Pixel Luminosity Ring:

physics simulation studies

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PLR Initial Design Review

Introduction

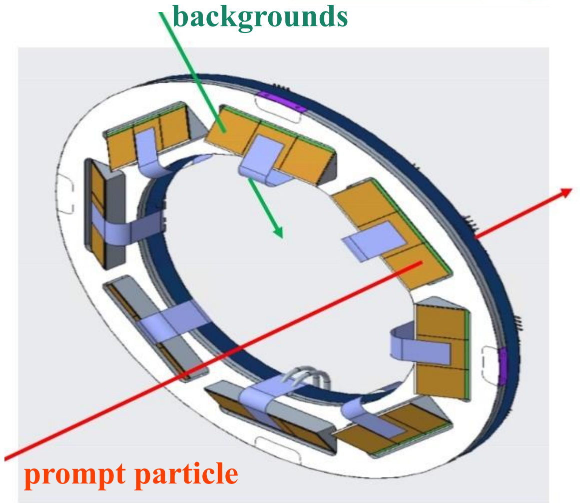
- Talk largely from Simone's presentation at the PLR IDR
  https://indico.cern.ch/event/1020733/

- Main changes since that time has been work by Deion Fellers to get the simulation installed in an official ATLAS release

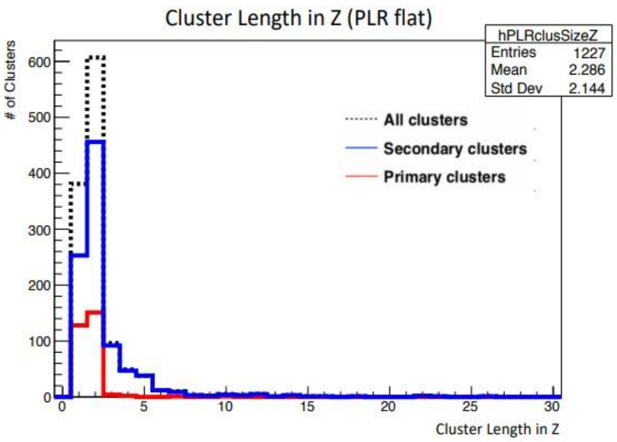
- PLR Goals:
  - Bunch-by-bunch luminometer (per-bcid)
  - Good statistical precision from mu ~ 1 (vdM) to mu ~ 200
  - Linear (using cluster counting)
  - Relatively stable response over a year

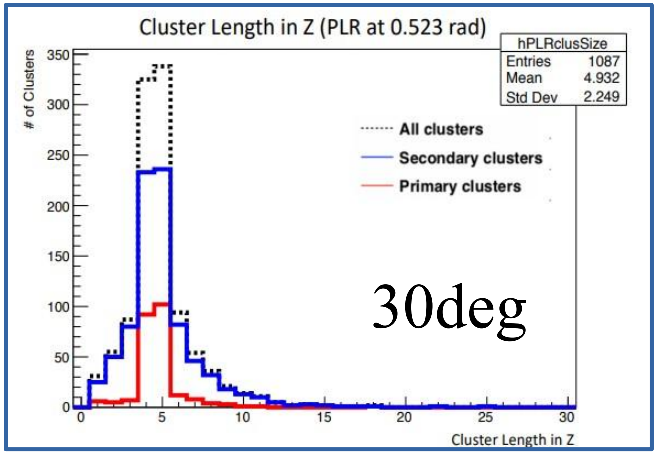
Luminosity measurement with PLR

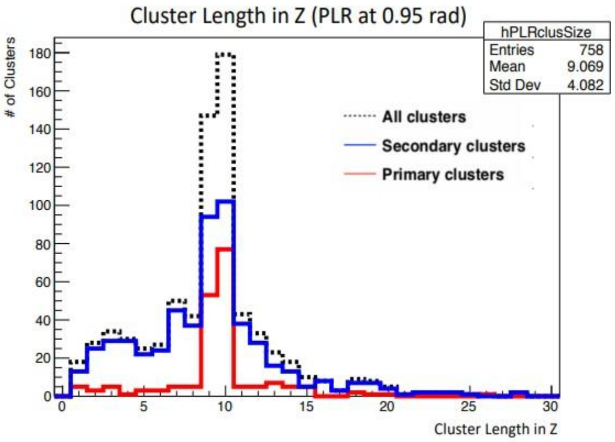
- Measure luminosity **counting the number of clusters**
- Inclination of modules provides separation from backgrounds
  - **30deg** → 4-5 pixels clusters for prompt particles
  - expect background to peak at low cluster size
  - the fine segmentation (25μm) in the radial direction of these modules helps
- Multiple modules provide redundancy and allow to correct effects due to movements of interaction point



Note: Size "Z" here refers to the direction of 25um segmentation (radial) and is misleading. It will be changed in the next version.







Simulation Needs

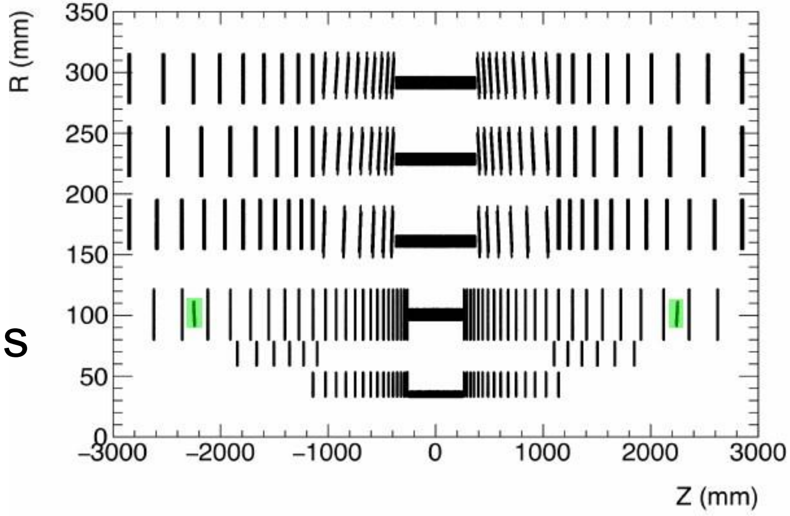
- We wanted a physics simulation to inform and validate design choices for the following key points

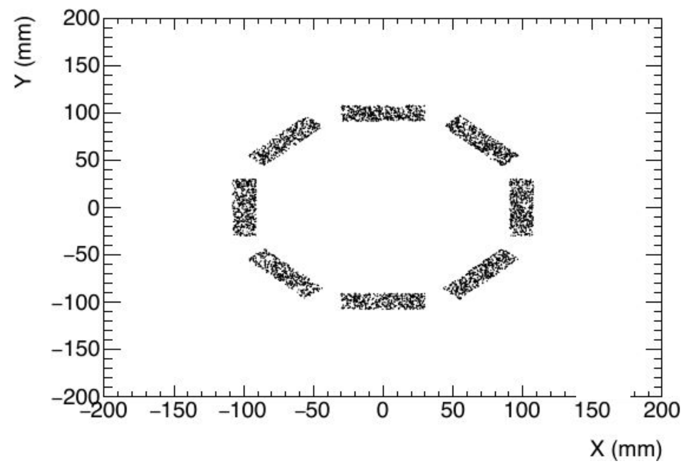
- Performance:
  - Statistical power
  - Linearity
  - Geometry choices
  - Data rates

- Backgrounds
  - Pileup (in-time and out-of-time)
  - Afterglow
  - Background mitigation

Simulation setup

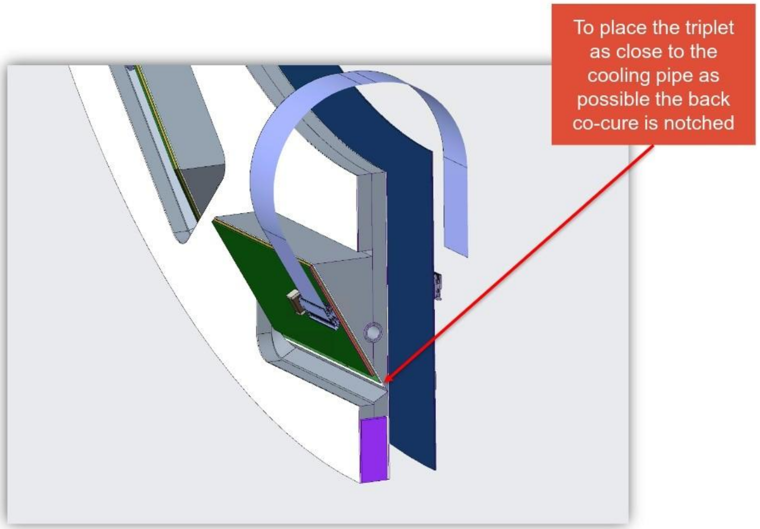
- PLR geometry implemented on top of release 21.9.10
- Starting from ATLAS-P2-ITK-23-00-00
  - Including final number and position of pixel rings and innermost barrel
- No PLR services and support ring
  - expect a minor impact on the results
- For most studies, same digitization settings as used for ITk pixel
  - FE threshold = 600 e^-
  - charge ↔ ToT "calibration" (non-optimal)
  - consider only [-1,0,+1] BCs
- Standard tracking (p_T > 900/400 MeV)
- Pile-up in trains of 72 bunches (25ns), μ=200
- Most sample have an "empty" hard-scattering to emulate a zero-bias



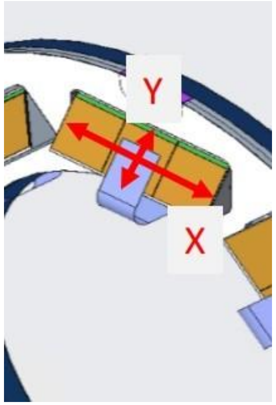


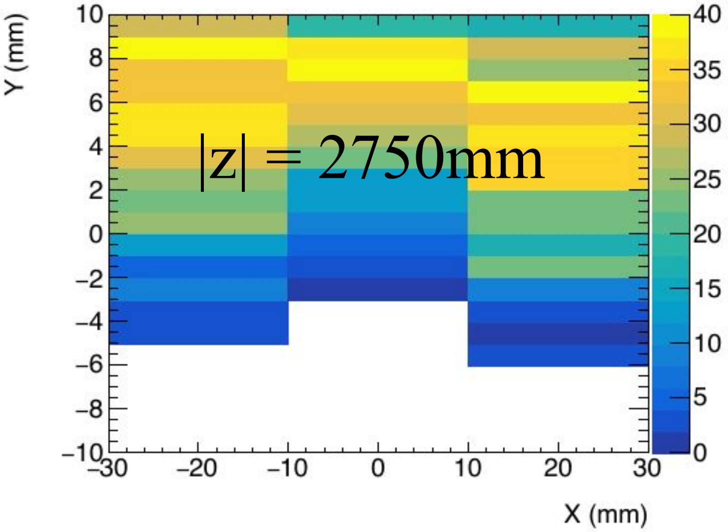
Ring Position

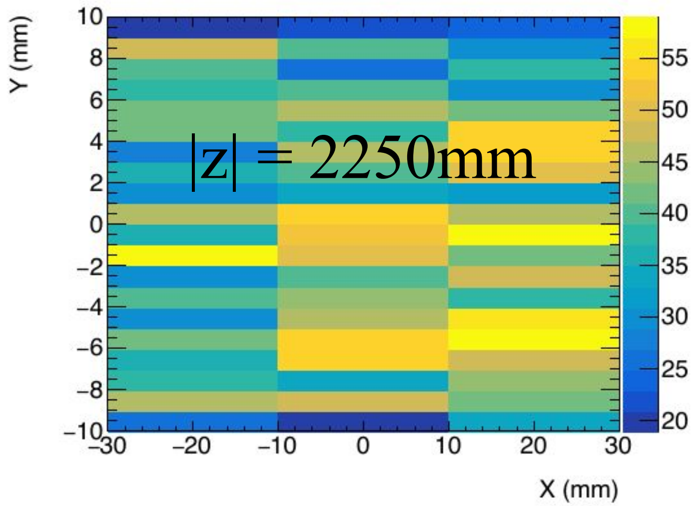
- Thermal performance constrains maximum inner **radius to 91mm**
- Investigated available |z| positions
- Essential to have tracking coverage:
  - Extrapolate tracks to PLR to measure cluster efficiency in-situ
  - Needed to achieve low systematics with respect to time-dependent effects



- Only **|z| = 2250mm** ensures tracking can map the full sensitive area

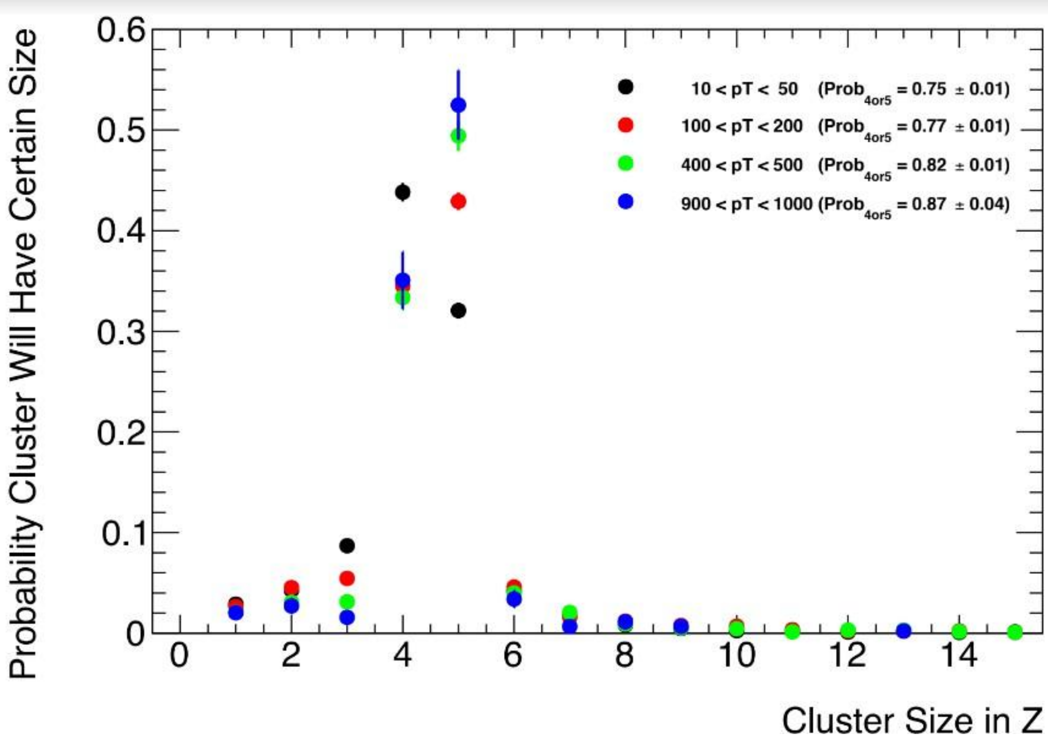


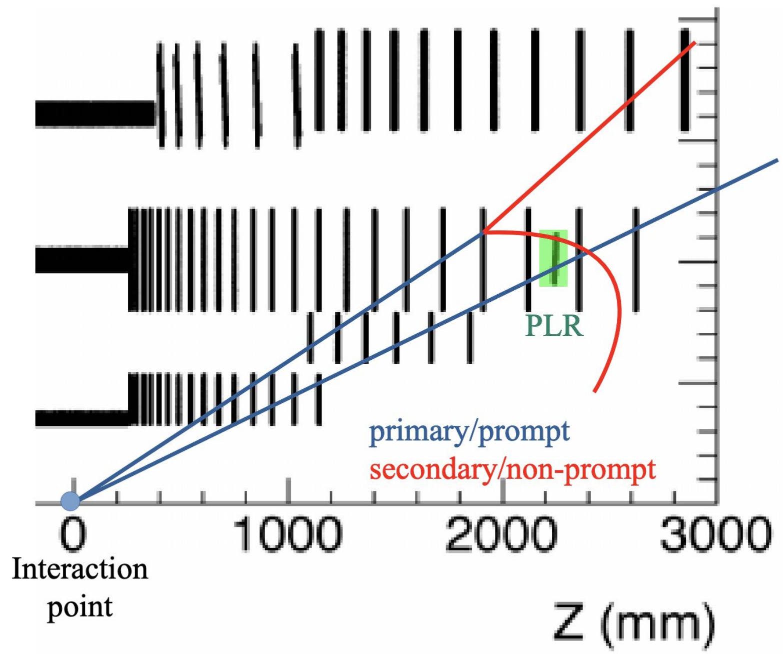




Aside: PLR cluster composition

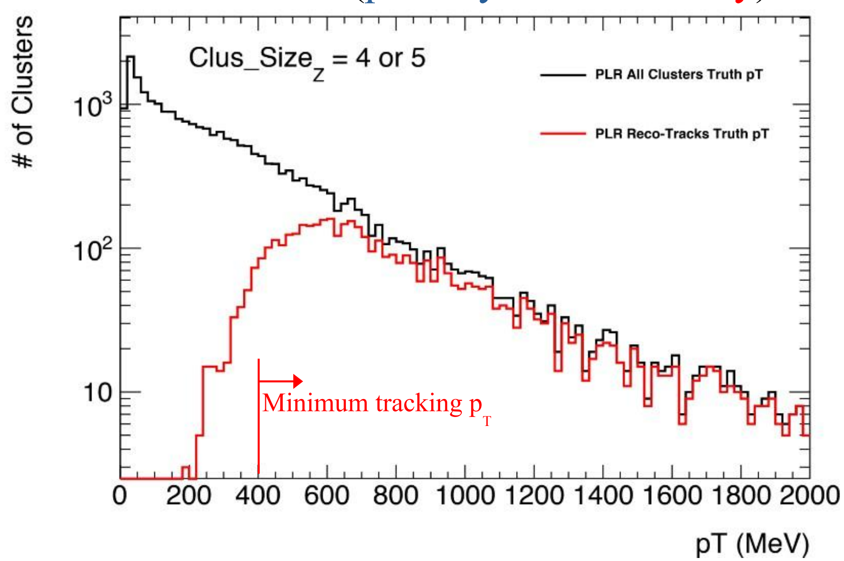
- Cluster properties quite stable for most p_T range of truth particles
- Some significant differences at very low p_T
- Main effect: this p_T range is dominated by secondary particles
  - Different primary/secondary particle composition vs p_T



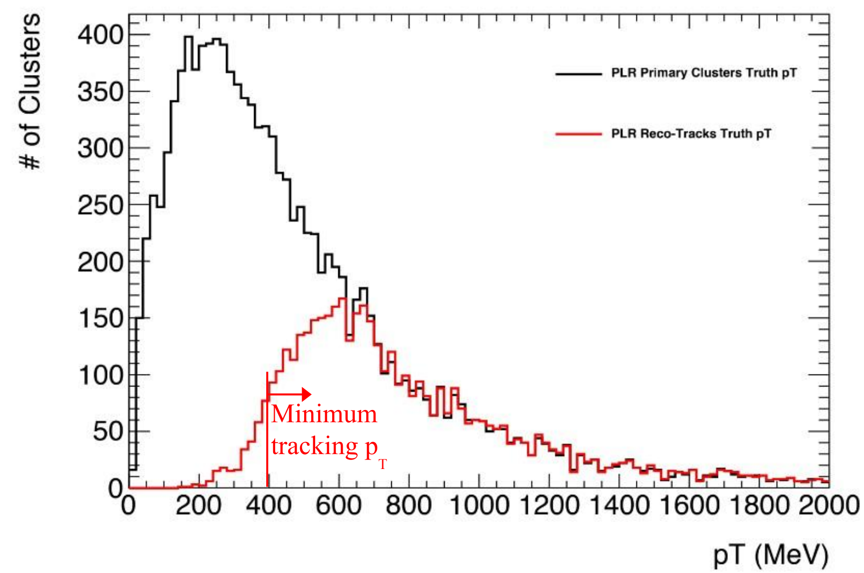


Aside: tracking for PLR

All Clusters (primary and secondary)



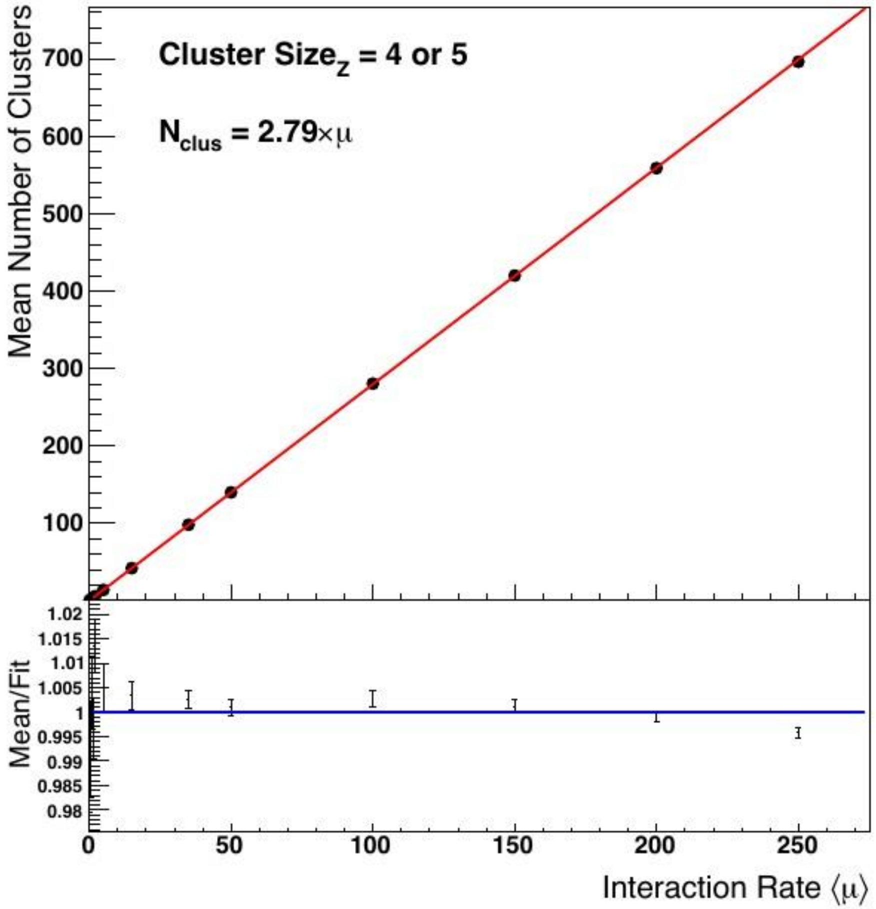
Only clusters associated to primary particles

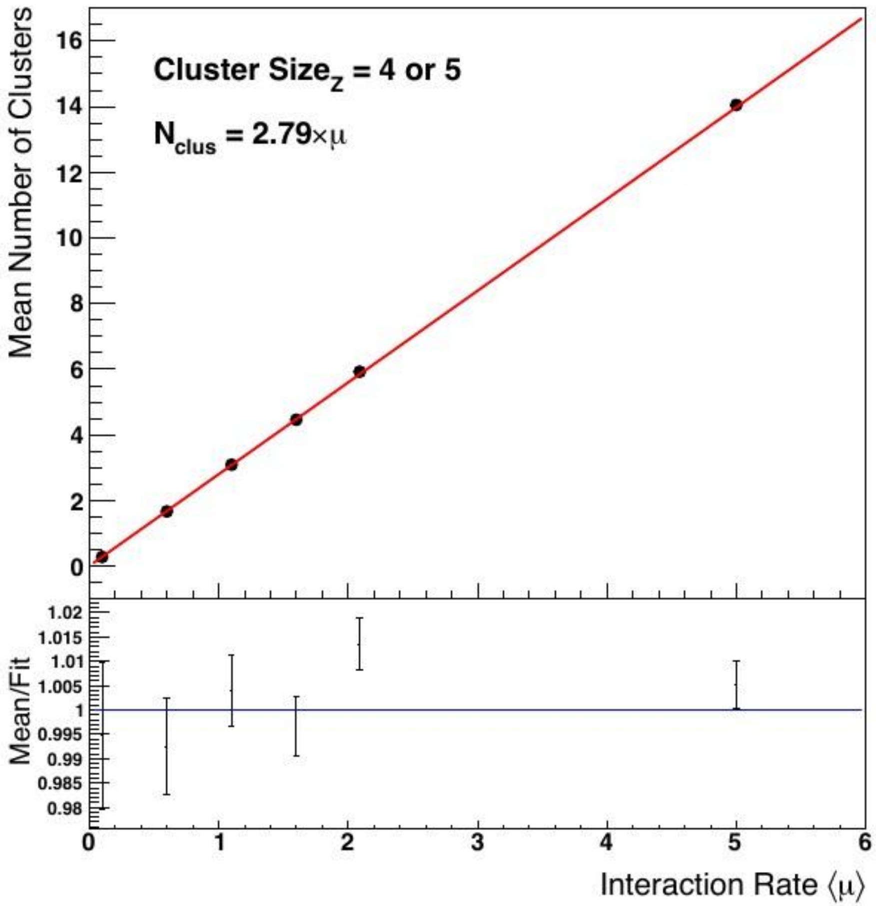


- P_T spectrum of primary/secondary particles very different
- Useful if we can improve low-p_T (and high d_0) track reconstruction for dedicated PLR cluster efficiency (ε) measurements to probe more secondary
- Many of the experimental effects we want to control are the same for clusters originating by primary and secondary, i.e. cancel in the ratio $\varepsilon_{primary} / \varepsilon_{secondary}$
  - Less sensitive to primary/secondary composition of on-track clusters and all clusters
  - Fraction of primary/secondary particles driven by detector geometry

Linearity with μ

- **Linearity** in simulation to **better than 1%** with crude analysis
  - Only clusters of size 4-5, no further attempt of background subtractions
  - Error bars only represent statistical uncertainty of the simulated sample
  - Main effect overlapping clusters, will mention masking later



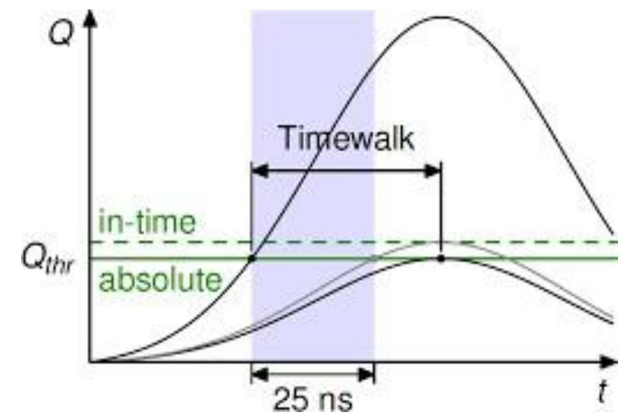


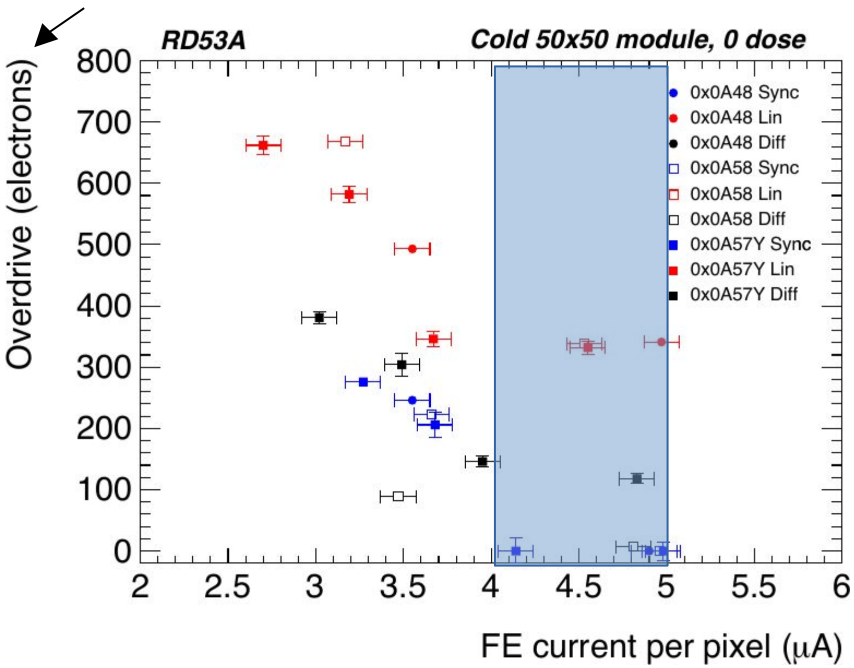
Backgrounds

- Three main classes of backgrounds
  - Out-of-time pile-up effects
    - Timewalk (low-charge assigned erroneously to the next BCID)
    - Masking (a signal in previous BCIDs still “high” when a new particle arrives)
  - Afterglow (slow-particles un-related to current BCID)
  - Beam-induced backgrounds (beam-halo, beam-gas, etc..)
    - Expected to be very small and no simulation easily available or reliable
- All sources above:
  - Could spoil the linear relationship of #clusters vs μ
  - Are potentially not very well simulated, at least out-of-the-box
  - Are expected to peak at low cluster size
- **Cluster size expected to be a very powerful method to reduce them to negligible levels!**

Out-of-time pile-up: timewalk

- Only affects hits with small charge
  - Either isolated (no problem) or mostly at the end of the cluster (decreases size)
- Lab tests on chip prototype using 1 ke$^-$ FE threshold
- Overdrive = “in-time” – “absolute” threshold

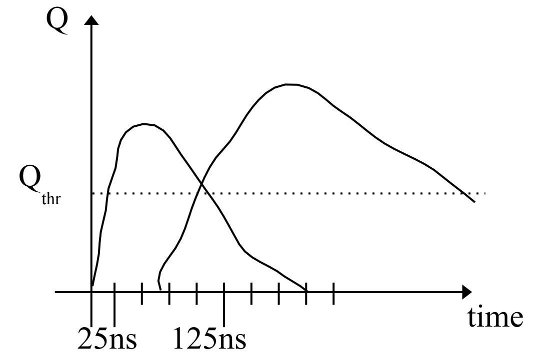




- ATLAS will use the “Diff” FE
- Operating point 4-5 μA / pixel
- Expect tiny time-walk effects
- Not included in simulation
  - Low-priority: we can check the effect of such timewalk is negligible in simulation using these measurements

Out-of-time pile-up: masking

- Earlier hit can mask a signal
- Simulation only considers -1,0,+1 BCIDs
  A signal can last much longer
  - Typical time-over-threshold (ToT) ~ 8*25ns



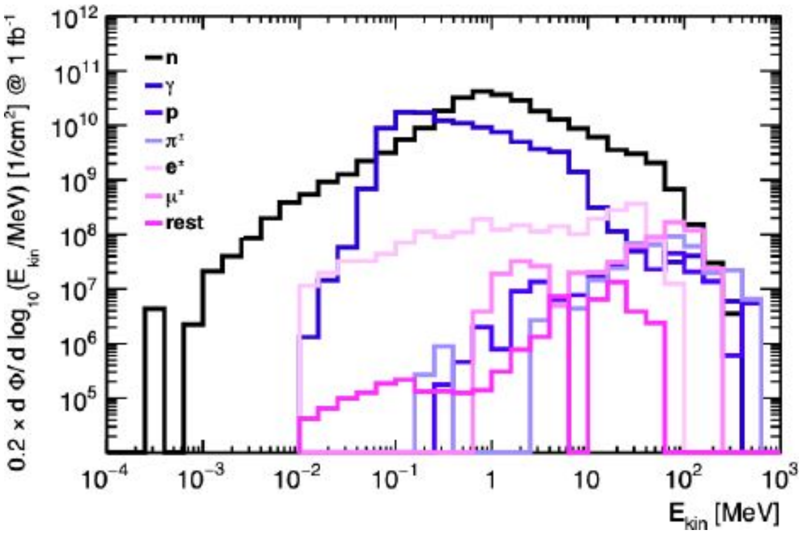
- Tweaked digitization to consider up to 14 previous bunch crossings
  - If hits in the BC of interest overlap, the hit is assigned to the earlier BC

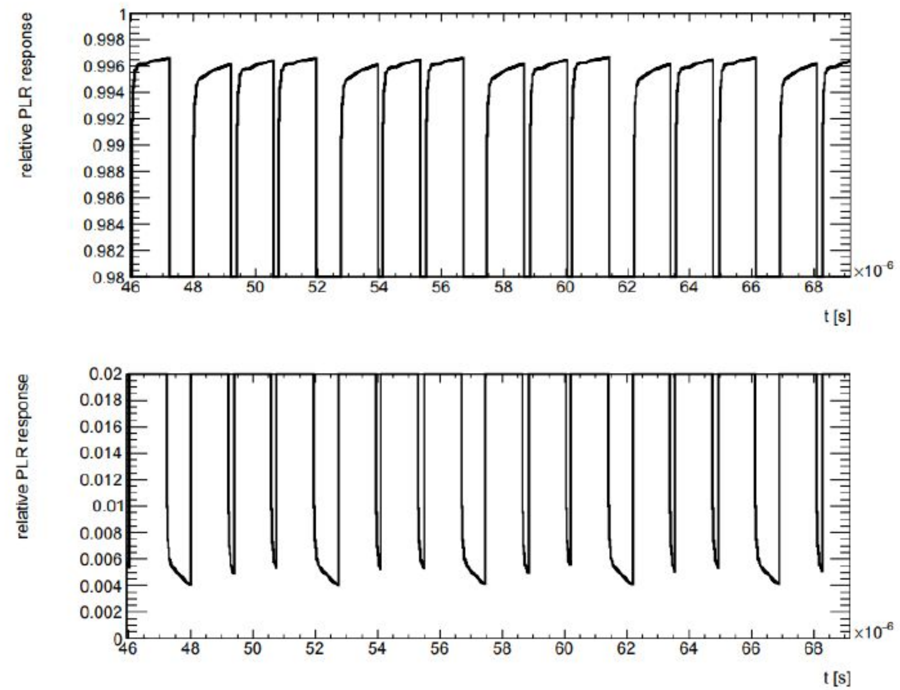
1000 events	Default	ToT masking	ratio	
Bunch crossing	[-1, 0, 1]	[-14, …, 0, 1]		
# PLR clusters	864,002	865,378	0.0010	Cluster breaking
#PLR hits	4,586,635	4,582,042	-0.0019	-0.2% masking
# PLR clusters with size 4 or 5	591,261	591,129	-0.0005	-0.05% ✓
# PLR clusters with size 1	27,717	28,280	0.0191	Cluster breaking

Note: back-of-the envelope effect estimated in the document was < 1%

Afterglow

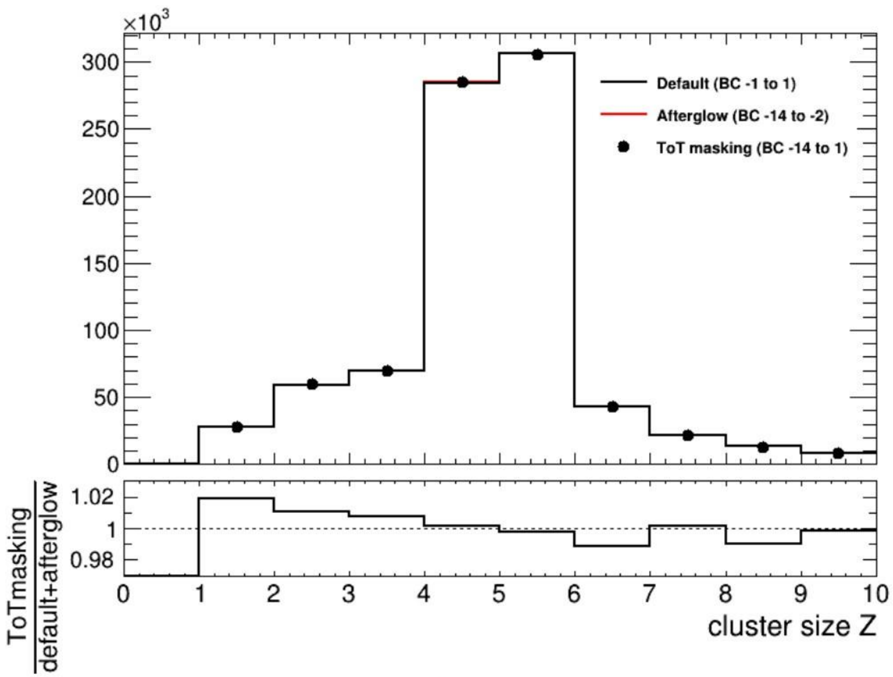
- Due to slow particles that are produced in previous bunch crossings
- Time-dependent G4 simulation (thanks to Sven Menke)
  - same setup used to estimate dose/fluences for ITk (and all ATLAS)
- Integrates energy deposit (TID) expected on PLR sensors
  - Keep track of particles types: ~98% neutrons and photons
  - 99.9% contribution within 100ns of the BC of interest
- Results in a train-dependent effect
  - At most ~0.5% effect in TID





Afterglow - II

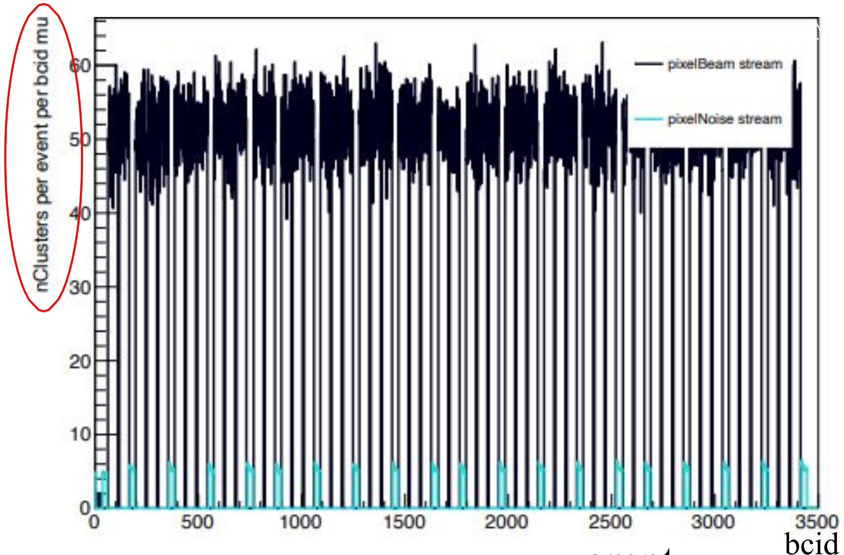
- Response in TID not the same as clusters!
  - expected that afterglow gives mostly small (low-ToT) isolated hits
  - they can be reduced by cuts on cluster size and ToT
- Not easy in previous simulation to digitize those particles
- Re-used the modified setup used for masking: -14, …, 0, 1 BCIDs
  - Note: had to disable noise due to its implementation assumptions



1000 events	Default	Afterglow	
Bunch crossing	[-1, 0, 1]	[-14, …, -2]	
# PLR clusters	864,002	534	
#PLR hits	4,586,635	4,213	
# PLR clusters with size 4 or 5	591,261	149	+0.03% ✓
# PLR clusters with size 1	27,717	32	

Run 2 Data

- While detector characteristics are different, the current dataset can offer insight on backgrounds and agreement with simulation
- **Agreement** data/MC in randomly-triggered events **within 10%** for size==1 (bkg enriched) clusters in the last pixel disk
  - Some subtleties due to slightly different data/MC configuration of FE
- Study a 2018 data run, looking at **afterglow in empty bunches** and comparing rate with filled bunches (randomly triggered)



IBL, ~10% #clus/evt/μ $\frac{\text{empty}}{\text{filled}}$

Studied cluster properties and effect of ToT / size selections

	ToT Cut	ToT Cut + Length > 1	ToT Cut + Length > 2
IBL	7%	1%	0.3%
B-Layer	2%	0.4%	0.2%
Disk 3	.18%	0.4%	1%

Can be reduce to < 0.1 clusters/event/μ

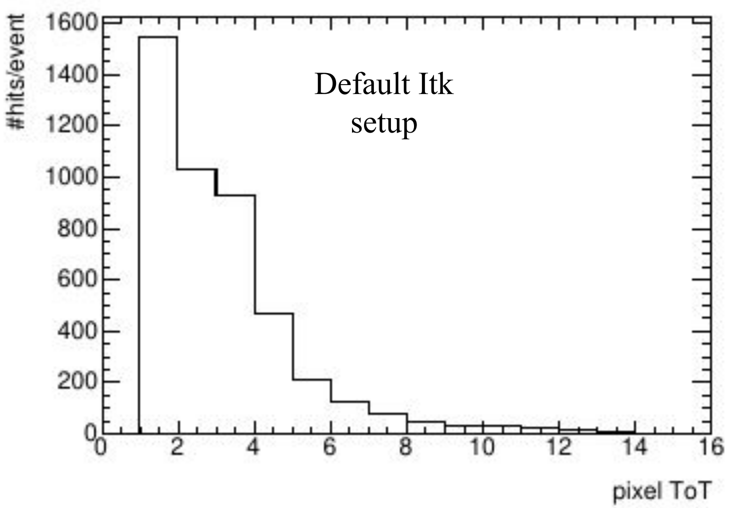
Run3 studies ongoing

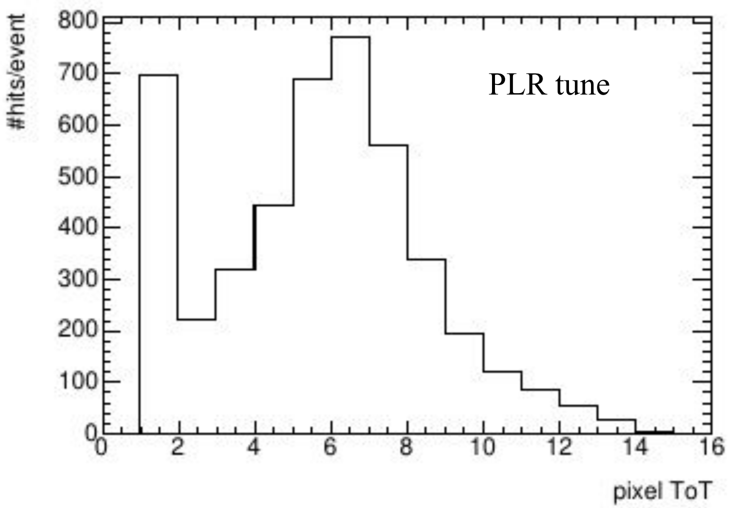
ITk Pixel FE chip configuration

- Current simulation quite aggressive in FE threshold settings
  - Can tolerate significant higher threshold with little loss of statistics
  - Indirectly gives some idea of the effects of radiation damage

Discriminator threshold	N_{hit}	N_{clus}	N_{clus} w/ $Size_Z$ = 4 or 5	Average $Size_Z$
600 e^- (2.1 keV)	22.9	4.34	3.00	4.37
1000 e^- (3.6 keV)	21.2	4.34	2.99	4.17
1250 e^- (4.5 keV)	20.4	4.35	2.94	4.06
1500 e^- (5.4 keV)	19.5	4.37	2.81	3.93
1750 e^- (6.3 keV)	18.6	4.44	2.60	3.78
2000 e^- (7.2 keV)	17.7	4.52	2.32	3.51

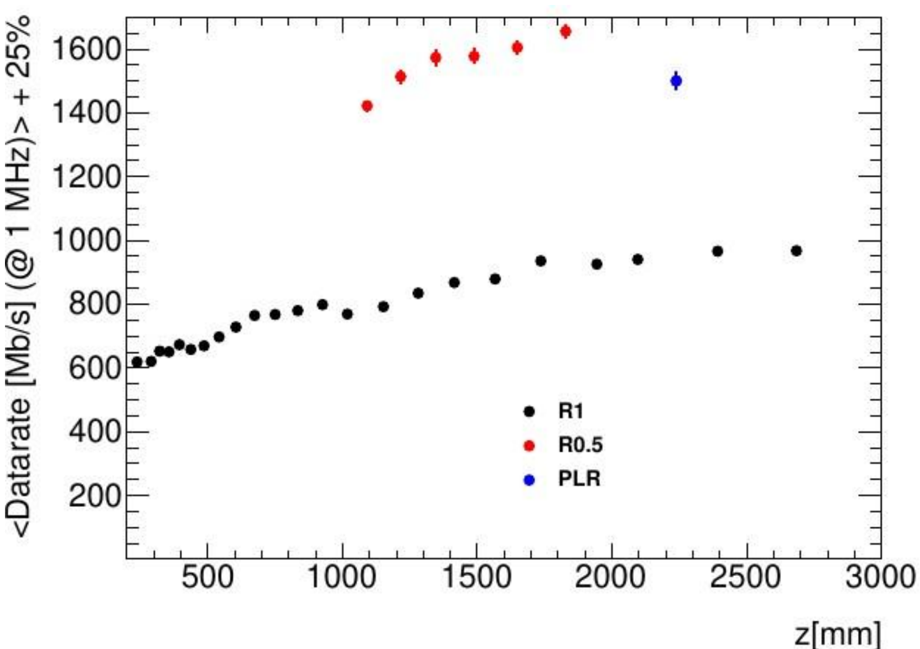
- Re-tuned existing charge ↔ ToT relationship specifically for PLR
  - Not included in most studies so far (apart from masking)

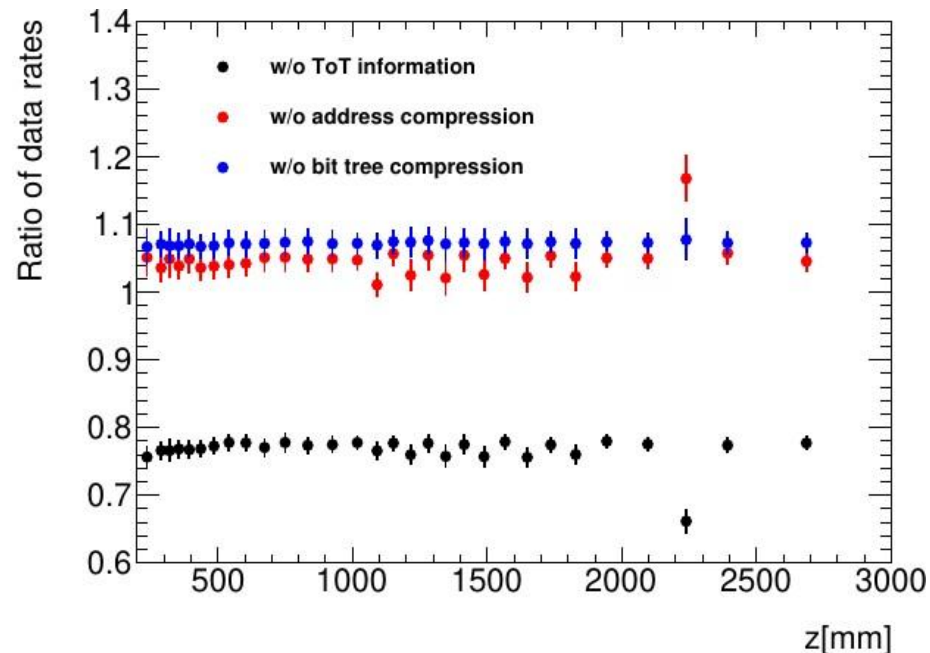




Data rates

- Hit occupancy from full simulation: ~$7 \cdot 10^{-4}$ hits/pixel/event for μ=200
- Code used for ITk data rates to take into account chip compression and data encoding (we can reproduce the existing results)

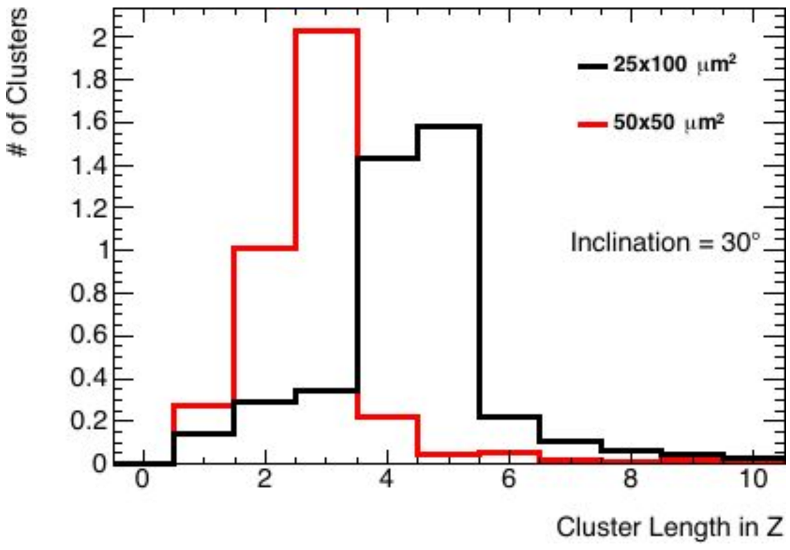


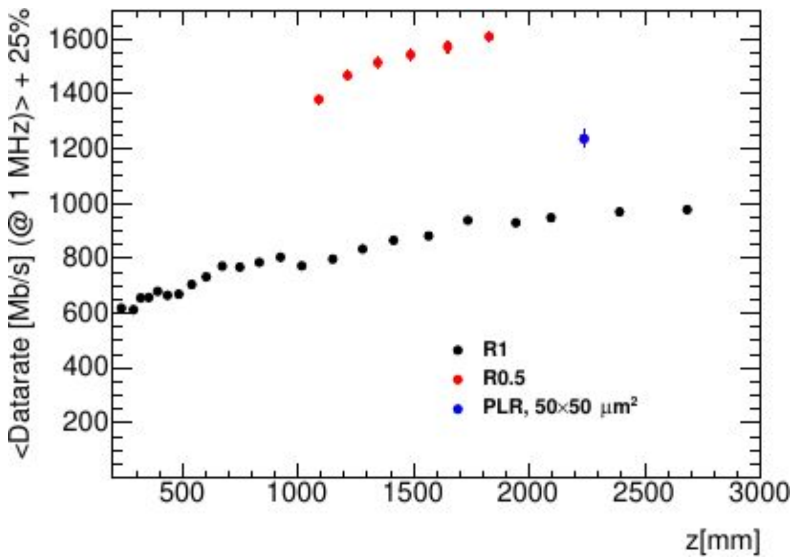


- Translates into a **maximum readout rate** (assuming max 50% FE link occupancy) of **1.5 (1.1) MHz, if using 4 (3) links/FE**
- Larger data rate expected for PLR due to longer cluster size
  - On-chip compression helps even if orientation is non-"standard"

Aside: 25x100 vs 50x50 μm^2

- Tested effect of using a square pixel geometry

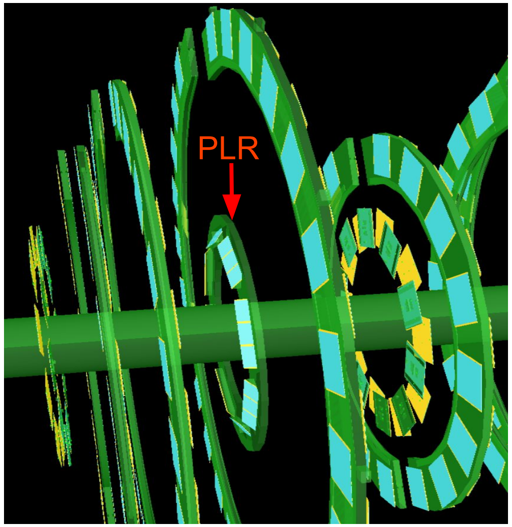


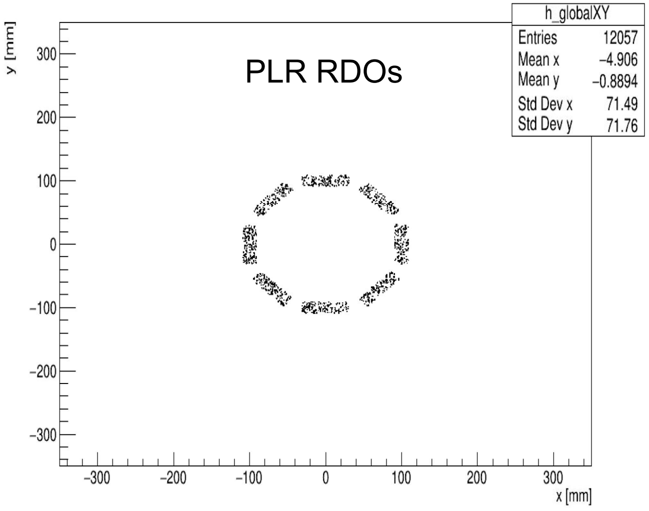


- Detrimental for signal/background separation
- Slightly less expected bandwidth utilization due to shorter clusters

Proper Simulation Implementation

- The PLR has since been properly added to Athena and ITKLayouts
  - Added PLR to ITk Geometry (ITKLayouts-MR183)
  - Introduced PLR into Athena and produced SiHits (athena-MR46234)
  - Created a PLR_ID class (athena-MR50881 and athena-MR51273)
  - Got basic digitization working (athena-MR52324 and athena-MR56784)
- Still need to implement PLR specific digitization functions and reconstruction
- Believe the code has been maintained since its implementation in 2021
  - Has not been tested since 2021
  - There have been discussions about dropping PLR support in athena





Conclusions

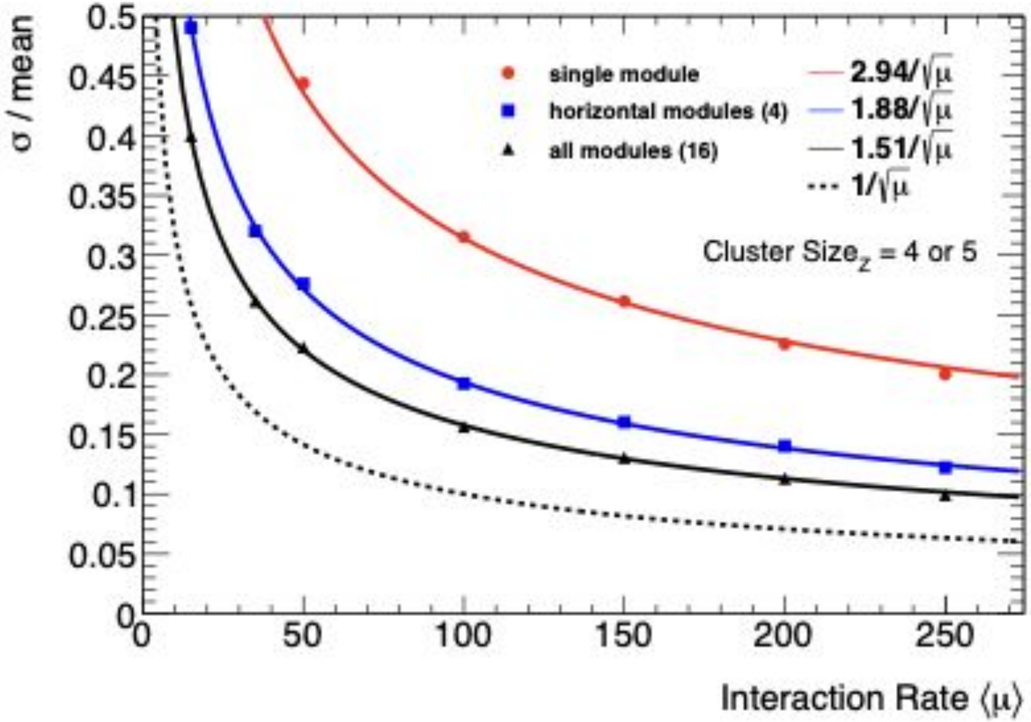
- Simulation setup to study PLR performance
- Several developments and dedicated studies to address questions that are specific to PLR
- Current studies provide already useful information on how the current baseline configuration well fits the needed requirements for an accurate luminosity measurements
- Work to be done
  - Run3 PCC measurements - compare to afterglow simulations of existing detector
  - Look at radiation damage simulation for 25x100 3D sensors (although it's not a substitute for relevant testbeam data)
  - Improve digitization (esp. TOT - charge relationship)

Don't believe there are any show-stoppers from simulation that this wouldn't work!

Backup

Expected Performance

- Simulation predicts 2.8 selected clusters in PLR per pp interaction (per unit μ) or 0.175 clusters per triplet / μ
- Triplet statistics dominated by $\sqrt{N_{clus}}$ while full PLR more dominated by $\sqrt{\mu}$ (as clusters/μ > 1)
  - Physics correlations also important
- RMS of N_{clus} / N_{clus} (relative lumi error per crossing) scales as $A/\sqrt{\mu}$ in all cases
- Allows us to predict achievable lumi uncertainties



Beam (and module) position

- Moved beam +1mm in Y
  - A = 1.6 +- 0.4(stat.) %

$$A = \frac{N_{Right} - N_{Left}}{N_{Right} + N_{Left}}$$

- Beam can easily be offset by ~1mm
- Movements between or within runs usually well within 100µm
  - A ~ 0.16%
- Once averaging 4 modules in the 4 directions

  → A ~ 0 within stat
- Effect of movement in z gives an much smaller effect