Search for heavy, long-lived, charged particles with large ionisation energy loss in $p\,p$ collisions at $\sqrt{(s)} = 13$ TeV using the ATLAS experiment and the full Run 2 dataset

Ismet Siral

on Behalf of ATLAS Collaboration

La Thuile March 6-12, 2022

Paper is soon to be published:

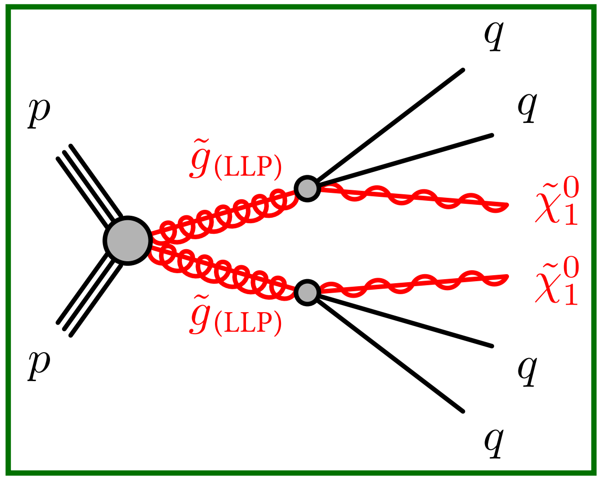
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-42/

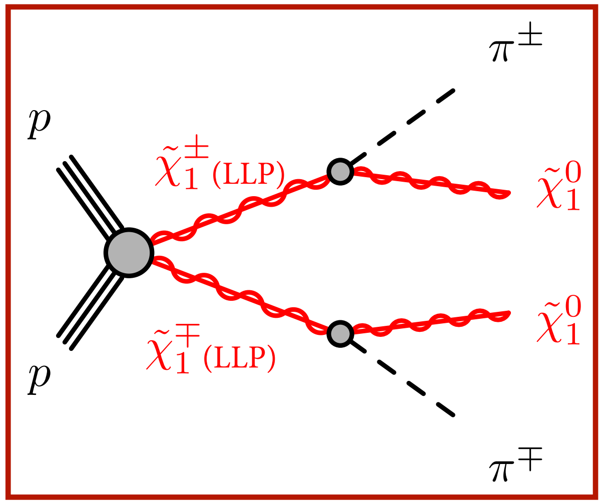
ATLAS EXPERIMENT

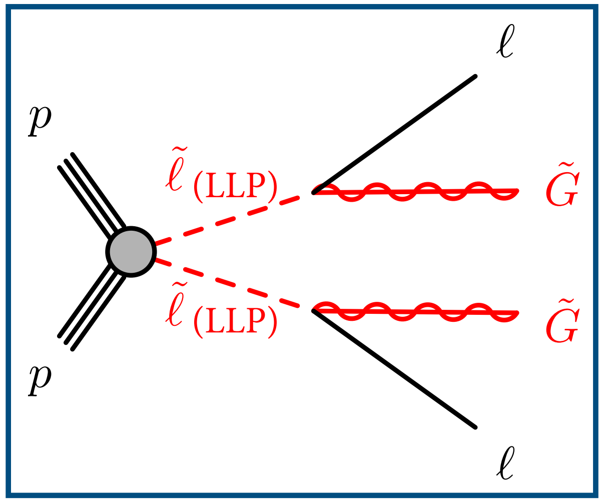
UNIVERSITY OF OREGON

Introduction

- In the SUSY dE/dx analysis, we attempt to detect the masses of long-lived particles that may or may not decay in the ATLAS detector, using the energy they deposit inside the pixel detector (dE/dx).
  - Using the ionization energy loss (dE/dx) we can extract the $\beta\gamma$
  - Reconstruct the mass of these tracks using $p/\beta\gamma = M$
- We are sensitive to majority of charged LLP with life-times longer than 1ns.
  - We are considering gluinos that form R-hadrons as well as sleptons and charginos, but the analysis is designed aimed to be model independent.
- The search strategy of this analysis is:
  - Identifying isolated tracks with high transverse momentum (p_T), and large specific ionisation.
  - Reconstruct the mass.
  - Generate data-driven background distributions
  - Identify mass windows containing good signal over background ratio as a function of signal model mass and lifetime and set limits or find excesses in those windows.

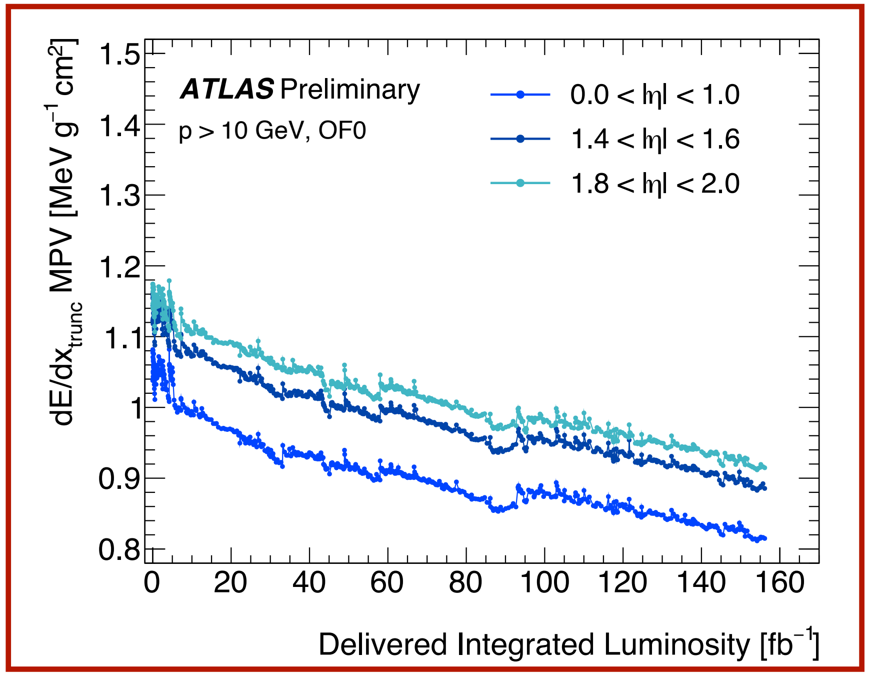






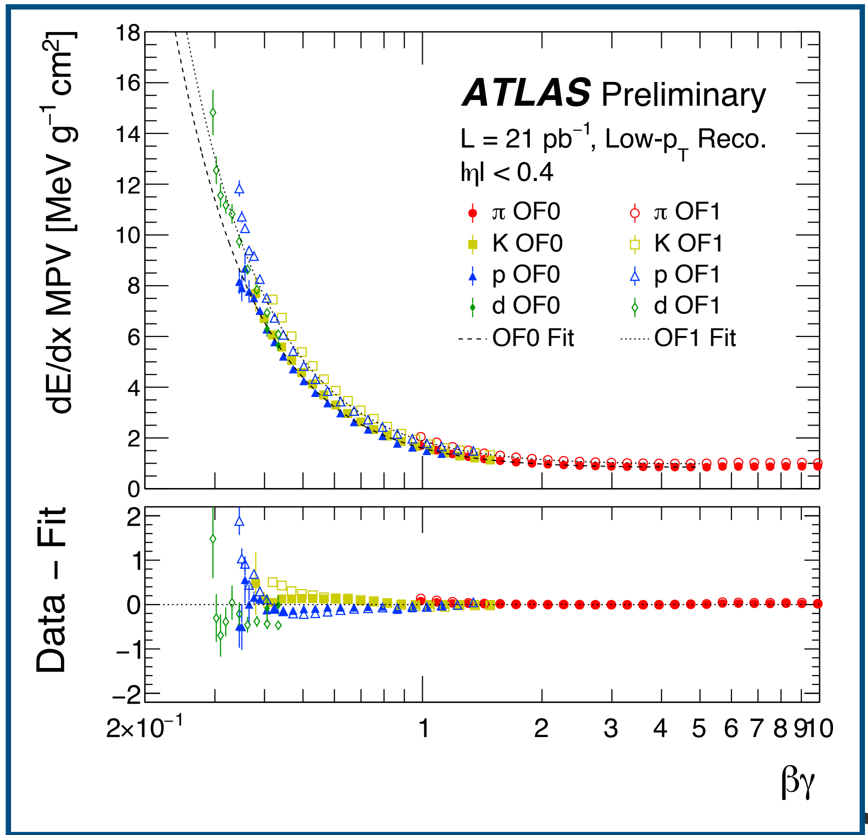
dE/dx Measurement, Calibration and $\beta\gamma$ mapping

- When charged particles pass through the inner detector layer, they deposit energy and multiple pixel hits across a pixel layer are recorded.



- The dE/dx measurement of an individual track is calculated by averaging the individual clusters that are associated with the tracks. ($< dE/dx >_{\mathrm{trunc}}$)

- The $< dE/dx >_{\mathrm{trunc}}$ values are $|\eta|$, detector conditions dependent. Each $< dE/dx >_{\mathrm{trunc}}$ measurement is calibrated as a function of run-number and $|\eta|$ to be flat on comparable. ($< dE/dx >_{\mathrm{corr}}$)



- Then a mapping of $\beta\gamma$ to $< dE/dx >_{\mathrm{corr}}$ is extracted in low-mu runs and are then used for extracting the $\beta\gamma$ of each individual track.

Selection of Events and Tracks

Events are triggered with a E_T^{miss} Trigger that varies between 70-110 GeV
An additional offline E_T^{miss} requirement is applied at 170 GeV

- The E_T^{miss} cuts are mostly a necessity for background reduction and trigger requirements.

Good quality , high $p_T > 120$ GeV, central $|\eta| < 1.8$ tracks are selected. The quality is ensured by hit requirements.

Tracks associated with jets, w bosons, tau's and electrons are removed by various isolation and $m_T(\text{Track}, E_T^{\text{miss}})$ requirements

An ionization cut $dE/dx > 1.8$ is applied in-order to identify particles that have low $\beta\gamma$ which is correlated to large dE/dx. The ionization cut varies across signal categories.

Signal Region Definitions

SR For Discovery

- SR-Inclusive_Low
- SR-Inclusive_High

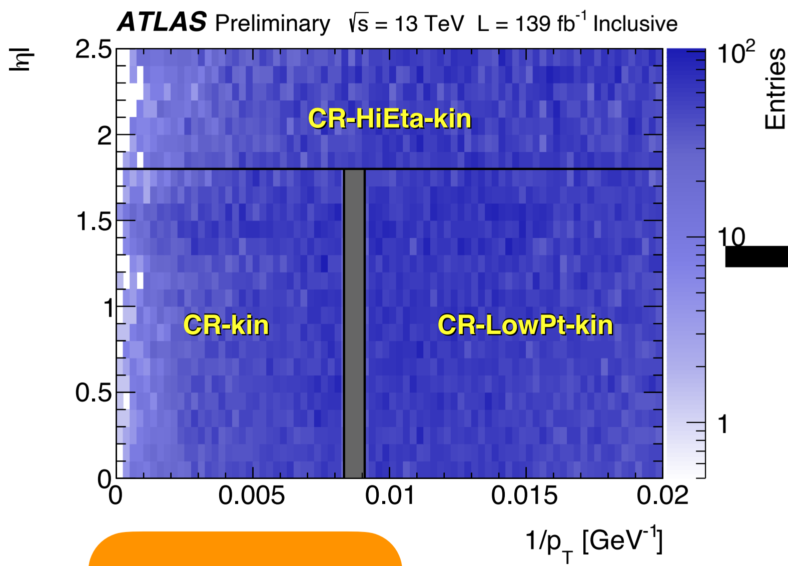
SR For Exclusion

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

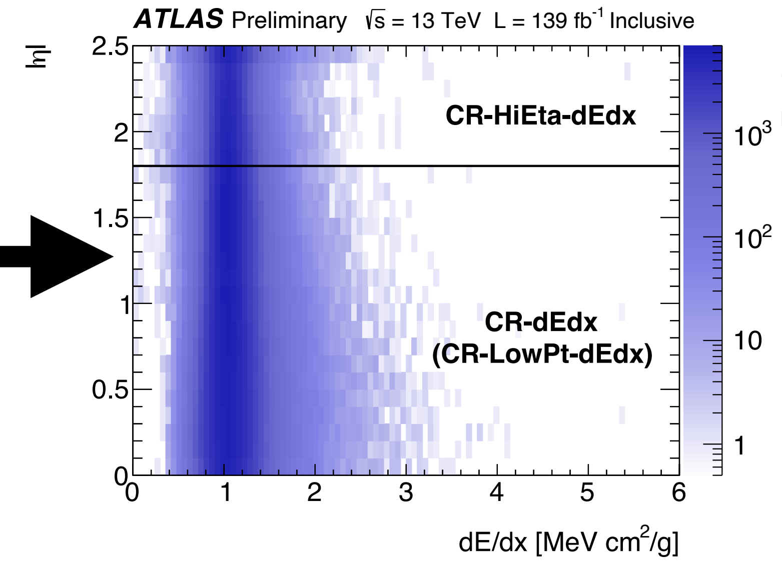
- 2 exclusive signal regions that are used for searching for new physics.
  - **dE/dx in (1.8, 2.4] (Low)**
  - **dE/dx in (2.4,∞] (High)**

- When we going for exclusion limits the events are categorized according to the selected track properties:
  - Matched to a Muon (Mu) or Not (Trk)
  - dE/dx in (1.8, 2.4] (Low) or (2.4,∞] (High)
  - Has a hit with an IBL Overflow (IBL1) {dE/dx > 1.8}

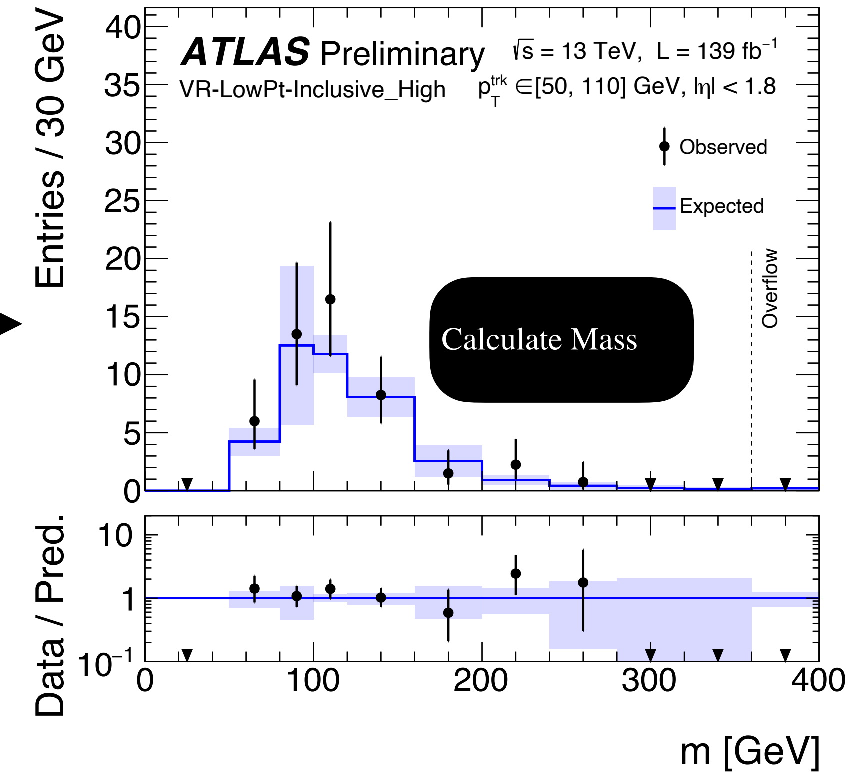
Background Estimation



Select a $(1/p_T, \eta)$



Select a dE/dx value according to η



- The analysis employs a fully data-driven background estimation that uses toys.
- The principle idea is to generate random toy tracks following the procedure below:

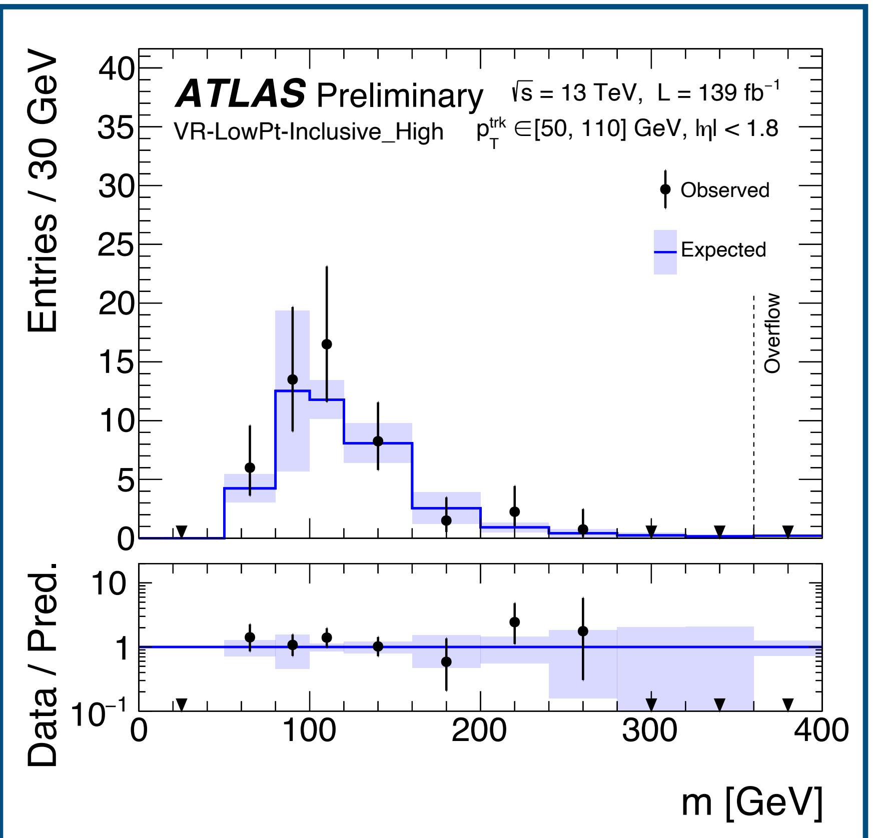
(1) Sample $(1/p_T, \eta)$ values from a region representing the kinematic profile of the SR (kinematic CR)

(2) Sample **dE/dx** value from corresponding from a region representing the dE/dx profile of the SR (dE/dx CR) (binned in η)

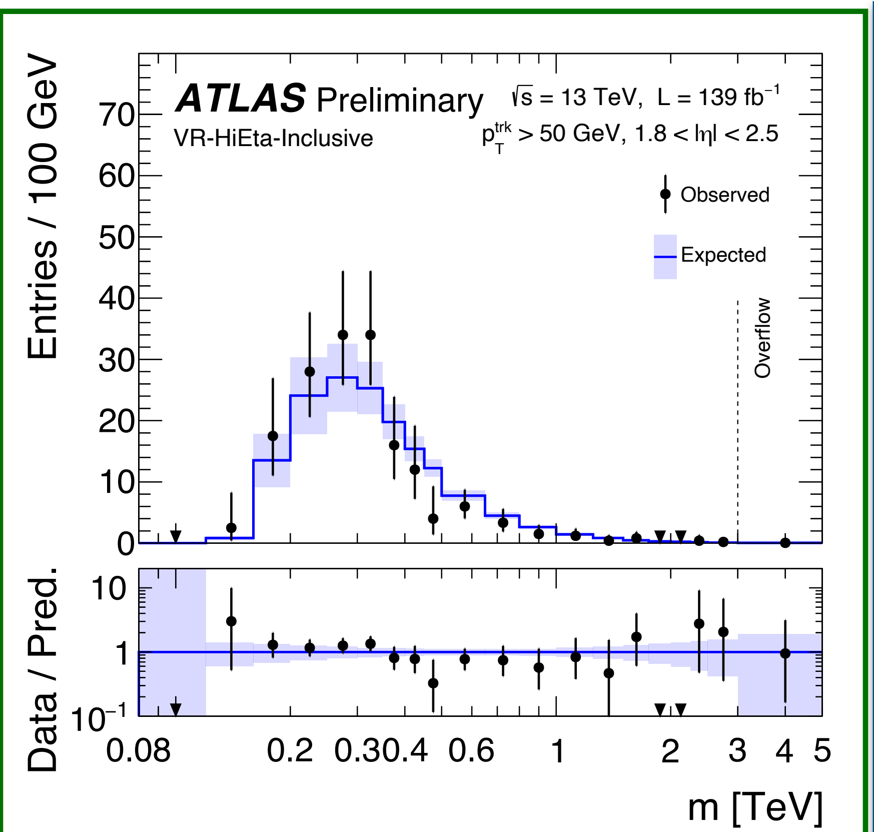
(3) Calculate mass of toy track from selected values $(m = p/\beta\gamma)$

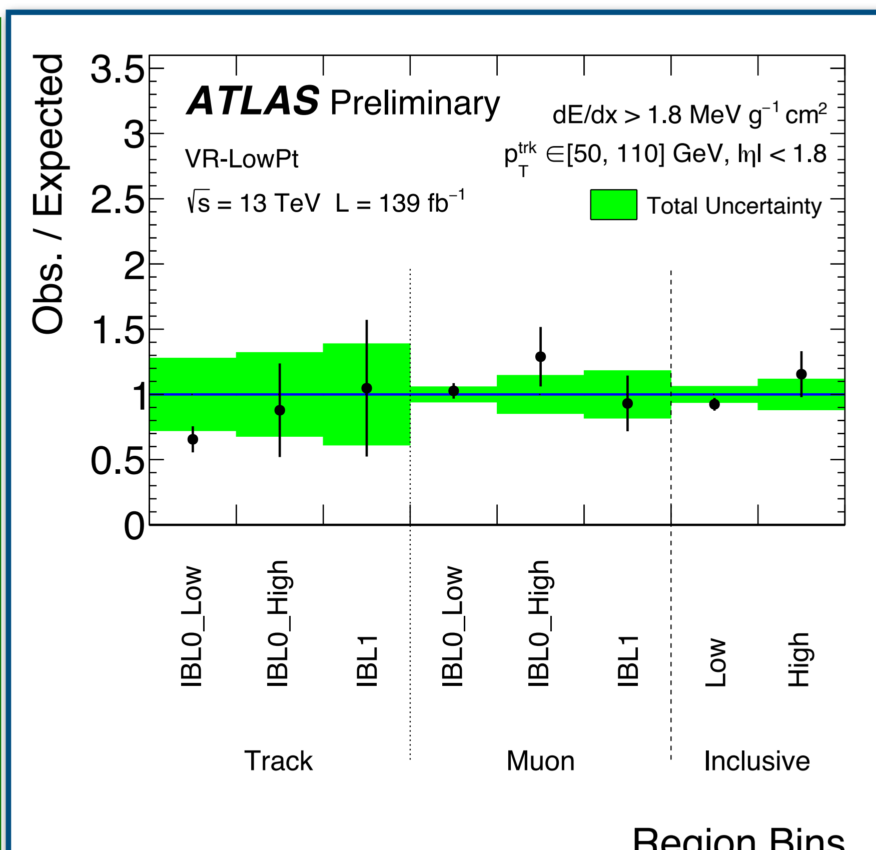
- This method is repeated millions of times for each category generating a mass distribution.
- The mass distribution is normalized to match the data on the low mass region where the signal contamination is negligible.
- Then a dE/dx cut is applied to the generated distribution and a new mass distribution is obtained that satisfies the new dE/dx cut.

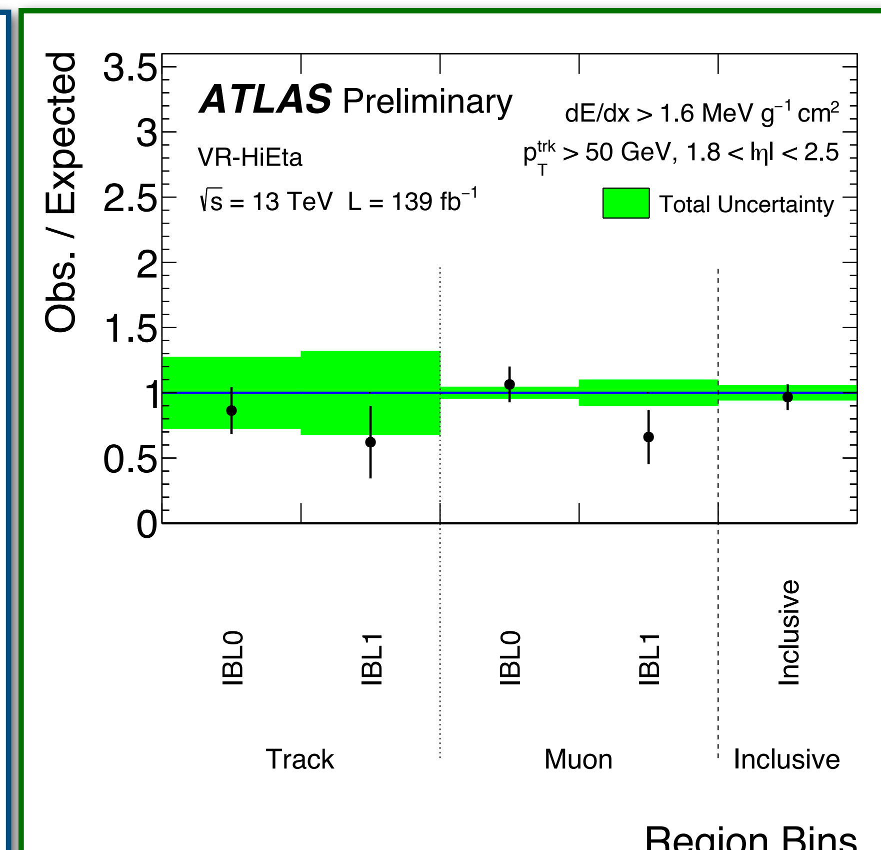
Validation of the Background Method



- In-order to validate the BG estimation method:
  - Low-pT validation region is defined by: $p_T > 120 \rightarrow 50 < p_T < 110$ GeV
  - High-η validation region is defined as: $|\eta| < 1.8 \rightarrow 1.8 < |\eta| < 2.5$ and $p_T > 120 \rightarrow p_T > 50$ GeV
- Each of these regions have exclusive kinematic and dE/dx templates, and BG estimation is done independently in these VR.
- Both Low-pT VR and High-η validation has a data-BG agreement within uncertainties across discovery and exclusion categories.



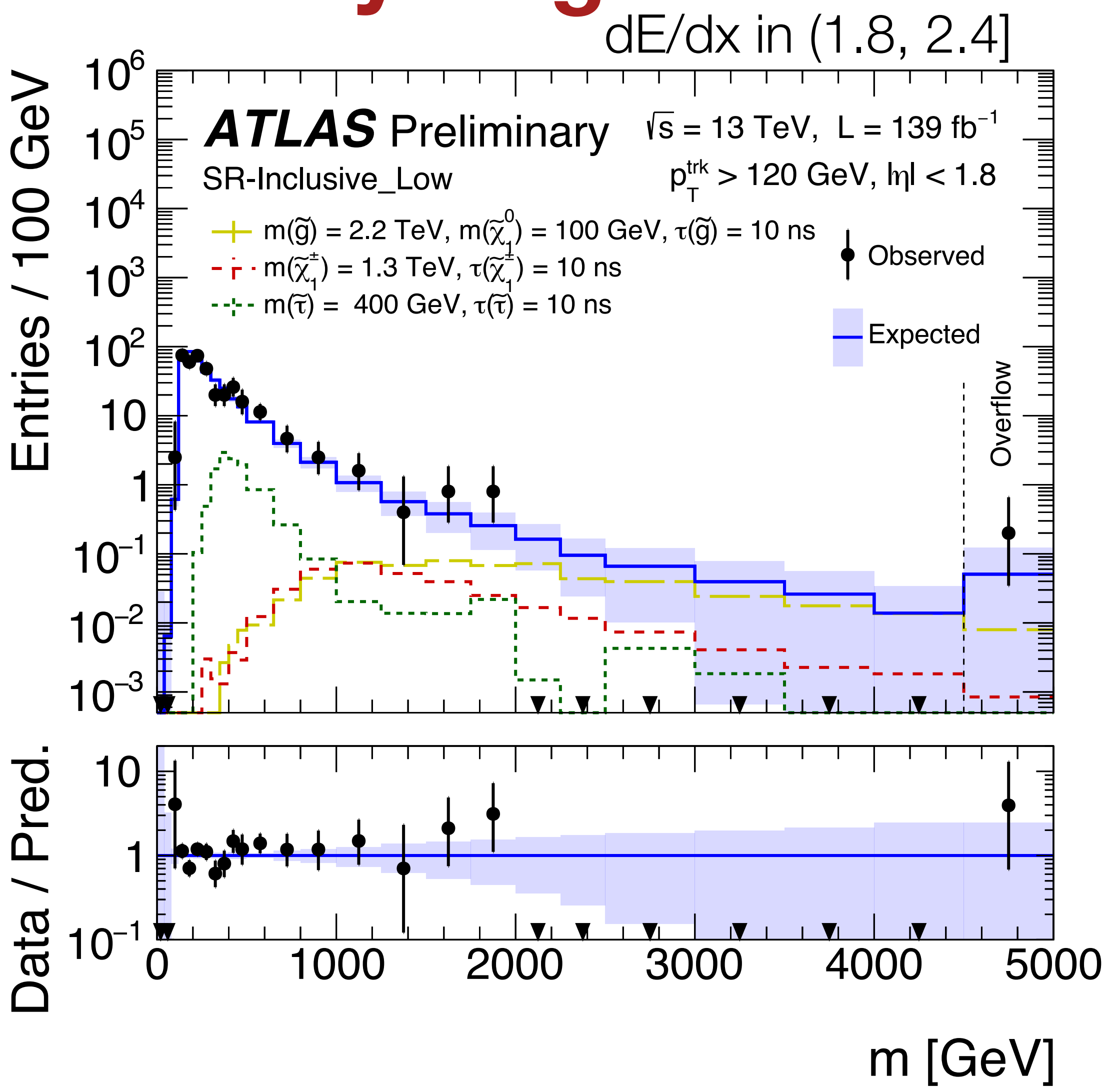


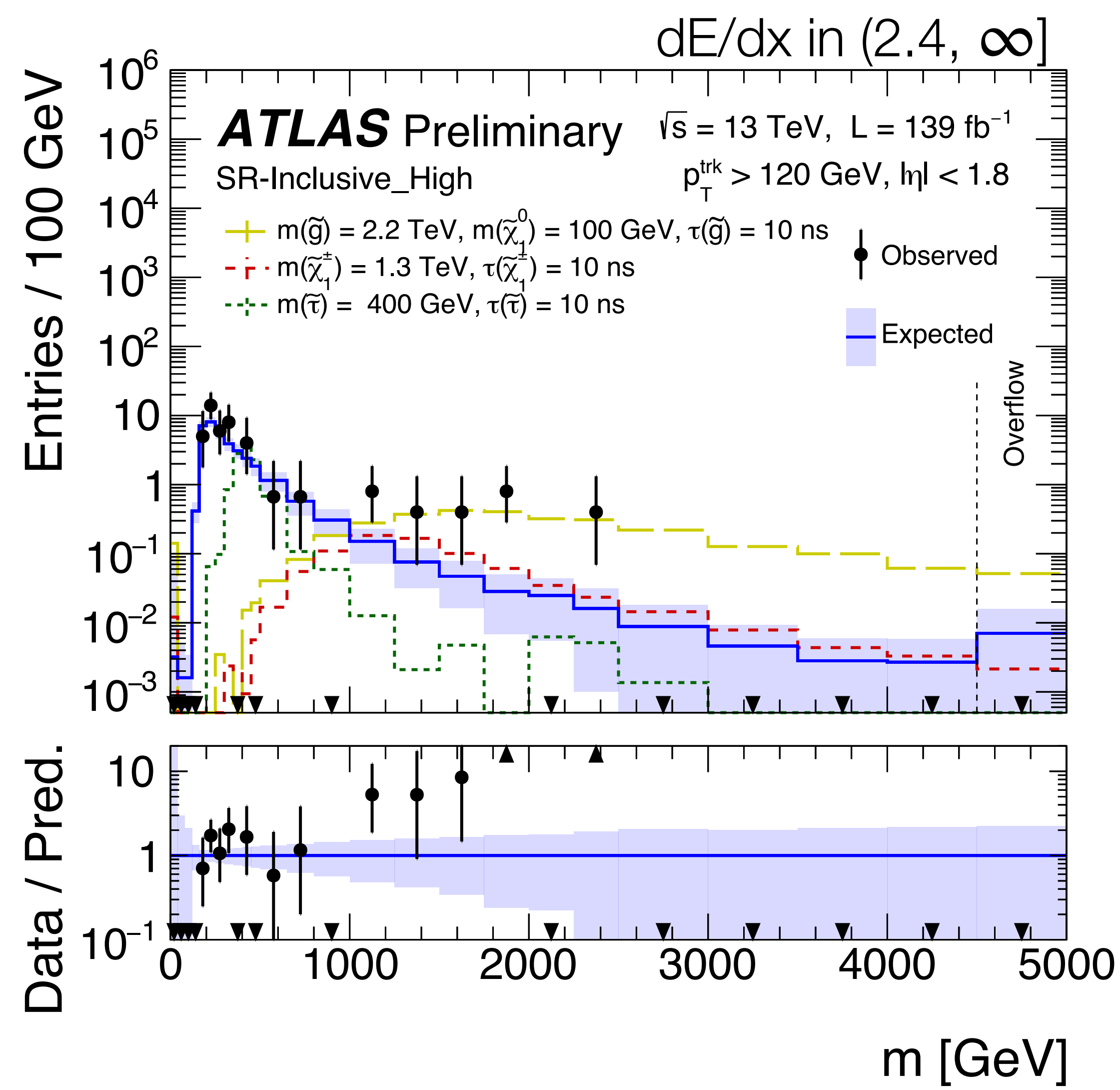


Results

Signal Region Plots

Discovery Regions

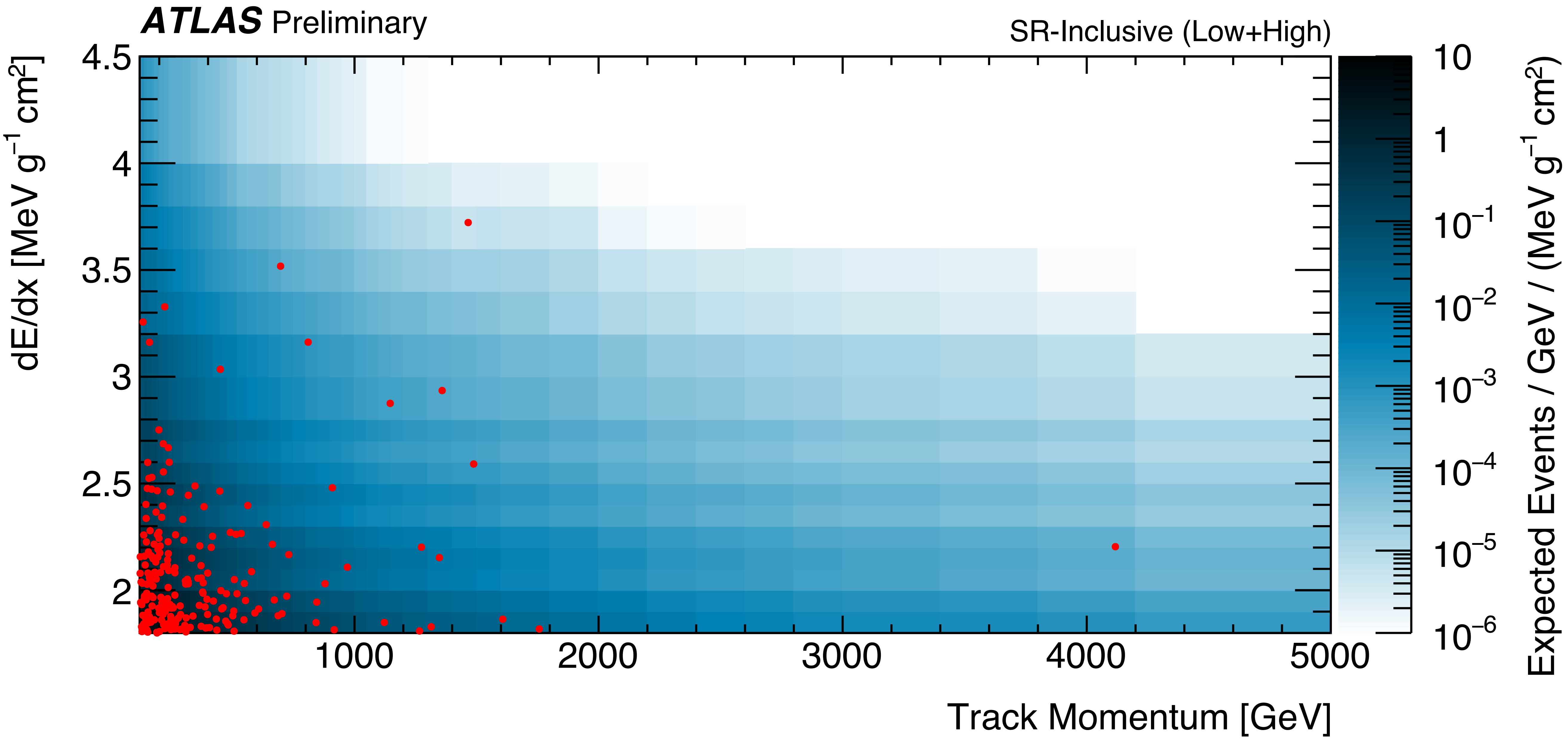




- Above are shown expected background distributions for discovery categories:
  - Overall a good shape agreement has been observed between data and expected background with the exception of:
    - An excess in the Inclusive-High category at m >1 TeV
- The observed excess events were examined individually for unexpected instrumentation effects and backgrounds.

Signal Region

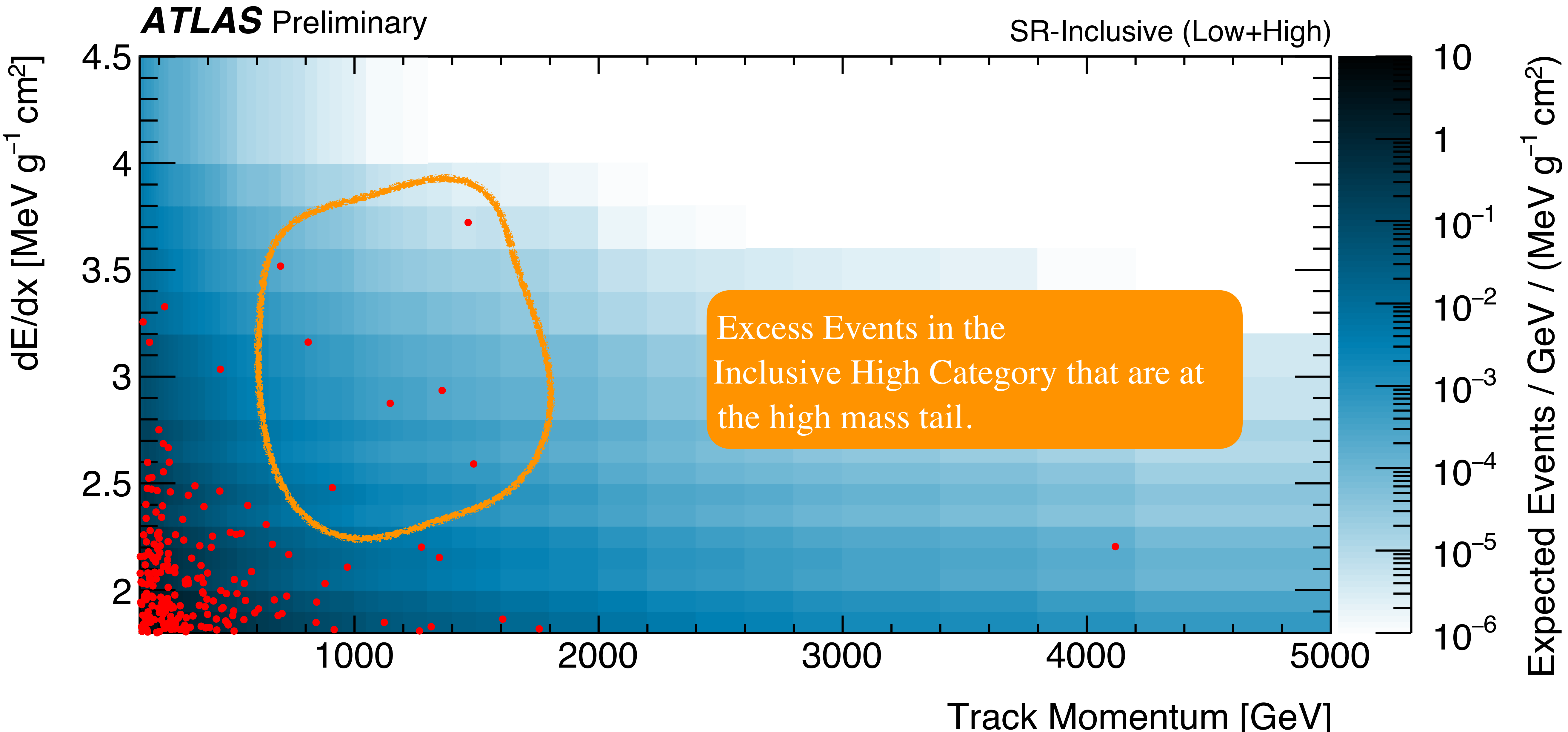
Excess Structure



- We extracted all the candidate events and if plot these event as function of dE/dx and Track Momentum we get the following plot.
  - The red points are the data.
  - The blue shadings are expected background distributions.

Signal Region

Excess Structure

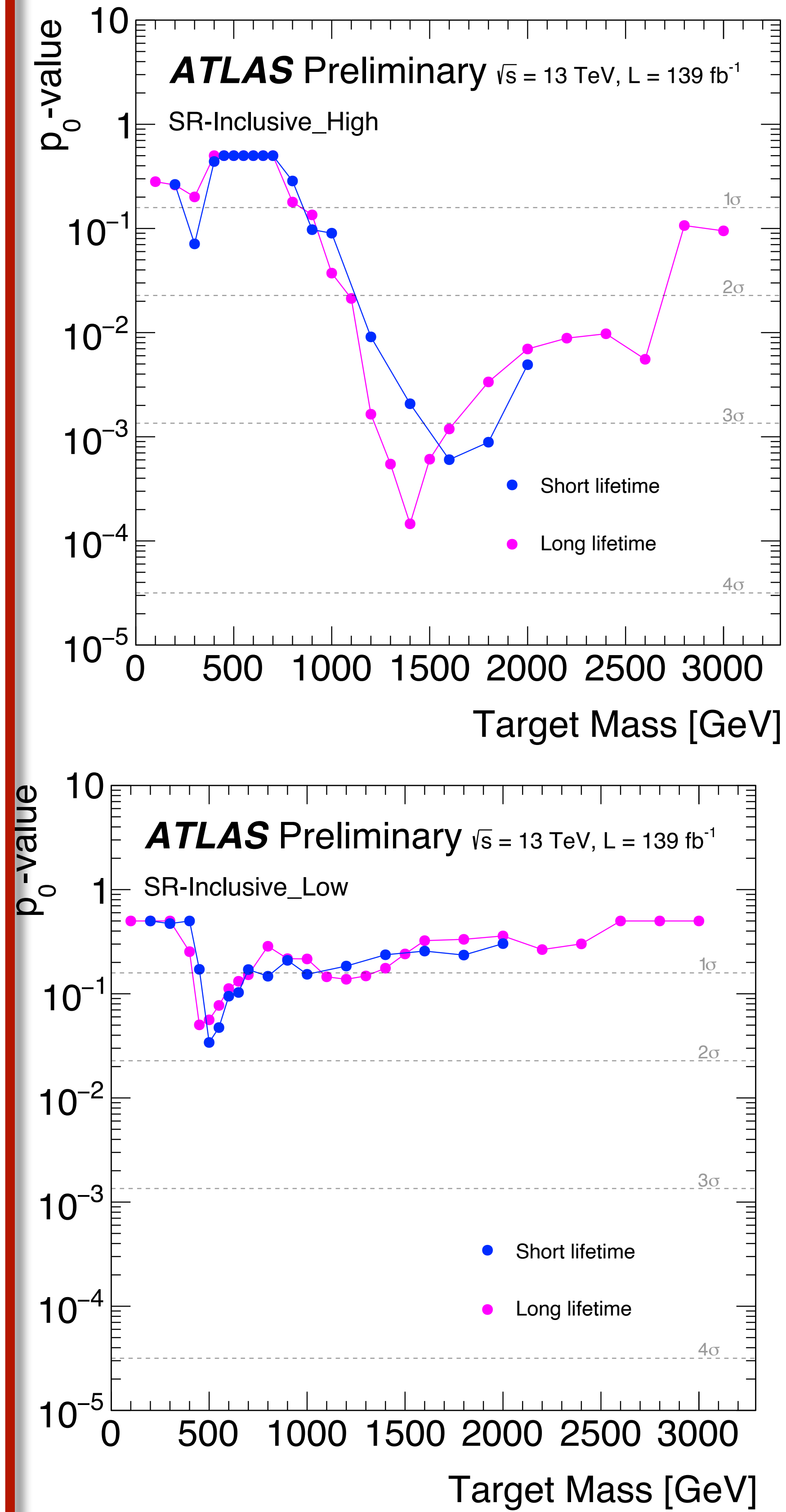


- The ones enclosed in the yellow circle is our events in the high mass excess events.
    - 4 of these are Muon events
    - 2 of these are non-muon (TRK) tracks with IBL overflow
    - 1 of these is a non-muon track without IBL overflow
- The observed events are kinematically different from the rest of the background events.
- Overall the events topology of these always have a counter balancing jet.
    - Only exception to this is an event with counter balancing MET
- **For further investigation: time of flight measurements of these excess event were also extracted from muon and calorimeter systems. In these studies, the excess events were observed to have a $\beta \approx 1$.**

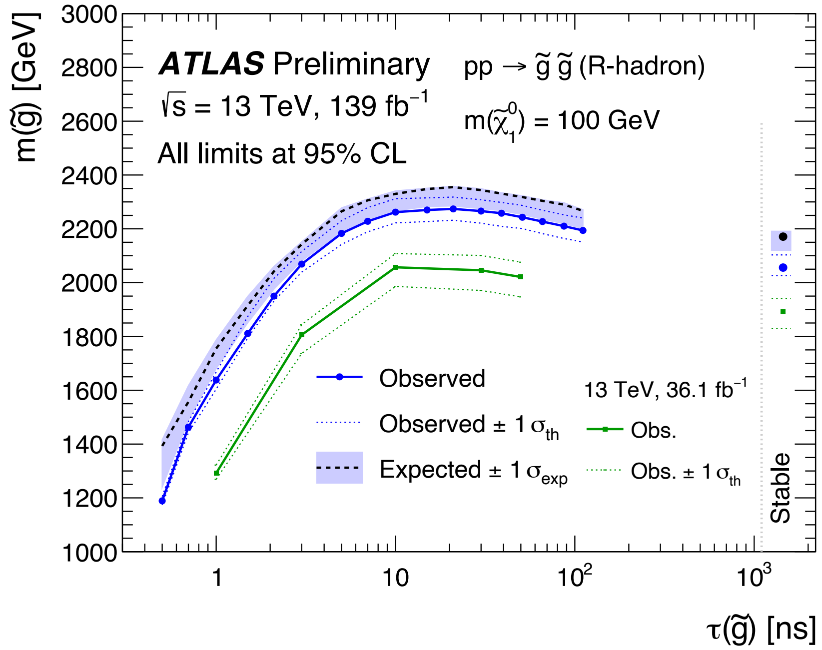
Statistical Interpretation

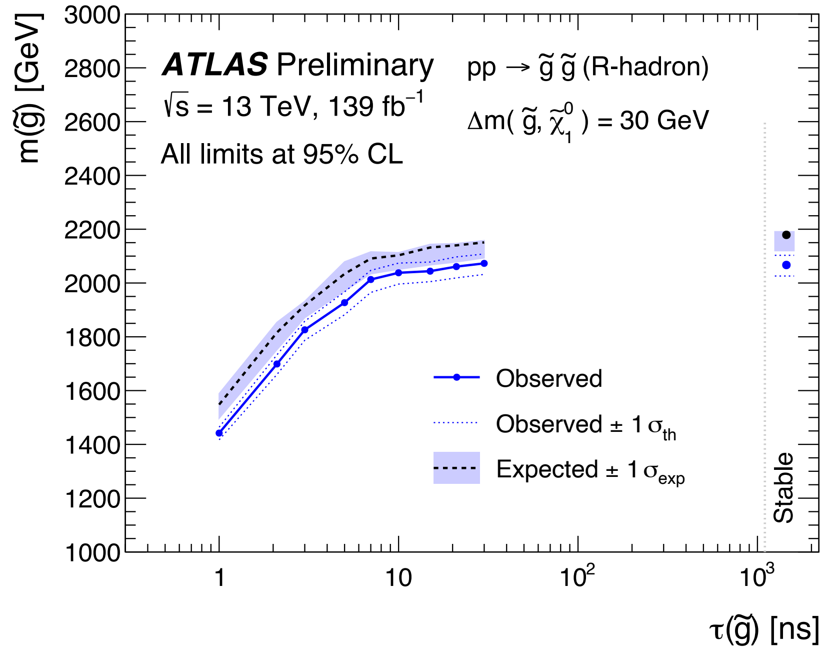
- For each signal MC a different mass windows is defined as function of signal model mass.
- For limit setting: Multi-bin fit over **Exclusion** signal categories using asymptotic formulae is used
- For significance calculation: Multi-bin fit over **Discovery** signal categories using asymptotic formulae is used
  - The fits were done individually for each mass window.
- The study shows that the observed excess in the SR-Inclusive-High region is responsible for a **local significance of 3.6 sigma and a global significance of 3.3 sigma.**
  - The maximum significance was found at 1.4 TeV (Mass window [1100,2800])
  - The observed p0 value is 1.5×10^{-4} for the target mass

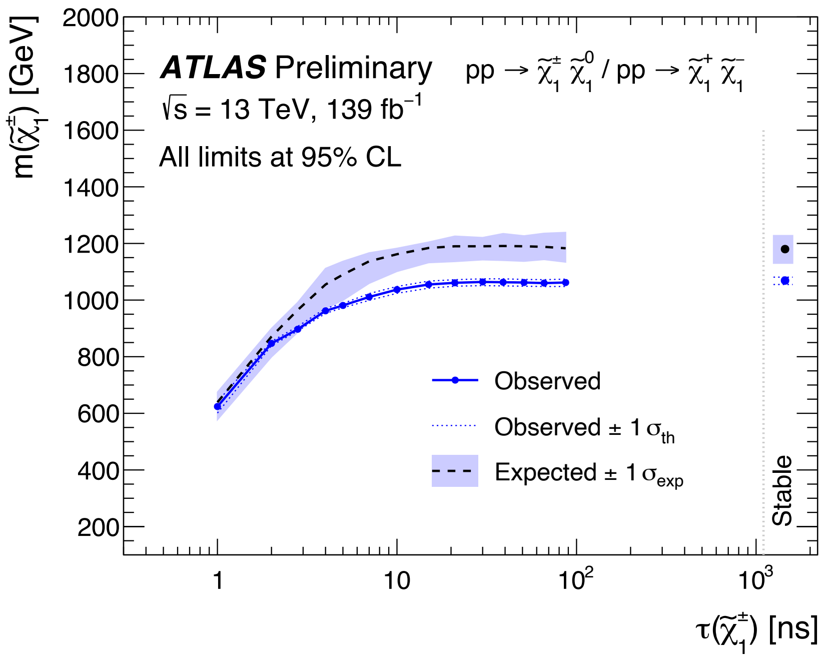
Discovery Categories

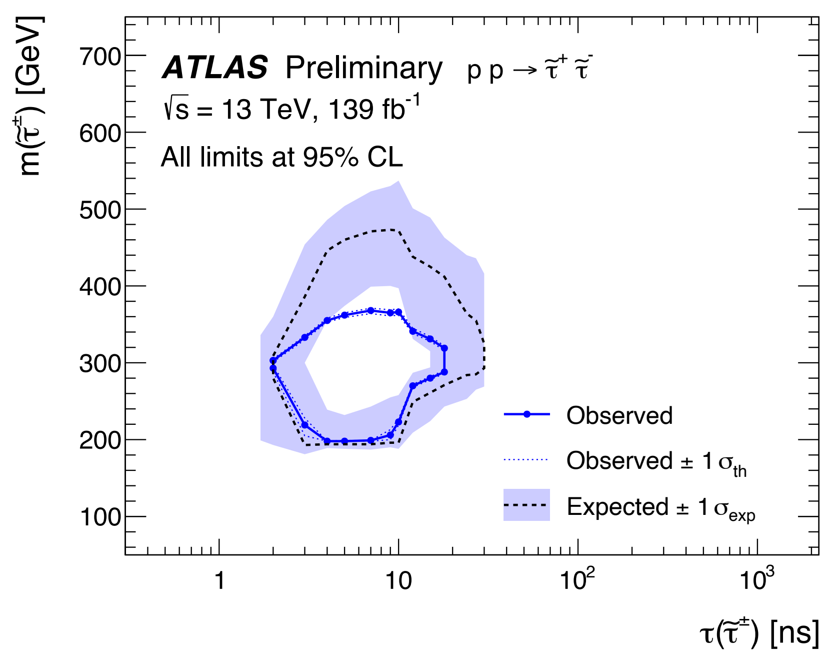


Limit Results









- Limits plots for pair produced R-Hadrons for $m(\tilde{\chi}_1^0) = 100$ GeV and $\Delta m(\tilde{g}, \tilde{\chi}_1^0) = 30$ GeV are shown on top and charginos and staus are shown on plots on the bottom.
- The highest limits are obtained at:
  - $m(\tilde{\chi}_1^0) = 100$ GeV , $\tau = 20$ ns at 2.27 TeV
  - $\Delta m(\tilde{g}, \tilde{\chi}_1^0) = 30$ GeV , $\tau = 30$ ns at 2.06 TeV
  - For charginos, the highest observed mass limit is at 1.07 TeV with $\tau = 30$ ns
  - For staus, the mass range of 220-360 GeV is excluded at 10ns.
- Due to the observed excess, the observed limits are lower than expected.

Conclusion

- An excess has been observed in the high mass range. All checks done do not show any instrumental or systematic effects which can account for this excess.

  - Only exception to this is that inner detector information point to the fact that these tracks have a $0.4 < \beta\gamma < 0.7$ while Time-Of-Flight measurements tell that these particles have a speed of c~1

  - The local (global) significance observed excess is 3.6(3.3) sigma at 1.4 TeV

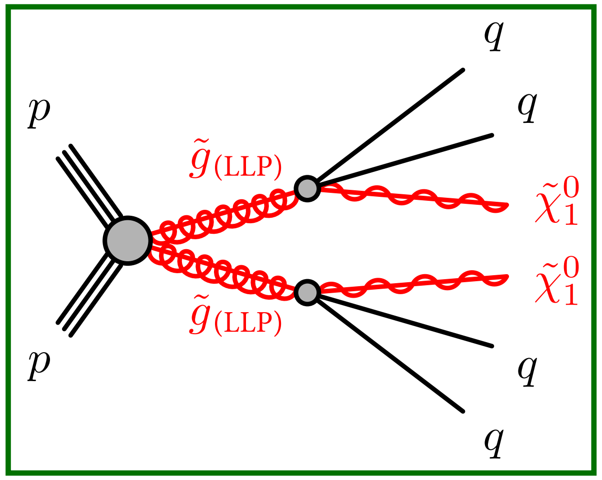
- Limits on chargino, R-Hadron and stau models have been set.

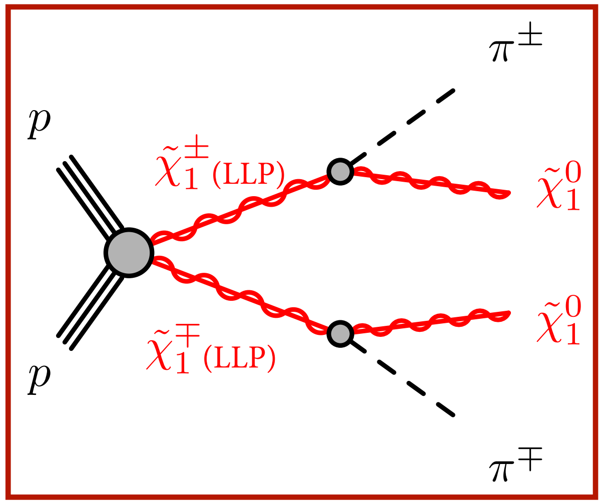
Thank you for listening

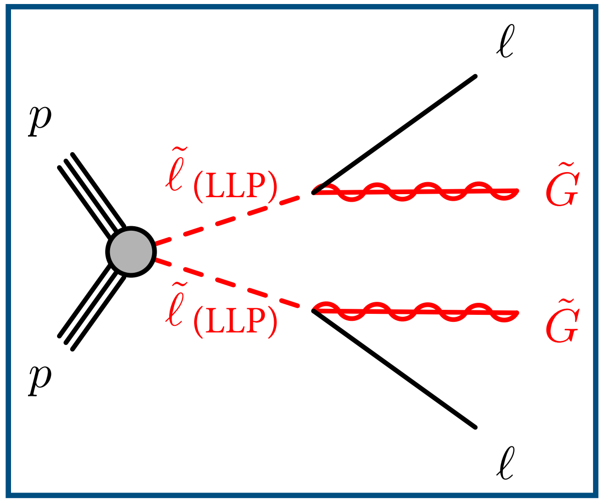
Backups

Considered Signal Models

- Long lived particle particles (LLPs) are predict by a large number of theories that extend the Standard Model (SM). Certain SUSY models predicted such LLP particles:
  - Gluinos ($\tilde{g}$) that form R-Hadrons (can be charged or not).
    - In this paper pair produced glunio from 400 GeV to 3 TeV of 1 ns to stable lifetimes with two different neutralino mass schemes of $m(\tilde{\chi}_1^0) = 100$ GeV and $\Delta m(\tilde{g}, \tilde{\chi}_1^0) = 30$ GeV were considered.
  - Charginos ($\tilde{\chi}_1^{\pm}$) when the mass splitting between the neutralino ($\tilde{\chi}_1^0$) counterpart is highly degenerate.
    - In this paper $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) = 160$ MeV with masses between 400 GeV to 1.6 TeV with 1ns to stable lifetimes were considered.
  - Staus ($\tilde{\tau}$) when the quasi-massless gravitino is assumed to be the lightest neutral SUSY particle.
    - In this paper gravitinos are massless and Staus masses between 100 GeV to 1 TeV with 1ns to stable lifetimes are considered.
- As charged particles cross the detectors they have ionisation losses (dE/dx) along their paths which are recorded by the detector layers. Charged heavy particles are expected to have significantly higher ionisation losses as they have low $\beta\gamma$.
  - Using the deposited energy (dE/dx) the $\beta\gamma$ of the particle can be extracted in the range [0.3-0.9], which can be used to derive the mass of the particle.







Selection of Events and Tracks

Category	Item	Description
Event topology	Trigger	Un-prescaled 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

MET trigger varies from 70 GeV to 110GeV during the data taking periods

Offline E_T^{miss} variable contains:

- Baseline Electrons, Muons and Jets
- Soft tracks that are coming from PV not associated with other objects.

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	$m_{\mathrm{T}}(\text{track}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}) > 130$ GeV
Track quality	Impact parameters	Track associated 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 IBL (if this is expected), or a cluster in the next-to-innermost layer (if this is expected while it 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 $\Delta R < 0.3$)
	Electron veto	EM fraction < 0.95
	Hadron and tau 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 $\mathtt{OF}_{\mathrm{IBL}} = 0$
		`IBL0_High`: $\mathrm{d}E/\mathrm{d}x > 2.4$ MeV g^{-1}cm^2 and $\mathtt{OF}_{\mathrm{IBL}} = 0$
		`IBL1`: $\mathrm{d}E/\mathrm{d}x > 1.8$ MeV g^{-1}cm^2 and $\mathtt{OF}_{\mathrm{IBL}} = 1$

Tracks are reconstructed only using ID information, and is required to be high-pt low eta to veto the non-prompt background.

$m_T(\text{track}, p_T^{\mathrm{miss}}) > 130$ GeV is applied to reduce W boson background.

Hit requirements are applied to ensure track and dE/dx measurement quality.

Tracks associated with jets and electrons are removed.

An ionization cut is applied in-order to identify particles that have low $\beta\gamma$ which is correlated to large dE/dx. The ionization cut varies across signal categories.

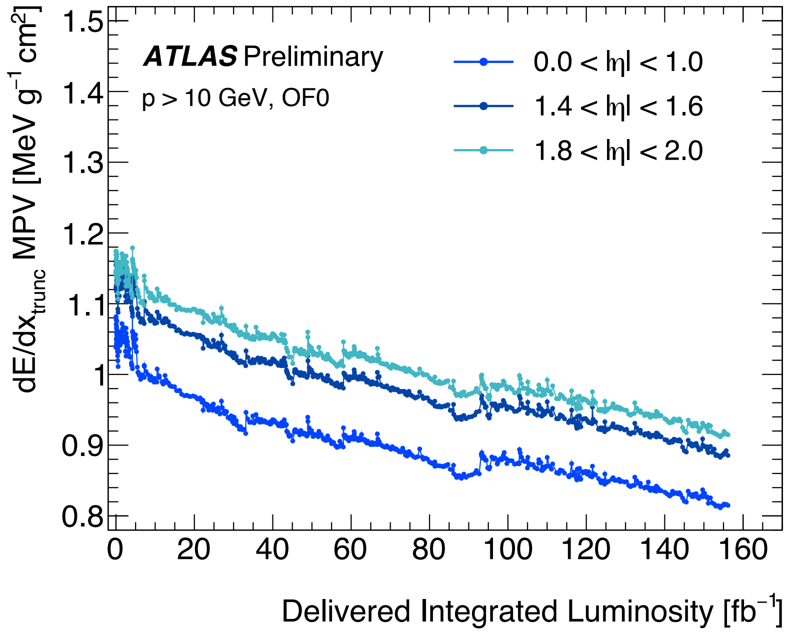
dE/dx Measurement

- When charged particles pass through the inner detector layer multiple pixel hits across a pixel layer are recorded.
  - The charge deposited on a cluster of hits is calculated by summing the charges over all pixels in a cluster.
  - In the IBL layer, If the deposited charge exceeds the dynamic range of a pixel (~2MIPs), an overflow bit is set. The tracks that use these energy deposits with overflows are referred in this paper as IBL overflow tracks (OF_{IBL}). All other pixel layers have much larger dynamic range (~10 MIPs), but no overflow bits
- The dE/dx measurement of an individual track is calculated by averaging the individual clusters that are associated with the tracks.
  - It's expected that the energy deposited by an individual track on a cluster should follow a Landau distribution.
  - To estimate the most probable dE/dx value for a track from the limited number of the dE/dx measurements associated to it a truncated mean method is used. The most probable dE/dx value is represented by $< dE/dx >_{\text{trunc}}$

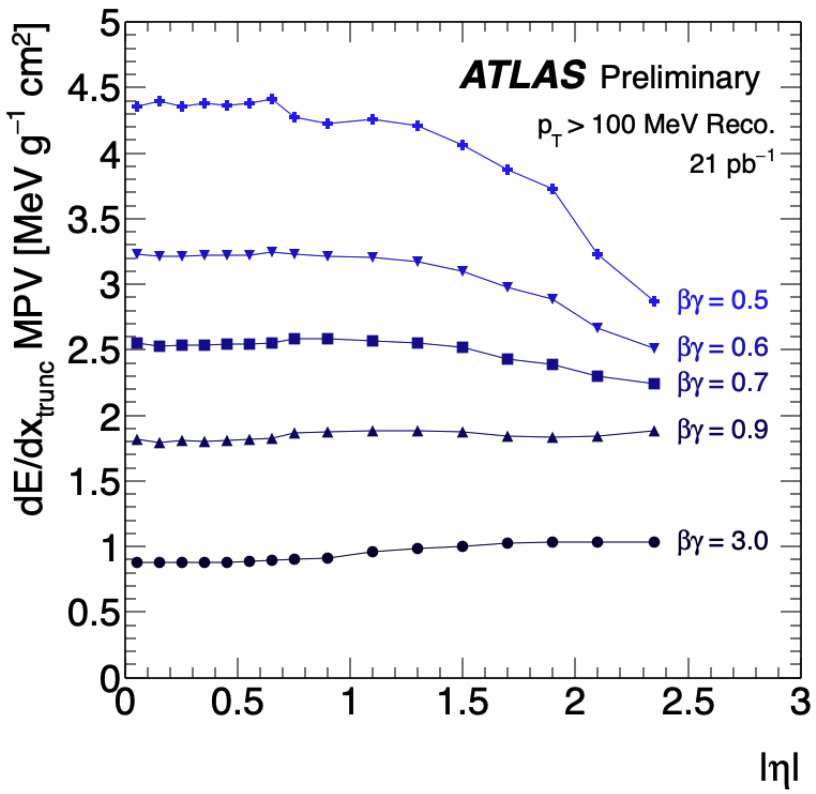
Ismet Siral, University Of Oregon

dE/dx Corrections

- The measured $< dE/dx >_{\text{trunc}}$ changes with data-period due to detector conditions as well as radiation damage.
    - $|\eta|$ dependence can be observed in the plots.



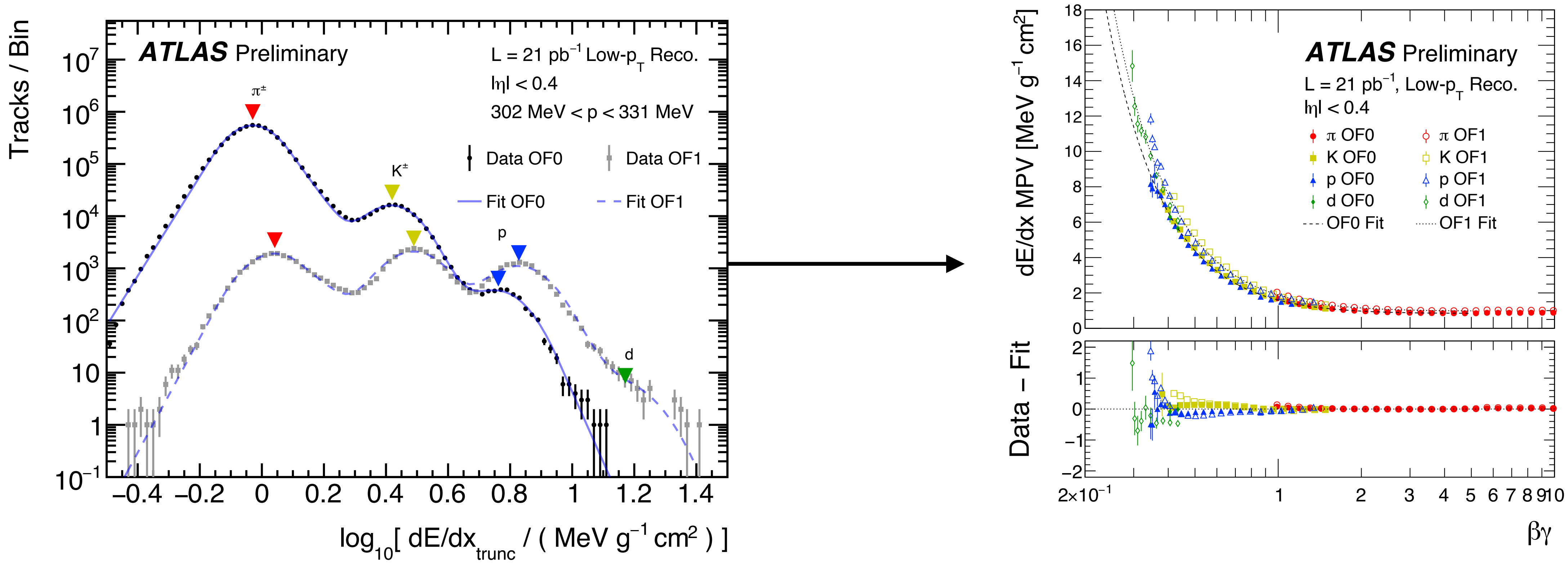
- To correct for these effects each run
    - Each run is corrected to a reference run as a function of $|\eta|$, OF_{IBL}
    - After run dependent corrections, $|\eta|$ corrections are done separately for tracks with/with IBL overflow.



- The resulting corrected dE/dx value is referred to as $< dE/dx >_{\text{corr}}$

Mass Calibrations

$$-\frac{dE}{dx} = Kz^2\rho\frac{Z}{A\beta^2}[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2}{I} - \beta^2]$$



- The $< dE/dx >_{\mathrm{corr}}$ to $\beta\gamma$ mapping is done using the low pile-up runs taken in 2017 with a luminosity of 21 pb^{-1} with low momentum reconstructed tracks.
    - Similar to dE/dx energy calibration, IBL overflow is treated separately.
- In the low pile-up runs, tracks as low as 100 MeV are used to measure the Bethe-Bloch curve.
- **This is done by plotting the dE/dx curves in eta and momentum slices.**
- Template fitting these slices to separate the pion, Kaon and proton contributions.
    - This way the most probable dE/dx value for a given momentum for each of these particle types is obtained, which can be converted in to the seen $\beta\gamma$ function.

Event Subsamples

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

Discovery Categories

- Instead categorize tracks by
  - dE/dx in (1.8, 2.4] or (2.4,∞]
- **2 exclusive signal regions**
- Also easier for re-interpretation

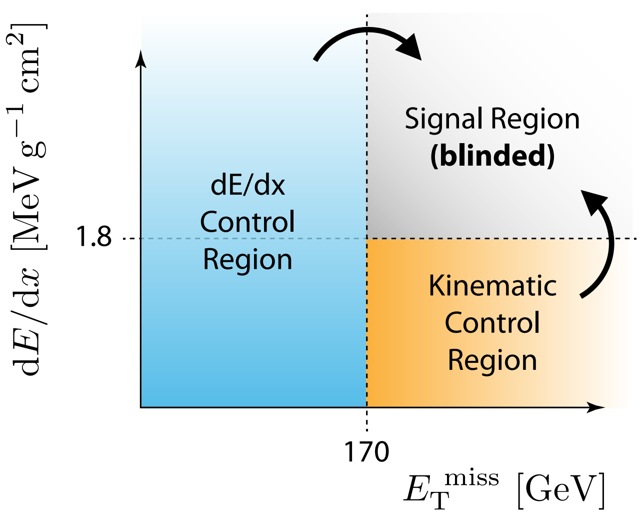
Exclusion Categories

- For exclusion limits, the events are categorized according to the selected track properties:
  - Matched to a Muon (Mu) or Not (Trk)
  - dE/dx in (1.8, 2.4] (Low) or (2.4,∞] (High)
  - Has a hit with an IBL Overflow (IBL1) {dE/dx > 1.8}

Definition of Control and Validation Regions

Table 3: Definitions of the control and validation regions.

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

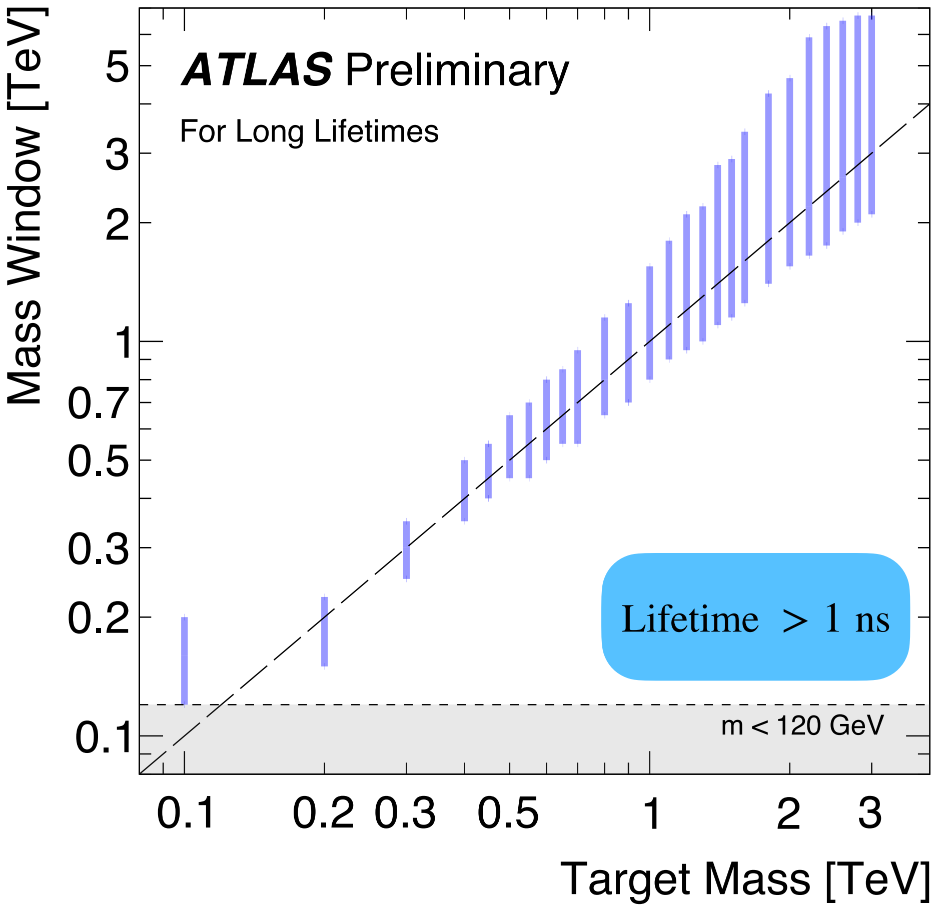


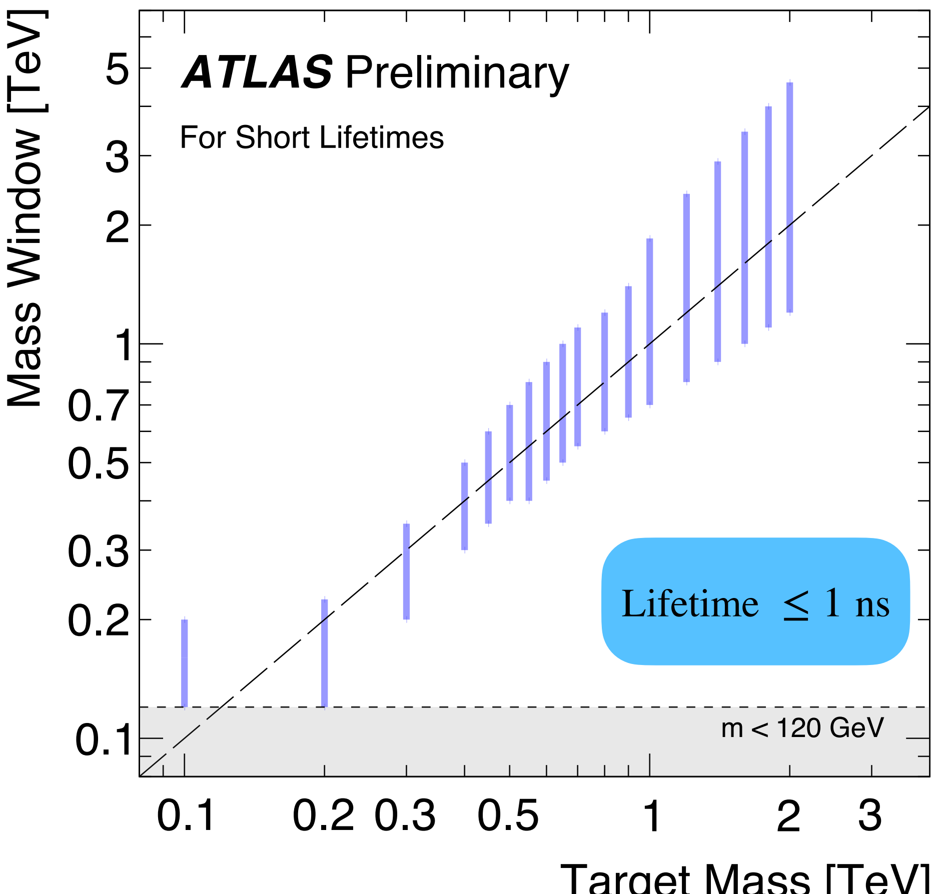
- In order to validate the generation background two separate VR has been designed:
  - **High-η VR:**
    - **SR:** $|\eta| < 1.8$ → **VR:** $1.8 < |\eta| < 2.5$
    - **SR:** $p_T > 120$ → **VR:** $p_T > 50$
    - **SR:** $dE/dx > 1.8$ → **VR:** $dE/dx > 1.6$
  - Shares a similar momentum spectrum with the SR but has a differentiated dE/dx spectrum due to eta differences.
  - **Low-pT VR:**
    - **SR:** $p_T > 120$ → **VR:** $50 < p_T < 110$
  - Shares identical dE/dx range and performance with SR but has a limited momentum range.

- In addition two control regions have been defined for every signal and validation region for background generation
  - Kinematic CR : dE/dx cut of >1.8 is reverted to <1.8 (1.6 for Hi-Eta VR)
  - dE/dx CR: MET cut of >170 GeV is reverted to <170 GeV and dE/dx cut is removed

Ismet Siral, University Of Oregon

Mass Windows

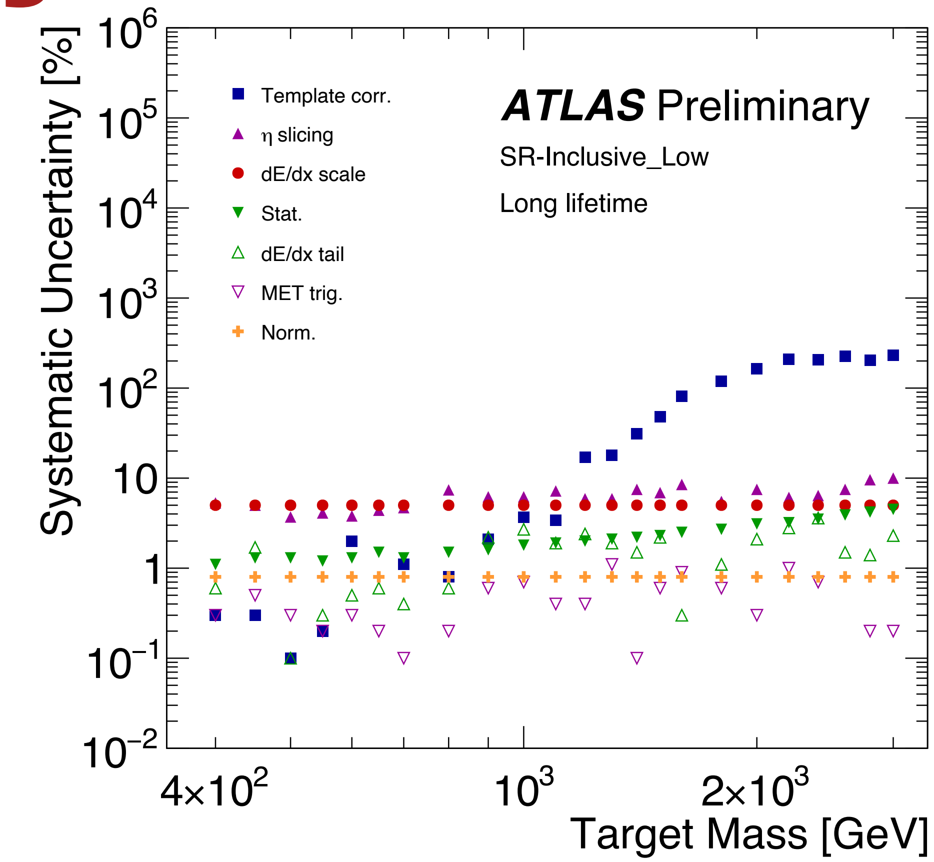


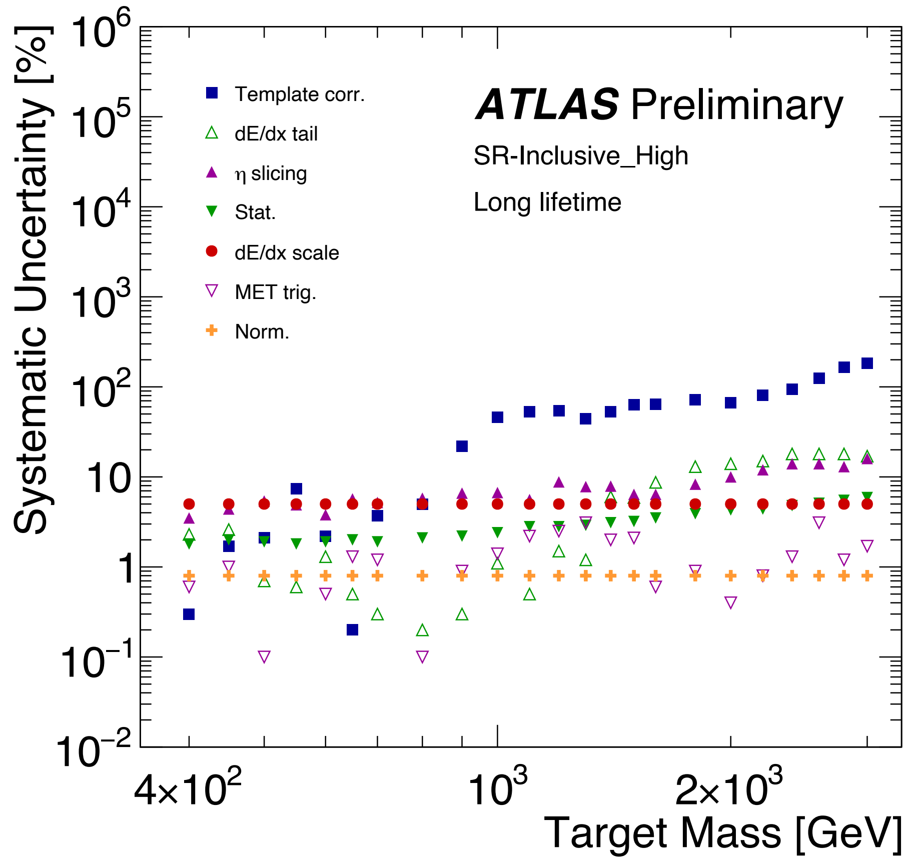


- The background is monotonically decreasing after 120 GeV, while the signal models peak around their central mass window.
  - Signal mass resolution is directly effected by our momentum resolution and the life time of the particle.
- When setting limits and fitting, different **sliding mass windows** are used for each individual signal mass point and life-time
- Two separate set off mass windows are defined which are a function of mass for two different life-times(short and long). They are optimized according to:
  - 70% signal MC are aimed to be captured by the signal mass windows.
  - Lower boundary is determined by maximizing $1/\sqrt{BG}$

The short-life time mass windows are broader to due worse momentum resolution for short life-time signatures.

Systematic Uncertainties





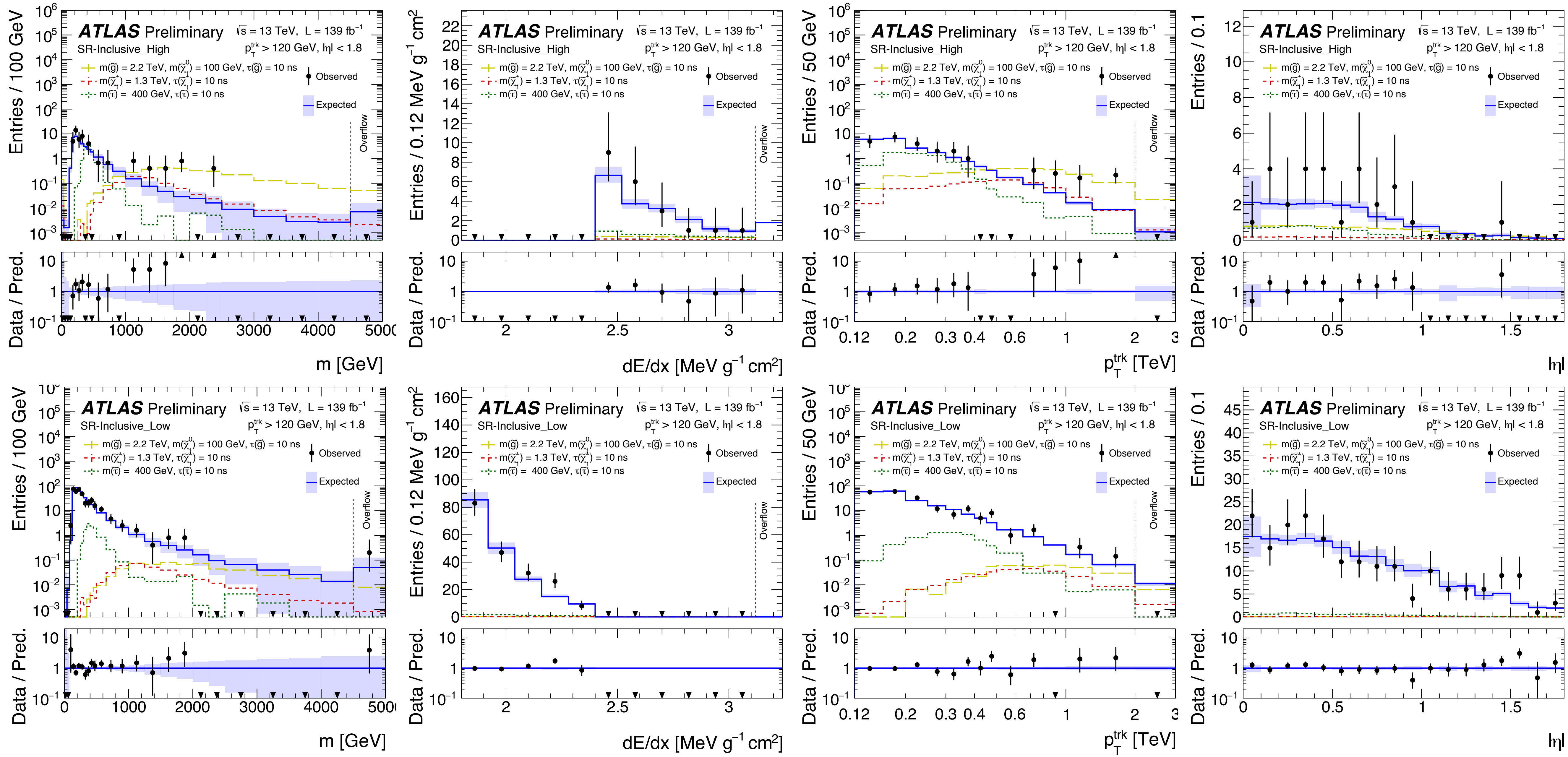
- Uncertainties are calculated **per each mass window** and the leading uncertainties are:
- **Template Corr:** Leading uncertainty. It evaluates for the data-driven BG the assumption that the kinematic and dE/dx template can be sampled separately to form a toy track. It's achieves that by generating a alternative BG solely using in dE/dx CR and comparing the data distribution in dE/dx CR.
- **η slicing:** It estimates the effect of the choice of η binning of the dE/dx templates
- **dE/dx Scale:** This uncertainty is introduced to cover the disagreement observed in the Low-pT VR - IBL0-Trk-Low.
  - The size of this additional systematic uncertainty is evaluated using VR-LowPt and VR-HiEta by making likelihood fit without other uncertainties.
- **dE/dx tail:** dE/dx tail statistical uncertainty estimated by using a fitted Crystal ball function instead of the raw template

Signal Systematic Uncertainties

- Signal systematic uncertainties are computed for model dependent limits.
  - The dominant signal uncertainty depends on the signal model but overall the dominating uncertainties are:
    - Scale/ISR Uncertainties: Created by generating alternative MC samples (truth only) with variations in factorization, normalization and merging scales as well parton/radiation shower tunes. and comparing the differences in alternative MC samples to nominal samples.
    - IBLSyst: IBL overflow fraction year dependence.
    - Uncertainties on physics objects like track momentum measurement, offline E_T^{miss} calculation etc.

Signal Region Plots

Extra Kinematic Plots



Statistical Interpretation

- For each signal MC a different mass windows is defined as function of signal model mass.
- Multi-bin fit over exclusion signal regions using asymptotic formulae is used for limit setting over the defined mass windows.
- The study shows that the observed excess in the SR-Inclusive-High region is responsible for a **local significance of 3.6 sigma and a global significance of 3.3 sigma.**
    - The maximum significance was found at 1.4 TeV (Mass window [1100,2800])
    - The observed p0 value is 1.5×10^{-4} for the target mass
    - The p0-value calculation was done with 1 million toys per mass-window.