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dE/dx – Measurements with ATLAS hybrid pixel

ELMA Workshop on "Energy loss measurements with MAPS"
Trieste, 10-11 September 2025

1 -Lawrence Berkley Lab
2 - Prague CU
3 - INFN Genova
4 - Oregon University
5 - Harvard University

ATLAS Pixel Detector

Charge measurements & Calibration – dE/dx

Handling radiation damage

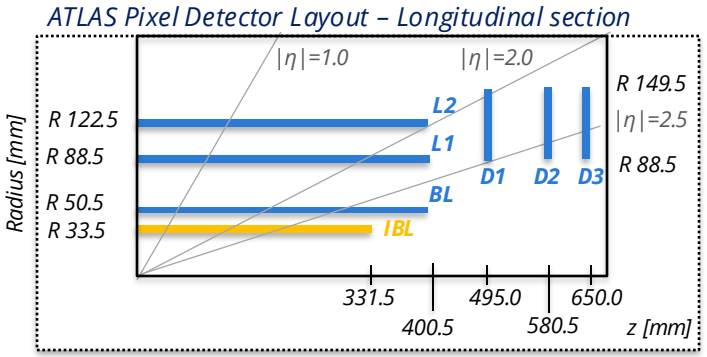
One application of dE/dx in ATLAS

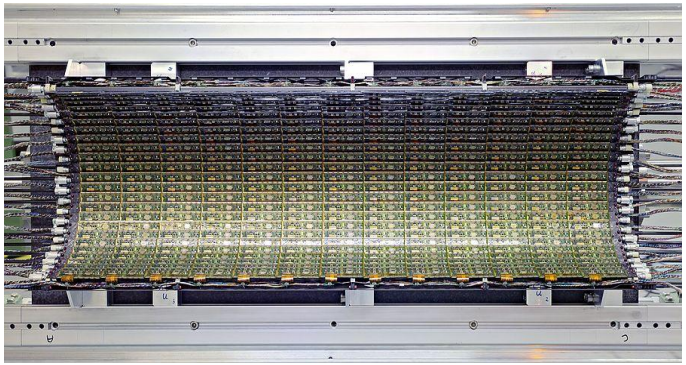
Little bit off-topic from MAPS … My favourite collection of topics that you may find interesting!

ATLAS Pixel & IBL Detector

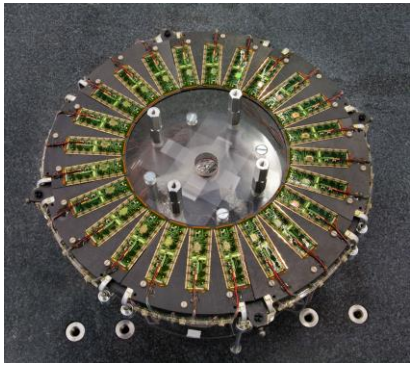
Pixel Detector - Operating since **2008**
- **Three barrel layers**, radii 50.5, 88.5, 122.5 mm
  - Staves: B-Layer, Layer-1, Layer-2
- **Three end-cap disks** (per side)
  - D1, D2, D3

IBL Detector - Operating since **2015**
- **Additional 4th barrel layer**, at radius **33.5 mm**
- Installed during LS0 to cope with increased lumi in Run 2/3

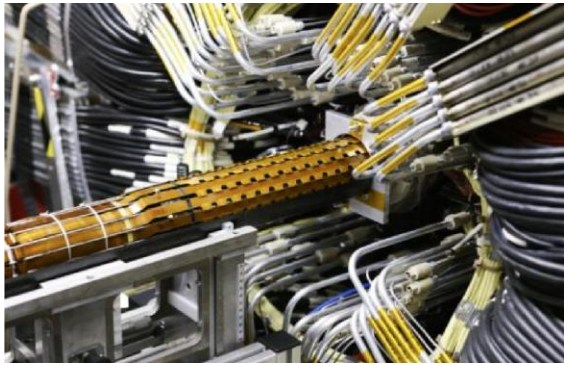




Pixel Detector – L2 – Half shell - 2007



Pixel Disk - 2007

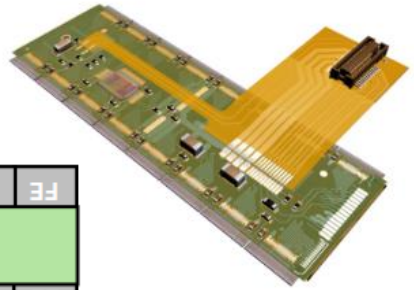


IBL Insertion in ATLAS - 2014

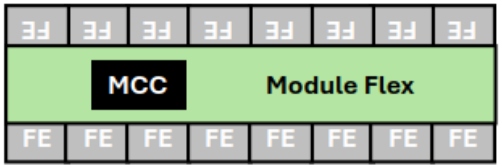
ATLAS Pixel & IBL Detector

Pixel Detector - 2008

- **Hybrid modules**
  - 16 FEs per module in 250 nm technology (FEI3)
  - 1 **planar sensor** n-in-n per module, 250 µm thick
  - **Expected 20ke** for a MIP before irradiation
  - Dynamic range up to 200ke
  - No overflow mechanism
  - **Rad Hard**: 50 Mrad and **~ 1e15 n_{eq} / cm^2**

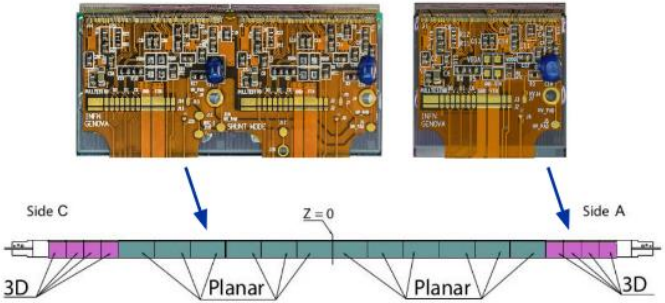


Pixel Module schema



IBL - 2015

- **Hybrid modules**
  - FE technology 130 nm CMOS (FEI4)
  - **Planar sensors** 200 µm thick, **low |η| (2 FEs)**
  - **Expected 16ke for a MIP before irradiation**
  - **3D sensors** 230 µm thick, **high |η| (1 FE)**
  - Dynamic range up to 30ke
  - Overflow mechanims – 1 Bit in the data stream
  - **Rad Hard**: 250 Mrad and **~ 5e15 n_{eq} / cm^2**



ATLAS Pixel Detector

Charge measurements & Calibration – dE/dx

Handling radiation damage

One application of dE/dx in ATLAS

ATLAS modules – Charge collection

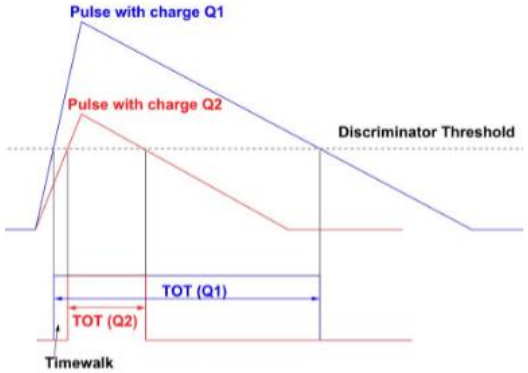
ATLAS FEs able to measure of Time-over-Threshold (ToT)

- Time that the signal generated by the crossing charged particle hang above the discriminator threshold

*Almost **linear relation** between charge released by the crossing particle and ToT*

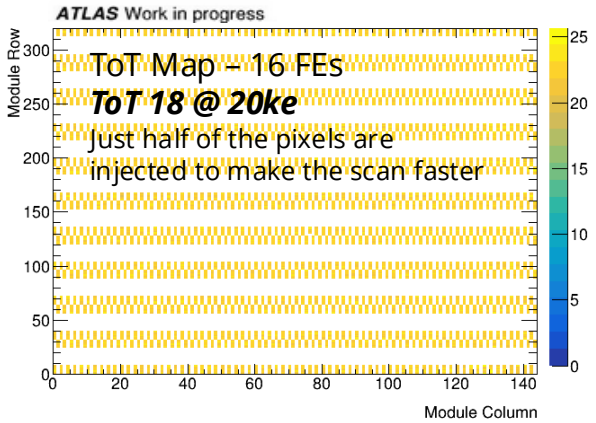
ToT-Charge tuning pixel-by-pixel

- Global register – 8 bits
- Single pixel registers – 4 bits– for fine tuning



BEFORE DATA TAKING		→ DATA TAKING →	DATA PROCESSING (OFFLINE)	
ToT-Charge Calibration via injection circuit	Calibration saved to Config. Database	***ToT is readout*** in the data stream **8 bits for Pixel 4+1(Ovf) bits for IBL**	***ToT-to-Charge conversion*** using Config Database	Charge info are saved in ATLAS dataframe

Pixel Detector ToT Calibration & Config. Database

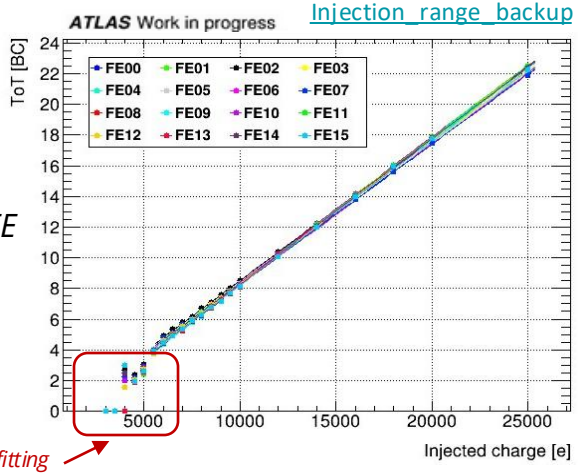


Charge injection
3ke →25ke

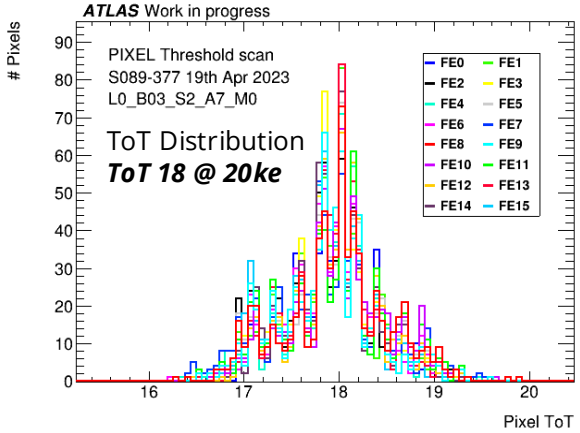
ToT Readout
Average ToT per each FE
Fit

(1) $\mathrm{TOT} = p_0 \frac{p_1 + Q}{p_2 + Q}$

Injection_range_backup



The first 5 points are not used in the fitting since they do not reflect the real behaviour



Calibration is performed via charge injection circuit

- *Mean value of ToT is plotted per each FE → Fit*
- ***Not enough space in Config DB to save a calibration at pixel-level!!***

Calibration, based on average FE ToT, per each FE

- ***Fit parameters saved to config DB at FE-level***
- *Offline: from ToT to Charge with inverse function of **(1)***

How to estimate the dE/dx of a charged particle ?

Per each cluster on a track we can calculate the cluster ***dE/dx***

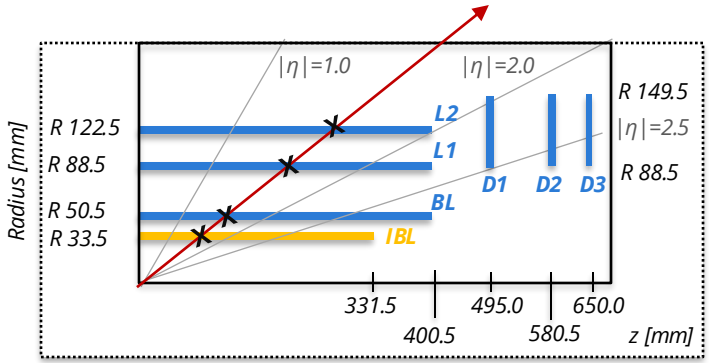
- ***dE*** from the ToT-Charge conversion
- ***dx*** from the track local incidence angle + thickness of the pixel sensor

On average *4 independent measurement of cluster dE/dx*

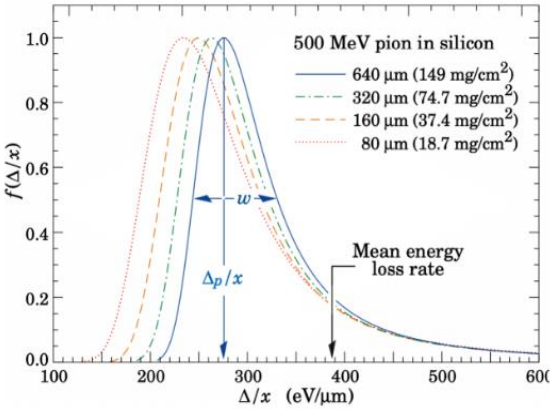
Truncated mean $\langle dE/dx \rangle_{trunc}$ of cluster on track *dE/dx*

- Good estimatore of MPV
- ***Drop the highest value of the cluster dEdx + mean of remaining***
- Robust against statistical fluctuations.

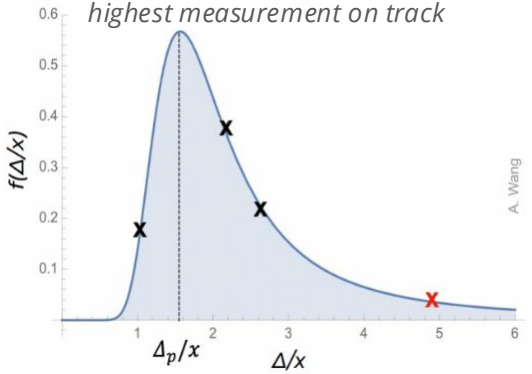
MIP Crossing the Detector



Landau distributions for thin silicon absorber



Truncated mean dropping the highest measurement on track

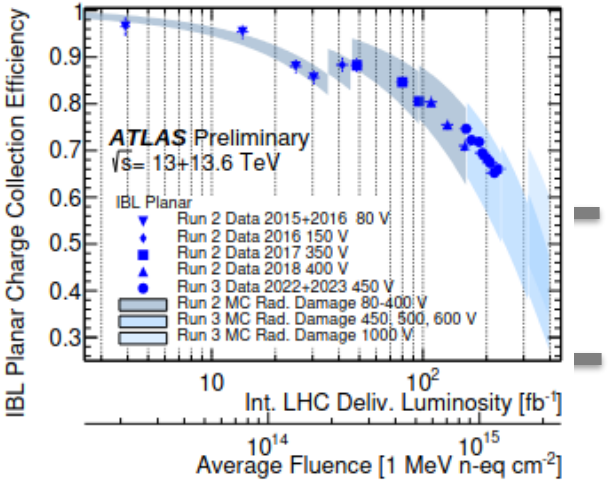


ATLAS Pixel Detector

Charge measurements & Calibration – dE/dx

Handling radiation damage

Charge Collection efficiency

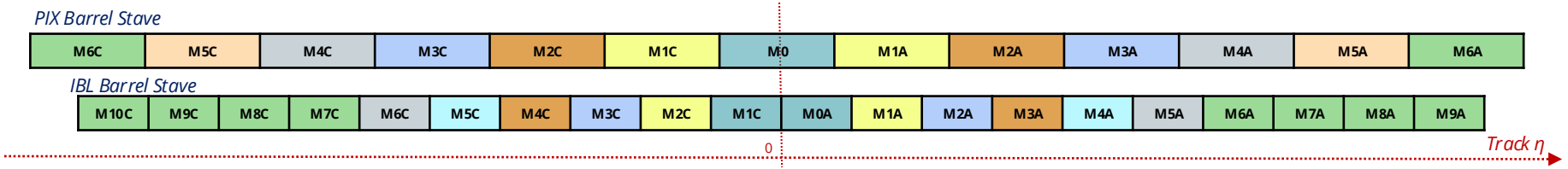


ATLAS has already collected more than 400 fb^{-1} since beginning of Run-1
Detectors are subjected to Radiation Damage that has a complicated dependece on the position of the modules in the detector (distance from i.p., material etc...)

One application of dE/dx in ATLAS

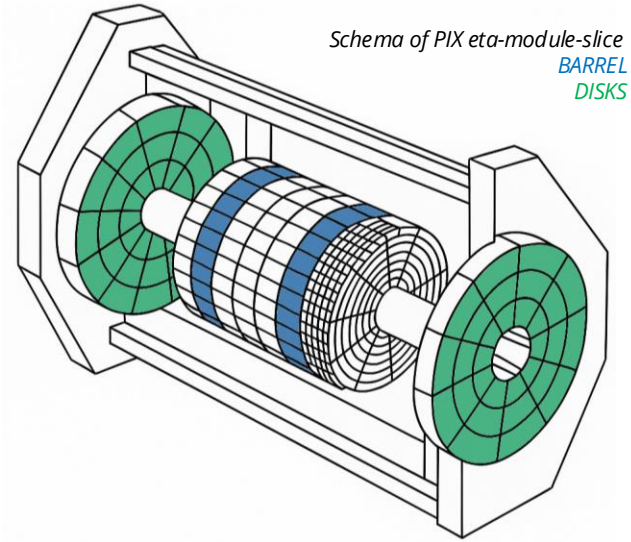
PIXEL_PUBLIC_PLOTS_RAD_DAMAGE

Eta Module Slice – An idea to study local Radiation Damage



How we build an etaModuleSlice **(Barrel)**:

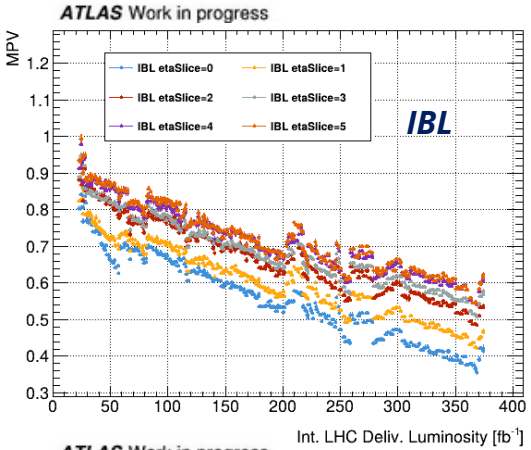
- *η Symmetry:* We *group modules that are mirrored in eta on the stave* [IBL 3D all together – out of tracking]
  - EtaModule 0 in PIX barrel is left alone, odd number of modules on a stave
- *Φ Symmetry*:
  - Per each layer we *group modules sharing the same position on the stave*

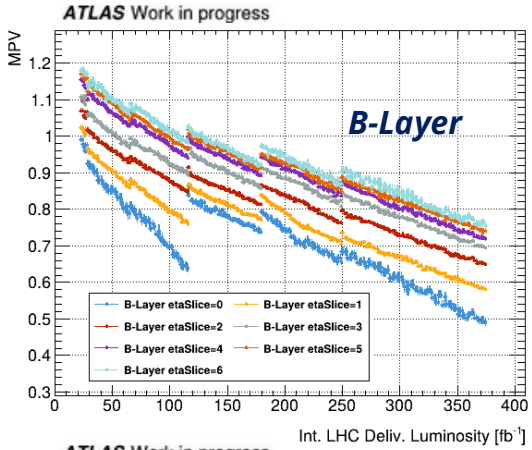


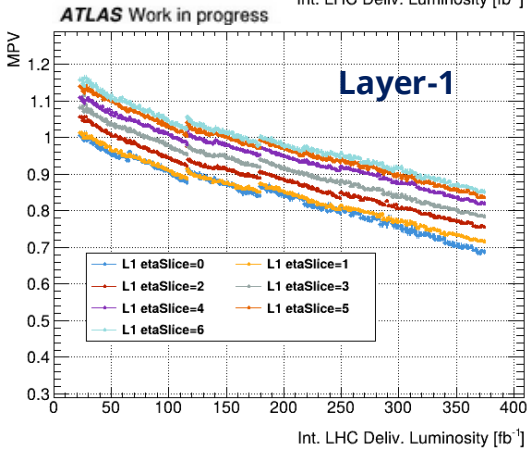
How we build an etaModuleSlice **(Disks)**:

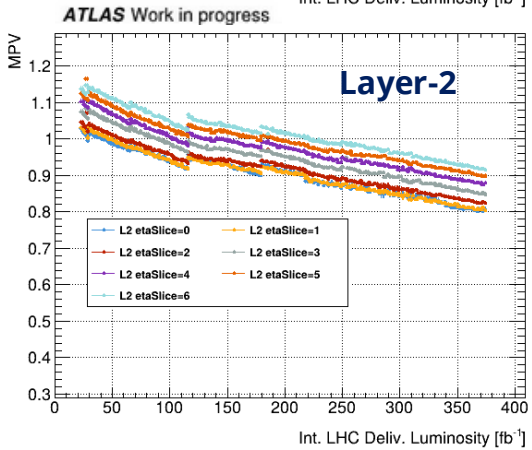
- We group together all the modules on the same disk
- We group together Side A & C disks

Clusters MPVs trends – 2015 / 2024









As expected radiation damage is more and more severe close to the interaction point

Example (***layer dependency***)
At central eta (eta-module-slice 0) the MPV degradation in 2024 respect to *2015* is:

- ***IBL ~ 55%***
- ***B Layer ~ 50%***
- ***Layer 1 ~ 30%***
- ***Layer 2 ~ 20%***

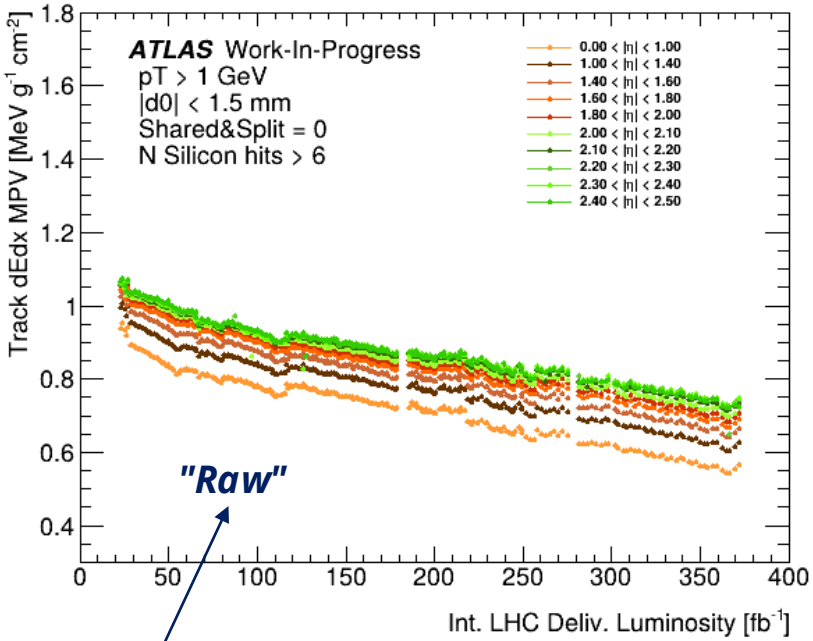
Example (***eta dependency***)
MPV degradation in B-Layer:

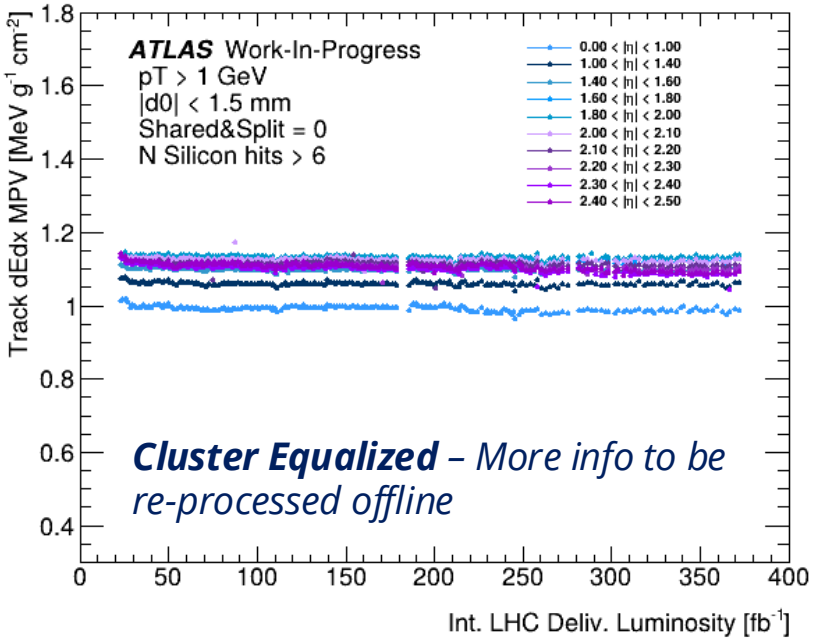
- ***Eta-module-slice-0 ~ 50%***
- ***Eta-module-slice-2 ~ 35%***
- ***Eta-module-slice-6 ~ 25%***

Occasional jumps in the trend (e.g. at around 120 fb^{-1}) indicate changes to the Pixel detector main working point conditions, such as threshold and bias voltage, mainly happening during technical shutdowns.

Using $\langle dE/dx \rangle_{trunc}$ for physics analysis – More in BACKUP

To use $\langle dE/dx \rangle_{trunc}$ we need uniform and stable response over time …. Equalisation!





Cluster Equalized *– More info to be re-processed offline*

$$\left\langle \frac{dE}{dx} \right\rangle_{trunc} = \frac{(dE/dx)^{i}_{cluster}}{N-n} \rightarrow \left\langle \frac{dE}{dx} \right\rangle_{corr} = w_{run} \sum_{i}^{N-n} \frac{(w^{layer}_{\eta-module-slice})^{i} (\mathrm{d}E/\mathrm{d}x)^{i}_{clust}}{N-n}$$

ATLAS Pixel Detector

Charge measurements & Calibration – dE/dx

Handling radiation damage

One application of dE/dx in ATLAS

An application of dEdx in ATLAS - BACKUP

Direct search of ***Long-Lived charged Particeles*** (LLPs)

- **Stable or Metastable**

The signal is a potentially slow ($0.3 < \beta < 0.8$) highly ionising LLP

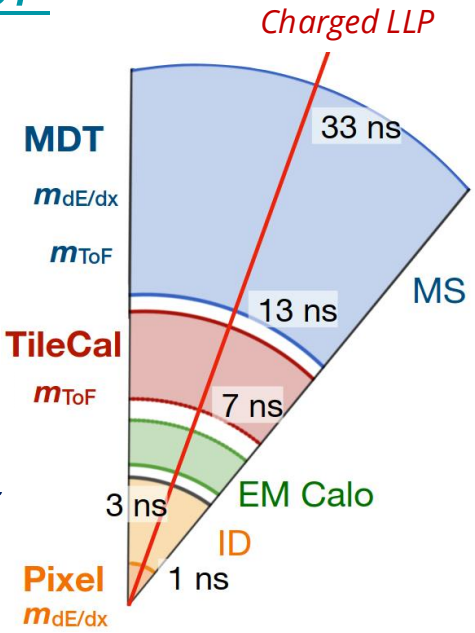
Each of the tracks will have up to 4 mass measurements:

- m_{dEdx} Pixel
- m_{dEdx} Muon
- m_{TOF} TileCal
- m_{TOF} Muon

βγ from calibrated Bethe-Bloch formula

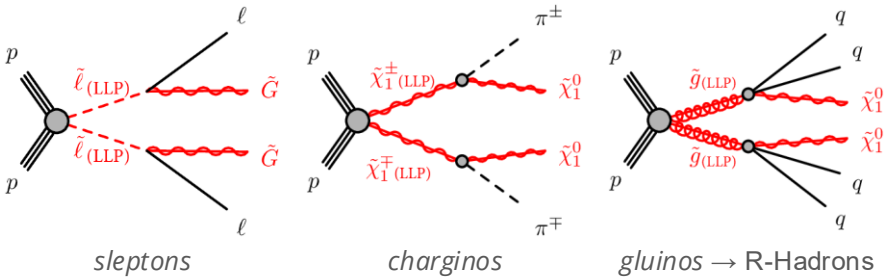
β from Time Of Flight

$m_{LLP} = p/\beta\gamma$



Credits to S. Nechaeva Indico

Benchmark signals



The search is ***model-independent*** and will allow to set the limits on the production cross-section of charged BSM particles within a given mass and lifetime range

Conclusions

Pixel & IBL operating in ATLAS since 2008 / 2015, playing crucial role in the ATLAS tracking/vertexing

Measure of the **charge release by a charged particle via ToT** with 8 bits / 4bits in Pixel / IBL dedicated in the readout chain

Calibration of ToT-Charge at FE-level due to space limitation in the Configuration DB

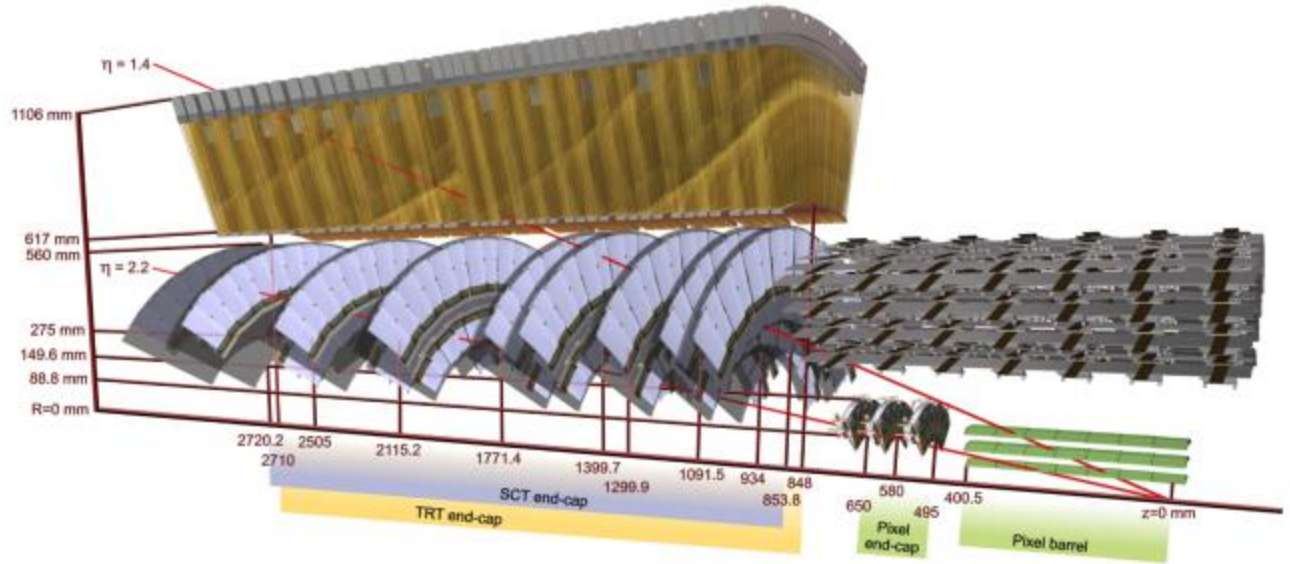
$\langle dE/dx \rangle_{trunc}$ as a good estimator of a charged particle MPV

Proposed a ***new* local equalisation of the track dEdx** via correction at cluster level before evaluating $\langle dE/dx \rangle_{trunc}$

dE/dx as a metrics for BSM searches in ATLAS via Bethe-Block calibrated relation

Backup

ATLAS Inner Detector



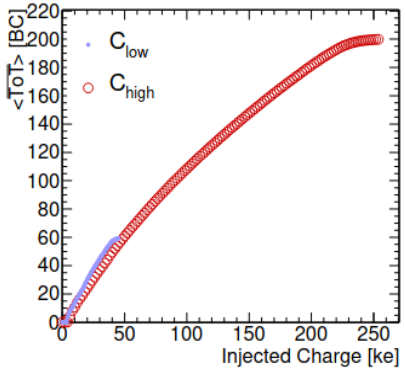
From the online ToT calibration to the Offline reconstruction

ToT Calibration in the Pixel Detector (B-layer, Barrel, Disks)

It is done in two steps:

- Low-Charge-Calibration (C_{low})
  - Injection from 3 ke to 25 ke
- High-Charge Calibration (C_{high})
  - Injection from 3 ke to 200 ke

http://cdsweb.cern.ch/record/1239019/
November 2009

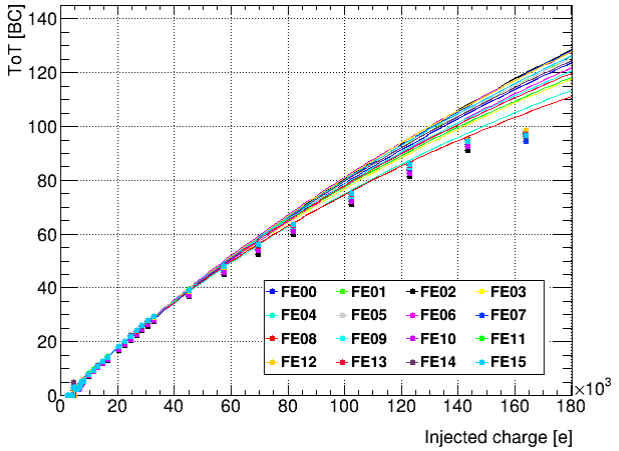


The **ONLINE calibration** ToT vs Injected_charge is done at **PIXEL level**.
[One calibration per each pixel]

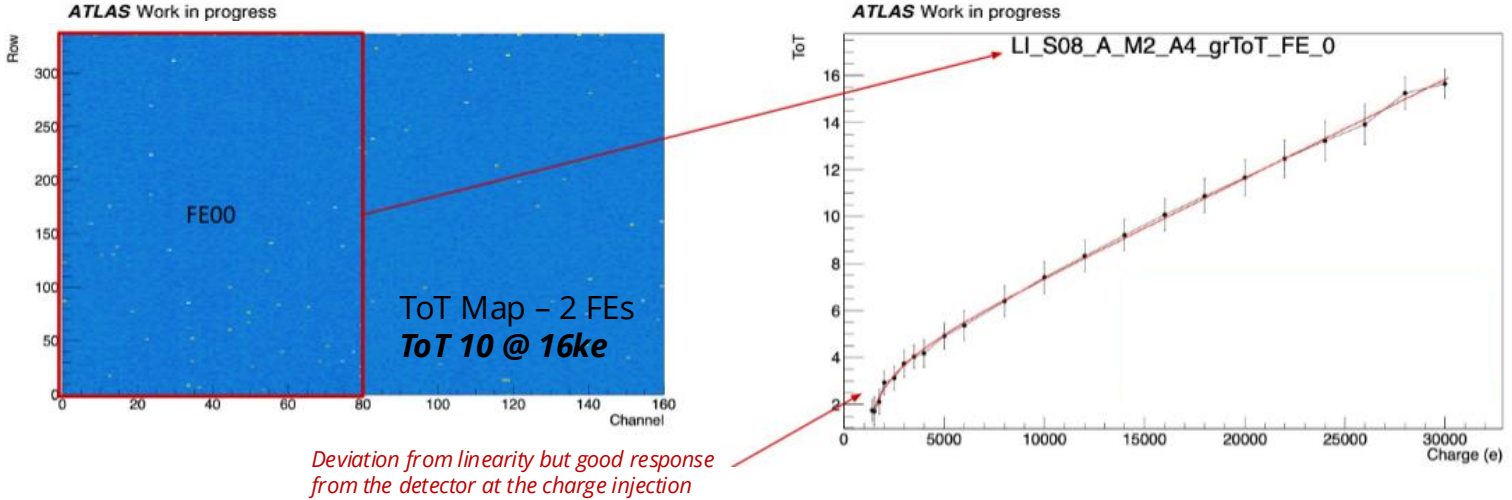
While the **OFFLINE calibration** is stored in the database at **FE level**.
[One calibration per each FE]

The parameters of the fitted curves (charge_vs_ToT) are saved into the database

- **The best parameters of the fitting function are derived only from the Low-Charge-Calibration results (Hence up to 25 ke).**



IBL Detector ToT Calibration & Config. Database



Calibration is performed via charge injection circuit (*1.5ke →30ke*)

- *Calibration is done pixel-by-pixel*

Calibration, based on average FE ToT, per each FE – NOT linear at low injected charge

- Hard to define a fit function
- ***Look-Up-Table is saved to Config DB:*** *linear interpolation to save ToT-Charge relation*

Reminder of dE/dx corrections – Run 2

Run 2 strategy

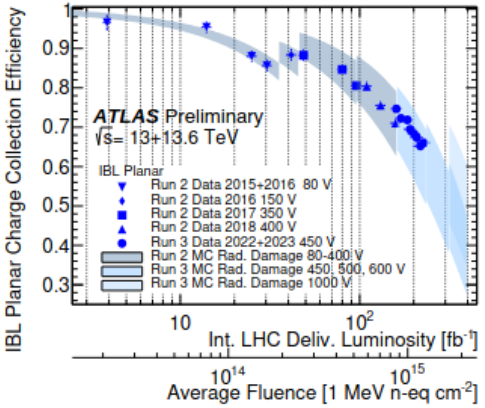
- Raw $\langle dE/dx \rangle_{trunc}$ from AOD must be corrected for
  - *Radiation damage* → deterioration of charge collected
  - *Detector condition changes* (e.g. bias voltage, theshold…)

- Derived **run-specific SFs** → equalize $\langle dE/dx \rangle_{trunc}$ MPV over all runs
  - Also equalize over η
  - Binned corrections in IBL overflow status

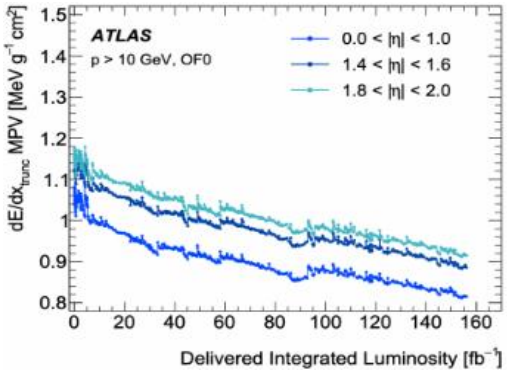
- Only have access to *track-level* $\langle dE/dx \rangle_{trunc}$ in AOD
  - Do not have dE/dx of each cluster

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

Charge Collection efficiency



Run 2 Scale Factors (SFs)



PIXEL_PUBLIC_PLOTS_RAD_DAMAGE

How to deal with radiation damage?

Radiation Damage is getting worse, especially for inner layers

- ***⟨dE/dx⟩$_{trunc}$ more likely to drop measurements for outer layers***
- ⟨dE/dx⟩$_{trunc}$ has complicated dependence on exact layers hit

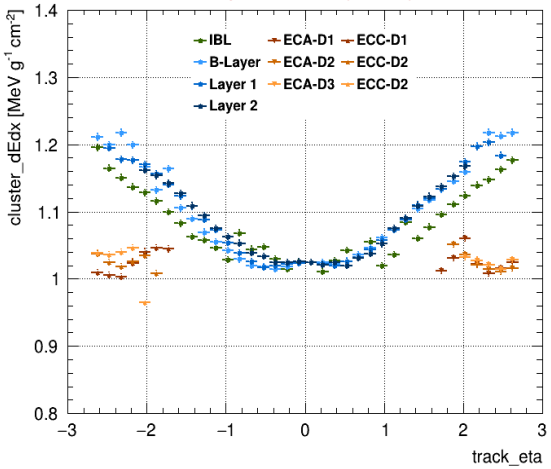
- Would be better to equalize *dE/dx* at cluster level, before taking the truncated mean
  - Separate SF for each ***run*** and ***eta-module-slice*** (*average over phi*)
  - **Local SF** to correct for **radiation damage – per layer and local position**
  - **Run Sf** to correct the residual **dependency of the track dE/dx in eta**

- Requires access to ***pixel clusters*** → special datasets → ***IDTIDE***
  - Enabling new metrics (e.g *dE/dx* RMS) and refined cluster definition

$$\left\langle \frac{dE}{dx} \right\rangle_{corr} = w_{run} \sum_{i}^{N-n} \frac{(w^{layer}_{\eta-module-slice})^{i} (\mathrm{d}E/\mathrm{d}x)^{i}_{clust}}{N-n}$$

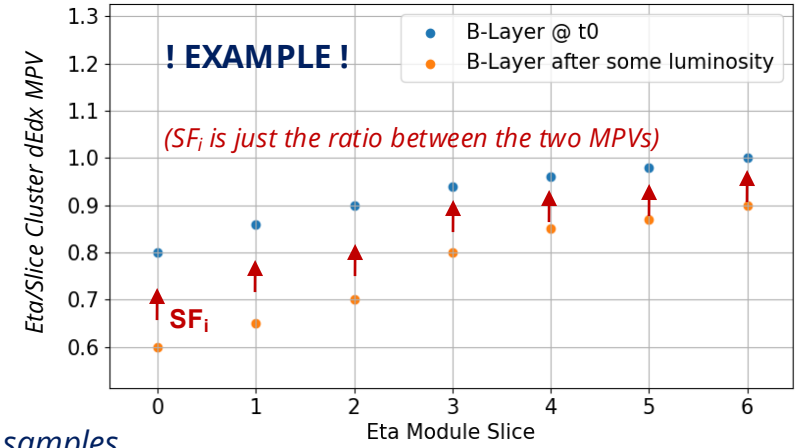
Scale Factors computation - Details

Zero-RadDam sample – First fb^{-1} of 2016



Strategy to compute scale factors:

1. Define the *initial value at which to equalise* (More in Backup)
   - Zero Radiation damage sample ***"t0"*** - First fb^{-1} collected in 2016
2. *Per each Run & layer we build the cluster dEdx distribution of each etaModuleSlice*
3. We fit the distribution to find the MPV
   - Using langaus function already by the LAR group (Indico)



4. *Scale the MPV* of each etaModuleSlice at its t0 value
   - ***Scale Factors "SF$_i$"***
   - ***Unique per each run/layer/eta-module-slice***
   - Ratio between the two MPVs

Note: the statistics in IDTIDE datasets is not huge

- *Gruop together several dataset of different Runs to have ~ 1 fb^{-1} samples*
- Will ***assign to all the runs in the 1 fb^{-1} sample the same Scale Factors***

Datasets production

Required datasets

- To derive module-specific scale factors, we need *datasets* with **cluster info** from every run
  - Pixel clusters are not transported to nominal AODs (only kept in raw)

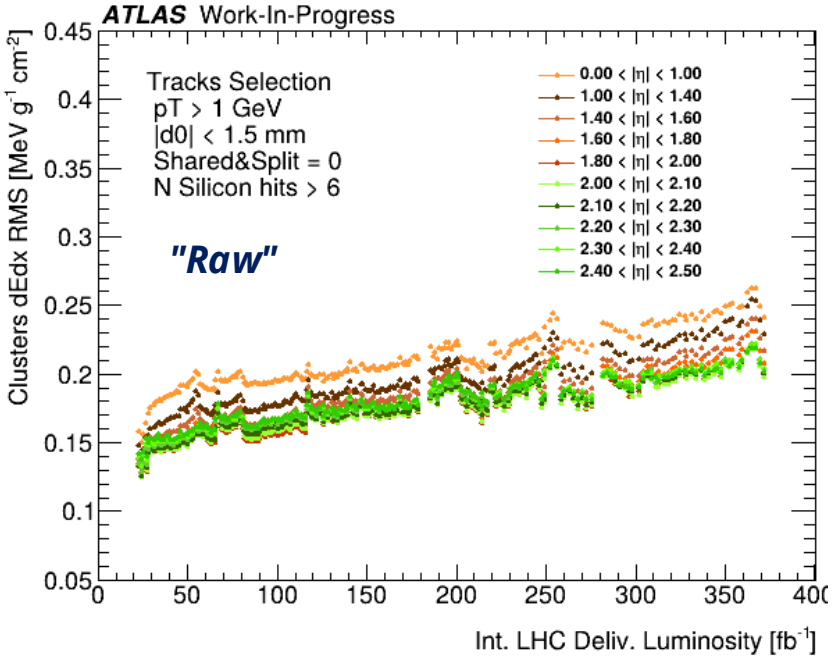
- Plan: *use IDTIDE DAODs for deriving dE/dx corrections and Bethe-Bloch calibrations only*

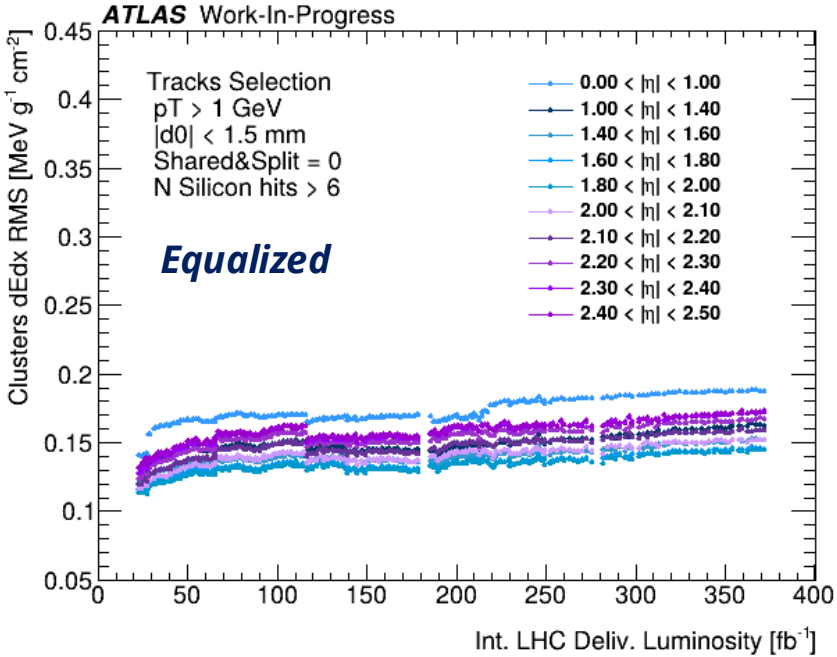
- Nathan developed an ntupler to make small trees from IDTIDE DAODs including *clusters dE/dx*

- Dario adapted Nathan's code to produce datasets for all runs including clusters dE/dx
  - **Ntuples for the module calibration** from DAOD_IDTIDE datasets for data15/16/17/18/22/23 **completed successfully** (Run 2 + Run 3)
  - DAOD_IDTIDE in **2024**: they have *not produced at Tier-0 since August 2024*, when the legacy triggers were disabled but not checked. So for most of 2024, we need to *wait for the Winter reprocessing* of all data. NOW is ongoing.

- We can now read the datasets and fit the *dE/dx* distributions to get the MPV and derive SFs

*Cluster on track RMS **Scaled** – 2015 / 2024*





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

Intra-module desynchronization

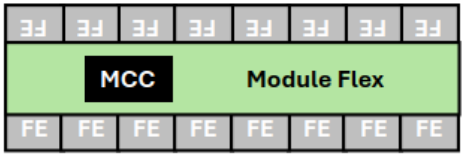
- A pixel module is made by multiple FEs and one controller (MCC)
- **If conditions get too harsh, a single FE can desynchronize,** leading to **unusable events** from the module **until the next ATLAS-Event-Counter-Reset (ECR), every 5 seconds.**

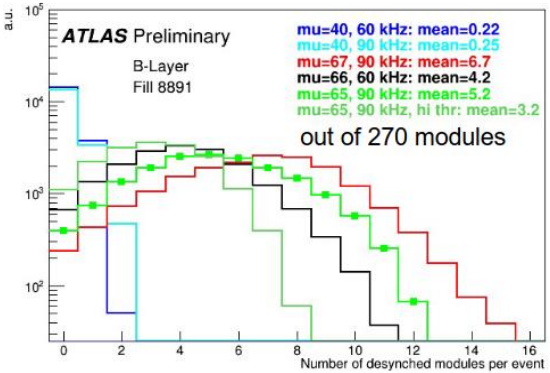
- **Increasing the threshold could help** because it decreases the number of digital hits inside the FE chip.

- **Constrains:**
  - **bandwith, hit-on-track efficiency** and **radiation damage.**

With increased machine performance, frontend limitations start to play a more significant role (next slides)

Pixel Module schema





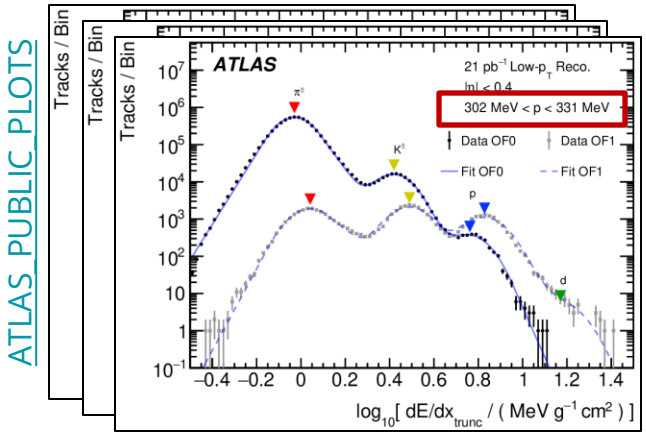
Pixel Threshold [electrons]

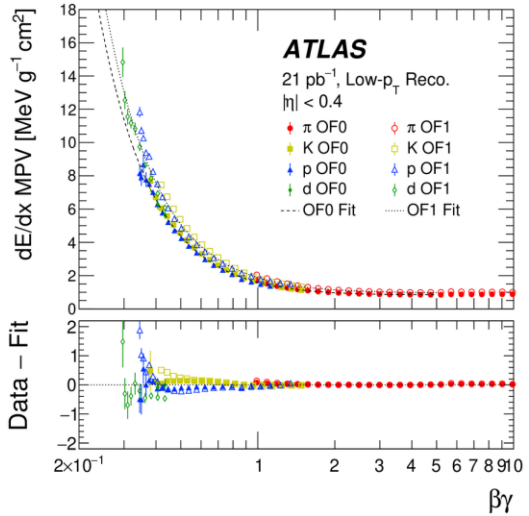
Layer	2015	2016	2017	2018	2022	2023/2024
IBL	2500	2500	2500	2000	1500	1500
B-Layer	3500	5000	5000	4300*	3500*	4700
Layer 1/2	3500	3500	3500	3500	3500	4300
Disks	3500	3500	4500	3500	3500	4300

*Only at low |η|. Higher in forward/backward regions.

Increased Threshold in 2023
2022 <μ> ~ 54
2023 <μ> ~ 62

An application of dEdx in ATLAS





Calculate the mass of hypotetical particle via:

Convert $\langle dE/dx \rangle_{trunc}$ *to* **βγ via calibrated relation**

Calibrate with low mass SM hadrons need low pT → ATLAS special runs with tracks reconstruction down to 100 MeV

- *Plot log($\langle dE/dx \rangle_{trunc}$) in narrow p-slices → can identify* π±, k±, p±
  - Peak dEdx MPV for βγ = π±, k±, p±

Repeat for many p-slice and fit with empirical function