Search for heavy charged long-lived particles in ATLAS using massive event picking

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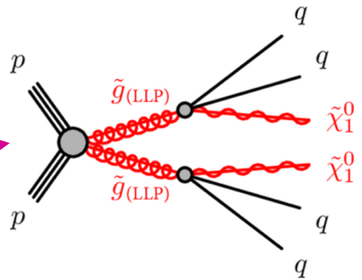
with contributions by many people

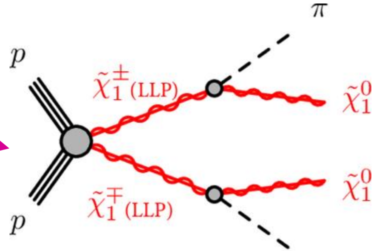
Outline

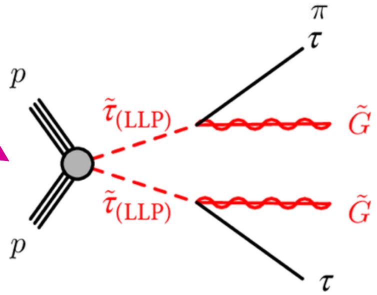
- Motivations for this search
- ATLAS detector and observables
- Past results with LHC Run 2 data
- Improvements to the analysis for Run 3 data:
  - Pixel dE/dx with charge calibration
  - MDT dE/dx and ToF for very long-lived particles
- Massive event picking technology
- Evolution

Massive charged long-lived particles

- Several beyond-standard-model (BSM) mechanisms can produce pairs of massive long-lived particles
- A few SUSY motivated models:
  - Gluinos can form R-parity violating hadrons that eventually decay to a neutralino and other normal hadrons
  - Charginos can be long-lived and then decay to neutralinos and normal hadrons
  - Sleptons, and staus in particular, can be produced in pairs and then decay to a gravitino and a normal lepton (tau)
- In this context, "massive" means that particles have masses > 100 GeV
- "Long-lived" means that particles have a minimum lifetime above a few ns, to be able to cross enough detector layers before decaying





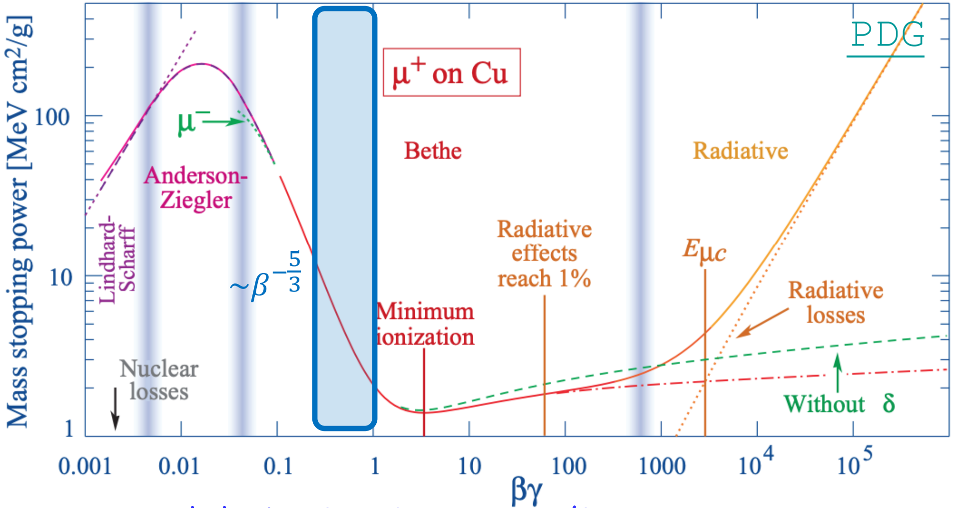


How to identify these particles?

- Measure the specific ionization dE/dx and the momentum, then derive the mass by inverting the Bethe-Bloch relation:

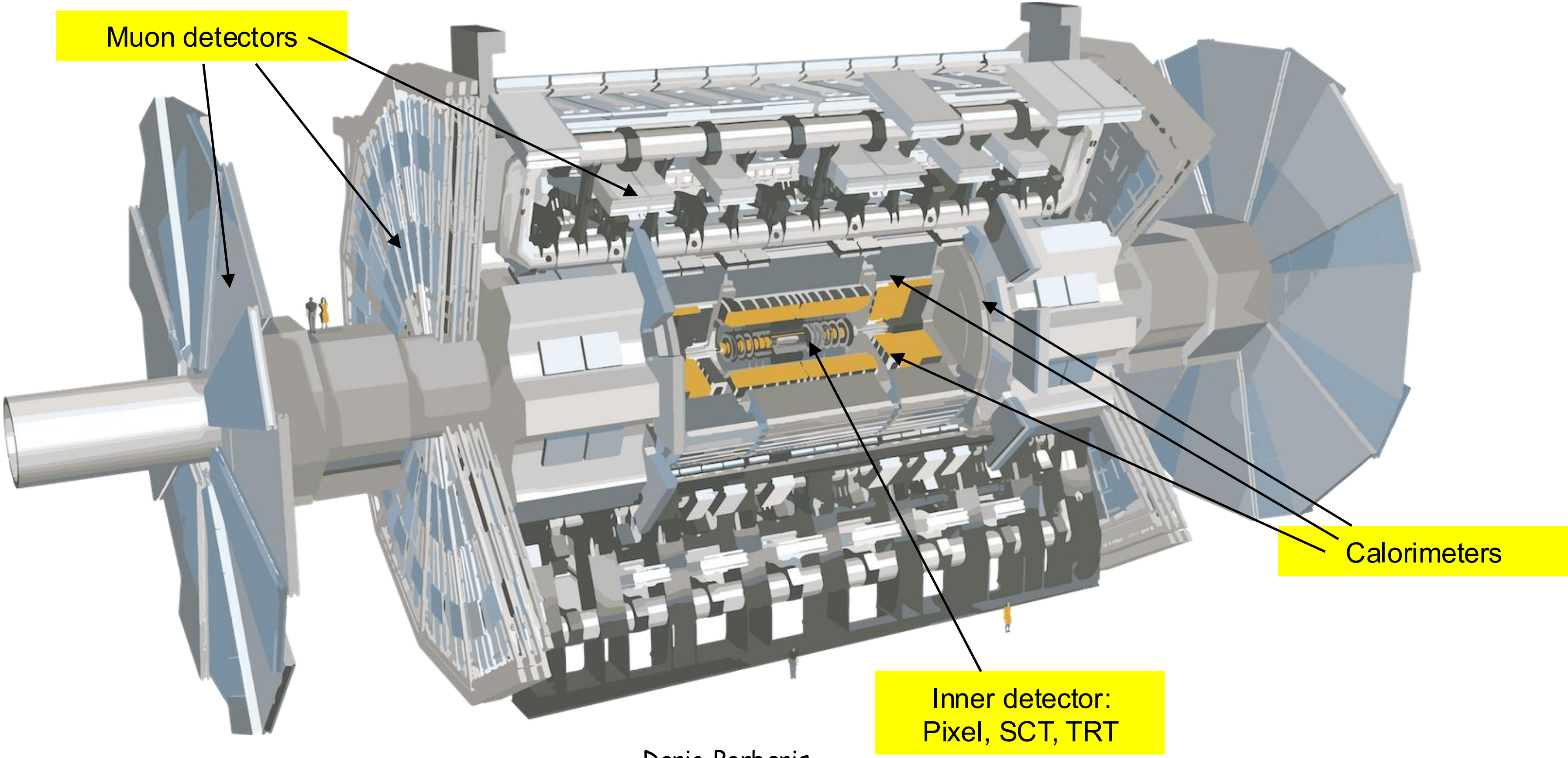
$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

  - In the range 0.3 < βγ < 0.9 ("slow" particles with 0.3 < β < 0.7) it is possible to make meaningful measurements of m = p/βγ



- Measure the Time of Flight to sufficiently distant detectors and derive β -> βγ -> m = p/βγ
  - Only for sufficiently long-lived particles that don't interact with other detector material before reaching the ToF detectors: Tile (Hadronic) Calorimeter and Monitored (Muon) Drift Chambers in ATLAS
  - Reach limited by the readout time range and the detector time resolution:
    - too slow particles arrive after the end of the readout gate — so β > 0.3
    - too fast particles cannot be distinguished from particles with β~1 — so β < 0.8 (TileCal) or 0.9 (MDT)

The ATLAS detector



Measurement possibilities in ATLAS

Each of the tracks will have **up to 4 mass measurements**:

- $m_{dE/dx}$ **Pixel**
- $m_{dE/dx}$ **MDT**

$\beta\gamma$ **from Bethe-Bloch formula**

Lifetime > ~3 ns

Lifetime > ~30 ns

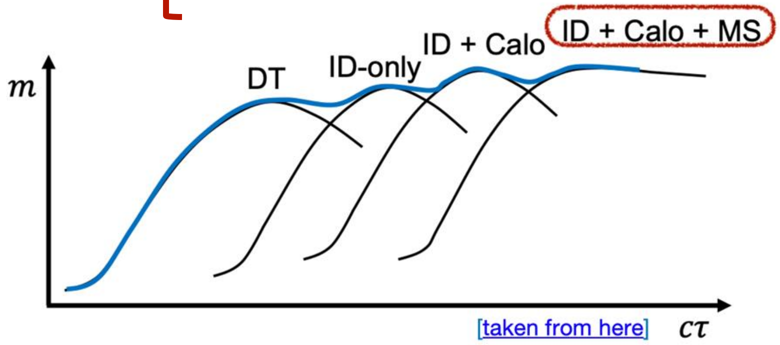
- m_{ToF} **TileCal**
- m_{ToF} **MDT**

β **from ToF**

Lifetime > ~10 ns

Lifetime > ~30 ns

$$m = \frac{p}{\beta\gamma}$$



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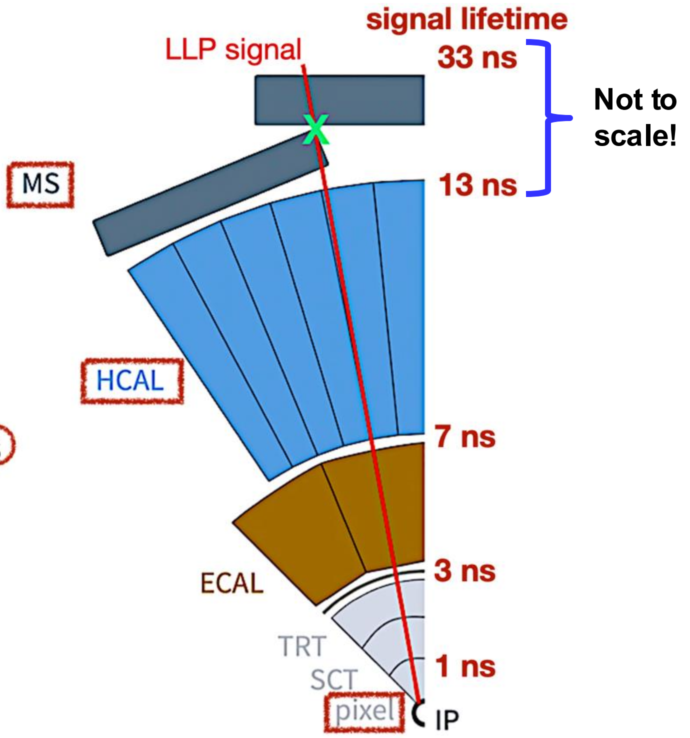


link to original figure

Pixel dE/dx measurement (1)

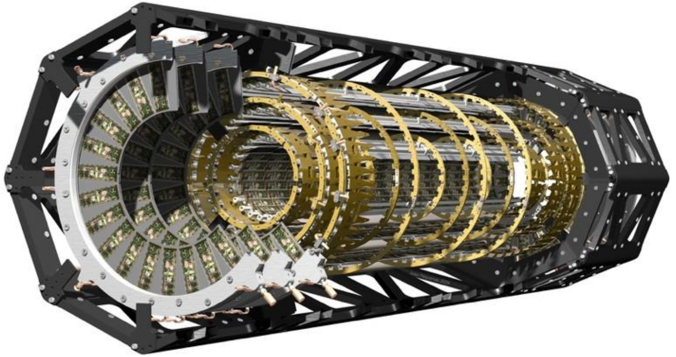
- The ATLAS Pixel detector consists of 4 barrel layers and 3 end-caps on each side
  - Most tracks cross 4 Pixel detectors with 50x400 μm^2 pixels (50x250 μm^2 in the innermost layer)
- Particles passing through pixel detectors ionize the silicon
- Front-end ASIC collects charge -> amplified signal ∝ collected charge
- Signal is discriminated and sampled every 25 ns
- Time-over-threshold (ToT) recorded, in units of 25 ns
- More charge -> larger signal -> longer ToT
- ToT is converted to charge using a calibrated relation
- Cluster charge q_{clus} = sum of pixel charges in a cluster
- From cluster charge, calculate cluster dE/dx using:

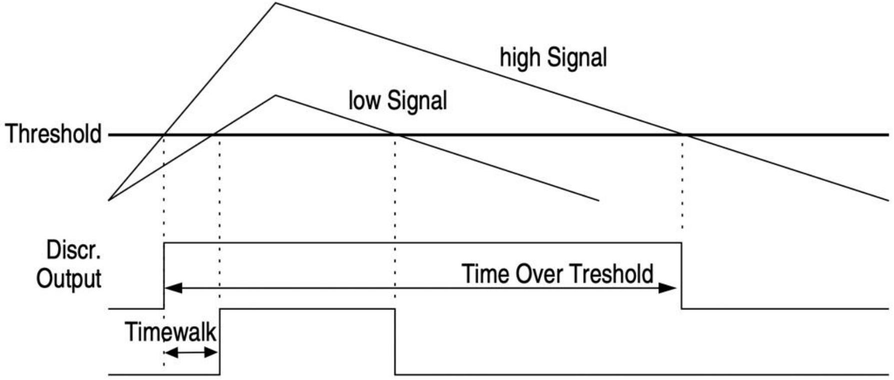
$$\left(\frac{dE}{dx}\right)_{\text{clus}} = [q_{\text{clus}}\, E_{e+h} / l] \,/\, \rho_{Si}$$

Electron-hole creation energy in Si = 3.68 eV

Path length of track through Si layer

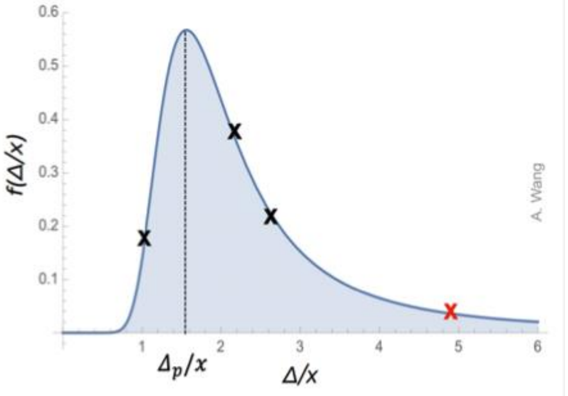
Density of Si

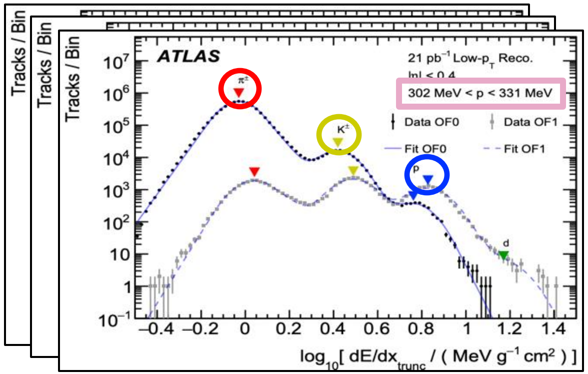


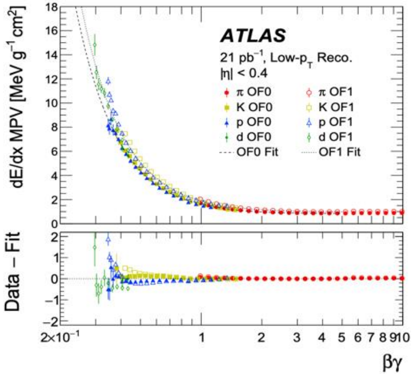


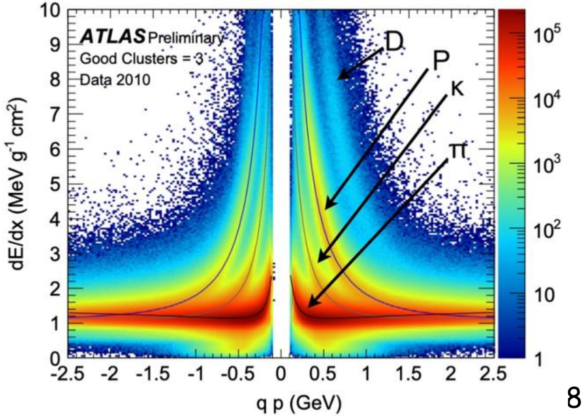
Pixel dE/dx measurement (2)

- Ionisation losses follow a Landau distribution
- A truncated mean $\langle dE/dx\rangle_{trunc}$ is used instead of mean value of dE/dx to estimate the most probable value (MPV) of the track
  - Remove the largest measurement, which is most probably in the Landau tail
  - MPV follows a relation similar to the Bethe-Bloch
- Instead of relying on theory, we calibrate the dE/dx -> $\beta\gamma$ relation with low-mass SM hadrons -> need low-p_T tracking to reach low $\beta\gamma$ -> use data from low-μ runs
  - Plot log(dE/dx_{trunc}) in narrow p-slices -> can identify $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ peaks
- Peaks indicate dE/dx MPV for a particle with $\beta\gamma$= $p/m_{(\pi/K/p)}$
- Repeat for many p-slices & fit with empirical function
- Bin in η to account for differing radiation damage, path length, etc.





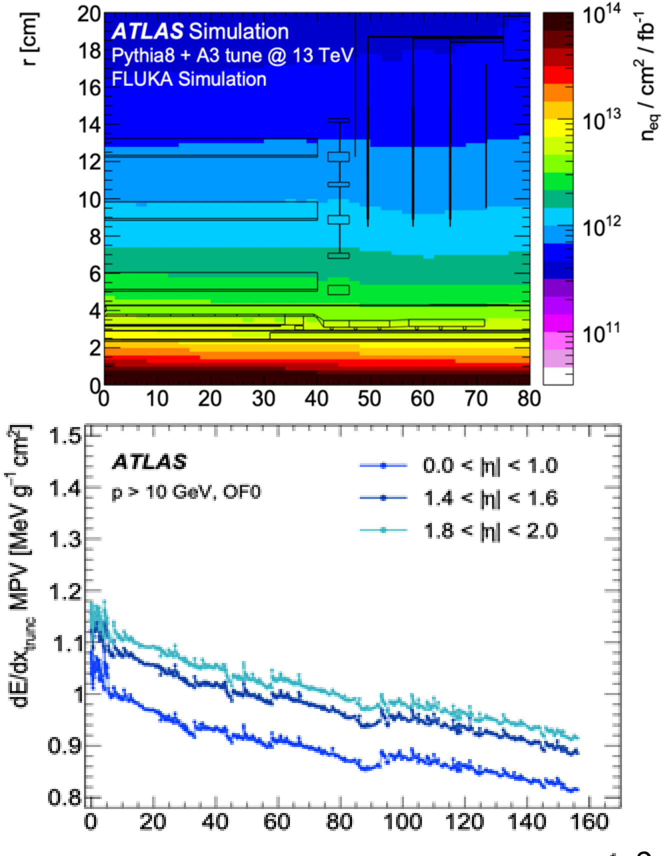




Pixel dE/dx measurement (3)

- Radiation damage affects the measured cluster charge in several ways:
  - Charge trapping in the damaged silicon lattice reduces the charge that reach the electrodes
  - More detector noise forces the increase of the individual pixel thresholds during detector operation
    - Clusters can lose the edge pixels if under threshold
- These effects can be partially compensated by increases in bias voltage but not indefinitely
- The strategy for the Run 2 analysis (data taken between 2015 and 2018) was to rescale the measured dE/dx MPV for each track with a scale factor that depended on the integrated luminosity since the start of operations, in |η| bins:

$$\left\langle\frac{dE}{dx}\right\rangle_{\text{corr}} = w_{\text{run},\eta} \left\langle\frac{dE}{dx}\right\rangle_{\text{trunc}}$$

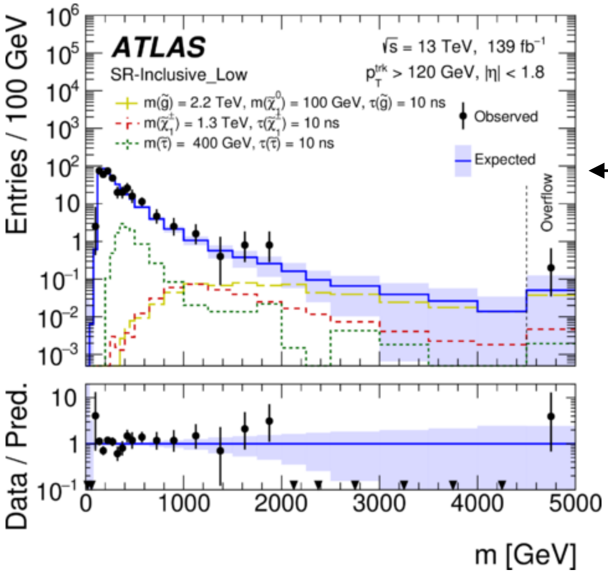


Analysis strategy (Run 2/1) (1)

- The strategy for the single-track analysis of Run 2 data consisted of a few simple steps:
  - Event selection:
    - Trigger: lowest-threshold un-prescaled missing E_T trigger
    - Offline missing E_T > 170 GeV
    - Reconstructed primary vertex
  - Track selection (signal region):
    - Track parameters: p_T > 120 GeV and $|\eta| < 1.8$
    - W veto: $m_T(\text{track}, p_T^{miss}) > 130$ GeV
    - Transverse impact parameter $|d_0| < 2$ mm and longitudinal impact parameter $|\Delta z_0 \sin\theta| < 3$ mm wrt primary vertex
    - Momentum resolution: σ_p/p < 10%—200% (increasing with p)
    - At least a pixel cluster on track in one of the two innermost layers
    - No shared or split pixel clusters
    - Number of SCT clusters > 5 (out of 8)
    - At least two clusters used for the $\langle dE/dx \rangle_{trunc}$ calculation
  - Track selection (signal region, cont'd):
    - $\Sigma(p_T^{track})$ < 5 GeV for all tracks within a cone size $\Delta R = 0.3$)
    - EM fraction < 0.95 if track matched to a calorimeter cluster
    - Hadron and τ veto: $E_{jet}/p_{track} < 1$
    - Pixel $\langle dE/dx \rangle_{corr}$ > 1.8 MeV g^{-1} cm^2
  - Kinematic control region:
    - Pixel $\langle dE/dx \rangle_{corr}$ < 1.8 MeV g^{-1} cm^2
  - dE/dx control region:
    - Missing E_T < 170 GeV, Pixel $\langle dE/dx \rangle_{corr} > 0$
  - Low-p_T validation region:
    - $50 < p_T < 110$ GeV
  - High-η validation region:
    - p_T > 10 GeV and $1.8 < |\eta| < 2.5$
  - Also, kinematic and dE/dx control regions matching the validation regions

Analysis strategy (Run 2/1) (2)

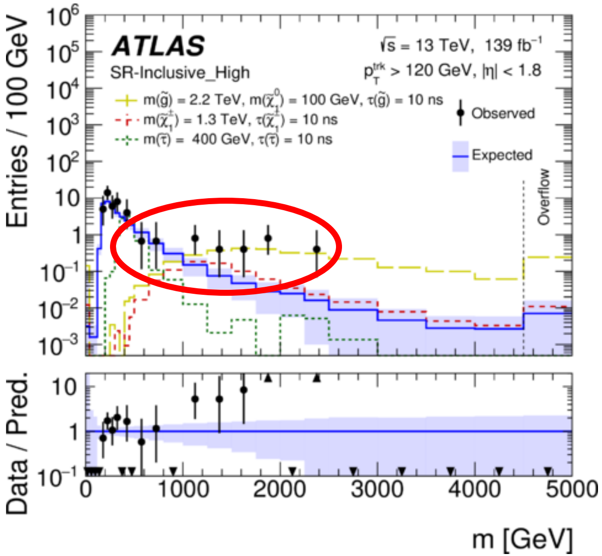
- The control and validation regions gave good confirmations of the correctness of the procedure before data unblinding, but the result after unblinding produced a surprise
  - A handful of events in a region where the background was expected to be very small
- Most of the 7 unexpected events turned out to be matched to tracks reconstructed in the muon spectrometer, and their time of flight to the hadronic calorimeter and/or the muon spectrometer was found to be compatible with β = 1
  - No confirmation that these were slow and massive particles



Inclusive-low region:
1.8 < dE/dx < 2.4

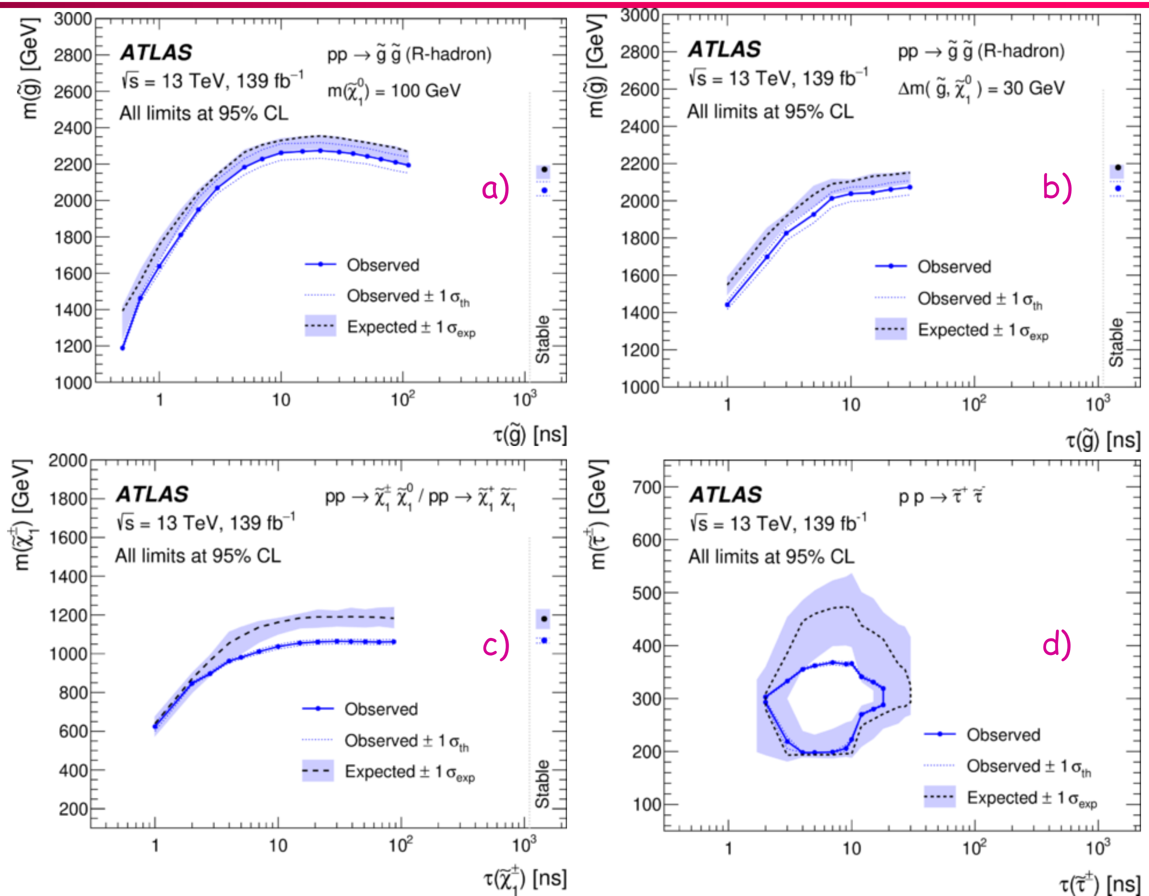
JHEP paper (2023)

Inclusive-high region:
dE/dx > 2.4



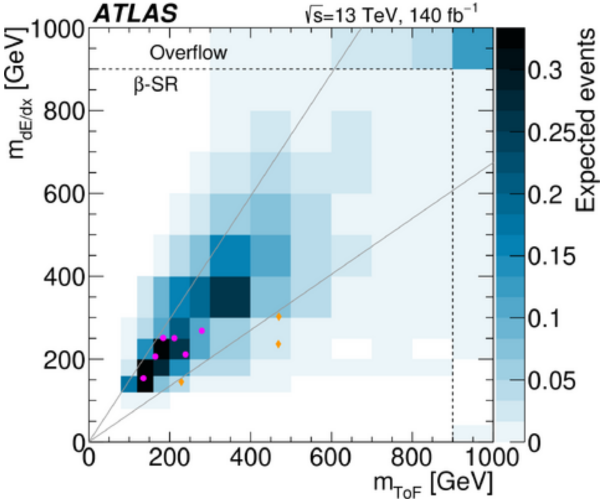
Analysis strategy (Run 2/1) (3)

- The measurement can be interpreted as limits on the masses of BSM particles, as function of their lifetimes:
  - a) Gluino mass, from gluino R-hadron pair production, for neutralino mass of $m(\chi_1^0)$ = 100 GeV
  - b) Gluino mass, from gluino R-hadron pair production, for neutralino mass with $\Delta m(g, \chi_1^0)$ = 30 GeV
  - c) Chargino mass, from chargino pair production
  - d) Contour around the excluded mass-lifetime region for stau pair production
- All observed limits are lower than expected because of the excess of events shown in the previous slide



Analysis strategy (Run 2/2) (1)

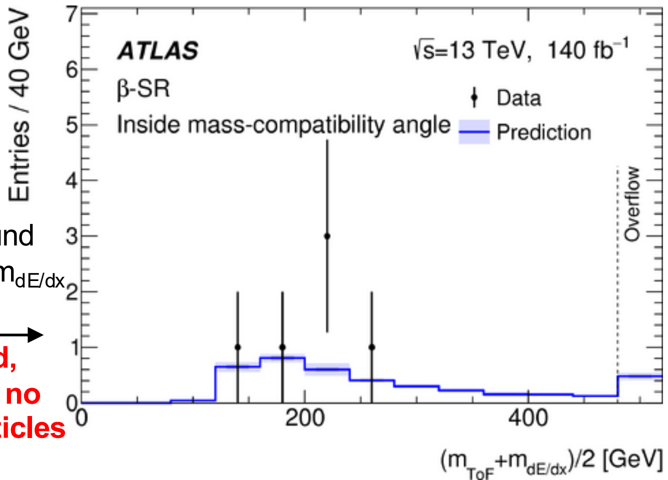
- The second round of Run 2 analysis added requirements to the event or track selections to be able to lower the dE/dx cuts (https://arxiv.org/abs/2502.06694), optimized for different long-living particles
  1) Consider only tracks that cross the Tile (Hadronic) Calorimeter and ask that the mass calculated using β measured from TileCal time of flight matches the one calculated from Pixel dE/dx
     - Muon-like tracks usually cross 3 TileCal modules, each one providing a measurement of β
     - β_{calo} **for the track is then calculated from the error-weighted average of 1/β for each measurement**
     - Z -> μμ events are used to calibrate β **for each detector module**



$m_{dE/dx}$ vs m_{ToF}: dE/dx > 1.8

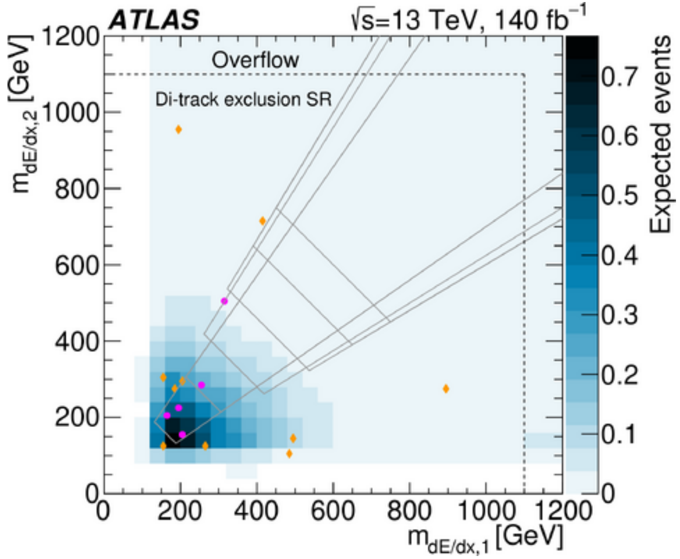
Data compared to background expectation for compatible $m_{dE/dx}$ vs m_{ToF} and dE/dx > 1.8

No excess is observed, confirming that there is no sign of slow massive particles



Analysis strategy (Run 2/2) (2)

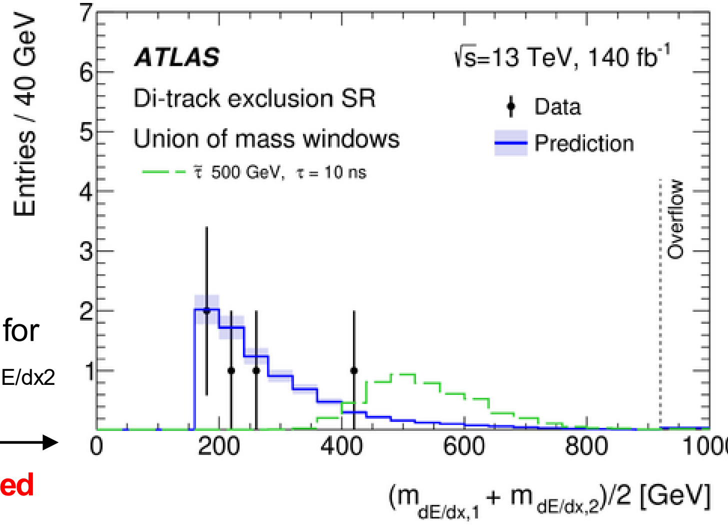
- The second round of Run 2 analysis added requirements to the event or track selections to be able to lower the dE/dx cuts (https://arxiv.org/abs/2502.06694)
  2) Given that all BSM particles in these searches are produced in pairs, look for 2 tracks with the same properties and matching measured masses in the same event — target the slepton search in the low-mass range relaxing the dE/dx cut



$m_{dE/dx2}$ vs $m_{dE/dx1}$:
dE/dx > 1.6/1.3

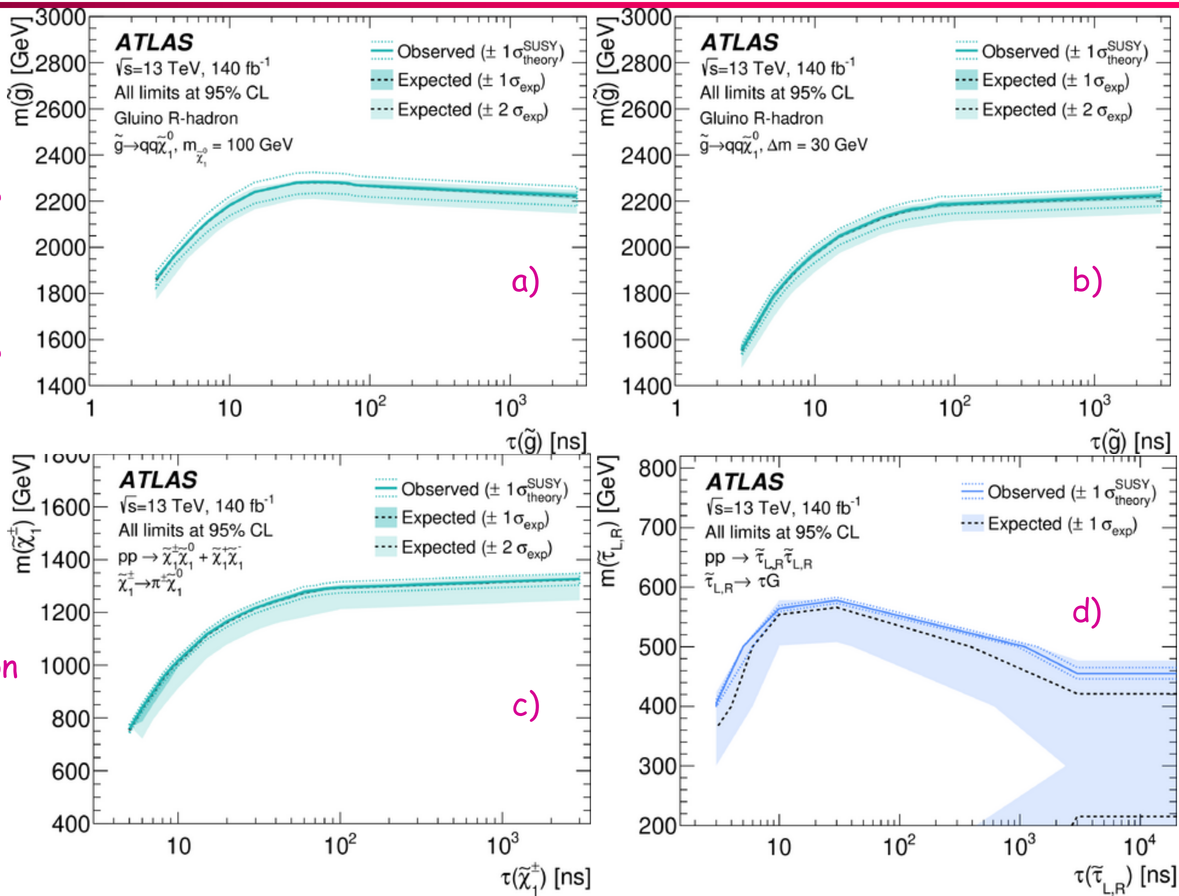
Data compared to background expectation for compatible $m_{dE/dx1}$ vs $m_{dE/dx2}$ and dE/dx > 1.6/1.3

No excess is observed



Analysis strategy (Run 2/2) (3)

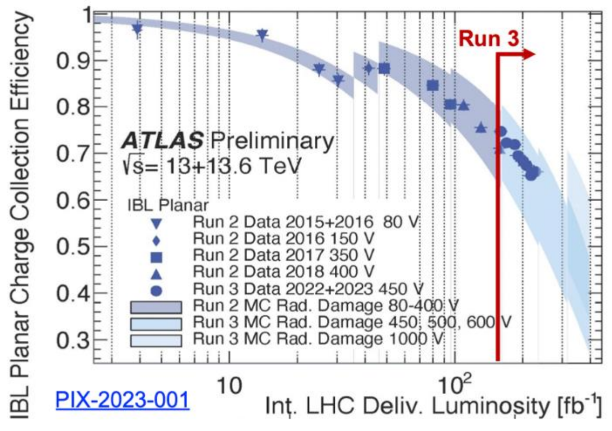
- The measurement can be interpreted as limits on the masses of BSM particles, as function of their lifetimes:
  - a) Gluino mass, from gluino R-hadron pair production, for neutralino mass of $m(\chi_1^0)$ = 100 GeV (β_{calo} search)
  - b) Gluino mass, from gluino R-hadron pair production, for neutralino mass with $\Delta m(g, \chi_1^0)$ = 30 GeV (β_{calo} search)
  - c) Chargino mass, from chargino pair production (β_{calo} search)
  - d) Contour around the excluded mass-lifetime region for stau pair production (di-track search)
- All observed limits extend the measurement ranges of the previous analysis and/or are more stringent

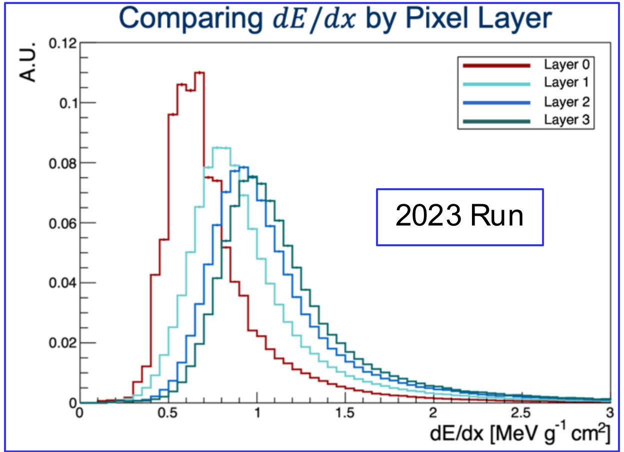


Improvements to the analysis for Run 3 data

- Run 3 (2022-2026) will provide an increase in recorded luminosity by a factor ~3
  - Not enough to make any large difference if the analysis is kept the same
  - The increased centre-of-mass energy 13.0 -> 13.6 TeV will make little practical difference
- To extend the coverage in terms of lifetimes and the mass reach, we need to add new conditions and/or improve the resolutions of the current measurements:
  1) Improve the resolution of the dE/dx measurement in the Pixel detector and compensate the effects of radiation damage
  2) For long lifetimes, add the measurement of Time of Flight and dE/dx in the MDT (muon) detectors
- Each of these conditions needs work on software development, calibrations and data handling

Radiation damage in Pixel detectors





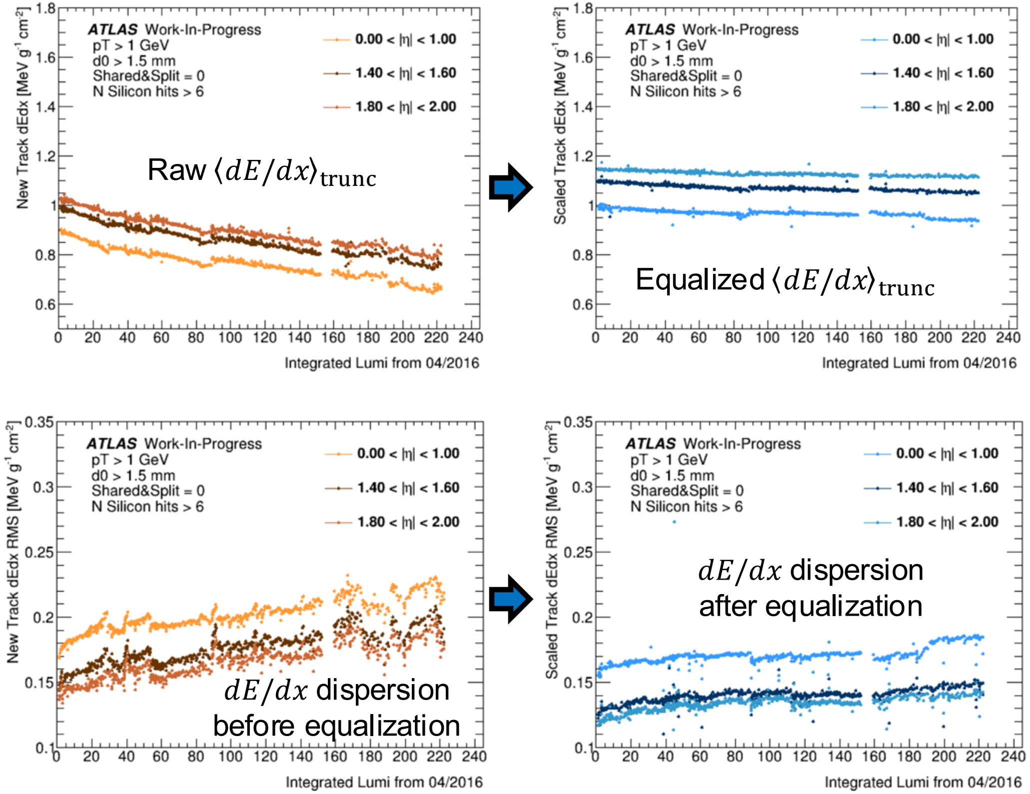
- dE/dx measurements are sensitive to:
  - Radiation damage
  - Operating conditions (bias voltages, thresholds, feedback currents)
- Radiation damage to silicon bulk -> lower charge collection efficiency -> lower dE/dx
  - Worse for innermost layers:
    - Truncated mean more likely to drop measurements in outer layers
  - Can recover *some* efficiency by increasing bias voltage
- New Run 2+3 strategy:
  - Equalize dE/dx at cluster level, before taking the truncated mean
  - Need separate scale factors for each run and module:

$$\left\langle \frac{dE}{dx} \right\rangle_{\text{corr}} = \sum_{i}^{N-n} \frac{w_{\text{run},\eta}\; w^{i}_{run,\text{module}}\; (dE/dx)^{i}_{\text{clus}}}{N-n}$$

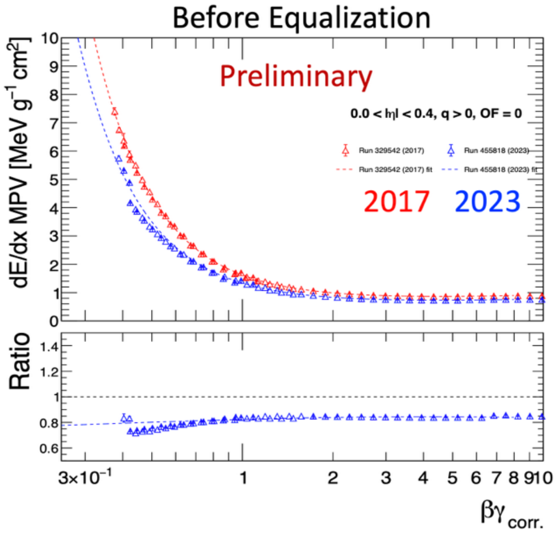
  - Beware: $(dE/dx)^{i}_{\text{clus}}$ is not in the standard track records in analysis formats

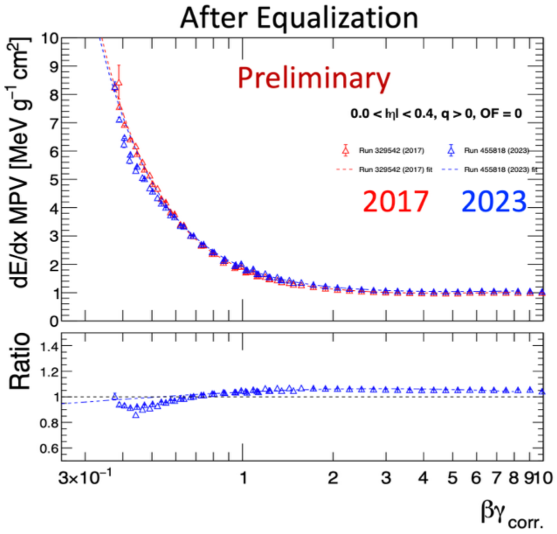
dE/dx Equalization (1)

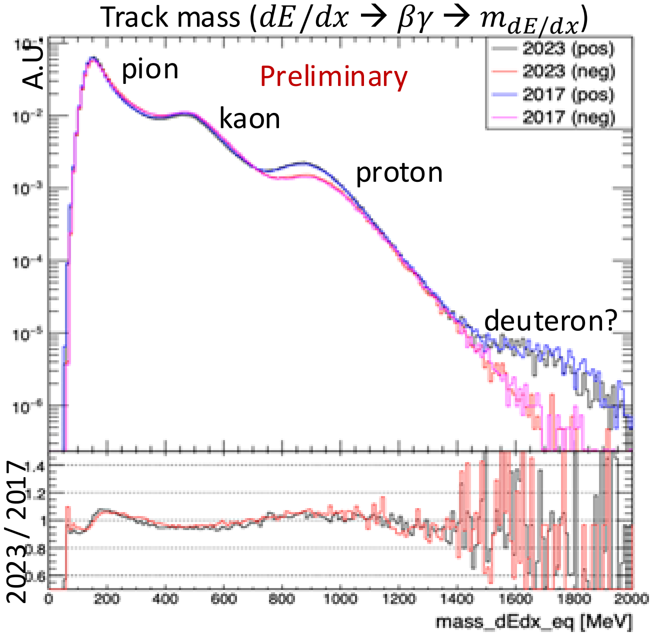
- Procedure:
  - Measure dE/dx MPV for every module in every run using high momentum tracks
    - Integrate over module ϕ & $\pm z$
    - Merge adjacent runs when stats are low
  - Identify reference data period with little radiation damage
    - ~1 fb^{-1} from early 2016
  - Derive module and run specific scale factors
    - Store them in a database
  - Develop code to correct a specific module's dE/dx MPV to its reference value
    - Initially at analysis level
      - If Pixel clusters are available
    - Eventually already during bulk reconstruction



dE/dx Equalization (2)





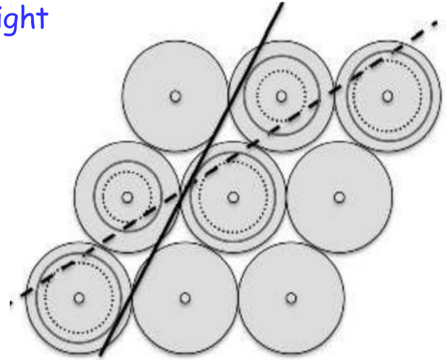


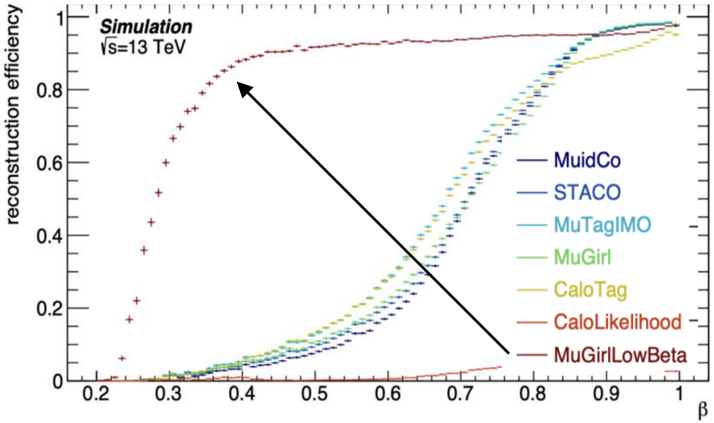
- Performed Bethe-Bloch calibration with data from 2017 and 2023 low pile-up runs
  - Using very preliminary scale factors.
  - Much better agreement after equalization.
- Applied calibration to check pion, kaon, proton mass stability.
  - Separated by year and sign of track charge.
  - Decent agreement, but some interesting features to study.

$$m_{dE/dx} = \frac{p}{(\beta\gamma)_{dE/dx}}$$

MDT β measurement

- The MDTs (Muon Drift Tubes) are the largest-radius detectors that can measure the time of flight
  - Each MDT tube measures the arrival time of the pulse at the end of the wire, which is a combination of several factors:
    - Arrival time of the particle that crosses the detector
    - Drift time of the ionised electrons to the wire in the centre of the tube
    - Propagation time of the electric pulse along the wire
  - Each track crosses on average 20 tubes in 3 stations, so it is possible to measure from a track fit the trajectory and also the velocity β
    - The track fit algorithm with β as a free parameter is very efficient but rather slow, so it cannot be run on all events





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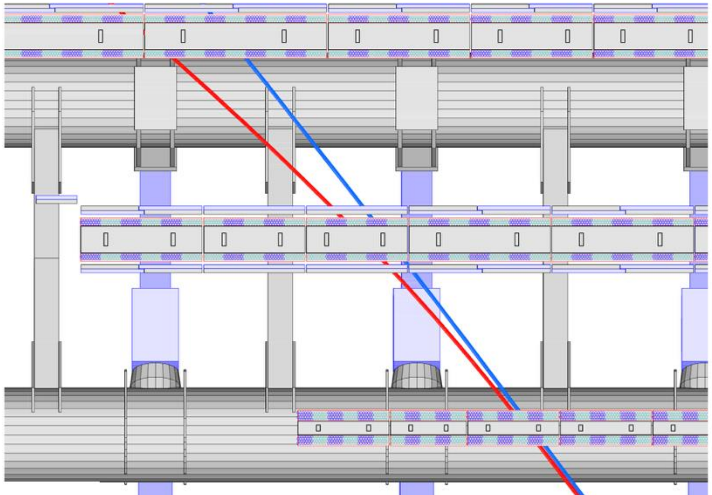
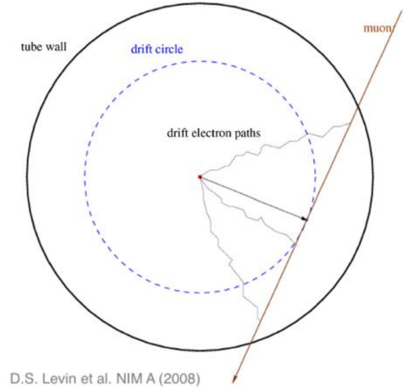
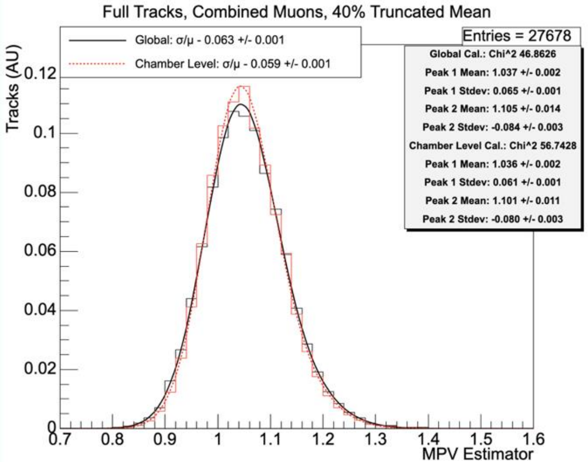


MDT dE/dx measurement



D.S. Levin et al. NIM A (2008)



- Use MDT ADC counts (charge collected in first 18.5 ns after threshold crossing) from each hit to form MDT dE/dx estimator on track
  - O(20) MDT hits per track in MS → estimator is truncated mean of ADC counts on track (excluding the 40% higher counts)
  - Corrected for various effects/operating conditions:
    - Drift radius
    - Temperature
    - Distance from hit to R/O electronics (propagation attenuation)
    - Amplifier gain variation
- Initial studies indicate estimator demonstrates good resolution for muons in data with subset of corrections (relative resolution ~6%)
- Calibration using muons from $Z\to\mu\mu$ data ongoing

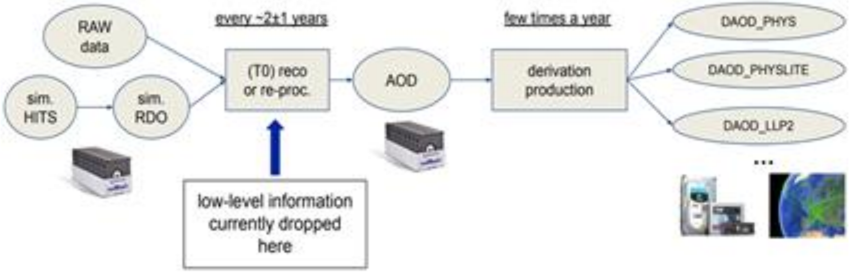
New workflow

- Want Pixel clusters for analysis:
  - Equalize dE/dx at module level
  - Develop new metrics for rejecting bkg (e.g. dE/dx dispersion)
  - Reject unusually large clusters with large dE/dx
- But clusters are not present in the standard data analysis format

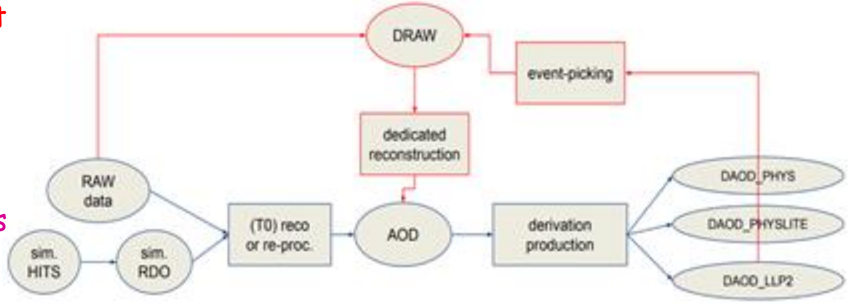
- Want to run the slow muon reconstruction algorithm
  - Too slow to run it on all events

- Solution:
  - Use event picking to produce custom datasets with RAW format
- Analysis workflow:
  - Identify interesting events using info in standard format
  - Use Event Picking Service + run dedicated reconstruction
  - Run additional slow algorithms on the handful of selected events
  - Use cluster-level dE/dx (and other cluster info) in analysis

Nominal Dataflow



Modified Dataflow



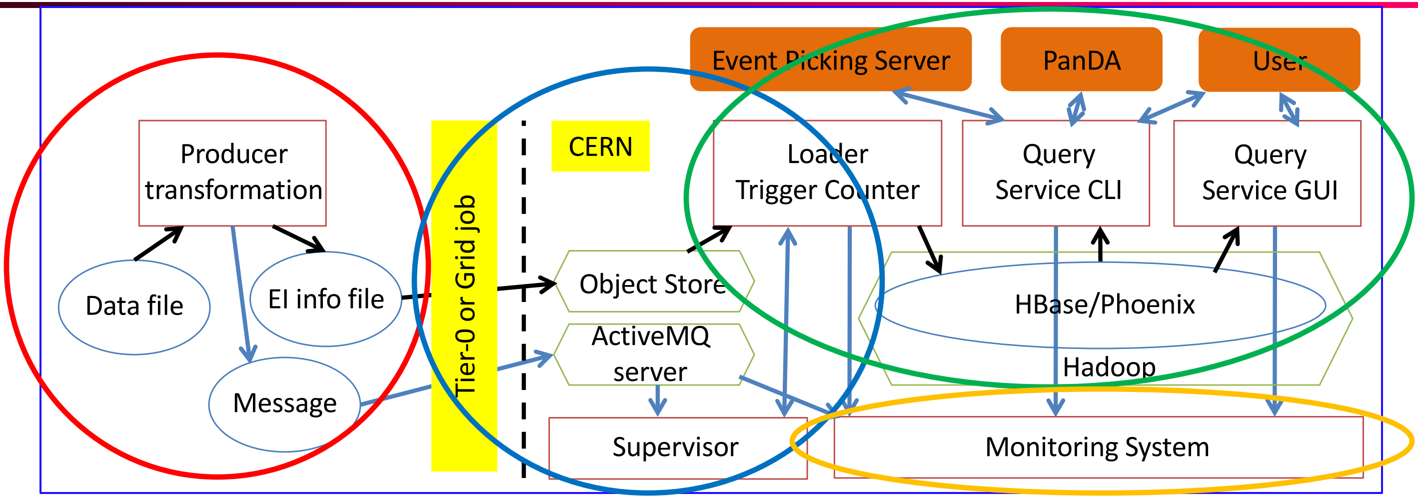
Simone Pagan Griso

The ATLAS EventIndex

- The ATLAS Experiment produces large amounts of data
  - several billion events per year (real and simulated data, several formats and versions)
- A database containing references to the events is necessary to efficiently access them in the distributed data storage system
- The ATLAS EventIndex provides
  - a way to collect and store event information using modern technologies
  - various tools to access this information through command line, GUI and RESTful API interfaces
  - an indexing system that points to these events in millions of files scattered through a worldwide distributed computing system
- It allows fast and efficient selection of events of interest from the billions of events recorded, based on various criteria

- EventIndex records contain the following fields:
  - Event identifiers
    - Run and event number
    - Trigger stream
    - Luminosity block
    - Bunch Crossing ID (BCID)
  - Trigger decisions
    - Trigger masks for each trigger level
    - Decoded trigger chains (trigger condition passed)
  - References to the events in all permanent files generated by central productions (for event picking):
    - GUIDs of the files containing each event (including provenance)
    - Internal reference within each file
- Indexed datasets:
  - Real data: all physics AOD and DAOD_PHYS(LITE)
    - GUIDs for RAW events can be retrieved from the provenance field of corresponding AOD and DAOD
  - MC data: all EVNT, AOD and DAOD_PHYS(LITE)

EventIndex Architecture



Partitioned architecture, following the data flow:

- Data production
  - Extract event metadata from files produced at Tier-0 or on the Grid
- Data collection
  - Transfer EI information from jobs to the central servers at CERN
- Monitoring
  - Keep track of the health of servers and the data flow
- Data storage and query
  - Provide permanent storage for EventIndex data
    - full info in HBase tables with a Phoenix interface (part of the Hadoop ecosystem)
  - Fast access for the most common queries, acceptable time response for complex queries
  - CLI for small queries, Event Picking Server for big ones

Event Picking Server

Use case:

- **Automate event picking for large requests**

  (from thousands to millions of events across all ATLAS data)

Workflow:

- The user submits a request through the GUI, supplying a list of run/event numbers, data type and (if needed) trigger stream, AMI tags and other auxiliary information
- The Daemon does the bulk of the work
  - splits the list by run number,
  - queries the EventIndex to retrieve the GUIDs of the files with the events,
  - submits event picking jobs to the ATLAS PanDA distributed workflow management system,
  - collects the output files into datasets placed at CERN,
  - notifies the user of completion.
- The user can monitor the progress through the GUI, then retrieve the output datasets and process the events

Architecture:

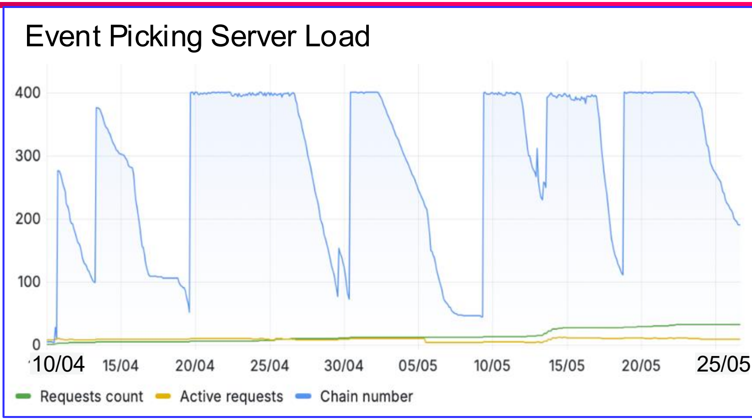
- Three components:
  - GUI for user requests, monitoring and results
  - Deamon to process the requests
  - Backend database (PostgreSQL) to store the requests and their status/progress

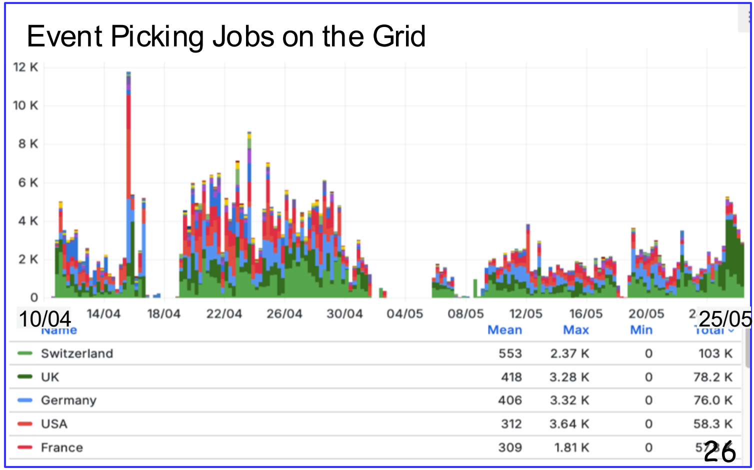
EPS operations for *dE/dx* analysis

- Event lists for Run 2 and Run 3 data (2015-2024) were built to include all signal, control and validation regions

Data year	Events	Submitted	Completed
2015	40k	29 Apr 2025	12 May 2025
2016	369k	30 Apr 2025	95% on 25 May
2017	486k	09 May 2025	95% on 25 May
2018	645k	18 May 2025	72% on 25 May
2022	229k	10 Apr 2025	24 Apr 2025
2023	249k	13 Apr 2025	27 Apr 2025
2024	949k	18 Apr 2025	99.9% on 25 May
Total	**2,969k**	**10 Apr 2025**	92% on 25 May

- The lists were submitted in sequence to the Event Picking Server to avoid overloading the EPS and also the Data Carousel that manages the staging of RAW data from tape at the Tier-1 computing centres
  - The EPS by itself also throttles submission of the PanDA tasks
  - The output files are directed to Grid group space at CERN and grouped into one container dataset per year of data-taking
- A couple of tape outages delayed the completion, but the overall performance is above expectations (we expected 3 weeks for each million events)





Outlook

- Physics analyses using massive event picking at the level of 10^{-4} of the input events are feasible
- The massive event picking operation went reasonably well
  - We had to retrieve many more events than initially thought, as the analysis was extended to use the muon detectors in addition to the original Pixel and Tile Calorimeter information
- Calibration of the Pixel cluster dE/dx and of the MDT ToF and dE/dx is making good progress
  - The algorithms to use the new calibrations in reconstruction and analysis are ready
- Processing of the selected events will start as soon as the last checks are completed

- Results will be ready and published (early) next year

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