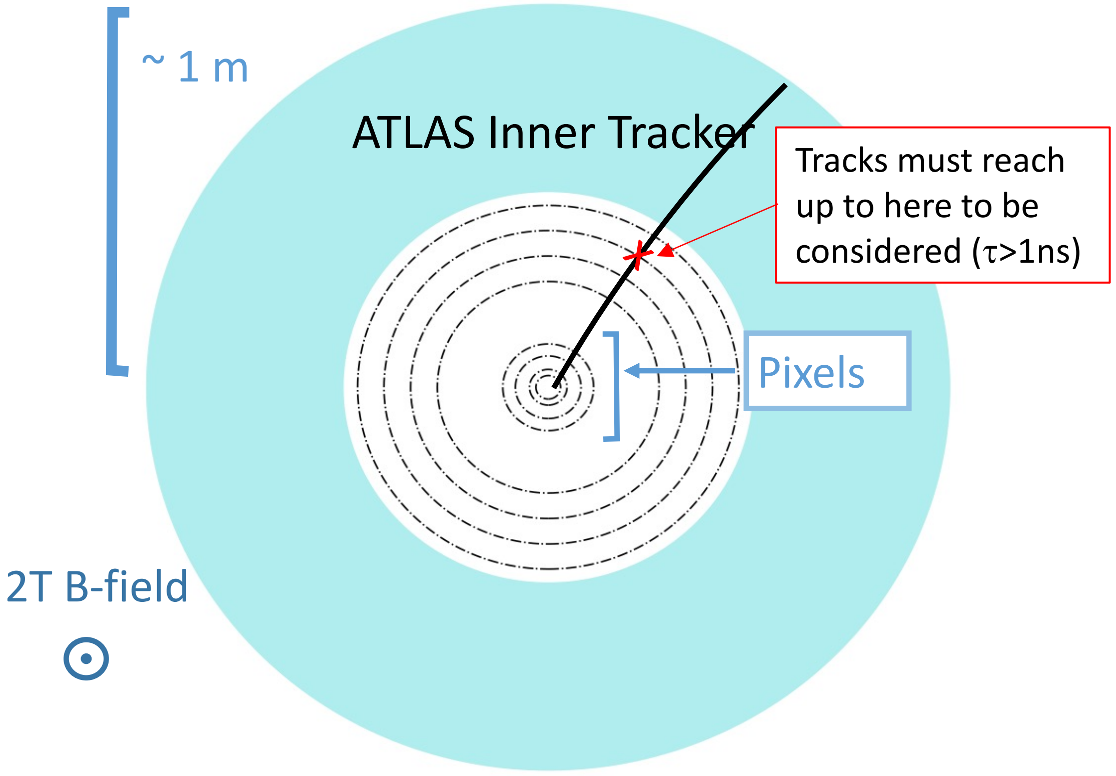


Low-p SM particles.
dEdx in a small momentum-slice shows “mass” peaks



Low-p SM particles.
Putting together all the dE/dx peaks in various momentum slices, we match a Bethe-Bloch distribution➔ this $\beta\gamma$ calibration (i.e. each dE/dx corresponds to a $\beta\gamma$) allows to measure the particle mass, when p is known.
MIP= 1.0 MeV g^{-1} cm^2
This analysis selects dEdx>1.8 MeV g^{-1} cm^2 ➔only ~1% of tracks survive.
Tracks are measured if $0.3<\beta\gamma<0.9$. The lower $\beta\gamma$-limit is related to the pixel dynamic range (~10MIPs).

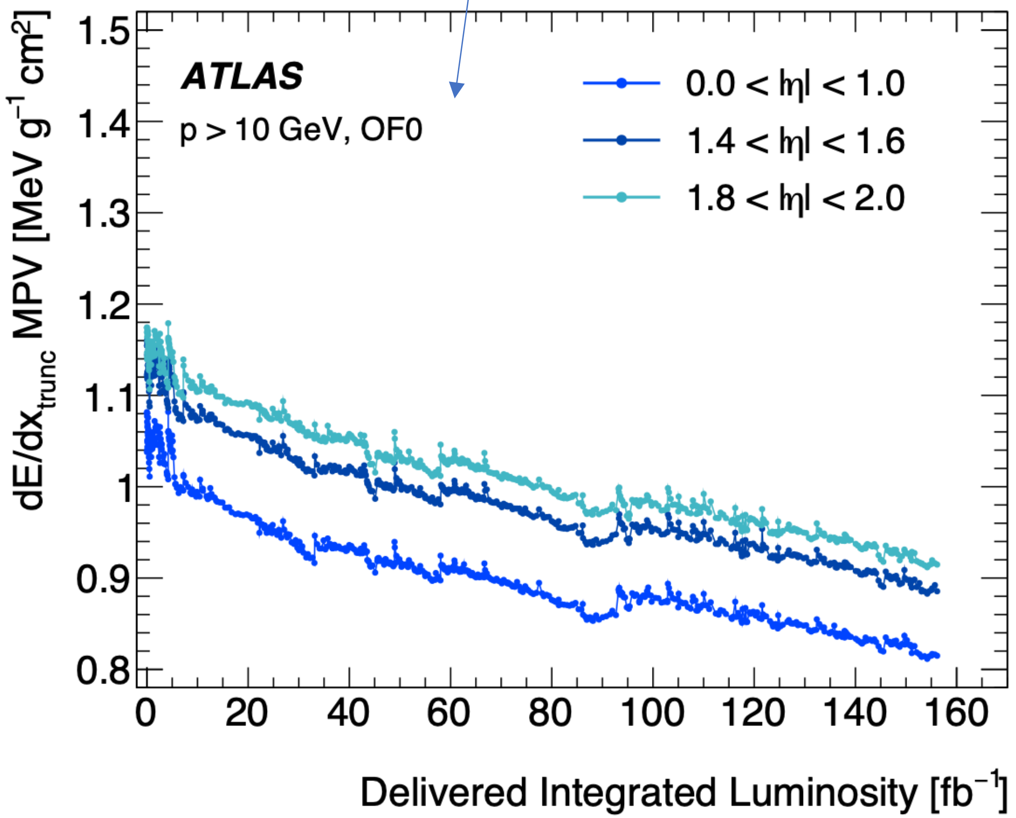
- The other ingredient to calculate the mass is the momentum. This is measured using the full ID (requiring track extension in muon spectrometer would exclude low lifetimes)

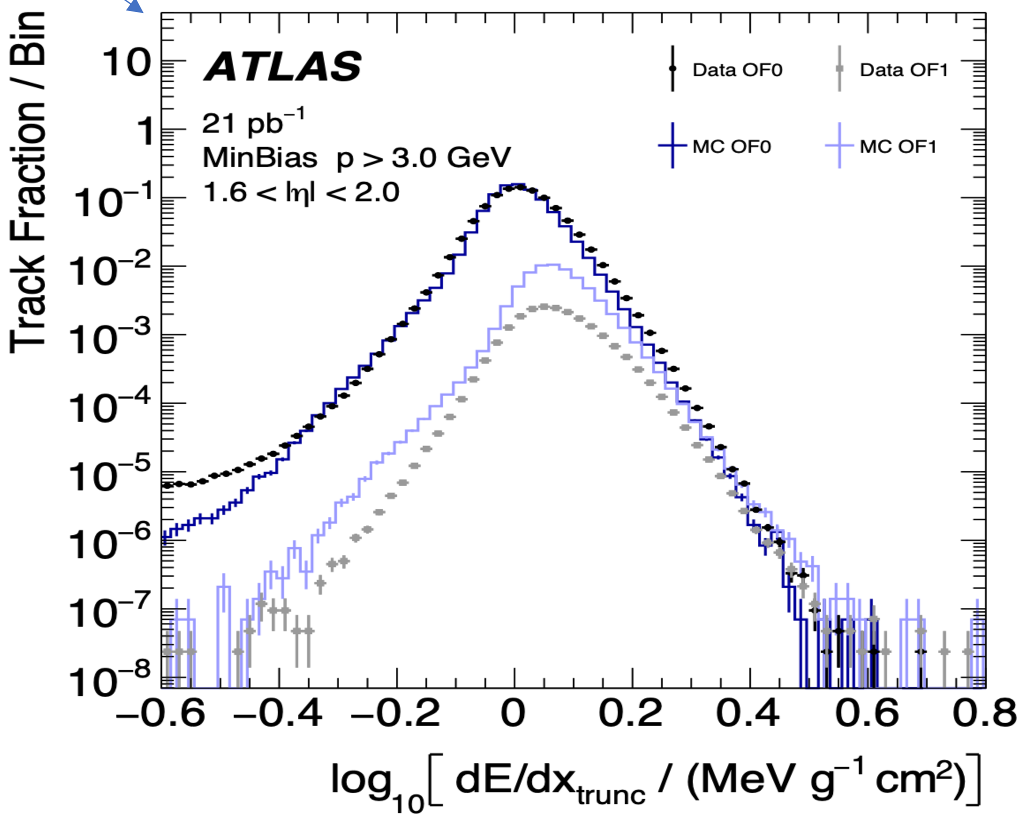


- The innermost pixel layer (IBL) has less dE/dx dynamic range, but has an overflow bit OF1 (set at ~2MIPs) useful to tag high ionization tracks.

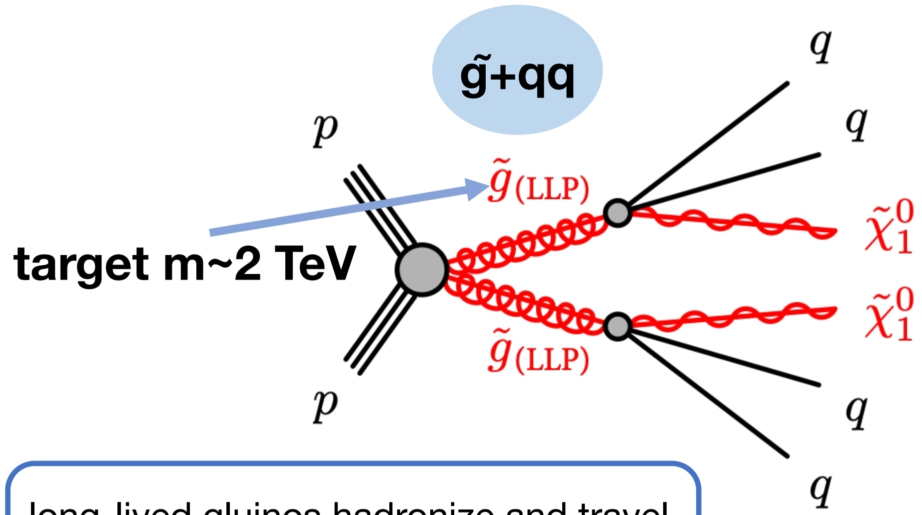
- The use of the Pixel dEdx requires a lot of custom analysis work. The most important effects which has been taken into account are:
  - Correction for radiation damage and detector operation effects
  - Use of data driven dEdx template instead than MC simulated values

OF0 = no IBL overflow bit
OF1= IBL overflow bit set

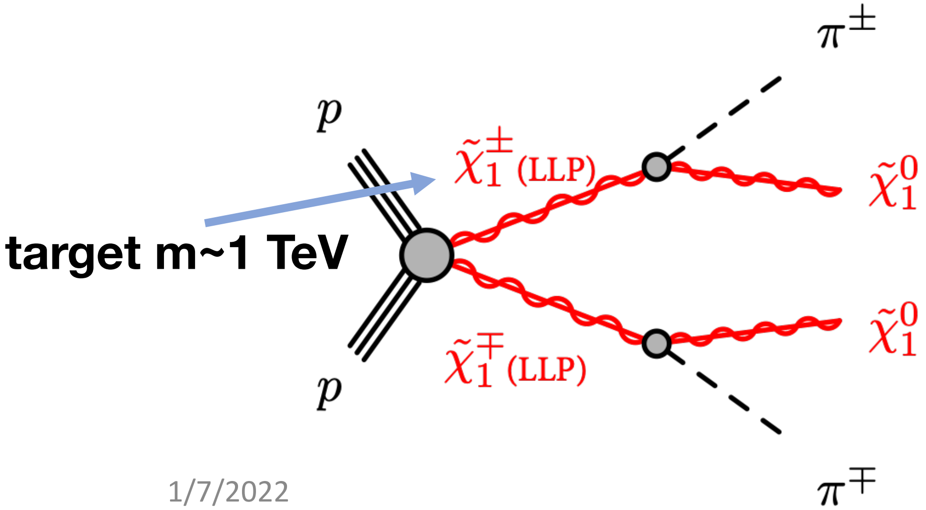


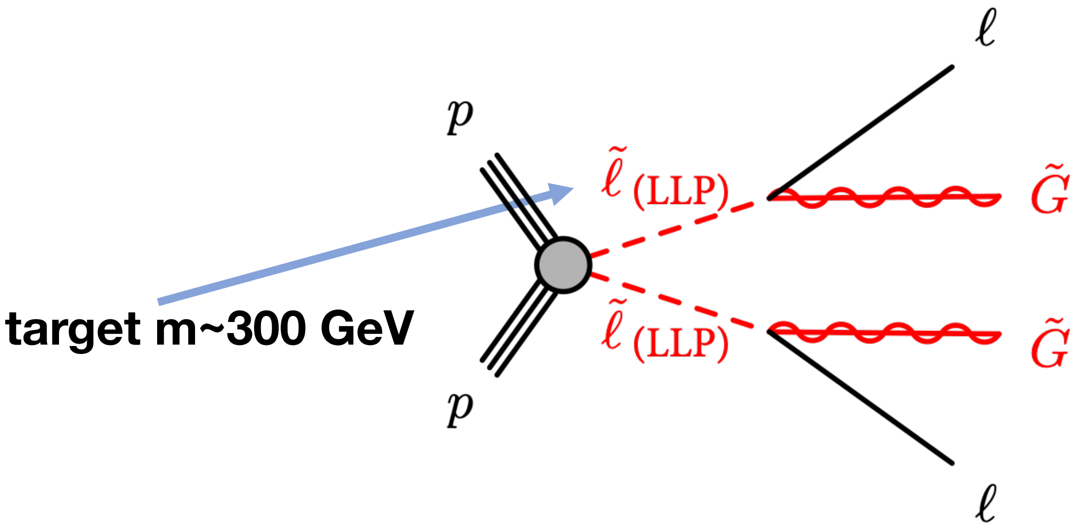


What this measurement is looking for?



long-lived gluinos hadronize and travel through the detector as *R-hadrons*





- Because the Bethe-Bloch relationship governs all charged particles, the analysis is relatively model-independent
- Have broad sensitivity to charged, long-lived, massive particles with lifetimes of ~ ns to stable
- With the full Run-2 dataset, targeting long-lived **gluinos, charginos, sleptons**
- Analysis is designed to be sensitive to a large range of masses and lifetimes

Event selection

Event selection

- Trigger on MET
- Offline MET > 170 GeV

→

Track selection

- p_T > 120 GeV, $|\eta|$ < 1.8
- Isolation & jet vetos, m_T > 130 GeV
- Good track quality
- dE/dx > 1.8 MeV g^{-1} cm^2

Select **highest p_T track** which passes requirements →

223 tracks

SR-Inclusive

Detailed event & track selection

Exclusion regions

SR-Mu-IBL0_Low	SR-Trk-IBL0_Low
SR-Mu-IBL0_High	SR-Trk-IBL0_High
SR-Mu-IBL1	SR-Trk-IBL1

- Categorize tracks by
  - Muon ID
  - Hit in IBL overflow?
  - dEdx in [1.8, 2.4] or [2.4,∞]
- **6 exclusive signal regions**

- -

Discovery regions

- SR-Inclusive_Low ← added sensitivity for low mass signals
- SR-Inclusive_High ← more sensitive

- Only categorize tracks by
  - dEdx in [1.8, 2.4] or [2.4,∞]
- **2 exclusive signal regions**
- **Also easier for re-interpretation**

Background estimation

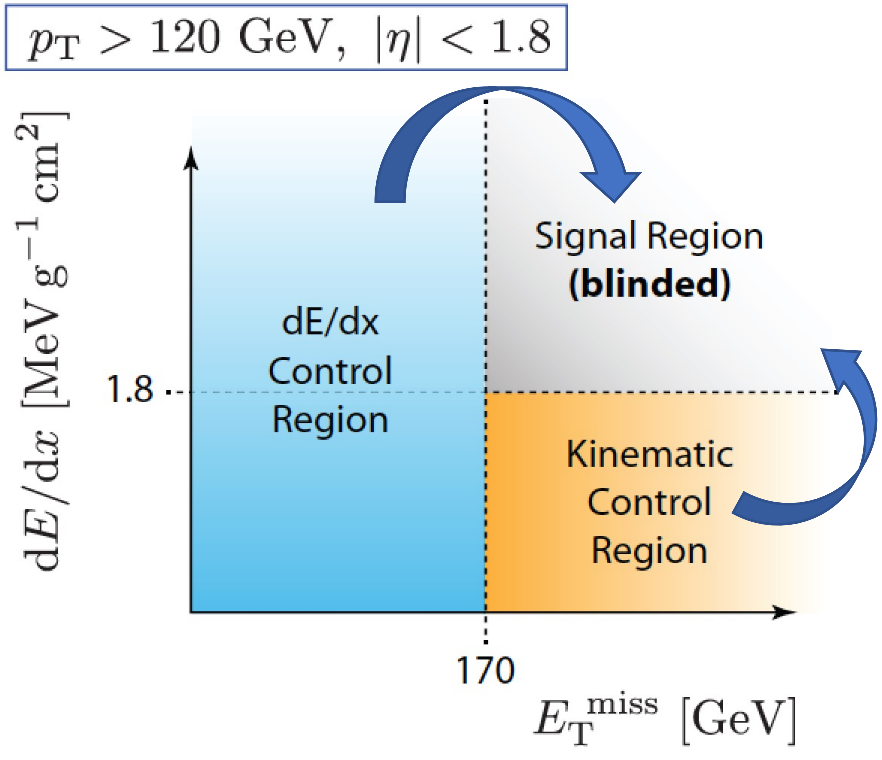
Background is difficult to be simulated (it should be made of high-p_T tracks that have excess dEdx for several possible reasons: close-by tracks, dEdx fluctuations, etc.). A data-driven technique is instead used.

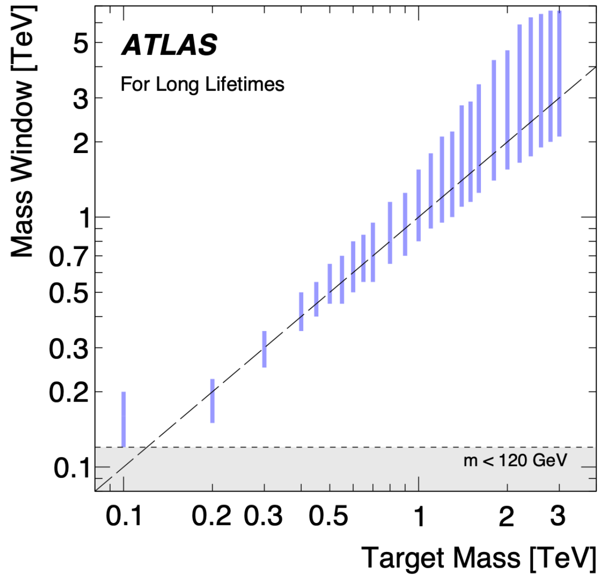
The background mass distribution is obtained using two orthogonal control regions: kinematic CR and dEdx CR (separated by the SR by, respectively, the dEdx-cut (1.8 MeV g^{-1} cm^2) and the MET-cut (170 GeV) and obtained inverting the above cuts)

Randomly draw p = ($1/p_T$, η) and dEdx (i.e. βγ) values from distributions in these regions and combine pairs to obtain mass (m = p/βγ).

Repeat O(10M) times and then normalize to the low-mass region (m<120 GeV) in the data (where signals have been already excluded).

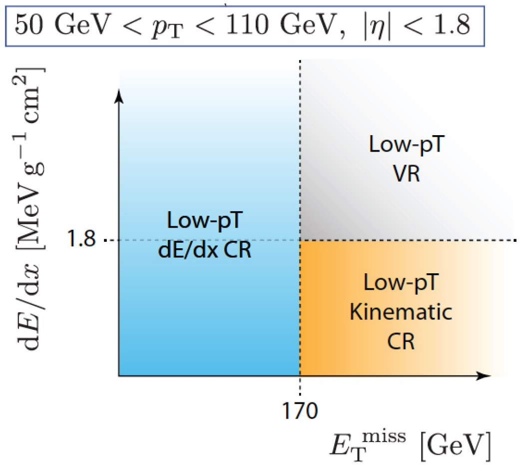
A set of sliding mass windows such to contain ~70% of signal of a LLP of mass **m** (and with optimized S/√B) is then defined. This is later used to calculate the statistical agreement between the data and the background at mass **m**.

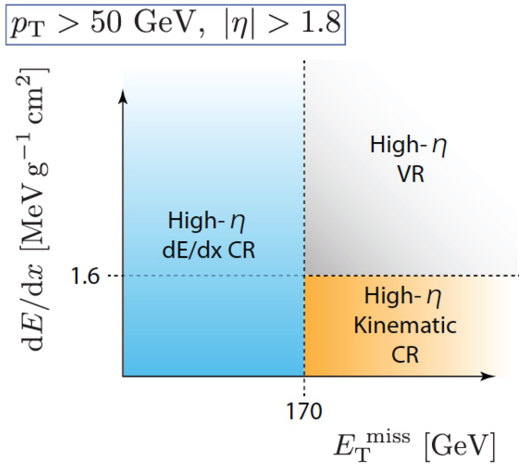




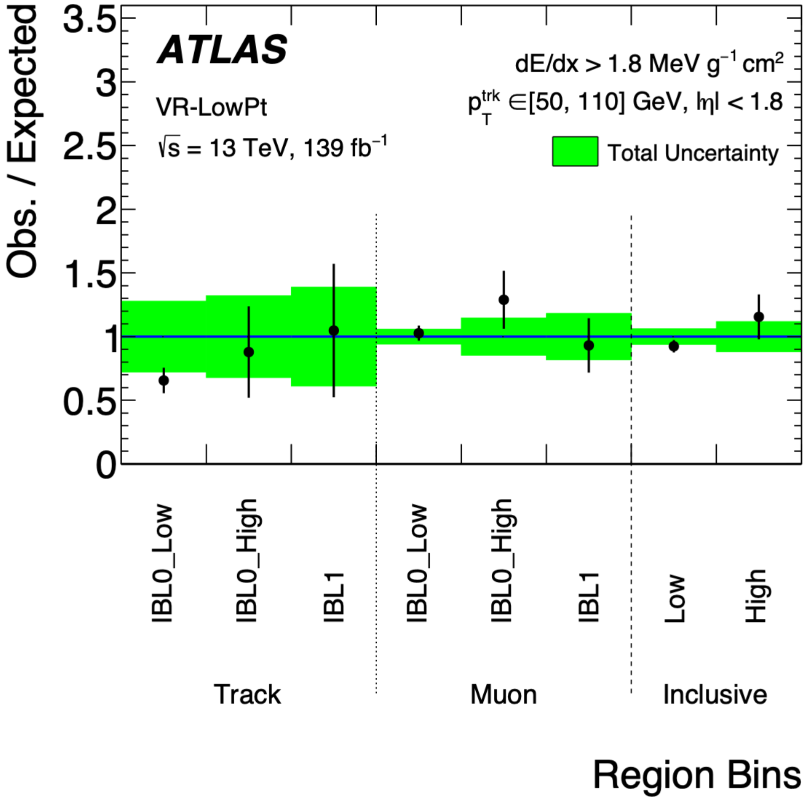
Background validation

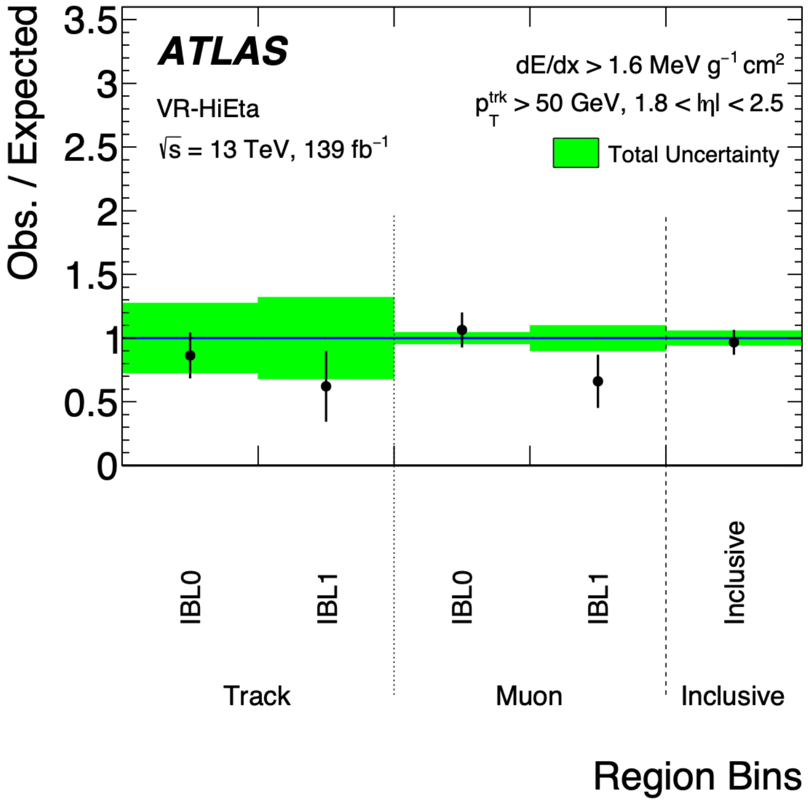
The background calculation is gauged in two validation regions orthogonal to the SR and separated by p_T (VR-LowPt) or by η (VR-HiEta). Both VR are expected to not contain signal contributions (because of p_T or η cuts).





Observed and expected yields show good agreement in both VRs.



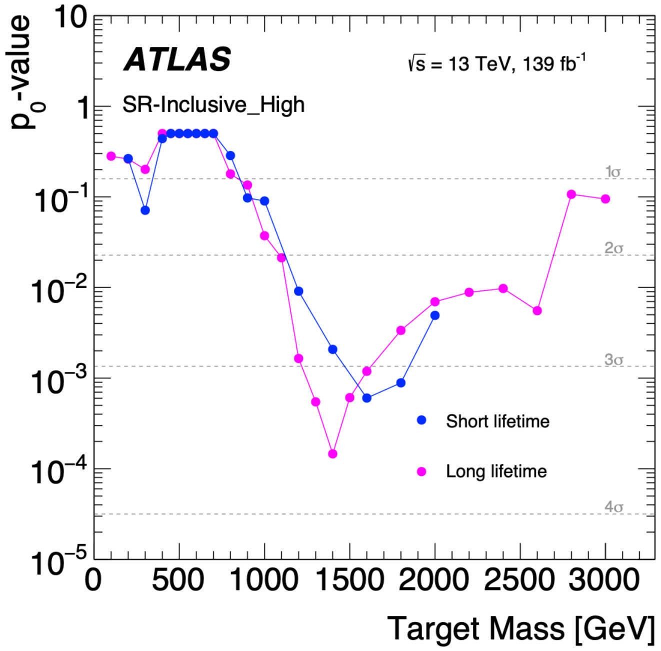


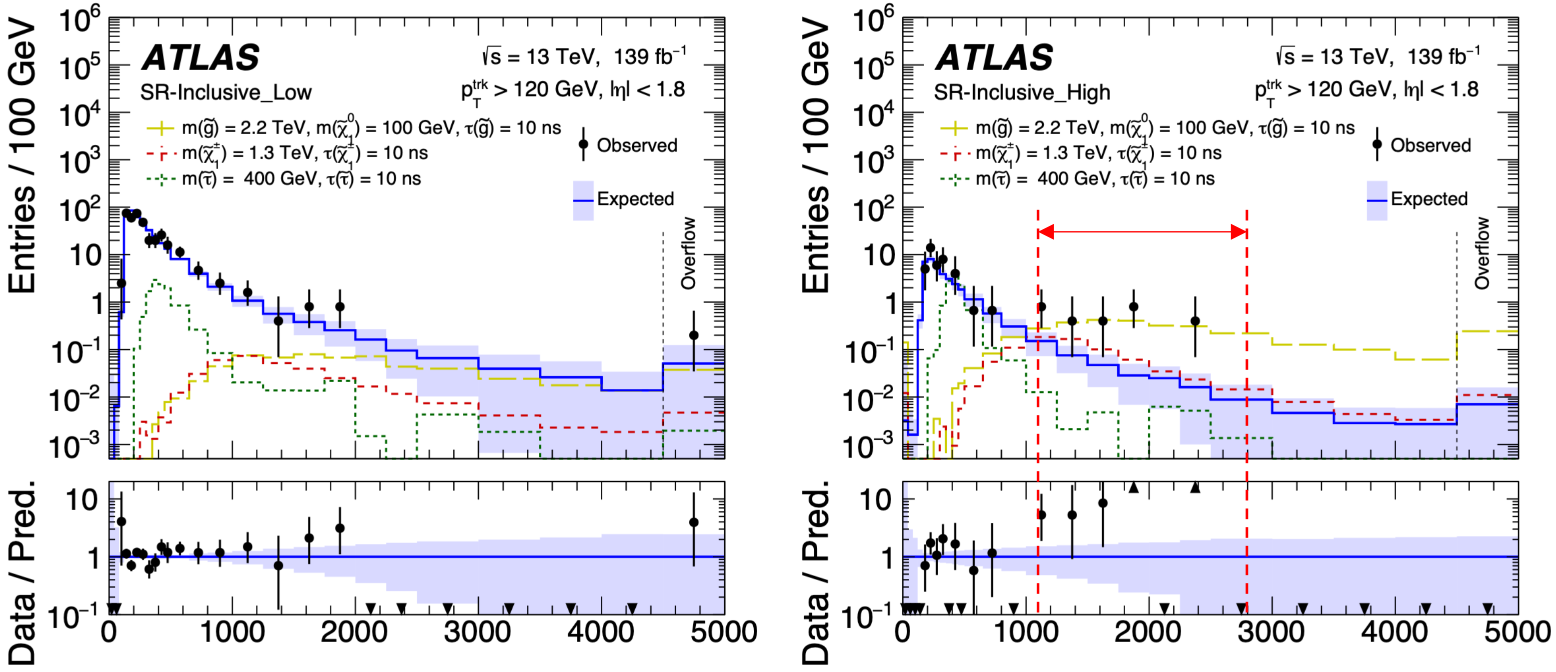
Results on the discovery regions

The selected events mass is plotted in comparison with the expected background.
Observed agreement in SR-Inclusive_Low and **an excess** in the **SR-Inclusive_High**

The largest deviation from the background expectations happens for m=1.4TeV (mass window 1.1<m<2.8 TeV) where 7 events are seen and 0.7 ± 0.4 are expected.

This translates into a local (global) significance of 3.6σ (3.3σ).





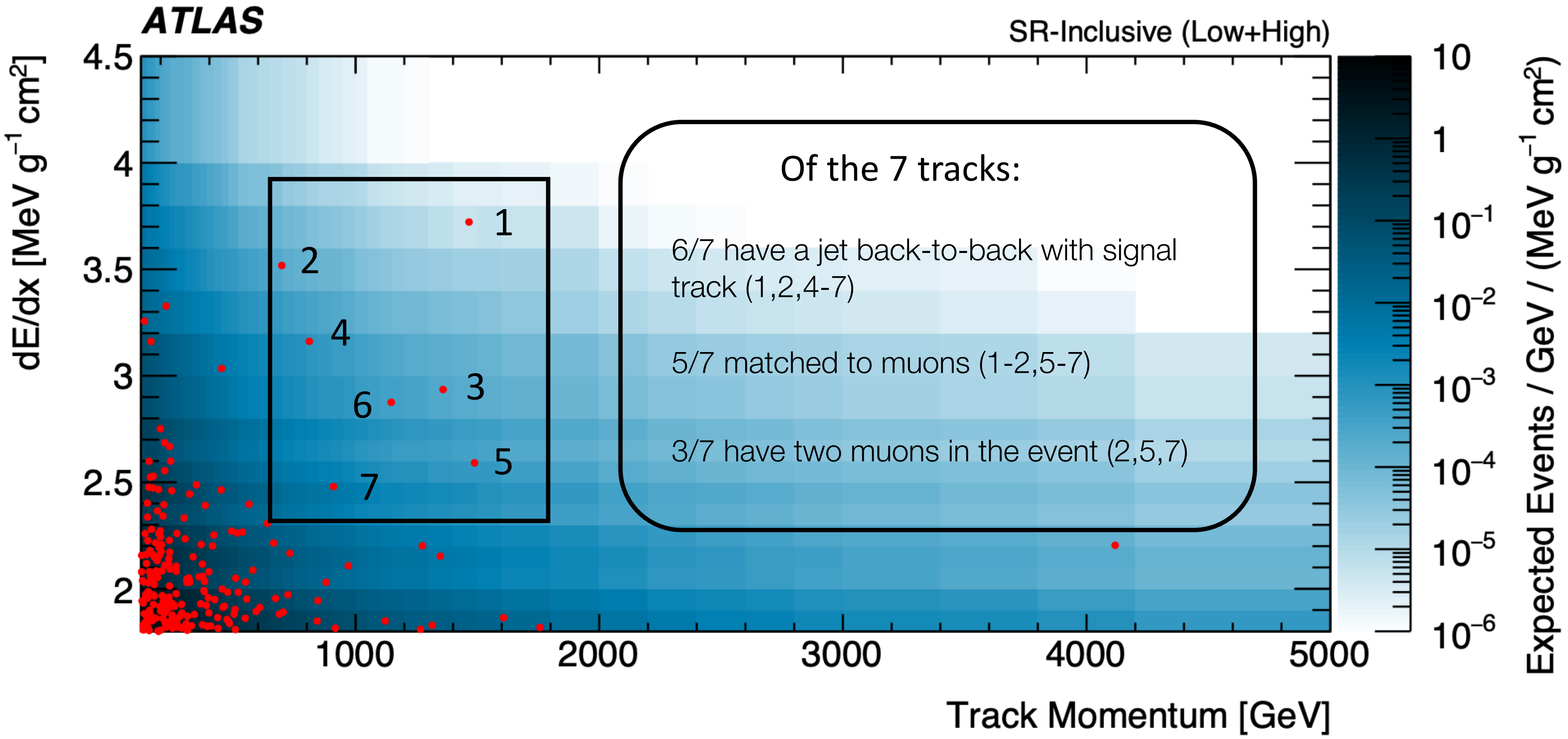
1.8 < dE/dx < 2.4 MeV g^{-1} cm^2

dE/dx >2.4 MeV g^{-1} cm^2

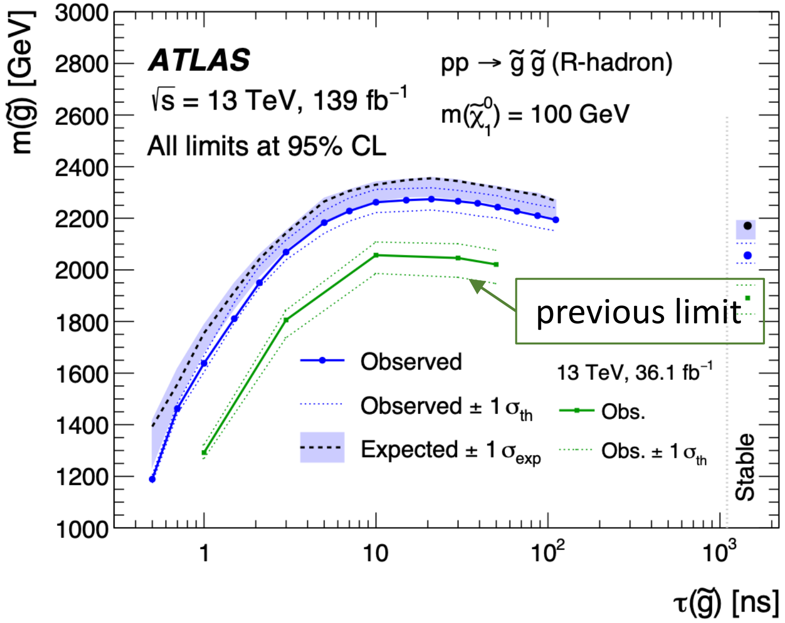
More on the excess tracks

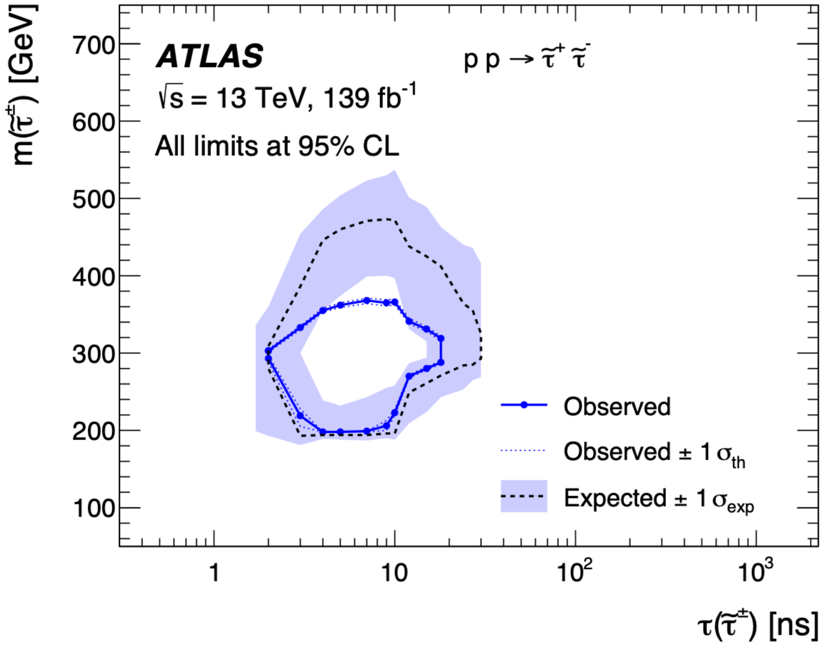
The 7 excess tracks were evaluated in detail to check for evidence of detector related effects (nearby tracks, anomalous pixel cluster, etc.) and none was found.
All tracks in the excess have high-p and high-dEdx. They all have low-probability in the dE/dx-momentum plane.

Evidence for those tracks to be slow (expect $0.5<\beta<0.6$ from pixel dEdx) has not been confirmed by ToF measurement from Calorimeter and μ-spectrometer (for the 5 tracks reconstructed as μ's).

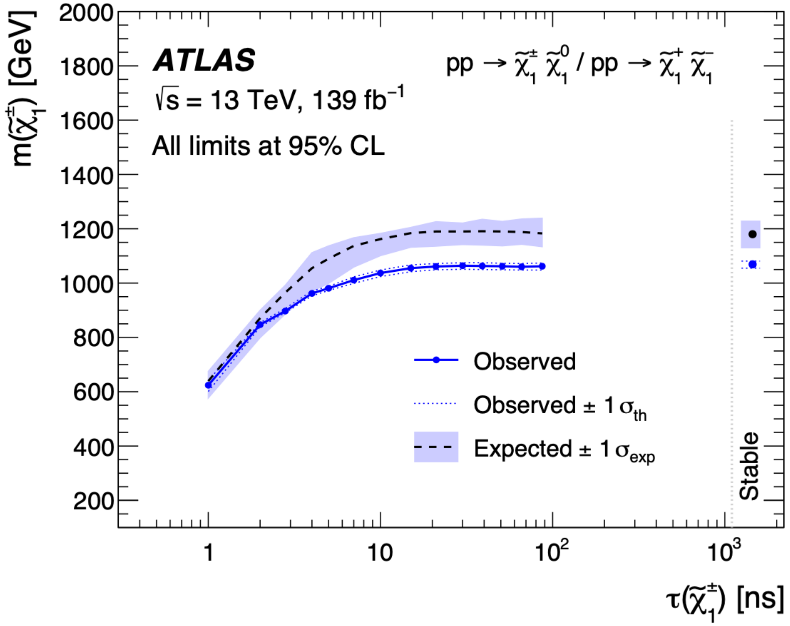


Results on the exclusion regions





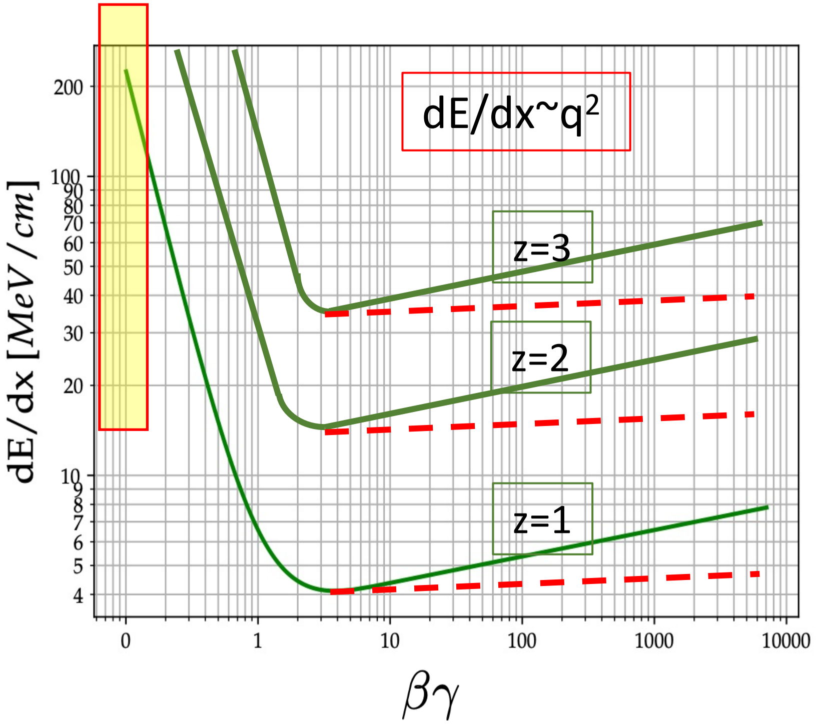
Limits are computed in the [pyhf framework]() using **toy experiments**, and a multi-bin fit over all of the **exclusion regions**



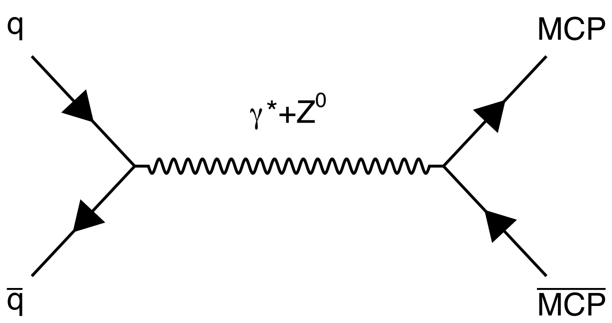
Metastable gluinos are excluded up to ~2.3 TeV for τ = 20 ns, while stable gluinos were excluded up to ~2.1 TeV for a 100 GeV LSP (compressed scenario in backup).
Charginos were excluded up to ~1.1 TeV for τ = 30 ns, and staus were excluded from 220-360 GeV at τ = 10 ns.
Results (at high mass) slightly worse than expectations because of the excess.

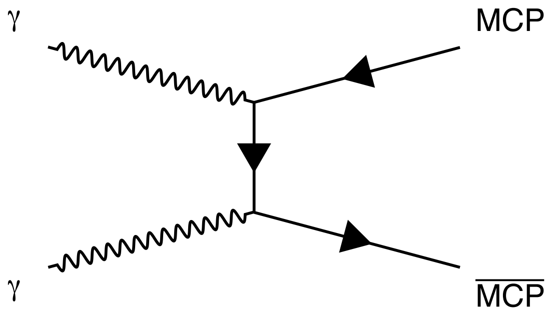
2) Search for heavy long-lived multi-charged particles in the full Run-II pp collision data at √s=13 TeV using the ATLAS detector:

(ATLAS-CONF-2022-034 : https://cds.cern.ch/record/2810156) Measurement assumption: high-dEdx is an indicator of a multi-charged (MCh-)particle (i.e. high dEdx also in MIP regime). This search is sensitive to $2 \leq z \leq 7$. Truncated dE/dx is measured in Pixel (R=0.1m), Transition Radiation Tracker (R~1.0m) and Muon chambers (R~10m) under the assumption that the particle lifetime is long enough to reach the μ-spectrometer.



The MC-particle production is simulated assuming DY or PF

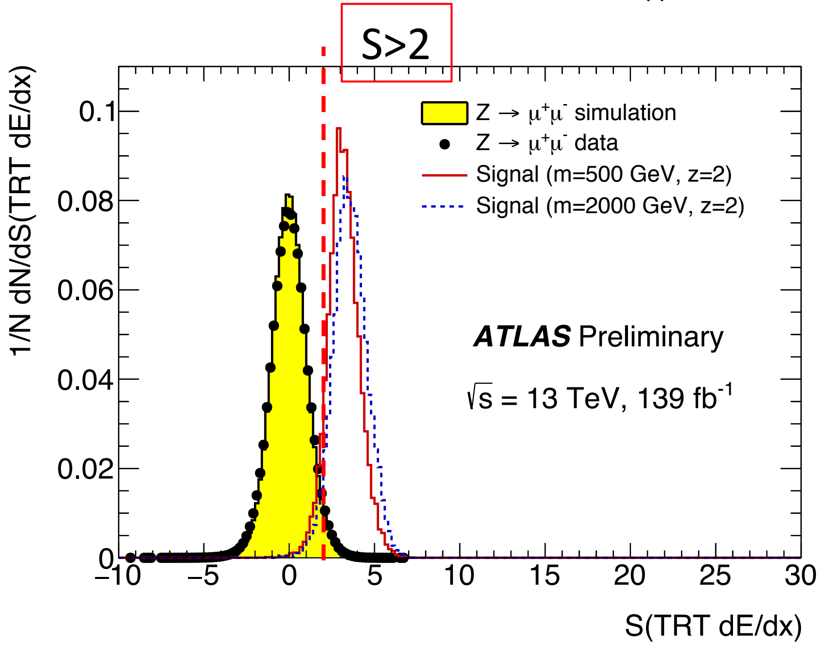


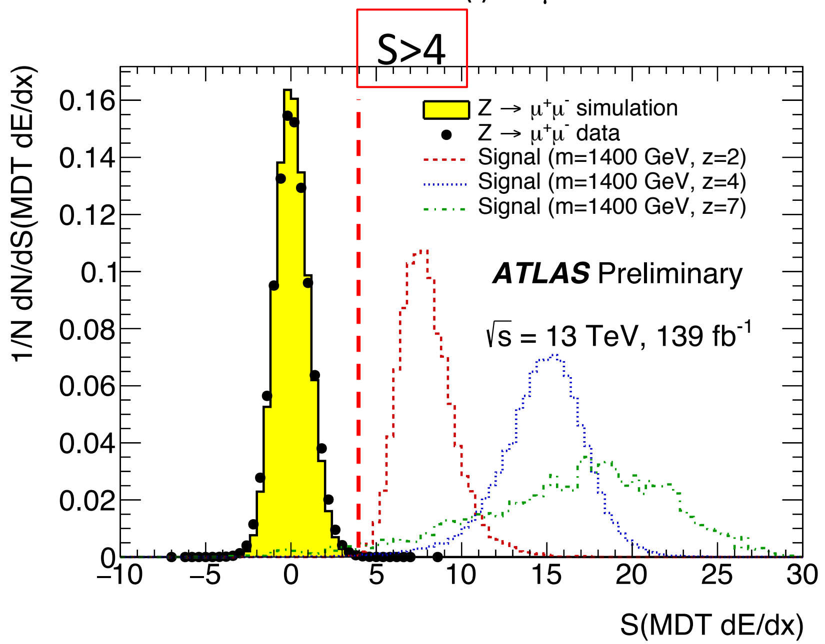


Events are triggered by ET_{miss} (same as in Pixel dEdx study) **OR** p_T>50 GeV muons **OR** p_T>10 GeV late muons. In the analysis only good quality isolated tracks are used.

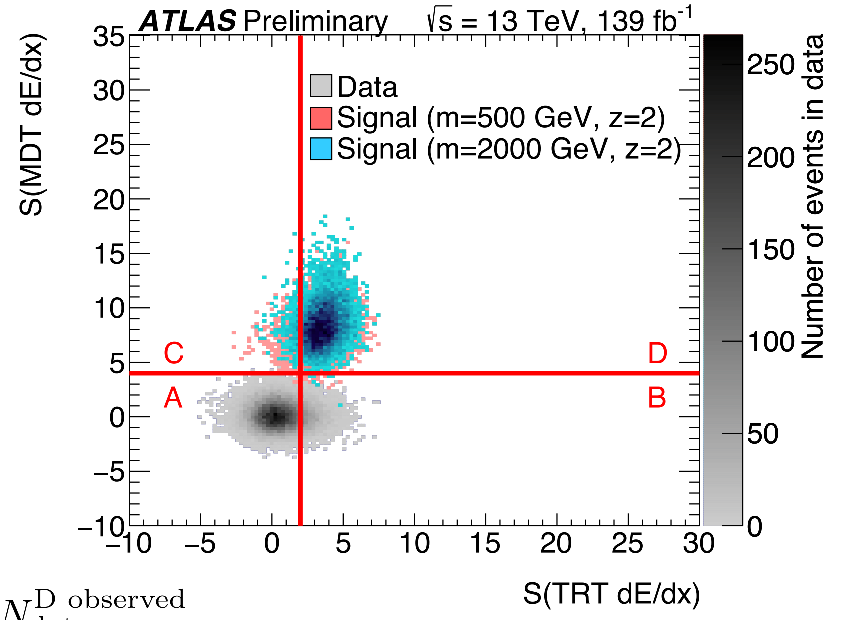
Selection is done not on the dEdx itself, but on the significance (S) defined with reference to the dEdx for muons from Z decay for each of the detector used in the dEdx measurement (σ from the gaussian fit of the core of the distribution)

$$S(dEdx)_{detector(i)} = [dEdx\ detector(i) - \langle dEdx \rangle_{detector(i)\ for\ \mu\ from\ Z}] / \sigma(dEdx)_{detector(i)\ for\ \mu\ from\ Z}$$





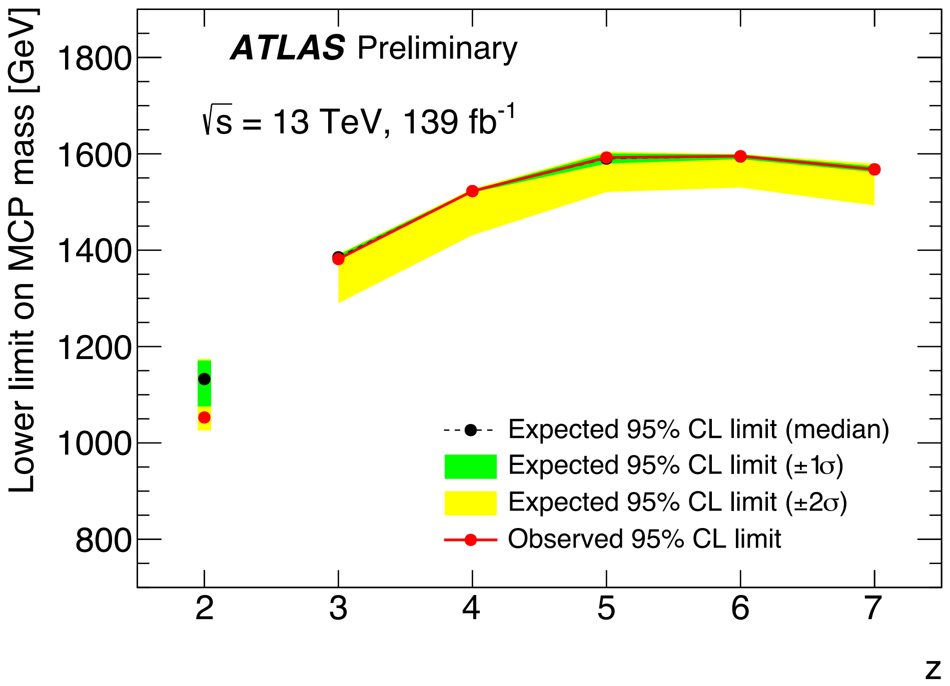
here S measured at 1m (TRT) and 10m (MDT) and their correlation compared with MCh-particles



Background is data driven and generated through the ABCD method (summing all S_{dEdx} contributions). Observed events is the sum of all those above $S_{threshold}$

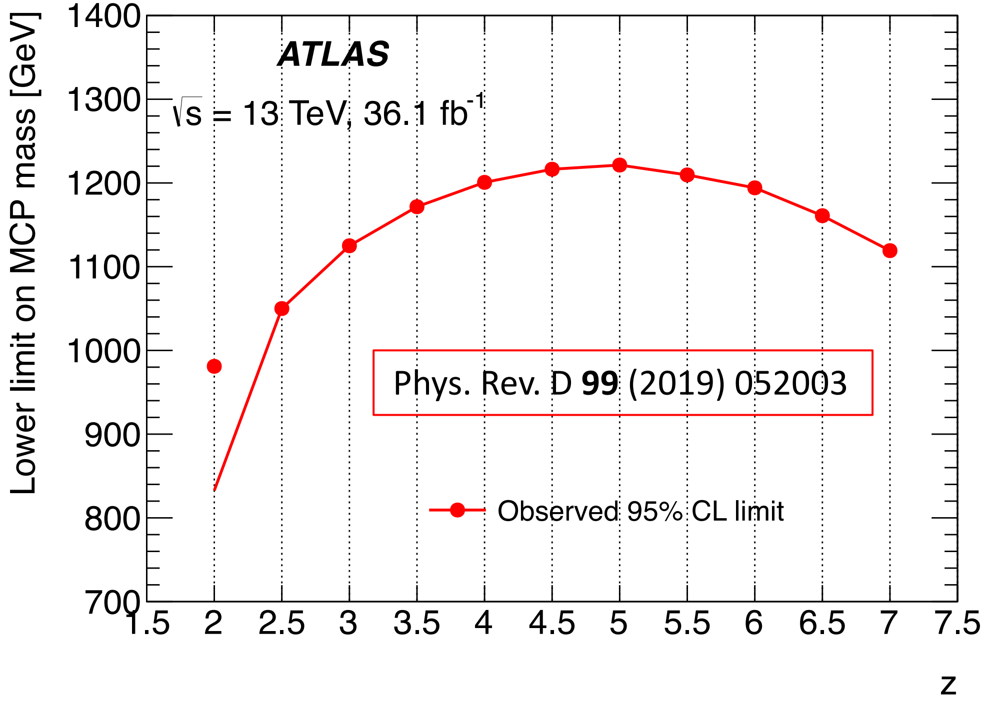
Selection	$N^{A\ observed}_{data}$	$N^{B\ observed}_{data}$	$N^{C\ observed}_{data}$	$N^{D\ expected}_{data}$	$N^{D\ observed}_{data}$
$z = 2$	24 294	4039	9	1.5 ± 0.5 (stat.) ± 0.5 (syst.)	4
$z > 2$	192 036 934	15 004	441	0.034 ± 0.002 (stat.) ± 0.004 (syst.)	0

p_0=6%



Observed and expected 95% CL lower mass limits of MCPs versus charge.

Improvement in mass limit of up to 400 GeV vs previous measurement thanks to increase integrated luminosity and addition of slow muon trigger (smaller improvement at z=2)



Conclusions

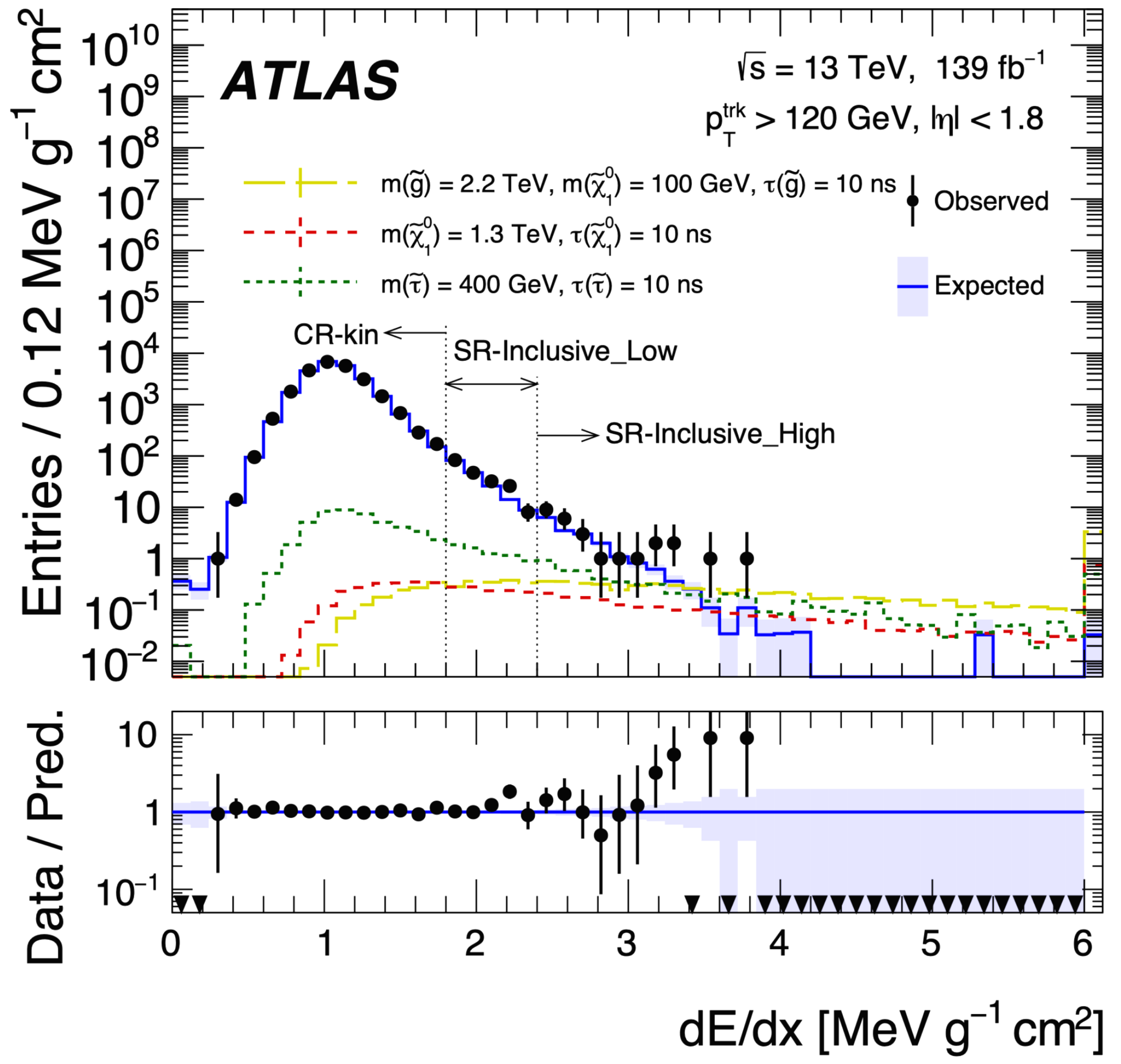
Measurements of large ionization losses (in the Pixel detector) has been used to

- Set competitive limits on gluino, chargino and stau models over a wide lifetime range
- In this search a 3.3σ excess has been observed for m~1.4 TeV. Detailed cross checks on data quality did not find any problem in the 7 tracks belonging to the excess.
- The slowness of these 7 particles has not been confirmed by ToF measurements from the calorimeter system and the muon spectrometer.

In a different analysis (using Pixel, TRT and MDT) long lifetime multi-charged (MCh) particles has been searched for and

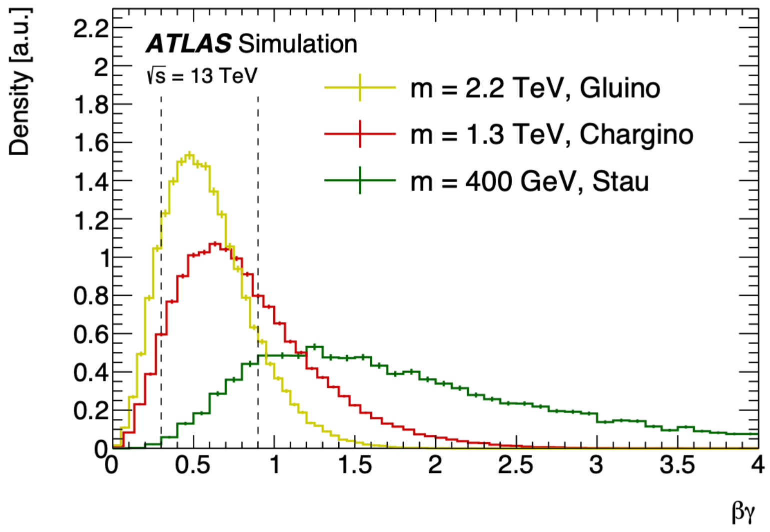
- Mass limits on hypothetical MCh particles has been set improving previous limits

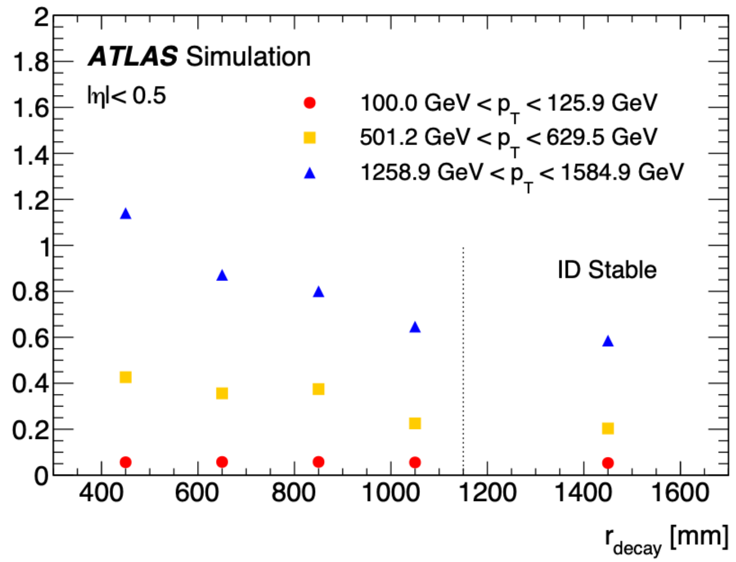
backup

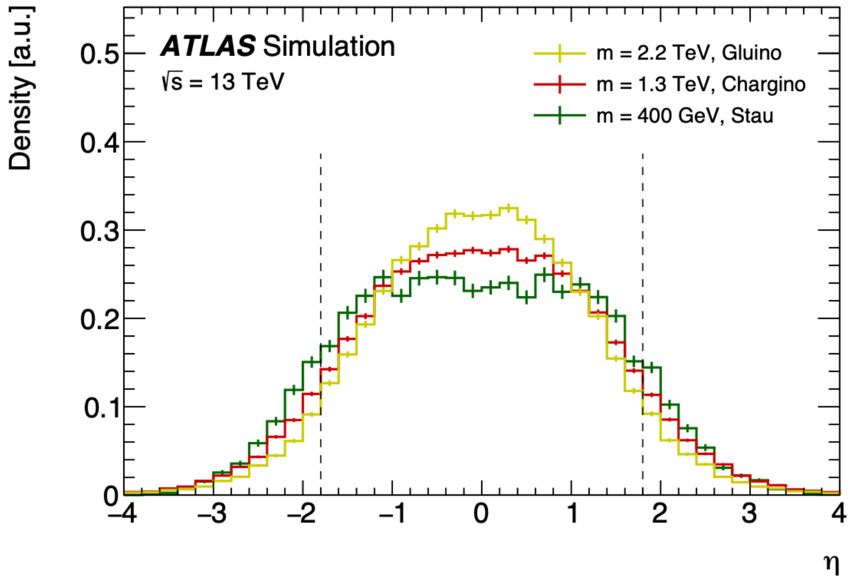


The event distribution in dE/dx in the inclusive signal region and the low-dE/dx range (CR-kin). The expected distribution has been derived from the CR-dEdx data sample properly normalised. The band on the expected background indicates the total uncertainty of the estimation. Downward triangle markers at the bottom of the panels indicate that no events are observed in the corresponding mass bin.

Signal kinematics

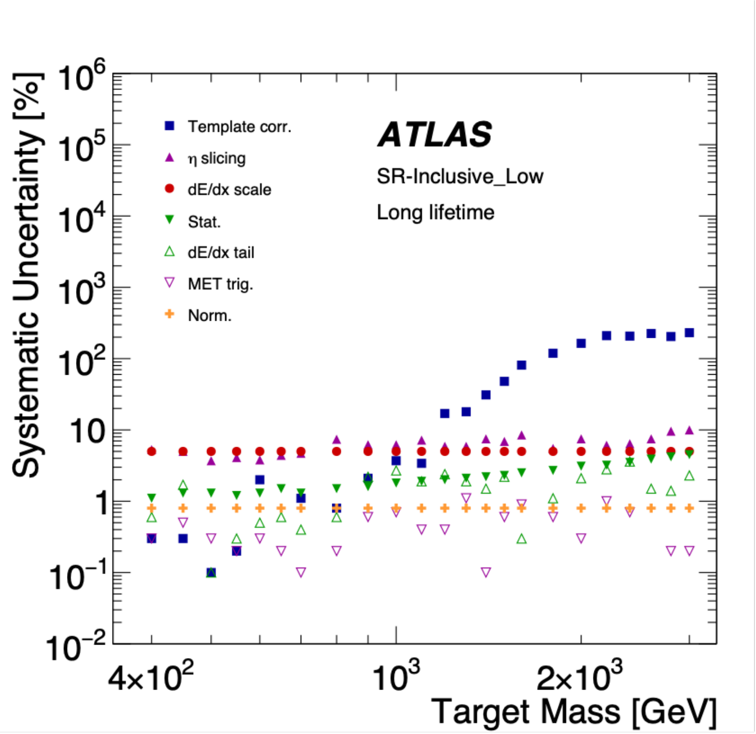


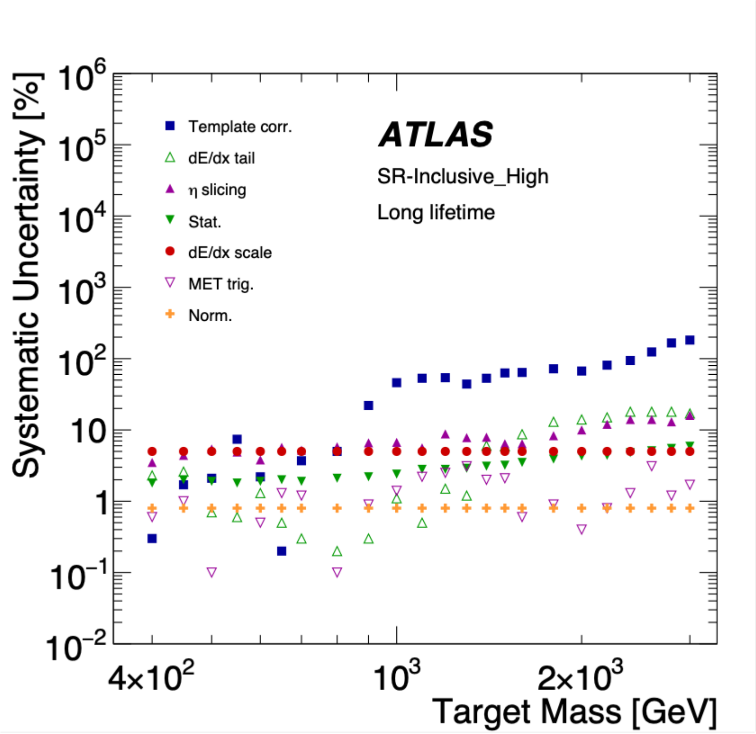




Heavy particles are produced centrally at the LHC

Background systematic uncertainties





- Systematic uncertainty is calculated for each SR as a function of target mass window
- Systematic uncertainty increases as a function of target mass
- Largest uncertainties for SR-Inclusive_High include the template correlations uncertainty and the dE/dx tail uncertainty

Background systematic uncertainties

Template correlation:

- The background estimation technique draws from the kinematic and dE/dx templates separately to calculate the toy mass distribution. This relies on the assumption that pT and dE/dx are not correlated for a given background track except through the dE/dx dependence on h (which is accounted for through h-slicing).
- To evaluate the validity of this assumption, a “fake” SR is created by inverting the ETmiss cut.
- Then compare background distribution obtained using both kinematic and dE/dx template of the “fake” SR with experimental data (of the ”fake”SR).

- Differences between “generated” and data must be due to unaccounted-for correlations and are then added as systematics.
- This systematics becomes dominant for m > 1 TeV

Background systematic uncertainties

dE/dx tail:

- Instead of generating toy dE/dx distribution from the dE/dx-CR directly, do a fit to the dE/dx tail and sample the analytic fit instead
- Then compare background distribution with nominal one
- Probes effect of tail statistics on the background estimation

MET Trigger:

- Due to the changing trigger threshold across Run-2, the fraction of tracks sorted into the dE/dx-CR (MET<170) vs SR (MET>170) will vary across data-taking periods. In the background estimation, we calculate a weight to correct for this and apply to the dE/dx-CR
- For the systematic, we turn the weights off, redo the background estimation, and compare to the nominal

Background systematic uncertainties

η slicing:

- Because the dE/dx distribution varies as a function of η, we slice the dE/dx-CR template into η bins
- To probe any bias that comes from the choice of bins, we choose a different binning and compare the difference in the background distribution

Statistics:

- The kinematic and dE/dx templates are poisson fluctuated to generate 20 alternative background distributions. The spread in these is taken as the uncertainty

Background systematic uncertainties

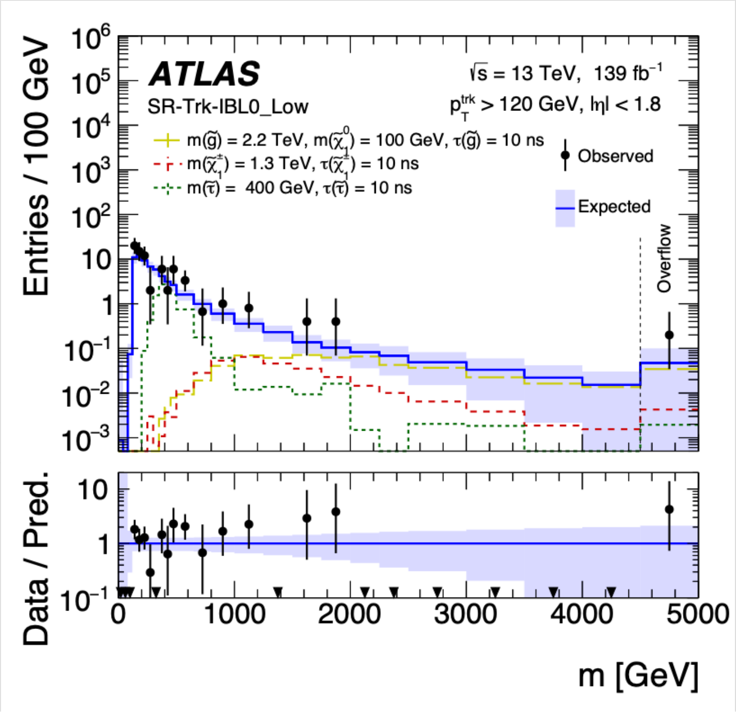
Normalization:

- Statistical uncertainty on the normalization factor which is used to scale the total amount of toys in the background distribution

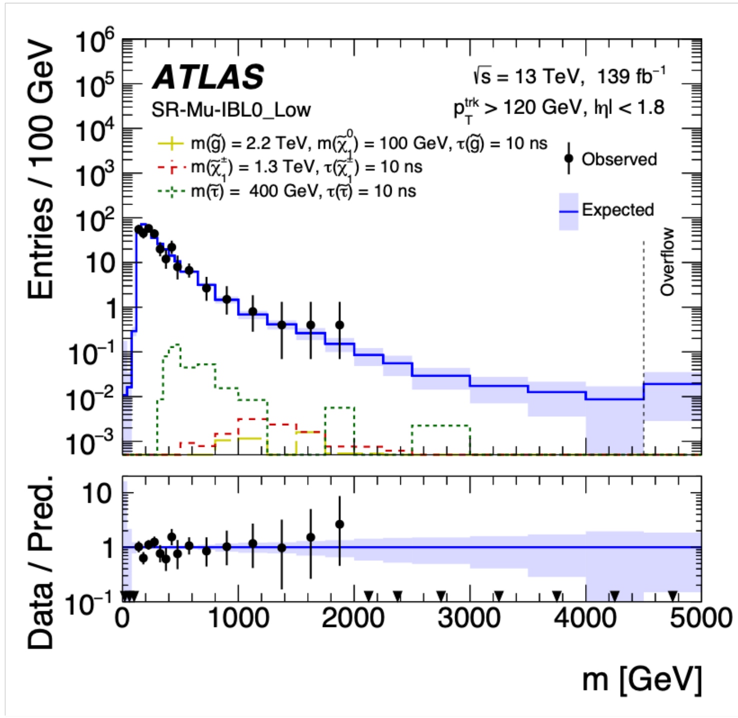
dE/dx scale:

- A disagreement was observed in one of the validation regions, VR-LowPt-Trk-IBL0_Low, where the estimated yield was **larger** than the observed data. A conservative uncertainty is quantified by fitting any discrepancies in the validation regions

Results



ATLAS
√s = 13 TeV, 139 fb⁻¹
SR-Trk-IBL0_Low
p_T^{trk} > 120 GeV, |η| < 1.8
m(g̃) = 2.2 TeV, m($\tilde{\chi}_1^0$) = 100 GeV, τ(g̃) = 10 ns
m($\tilde{\chi}_1^\pm$) = 1.3 TeV, τ($\tilde{\chi}_1^\pm$) = 10 ns
m(τ̃) = 400 GeV, τ(τ̃) = 10 ns
Observed
Expected
Overflow
Entries / 100 GeV
Data / Pred.
m [GeV]



ATLAS
√s = 13 TeV, 139 fb⁻¹
SR-Mu-IBL0_Low
p_T^{trk} > 120 GeV, |η| < 1.8
m(g̃) = 2.2 TeV, m($\tilde{\chi}_1^0$) = 100 GeV, τ(g̃) = 10 ns
m($\tilde{\chi}_1^\pm$) = 1.3 TeV, τ($\tilde{\chi}_1^\pm$) = 10 ns
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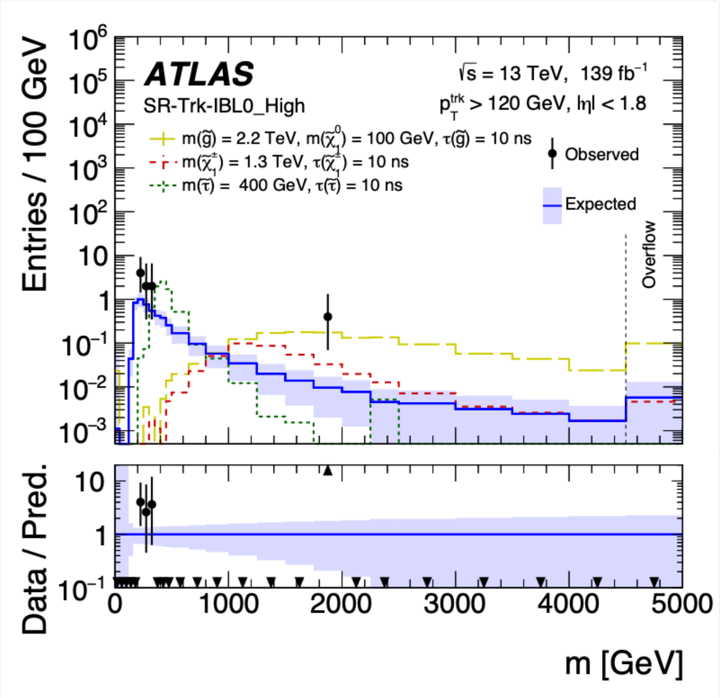
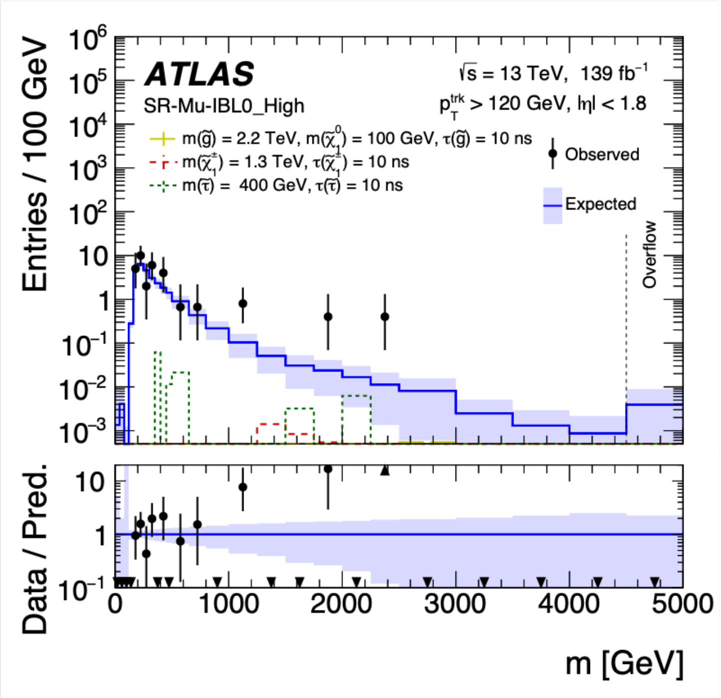
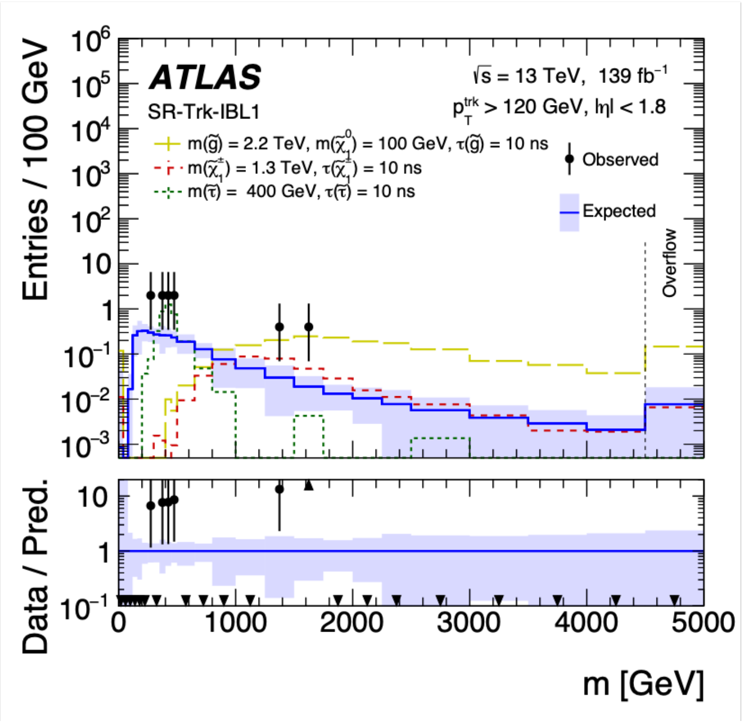
Observed
Expected
Overflow
Entries / 100 GeV
Data / Pred.
m [GeV]

Results

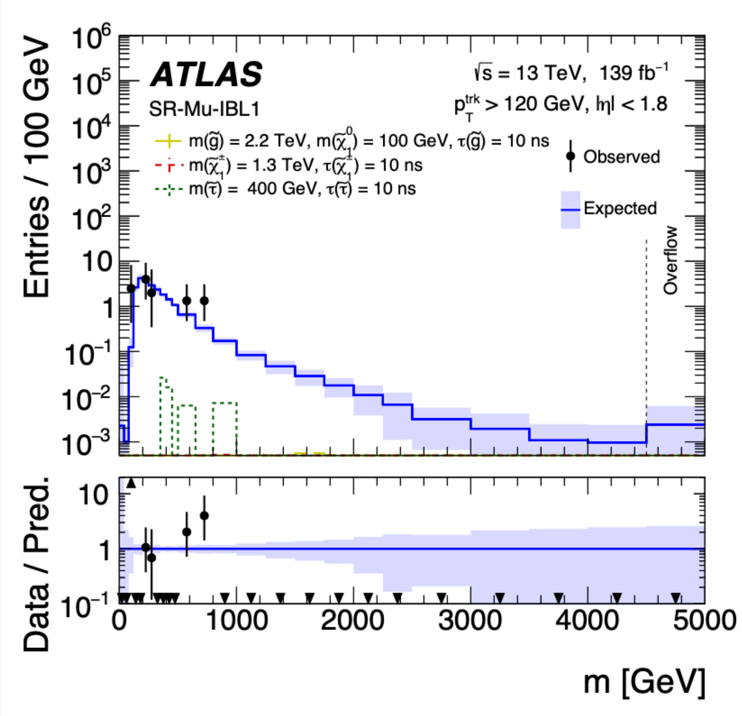

ATLAS
SR-Trk-IBL0_High
√s = 13 TeV, 139 fb⁻¹
p_T^trk > 120 GeV, |η| < 1.8
m(g̃) = 2.2 TeV, m(χ̃₁⁰) = 100 GeV, τ(g̃) = 10 ns
m(χ̃₁±) = 1.3 TeV, τ(χ̃₁±) = 10 ns
m(τ̃) = 400 GeV, τ(τ̃) = 10 ns
Observed
Expected
Overflow
Entries / 100 GeV
Data / Pred.
m [GeV]


ATLAS
SR-Mu-IBL0_High
√s = 13 TeV, 139 fb⁻¹
p_T^trk > 120 GeV, |η| < 1.8
m(g̃) = 2.2 TeV, m(χ̃₁⁰) = 100 GeV, τ(g̃) = 10 ns
m(χ̃₁±) = 1.3 TeV, τ(χ̃₁±) = 10 ns
m(τ̃) = 400 GeV, τ(τ̃) = 10 ns
Observed
Expected
Overflow
Entries / 100 GeV
Data / Pred.
m [GeV]

Results

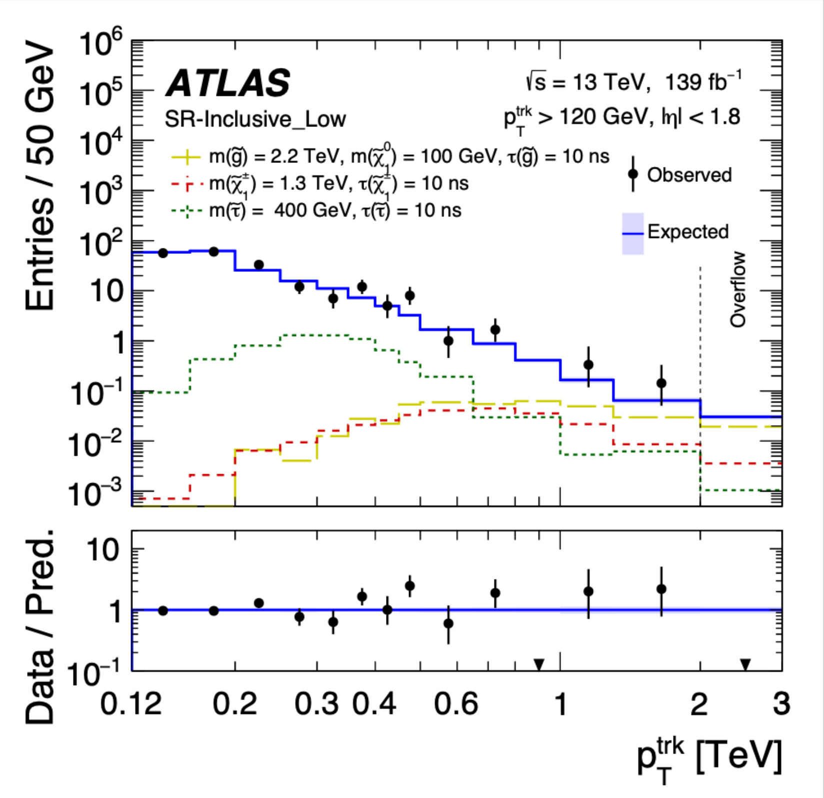


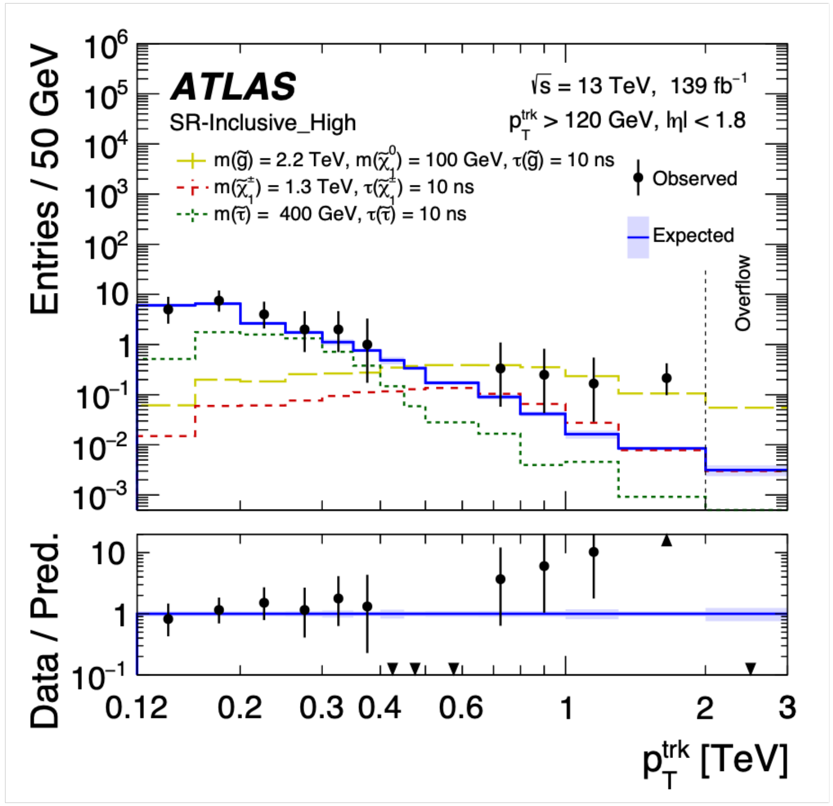
ATLAS
SR-Trk-IBL1
√s = 13 TeV, 139 fb⁻¹
p_T^trk > 120 GeV, |η| < 1.8
m(g̃) = 2.2 TeV, m(χ̃₁⁰) = 100 GeV, τ(g̃) = 10 ns
m(χ̃₁±) = 1.3 TeV, τ(χ̃₁±) = 10 ns
m(τ̃) = 400 GeV, τ(τ̃) = 10 ns
Observed
Expected
Overflow
Entries / 100 GeV
Data / Pred.
m [GeV]



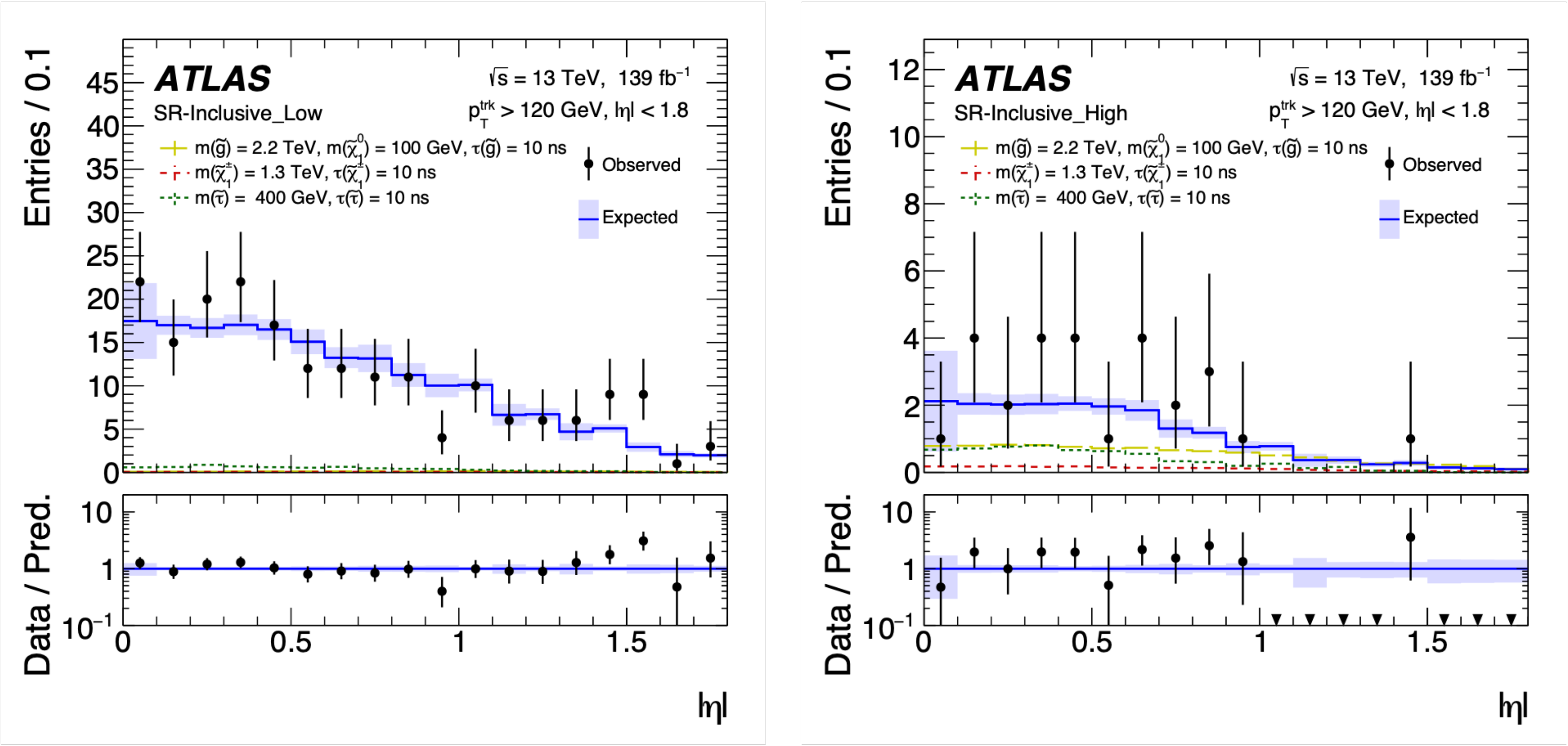
ATLAS
SR-Mu-IBL1
√s = 13 TeV, 139 fb⁻¹
p_T^trk > 120 GeV, |η| < 1.8
m(g̃) = 2.2 TeV, m(χ̃₁⁰) = 100 GeV, τ(g̃) = 10 ns
m(χ̃₁±) = 1.3 TeV, τ(χ̃₁±) = 10 ns
m(τ̃) = 400 GeV, τ(τ̃) = 10 ns
Observed
Expected
Overflow
Entries / 100 GeV
Data / Pred.
m [GeV]

pT, η, dE/dx distributions

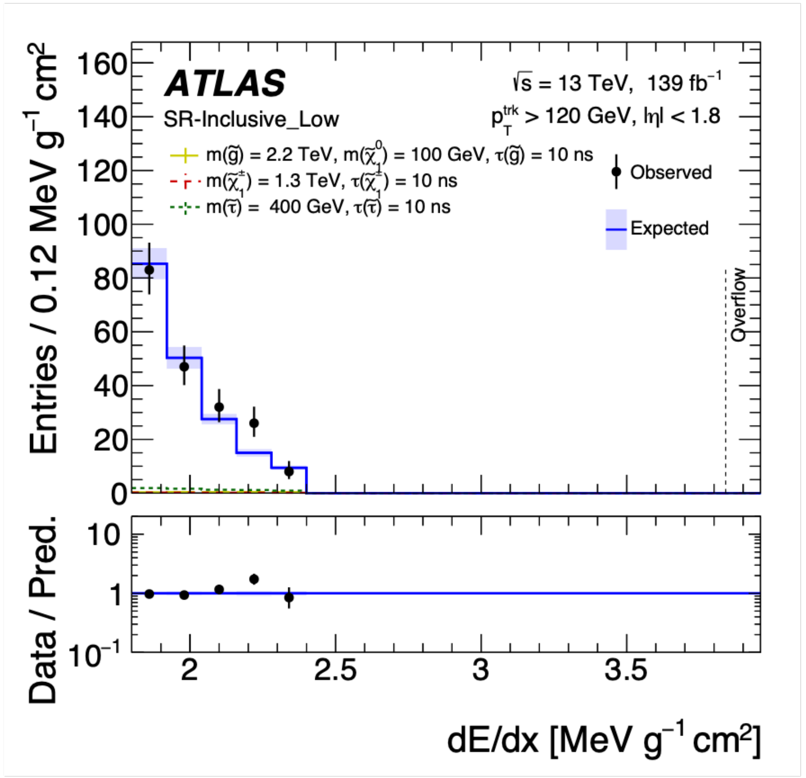


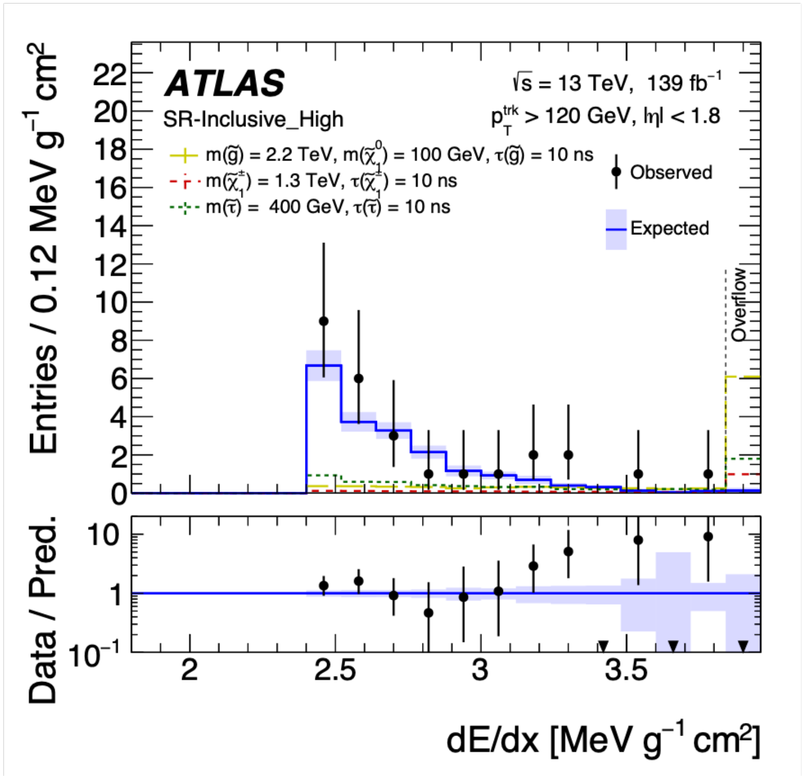


p_T, η, dE/dx distributions

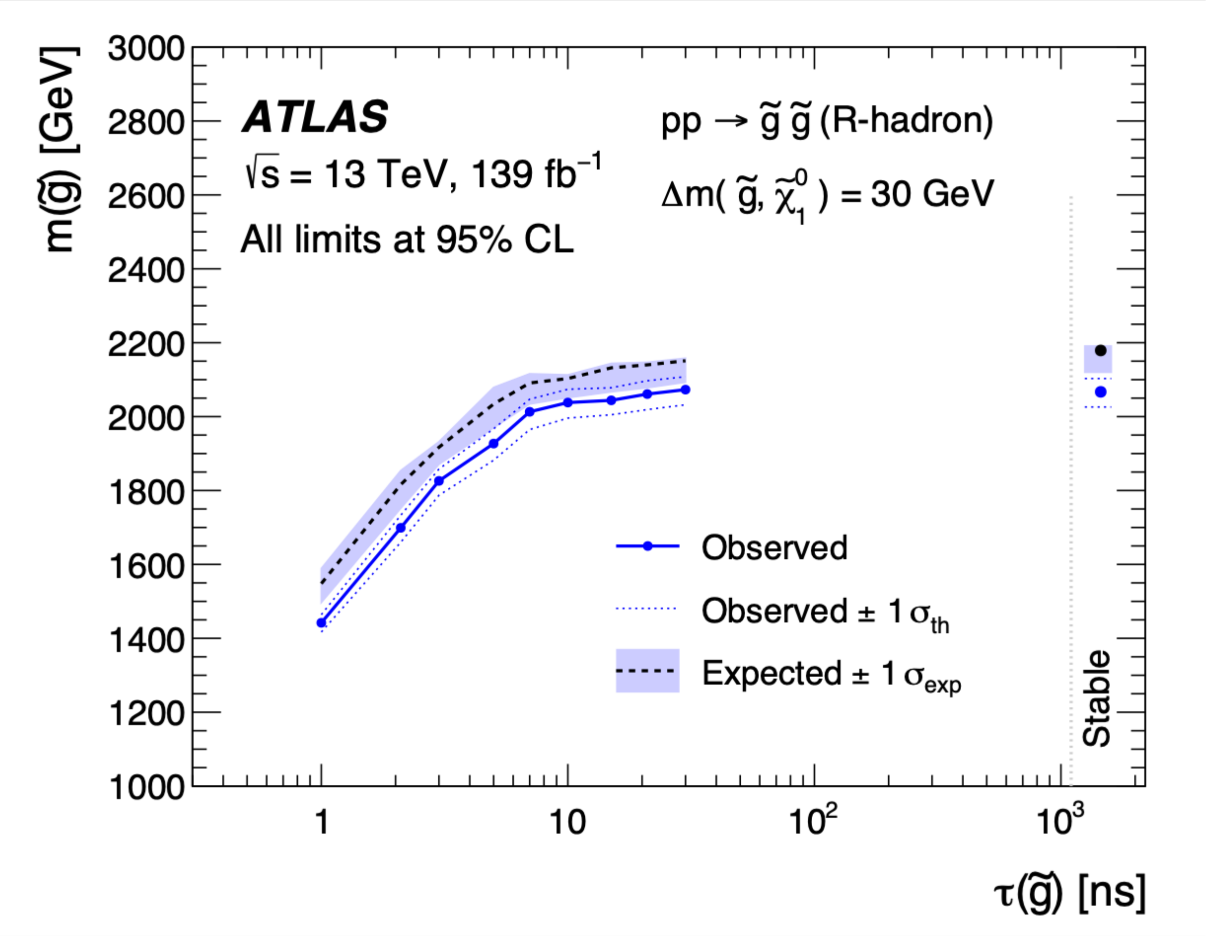


p_T, η, dE/dx distributions





Compressed R-hadrons



Efficiency for various LLPs

Mass [GeV]	0.3 ns	1 ns	3 ns	10 ns	30 ns	stable
100	0.000	–	0.000	0.000	0.000	0.000
200	0.001	–	0.006	0.004	0.002	0.000
300	0.010	–	0.021	0.016	0.010	0.001
400	0.012	–	0.035	0.031	0.020	0.005
450	–	0.034	–	0.040	–	0.006
500	0.013	–	0.056	0.049	0.034	0.010
550	–	0.053	–	0.058	–	0.012
600	0.025	0.056	0.074	0.064	0.046	0.015
650	–	0.068	–	0.074	–	0.020
700	0.019	0.075	0.090	0.082	0.058	0.022
800	0.032	0.090	0.110	0.095	0.066	0.027
900	0.031	0.098	0.119	0.110	0.080	0.034
1000	0.032	0.114	0.141	0.125	0.089	0.038

stau
1.8<dEdx<2.4

Mass [GeV]	0.3 ns	1 ns	3 ns	10 ns	30 ns	stable
100	0.000	–	0.000	0.000	0.000	0.000
200	0.001	–	0.003	0.002	0.001	0.000
300	0.001	–	0.013	0.012	0.007	0.001
400	0.003	–	0.025	0.028	0.019	0.004
450	–	0.018	–	0.040	–	0.006
500	0.005	–	0.043	0.047	0.033	0.008
550	–	0.027	–	0.059	–	0.012
600	0.006	0.030	0.060	0.066	0.045	0.014
650	–	0.033	–	0.080	–	0.017
700	0.008	0.043	0.082	0.086	0.063	0.021
800	0.004	0.047	0.094	0.111	0.080	0.027
900	0.015	0.060	0.117	0.134	0.093	0.033
1000	0.018	0.073	0.138	0.155	0.113	0.042

stau
dEdx>2.4

Mass [GeV]	0.2 ns	1 ns	4 ns	10 ns	30 ns	stable
90	0.000	0.000	0.065	0.000	0.001	0.001
200	0.000	0.003	0.122	0.008	0.007	0.002
250	–	–	–	–	0.016	0.005
300	0.000	0.007	0.127	0.027	0.027	0.002
350	–	–	–	–	0.039	0.012
400	0.000	0.014	0.037	0.046	0.046	0.015
500	0.000	0.023	0.041	0.063	0.067	0.024
600	0.000	0.029	0.063	0.076	0.034	0.033
700	0.000	0.036	0.076	0.031	0.095	0.003
800	0.000	0.041	0.082	0.098	0.000	0.046
900	0.000	0.048	0.096	0.108	0.115	0.053
1000	0.000	0.059	0.101	0.118	0.125	0.061
1100	–	–	0.112	0.124	0.134	0.064
1200	–	–	0.122	0.137	0.145	0.069
1300	–	–	0.127	0.146	0.154	0.077
1400	–	–	0.142	0.155	0.162	0.076
1500	–	–	0.147	0.164	0.169	0.087
1600	–	–	0.151	0.172	0.173	0.090

Chargino
dEdx>2.4

Mass [GeV]	0.3 ns	1 ns	3 ns	10 ns	30 ns	stable
400	0.022	0.036	0.055	0.058	0.053	0.031
450	–	0.043	–	0.077	–	0.039
500	0.000	0.054	0.095	0.095	0.081	0.048
550	–	0.071	–	0.111	–	0.054
600	0.036	0.078	0.127	0.127	0.104	0.061
650	–	0.088	–	0.140	–	0.067
700	0.000	0.101	0.156	0.159	0.131	0.071
800	0.010	0.123	0.183	0.188	0.145	0.081
1000	0.000	0.153	0.236	0.240	0.187	0.098
1200	0.000	0.192	0.292	0.290	0.229	0.111
1400	0.000	0.221	0.321	0.325	0.260	0.126
1600	0.090	0.303	0.366	0.375	0.294	0.132
1800	0.072	0.287	0.392	0.401	0.313	0.132
2000	–	0.315	0.432	0.425	0.330	0.137
2200	–	–	0.446	0.449	0.350	0.137
2400	–	–	0.465	0.466	0.362	0.132
2600	–	–	0.485	0.469	0.363	0.130
2800	–	–	–	0.482	0.373	0.120
3000	–	–	–	0.495	0.382	0.115

RH
dEdx>2.4

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	$\left(\Sigma_{\mathrm{trk}}\, p_{\mathrm{T}}\right) < 5$ 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 $\mathrm{g}^{-1}\mathrm{cm}^2$
		`High`: $\mathrm{d}E/\mathrm{d}x > 2.4$ MeV $\mathrm{g}^{-1}\mathrm{cm}^2$
	Binned	`IBL0_Low`: $\mathrm{d}E/\mathrm{d}x \in [1.8, 2.4]$ MeV $\mathrm{g}^{-1}\mathrm{cm}^2$ and $\mathrm{OF}_{\mathrm{IBL}} = 0$
		`IBL0_High`: $\mathrm{d}E/\mathrm{d}x > 2.4$ MeV $\mathrm{g}^{-1}\mathrm{cm}^2$ and $\mathrm{OF}_{\mathrm{IBL}} = 0$
		`IBL1`: $\mathrm{d}E/\mathrm{d}x > 1.8$ MeV $\mathrm{g}^{-1}\mathrm{cm}^2$ and $\mathrm{OF}_{\mathrm{IBL}} = 1$

Summary of signal selection.

Region	Category	Bin	Expected	Observed
`VR-LowPt`	`Trk`	`IBL0_Low`	65.6 ± 18.3	43
		`IBL0_High`	6.8 ± 2.2	6
		`IBL1`	3.8 ± 1.5	4
	`Mu`	`IBL0_Low`	292 ± 17	300
		`IBL0_High`	24.8 ± 3.6	32
		`IBL1`	20.4 ± 3.7	19
	`Inclusive`	`Low`	391 ± 24	361
		`High`	37.2 ± 4.4	43
`VR-HiEta`	`Trk`	`IBL0`	26.6 ± 7.3	23
		`IBL1`	8.0 ± 2.6	5
	`Mu`	`IBL0`	56.4 ± 2.5	59
		`IBL1`	15.1 ± 1.5	10
	`Inclusive`	—	101 ± 6	97

Expected and observed event yields in the validation-region bins.

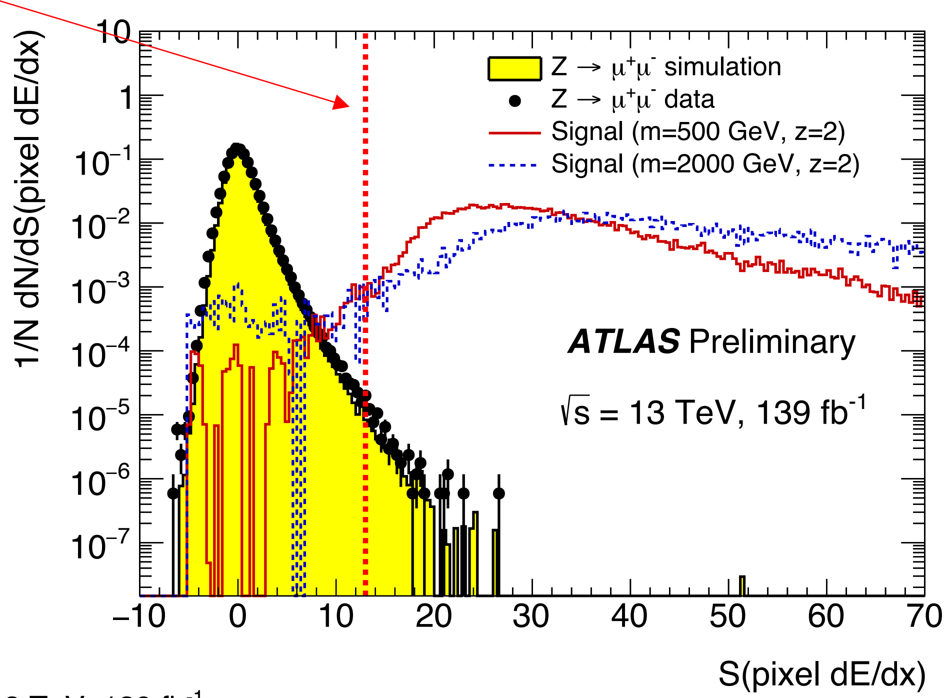
Region	p_T [GeV]	$|\eta|$	E_T^{miss} [GeV]	dE/dx [MeV $g^{-1}cm^2$]
SR			> 170	> 1.8
CR-kin	> 120	< 1.8	> 170	< 1.8
CR-dEdx			< 170	> 0
VR-LowPt			> 170	> 1.8
CR-LowPt-kin	[50, 110]	< 1.8	> 170	< 1.8
CR-LowPt-dEdx			< 170	> 0
VR-HiEta			> 170	> 1.6
CR-HiEta-kin	> 50	[1.8, 2.5]	> 170	< 1.6
CR-HiEta-dEdx			< 170	> 0

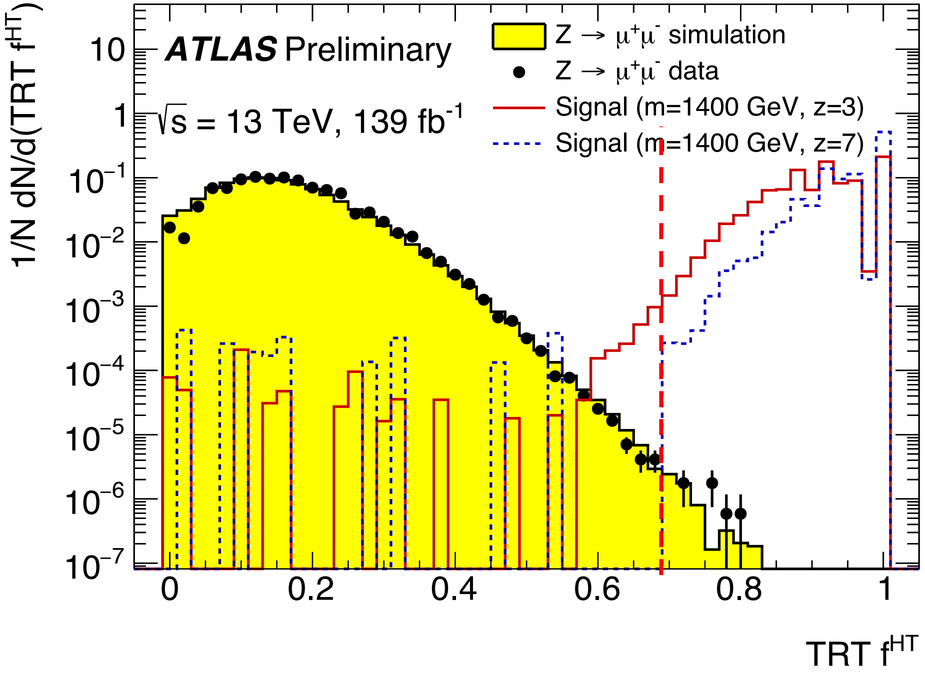
Definitions of the signal, control and validation regions.

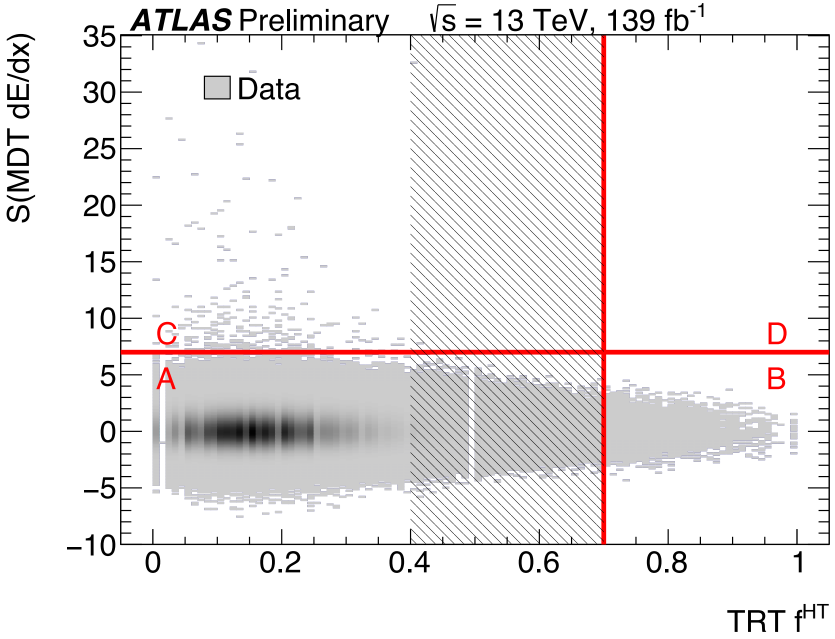
SR name	Discovery	Limit setting	Track category	IBL overflow	dE/dx [MeV $g^{-1}cm^2$]
SR-Inclusive_Low	✓		inclusive	yes or no	[1.8, 2.4]
SR-Inclusive_High	✓				> 2.4
SR-Trk-IBL0_Low		✓	track	no	[1.8, 2.4]
SR-Trk-IBL0_High		✓		no	> 2.4
SR-Trk-IBL1		✓		yes	> 1.8
SR-Mu-IBL0_Low		✓	muon tracks	no	[1.8, 2.4]
SR-Mu-IBL0_High		✓		no	> 2.4
SR-Mu-IBL1		✓		yes	> 1.8

Table of signal-region bins, showing their purpose (discovery or limit setting) and properties.

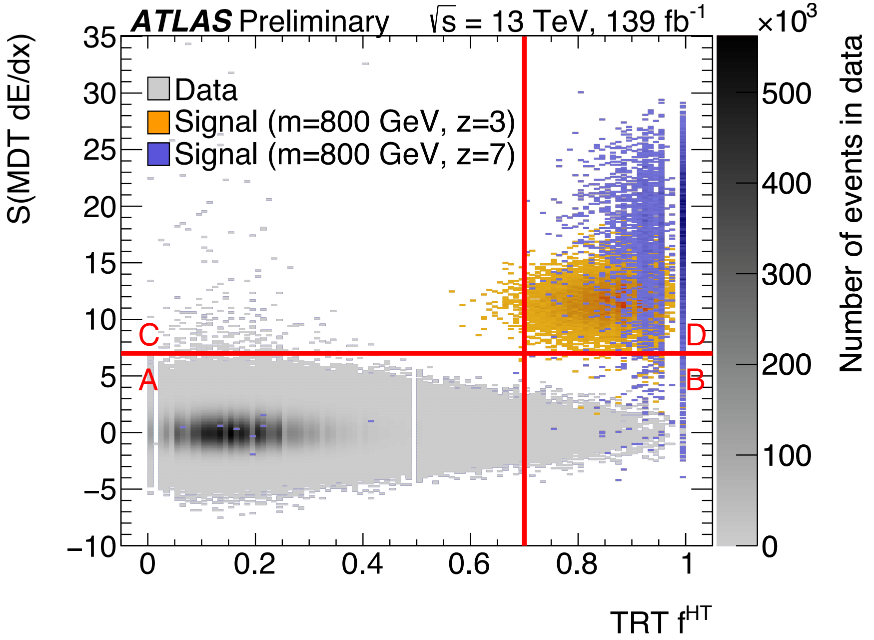
S>13 corresponds to dEdx>3.1 Mev $g^{-1}cm^2$

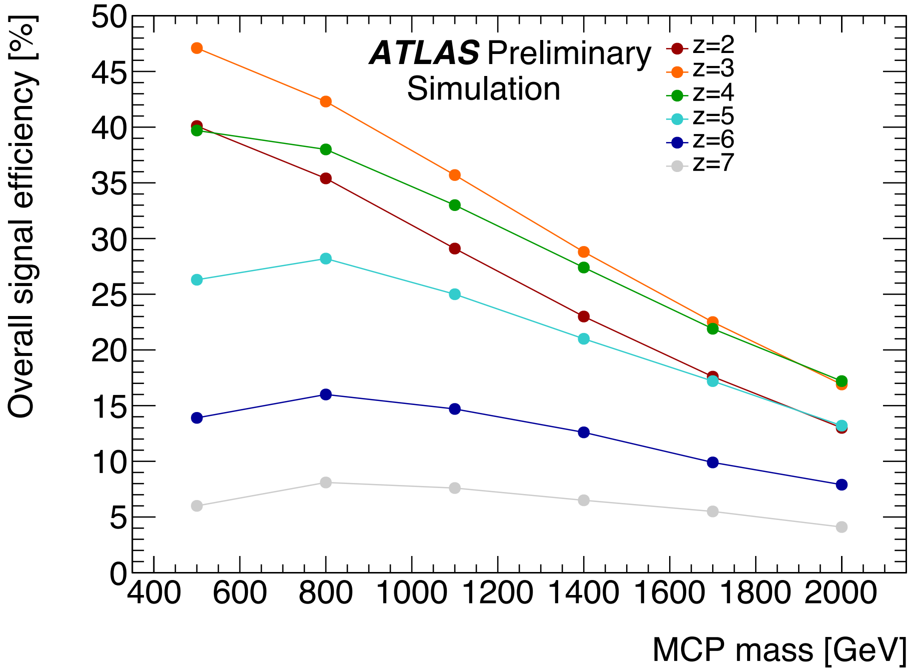


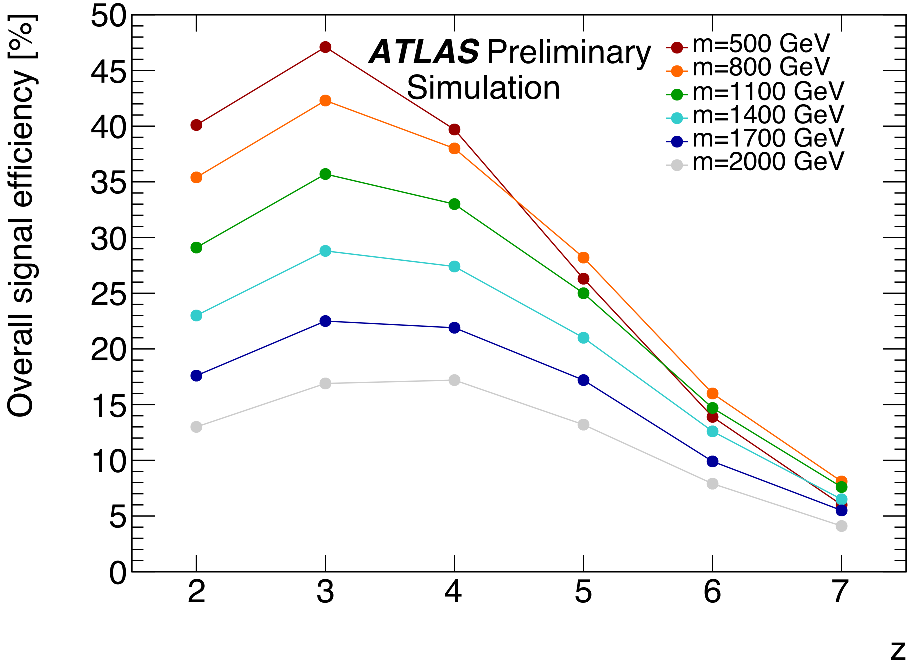


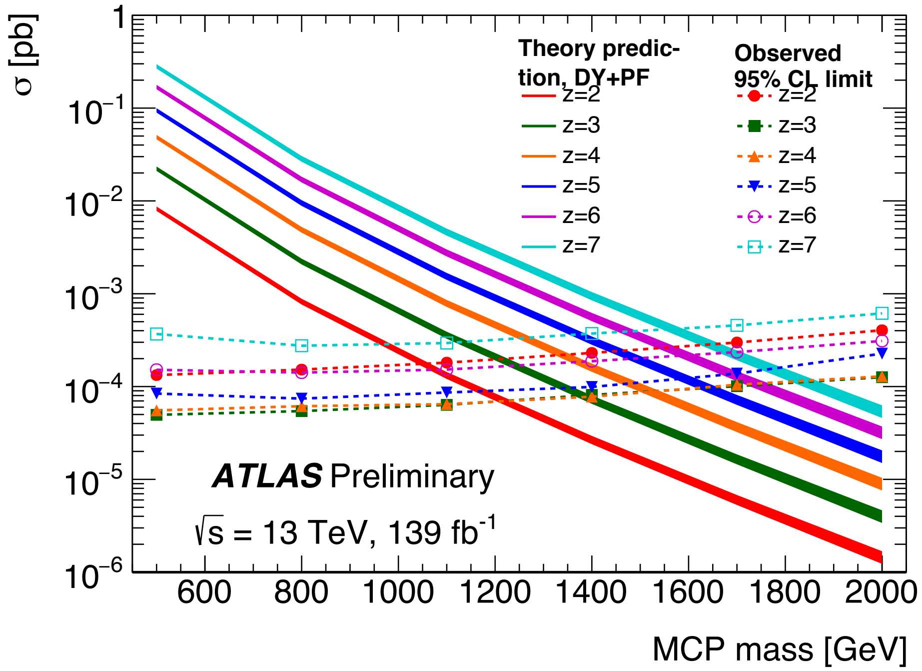


ABCD plane for the z>2 case used to assess the systematic uncertainty in the expected number of background events. Entries inside the ``masked region'' (here within $0.4 < f^{HT} < 0.7$, shown by the black shading) do not contribute to the background estimate.









Observed 95% CL cross-section upper limits and theoretical cross-sections as functions of the muon-like MCP's mass. Theoretical cross-section values are computed at LO and the uncertainty bands correspond to the PDF uncertainties