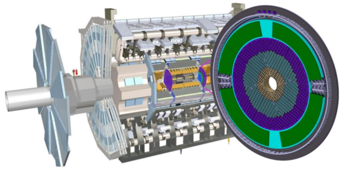
The ATLAS High-Granularity Timing Detector: test beam campaigns and results

Oleksii Kurdysh

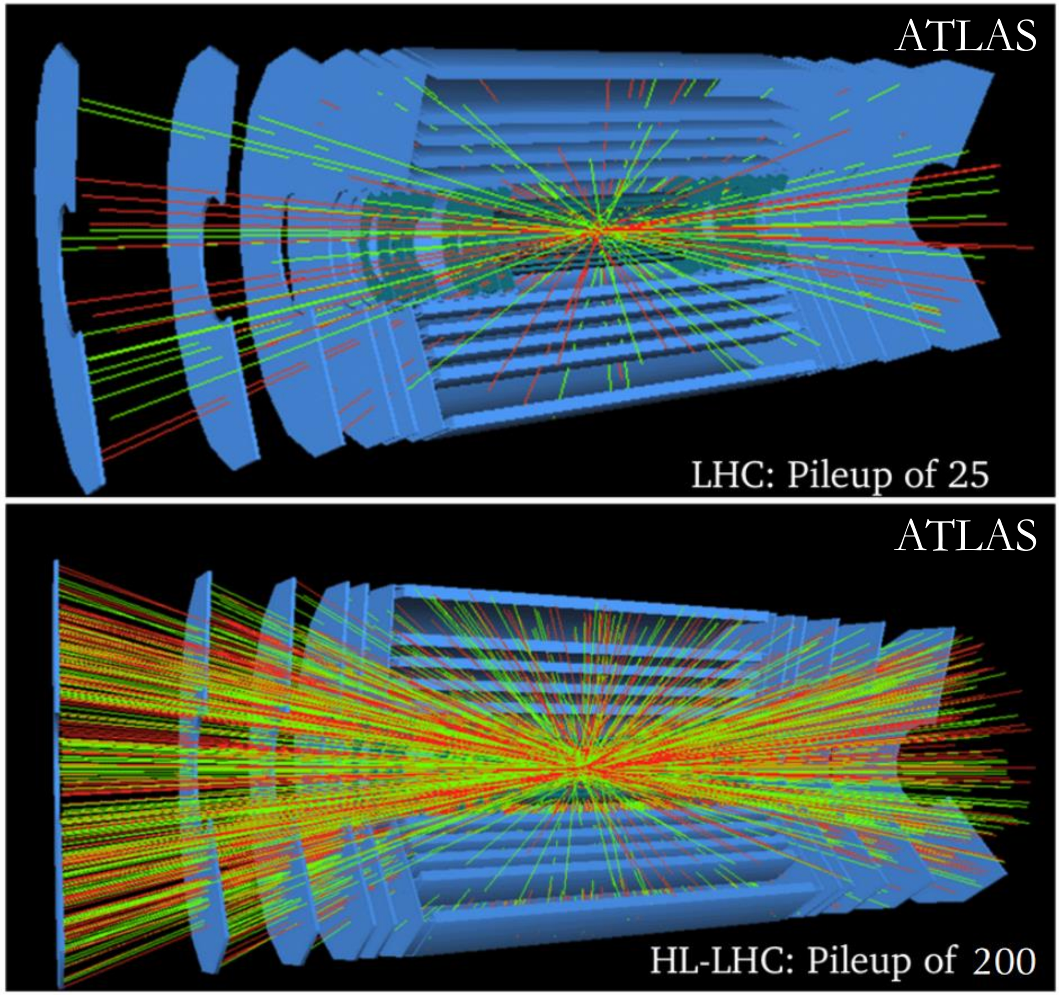


26Oct2023 / Journées de Rencontre Jeunes Chercheurs

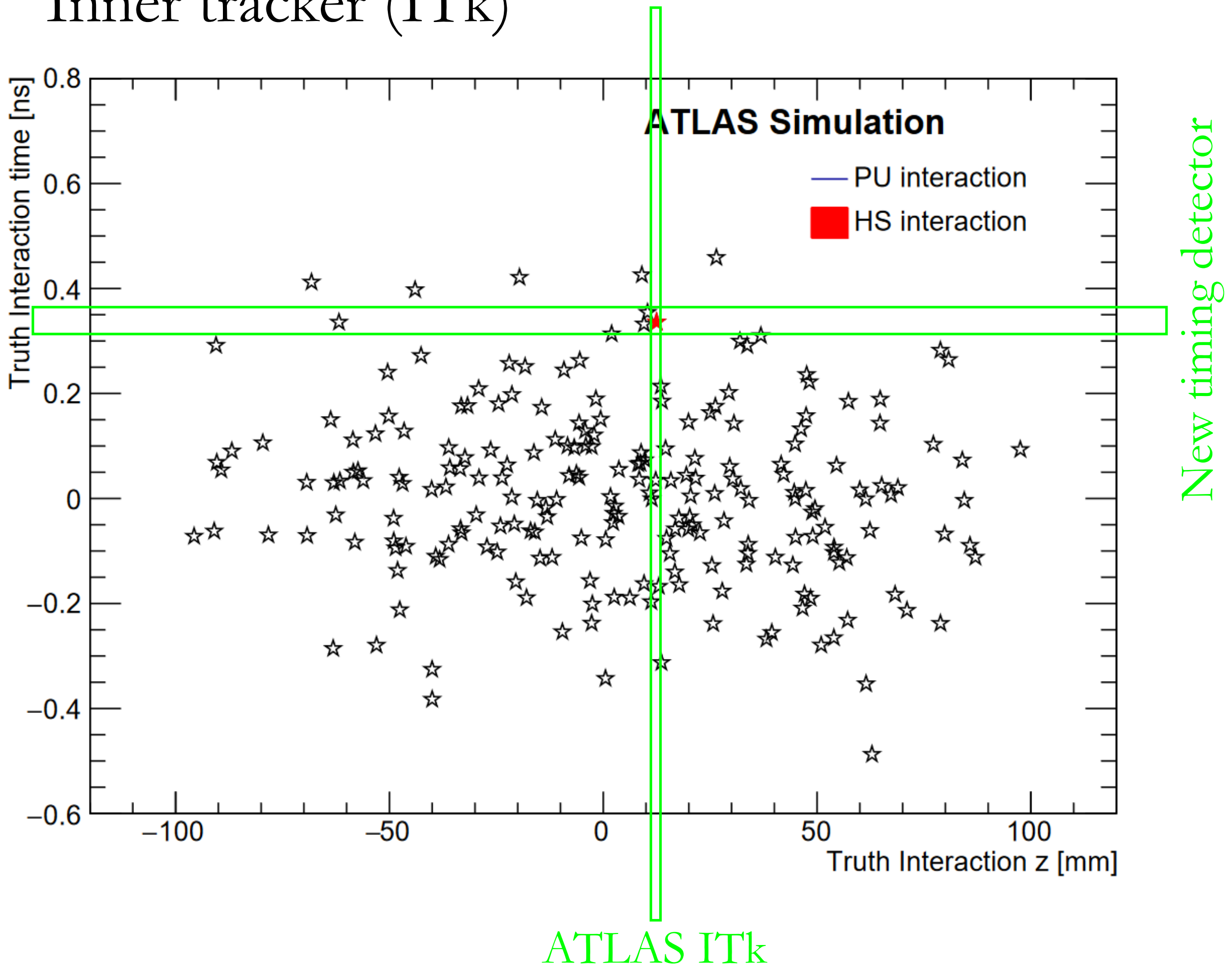
Part 1: Introduction

HL-LHC and timing

- For HL-LHC number of simultaneous pp interactions can be up to 200 and separating pile-up from event of interest becomes more challenging

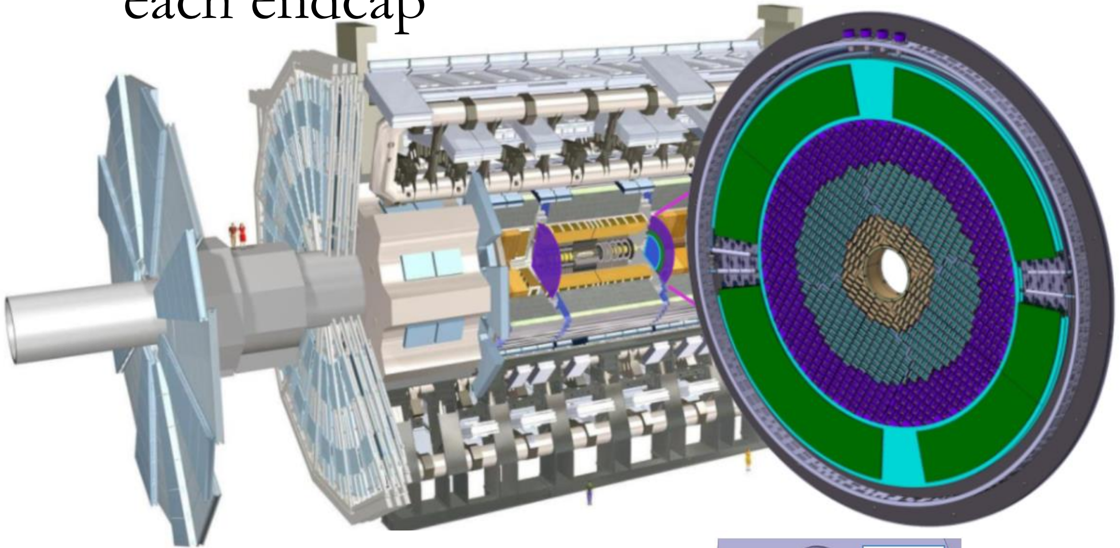


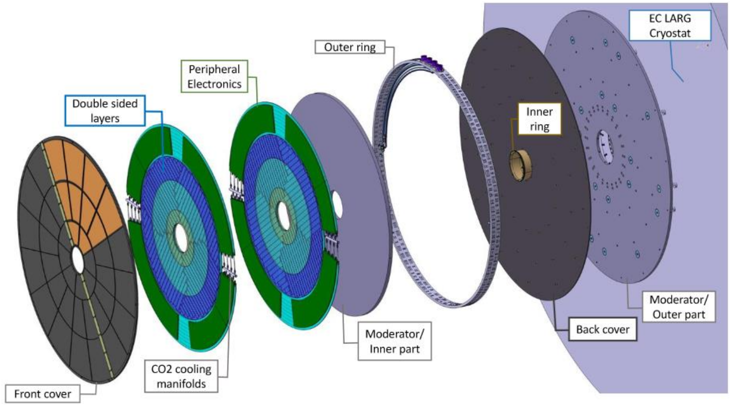
- Timing information can be utilized to reject PU, complementing the position measurement with the new ATLAS Inner tracker (ITk)



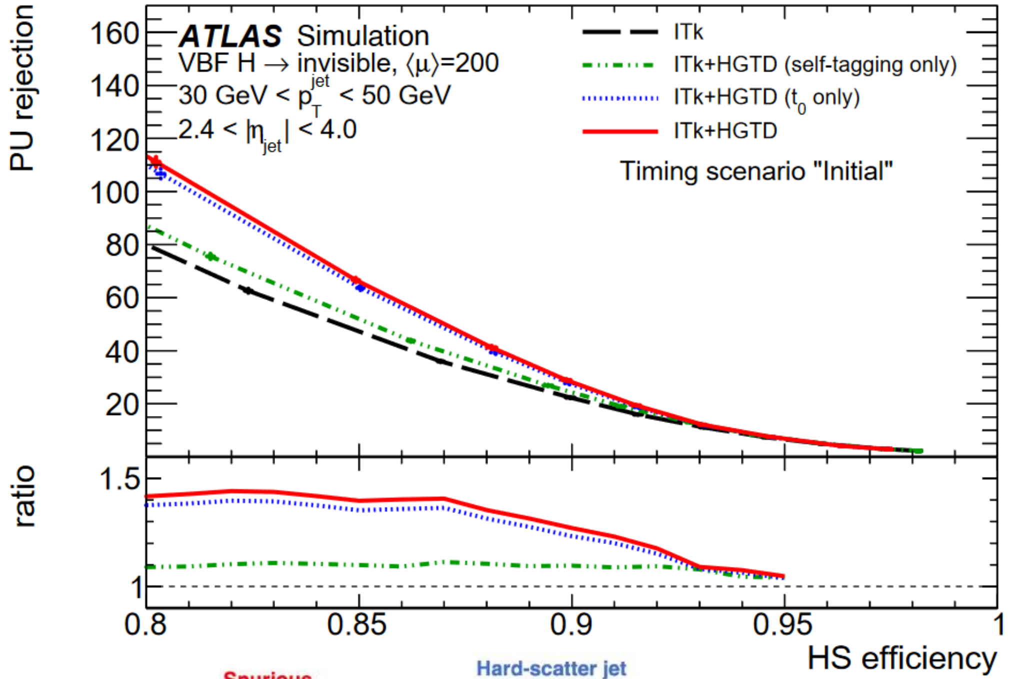
High Granularity Timing Detector (HGTD)

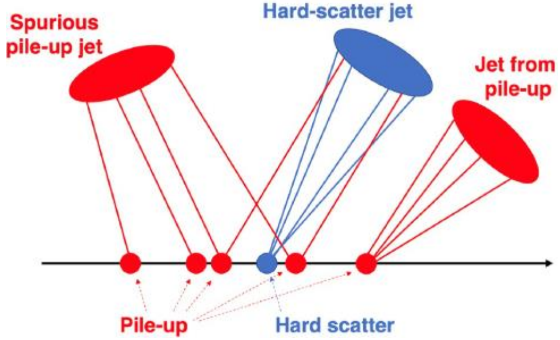
- HGTD will be installed in the forward region of ATLAS to provide precise timing information
- Two instrumented double-sided layers in each endcap





- Example: Using HGTD together with ITk gives improvement in forward pileup jet rejection by up to ~20% (compared to ITk only)



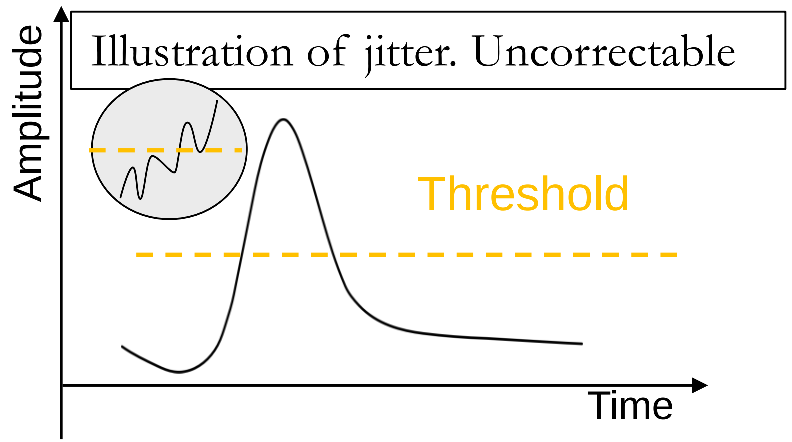


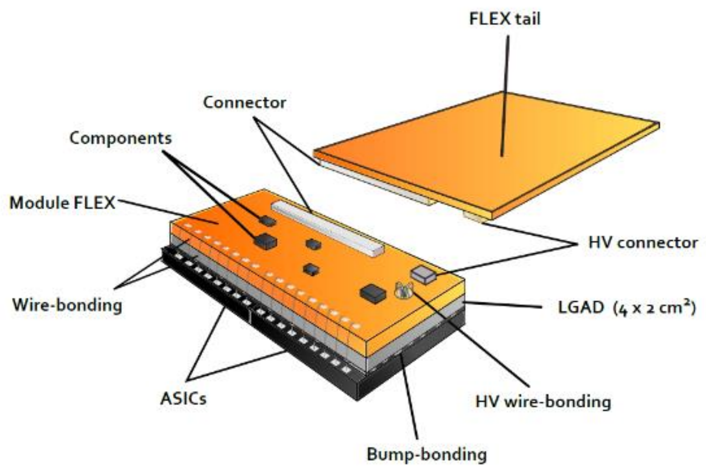
HGTD sensor and electronics

- HGTD must be able to provide time resolution
  - 35 ps/hit (start of operation)
  - 70 ps/hit (end of operation)
- Sensor also must survive the irradiation. Low Gain Avalanche Detector (LGAD) is capable and chosen as sensor

$$\sigma^2_{\text{module}} = \underbrace{\sigma^2_{\text{Landau LGAD}}}_{\sim 25\text{ps}} + \sigma^2_{\text{ASIC}} + \ldots$$

$$\sigma^2_{\text{ASIC}} = \underbrace{\sigma^2_{\text{TimeWalk}}}_{\text{corrected } <10\text{ps}} + \sigma^2_{\text{Jitter}} + \underbrace{\sigma^2_{\text{TDC}}}_{<10\text{ps}} + \underbrace{\sigma^2_{\text{LHCclock}}}_{<15\text{ps}}$$





- Sensors will be (partially) replaced several times after $2.5\text{x}10^{15}\ n_{eq}/cm^2$
- Need equally fast read-out electronics: use ALTIROC
- Will have ~8000 LGAD+ASIC modules in HGTD

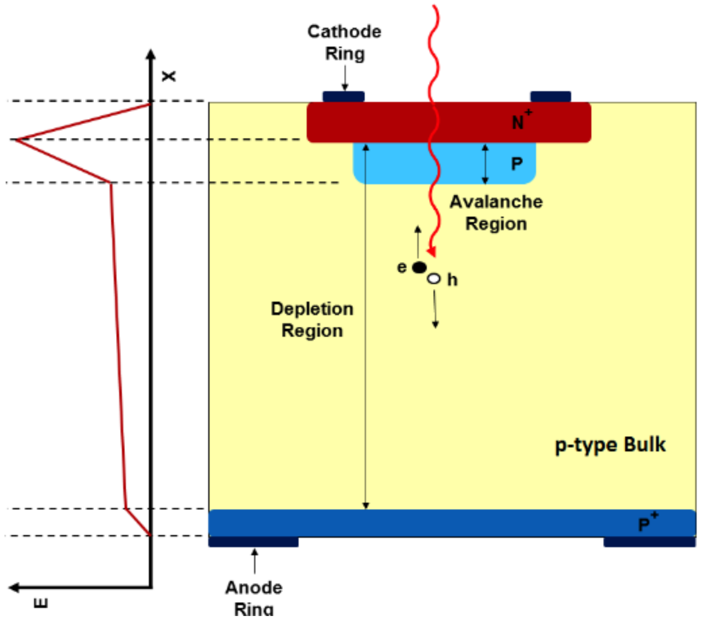
LGAD

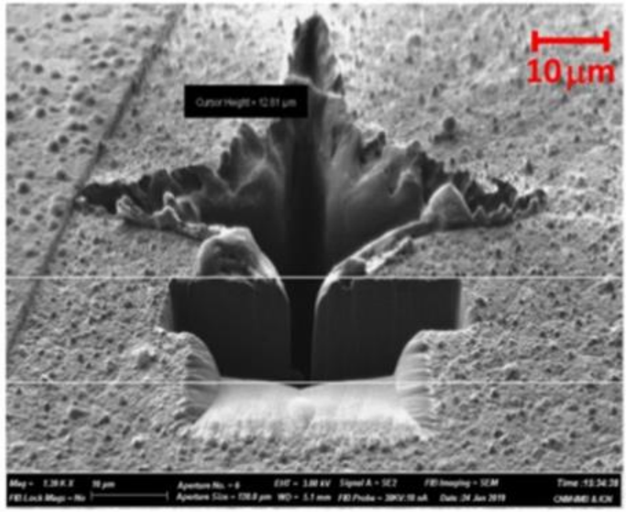
- Sensor must be thin to minimize landau fluctuations. But it cannot be too thin because this will drive the capacitance. Optimal thickness ~50um
- LGADs are n-on-p silicon detectors with an additional p-type doped layer containing charge multiplication to achieve an internal gain
- Gain must be low because otherwise noise grows

$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} \approx \frac{\sigma_n}{\left|\frac{S}{\tau_p}\right|} = \frac{\tau_p}{S/N}$$

- Current version of LGAD is carbon enriched since it allows to use lower operating voltage, which allows to avoid Single Event Burnout: sensor break with star-shaped pattern formed.
- This version of sensor performs as required after irradiation

arXiv: 2303.07728

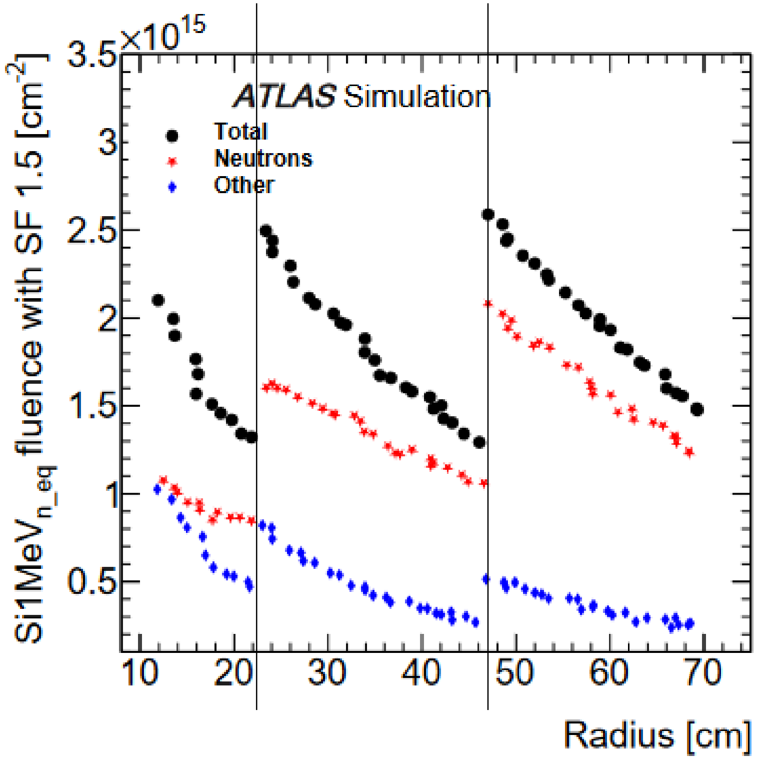




JINST, 17(07):C07020, 2022.
https://arxiv.org/abs/2306.12269

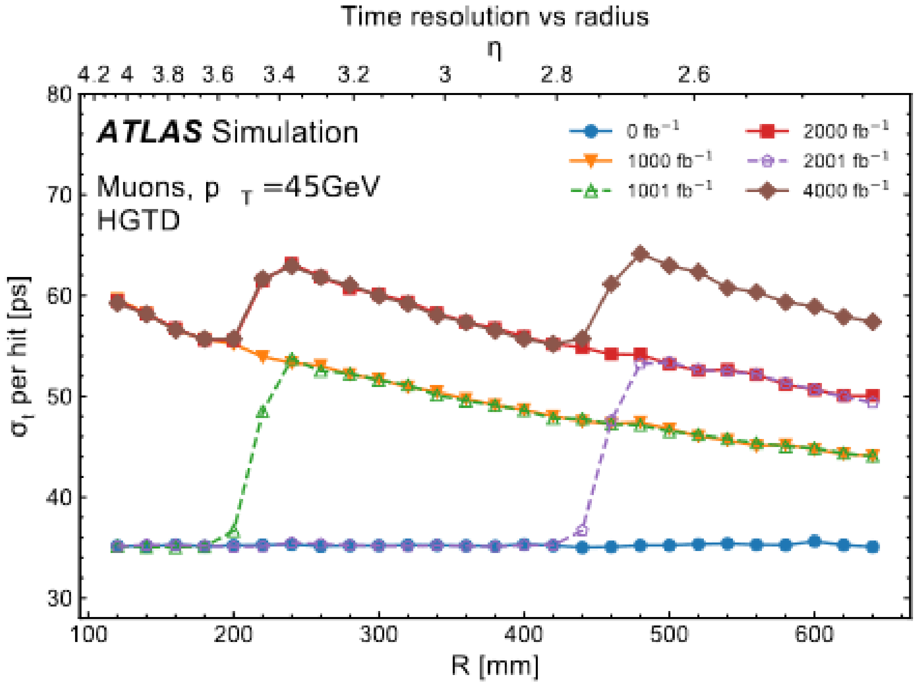
HGTD sensors replacement scheme

- The closer to the beam the higher the fluence
- Sensors only able to survive outer layer fluence therefore
  - inner ring sensors replaced every 1000 fb−1 (3 times)
  - middle ring sensors replaced at 2000 fb−1 (once)
  - Outer ring never replaced (42% of HGTD)



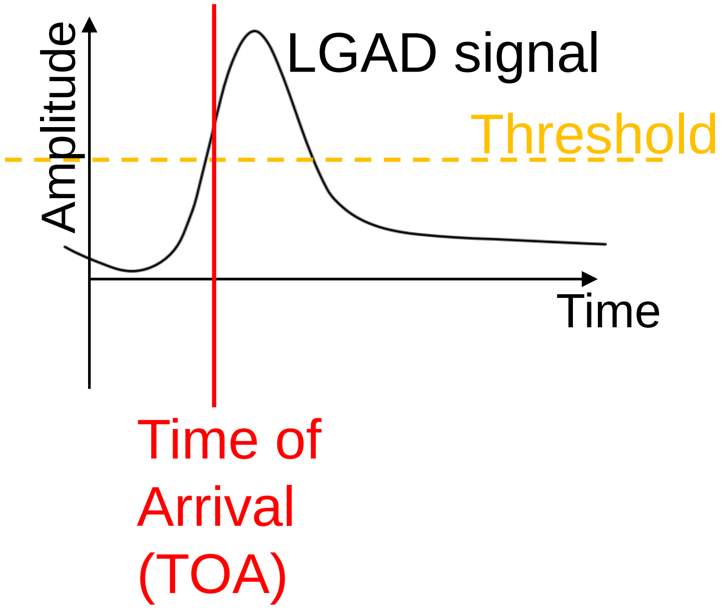
This plot shows fluence until the sensors are replaced

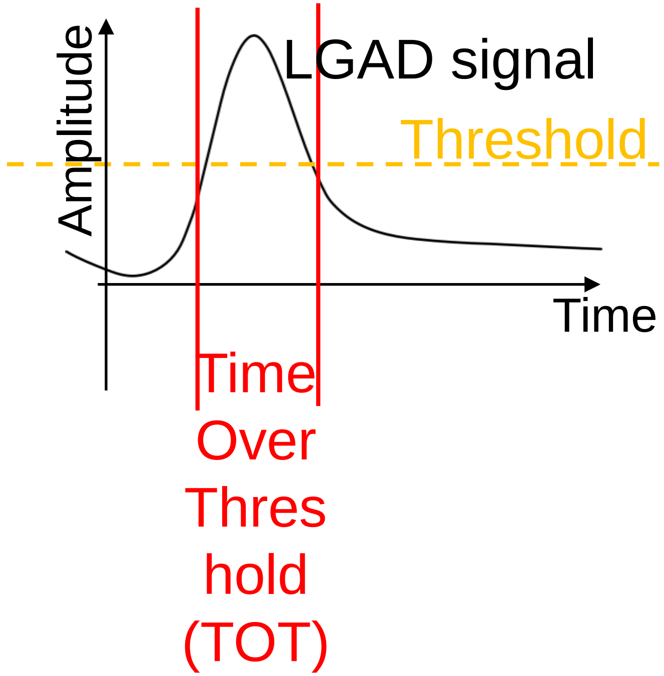
0: before irradiation
1000: before replacement of IR or the first time
1001: replaced inner ring, resolution for r<200 back to initial
…



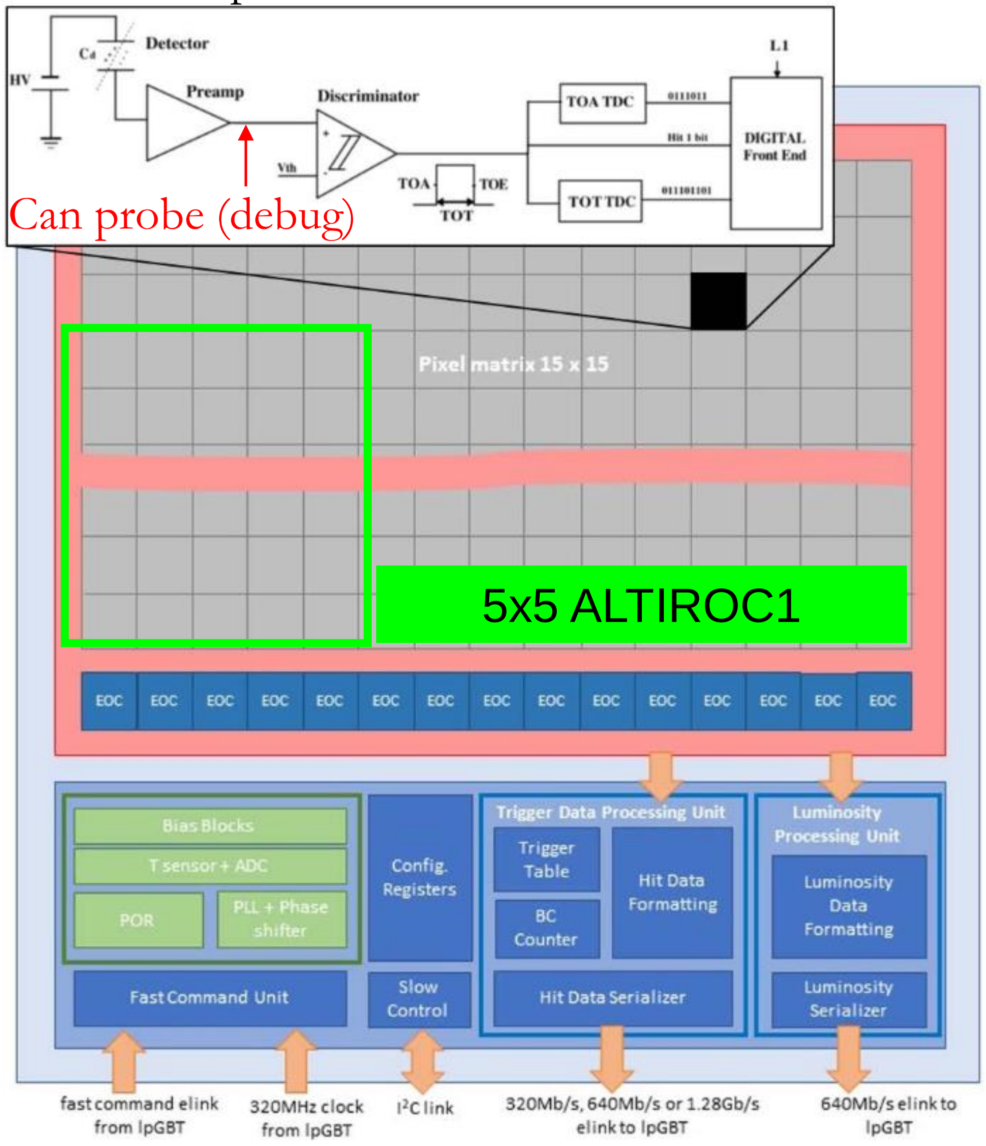
ALTIROC

- ALTIROC1 is small-scale 25 (5x5) channel prototype with all analog functionality
- ALTIROC2 is a full-scale prototype with 225 (15x15) channels
  - Should be close to final version
- Each ALTIROC channel will provide a TOA and TOT measurements of the LGAD signal for a given threshold.

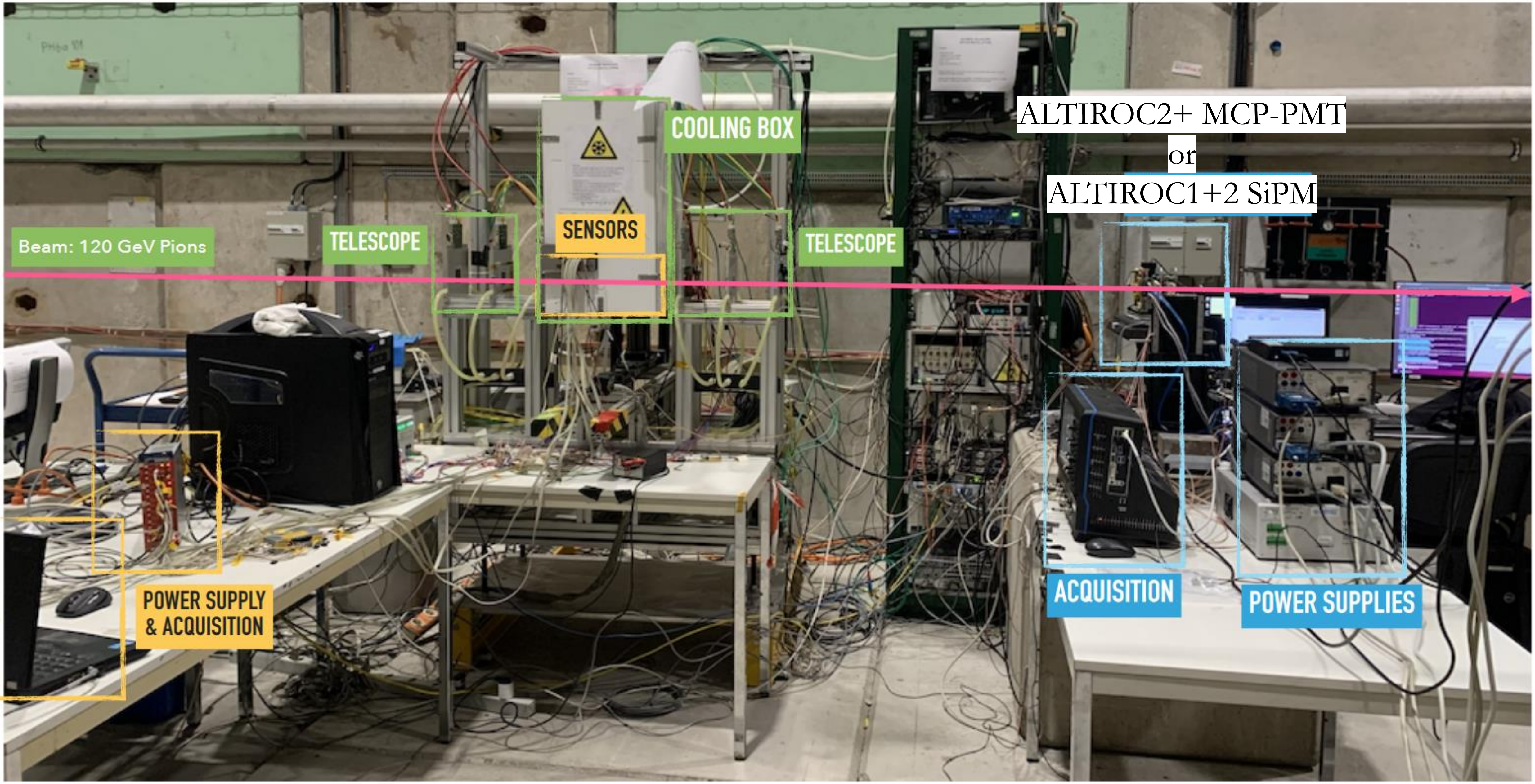




Structure repeated each ASIC channel



Testbeam setup at CERN SPS H6



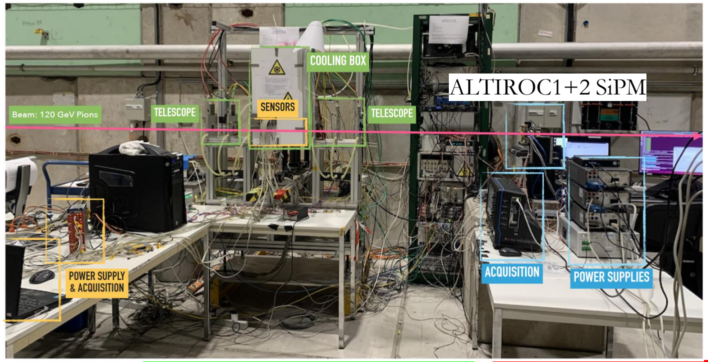
Part 2: ALTIROC1+sensor module tests

More in paper:

2023 JINST 18 P08019 / arxiv:2306.08949

ALTIROC1 testbeam setup

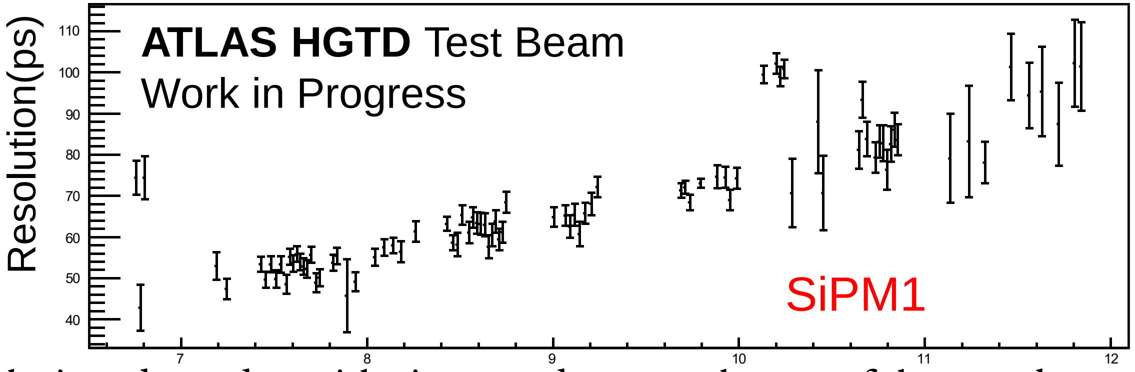
- ALTIROC1+LGAD tested at room temperature. Two SiPMs are needed in order to solve for module time resolution (LGADs mounted on custom readout boards were tested in parallel)



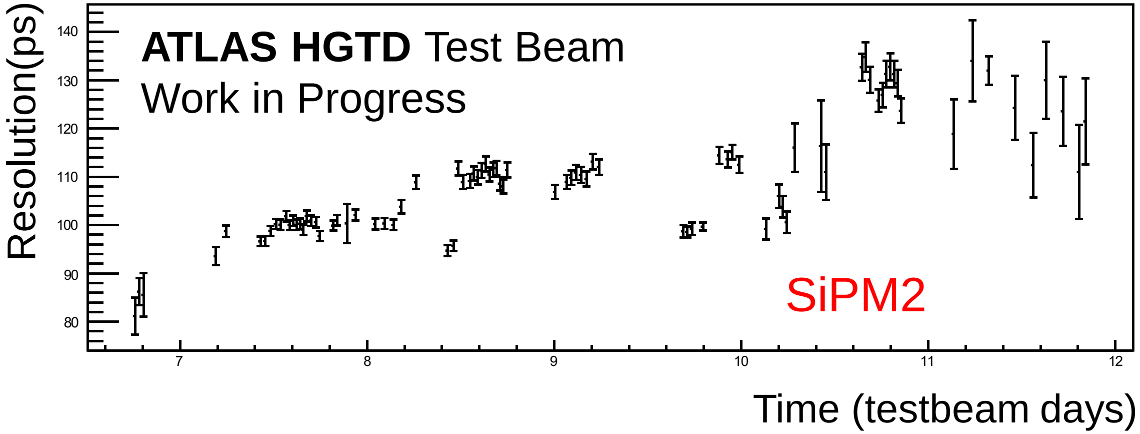
Known from fit of unique time difference histogram

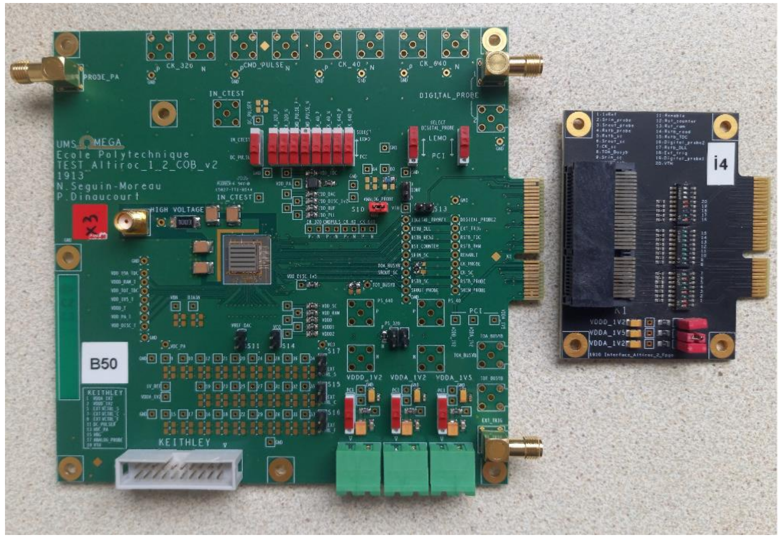
$$\begin{cases} \sigma_{\Delta T(SiPM1,SiPM2)} = \sigma_{SiPM1} \oplus \sigma_{SiPM2} \\ \sigma_{\Delta T(module,SiPM1)} = \sigma_{module} \oplus \sigma_{SiPM1} \\ \sigma_{\Delta T(module,SiPM2)} = \sigma_{module} \oplus \sigma_{SiPM2} \end{cases}$$

Want to determine



Resolution degrades with time so data gets less useful as testbeam goes on





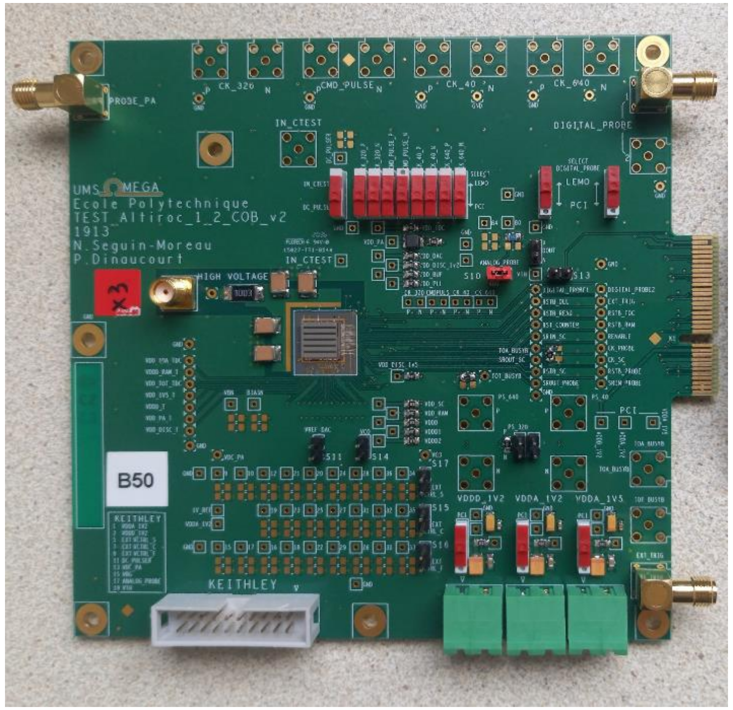
ALTIROC1+LGAD+test board

ALTIROC1 hybrid is like Préfou

LGAD

ASIC

ASIC board



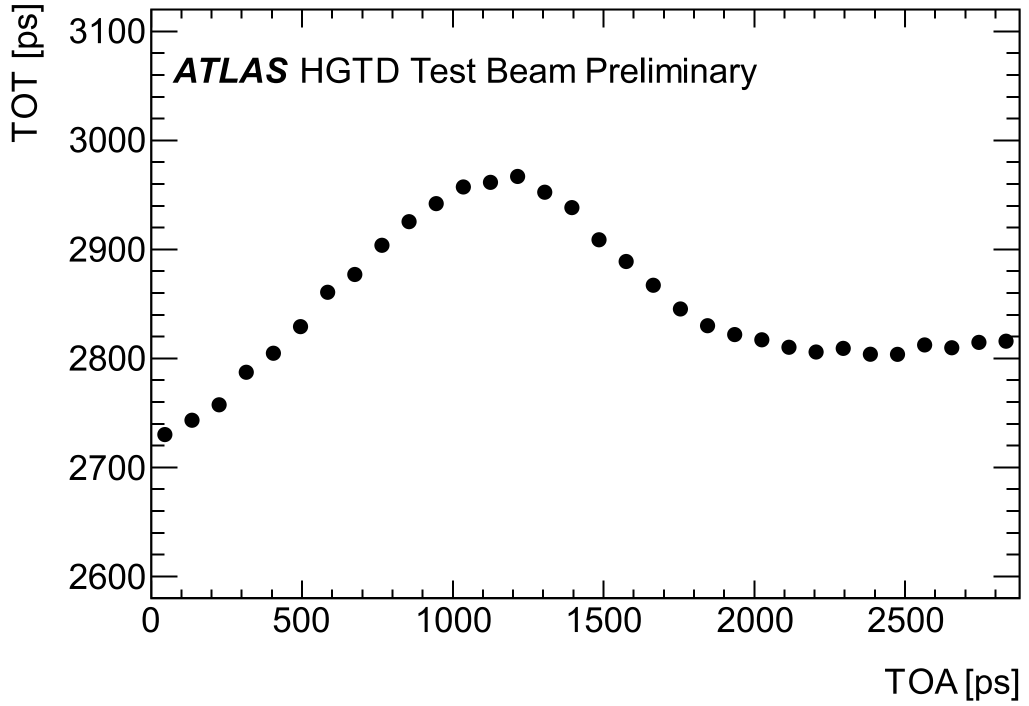
Garlic

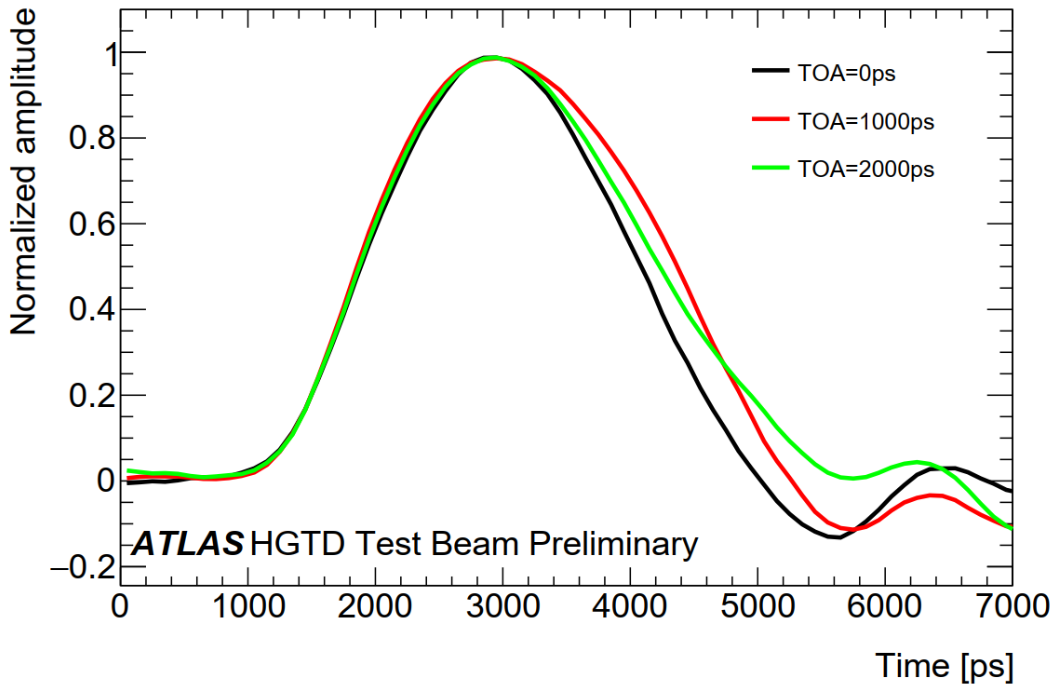
Butter

Bread

TOT-TOA coupling caveat

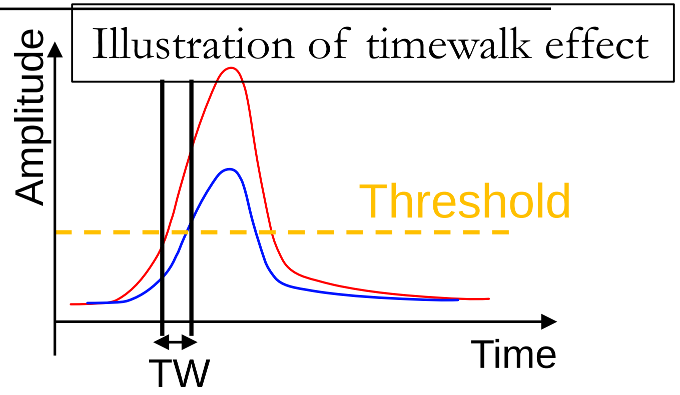
- TOA-TOT is expected to be flat but it's not. This is attributed to a digital coupling synchronized with the 40 MHz clock.
- This degrades timing performance
- Since we record pulses from preamplifier probe can see why TOT depends on TOA from average pulses

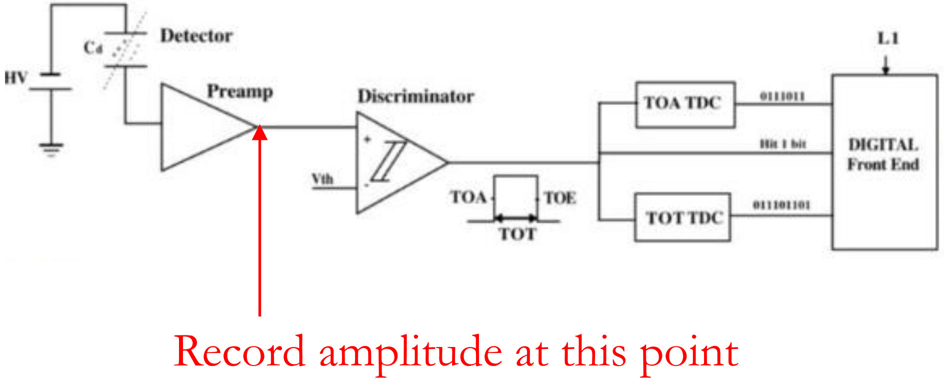


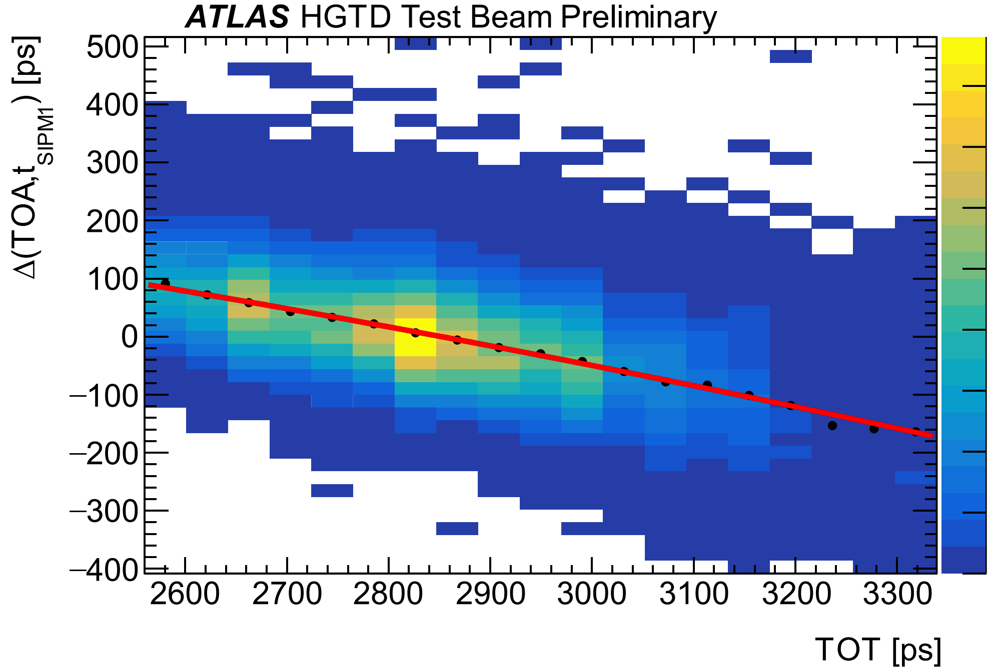


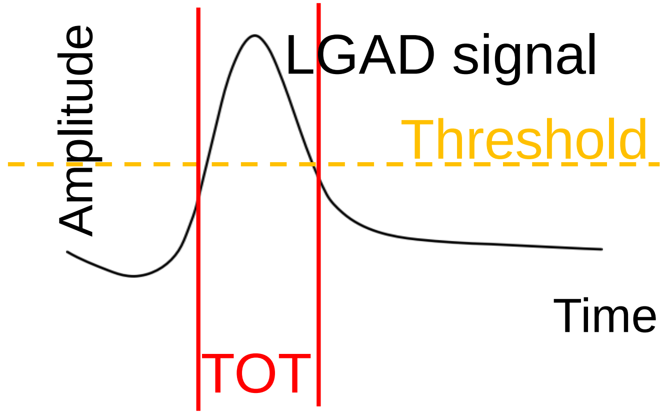
Timewalk

- Timewalk is one of the effects degrading the time resolution
- It can be mitigated if signal amplitude is known
- In ALTIROC prototypes have: probe amplitude (debug feature), TOT,...
- Example of probe timewalk for Δ_t(module,SiPM1)
- Correcting (for example with fit) means making Δ_t flat



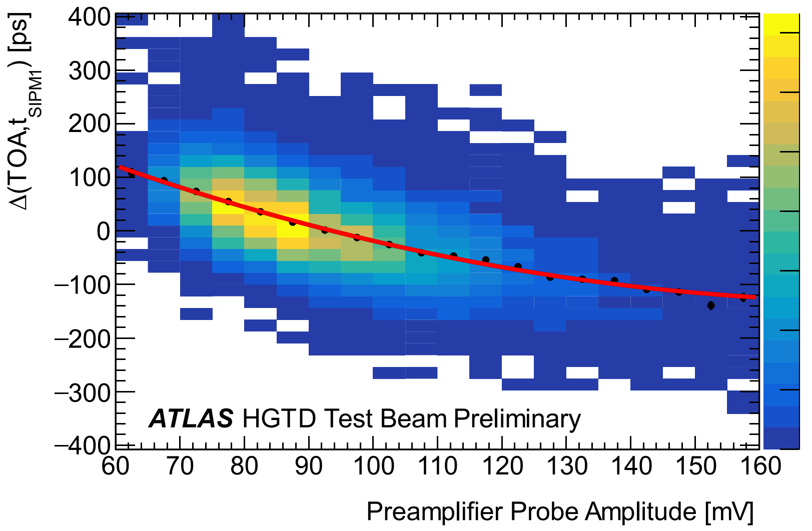


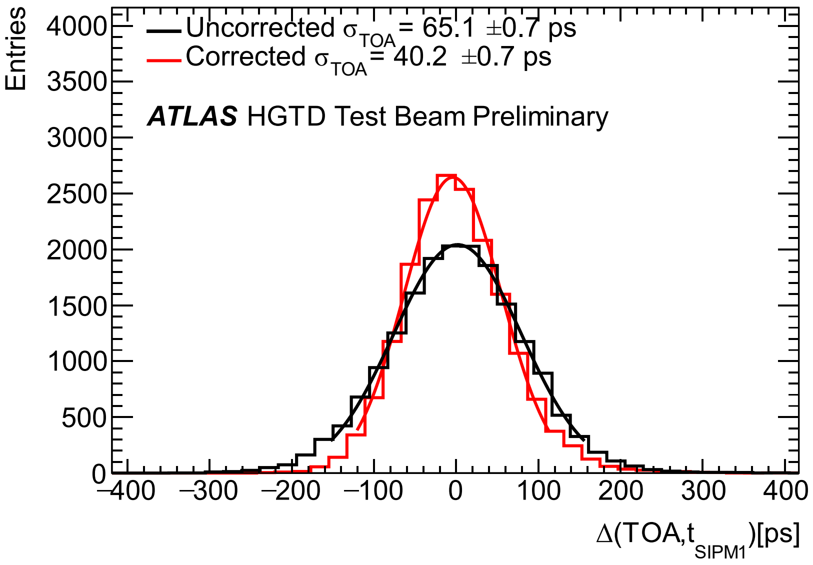


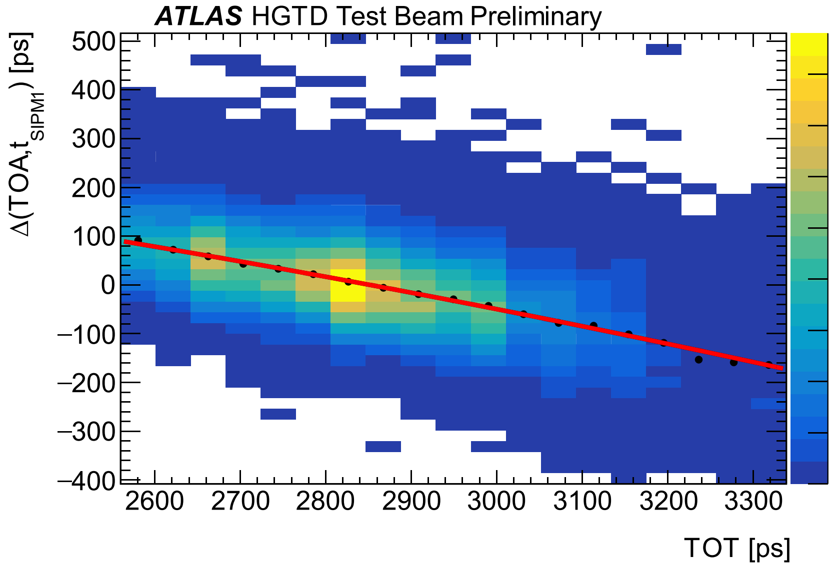


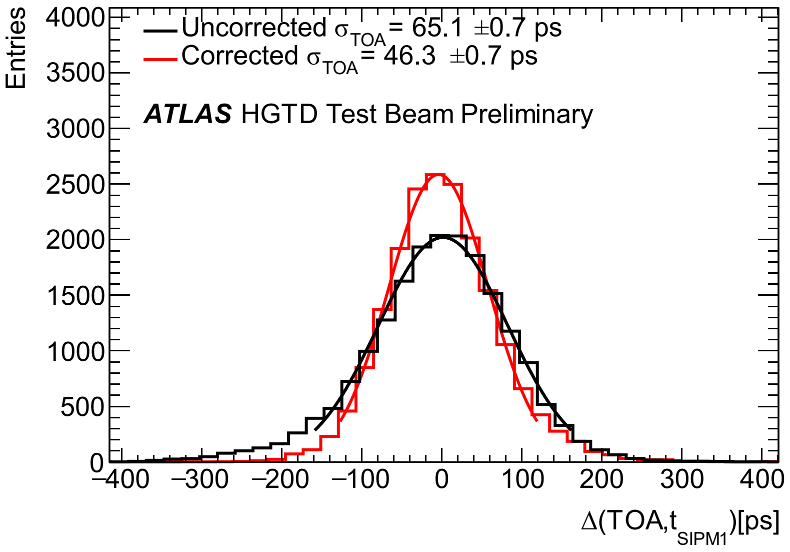
Time resolution

- Module time resolution
  - 40.3 ps with probe amplitude timewalk correction (will not be available in final detector)
  - 46.3 ps with TOT timewalk correction, in the region where TOA-TOT is flat (TOA>1600 ps)
  - Then residual timewalk can be estimated as 23 ps instead of required 10
- Probe is our best estimate of amplitude so it's expected that using it gives better result









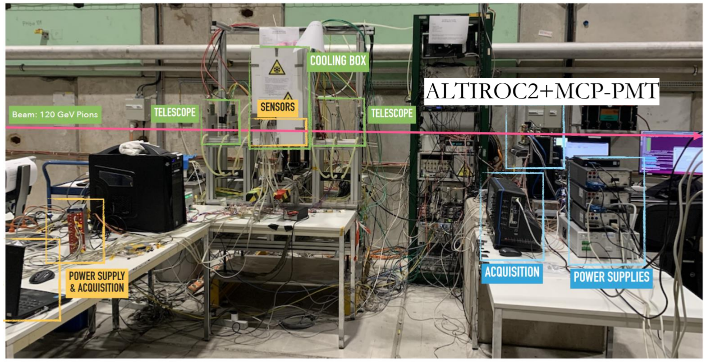
Part 3: ALTIROC2+sensor module tests

ALTIROC2 testbeam setup

- ALTIROC2 testbeam setup is similar to ALTIROC1 except that instead of two reference SiPMs, a single MCP-PMT was used
- MCP-PMT resolution is negligible when combined in quadrature with module(~40ps) and compared to SiPMs that were used for ALTIROC1 testbeam (~50ps at best)
- Now, no need to solve the 3x3 equation system, instead do

$$\Delta t = -\mathrm{TOA}*\mathrm{LSB} - (t_{MCP} - t_{clock})$$

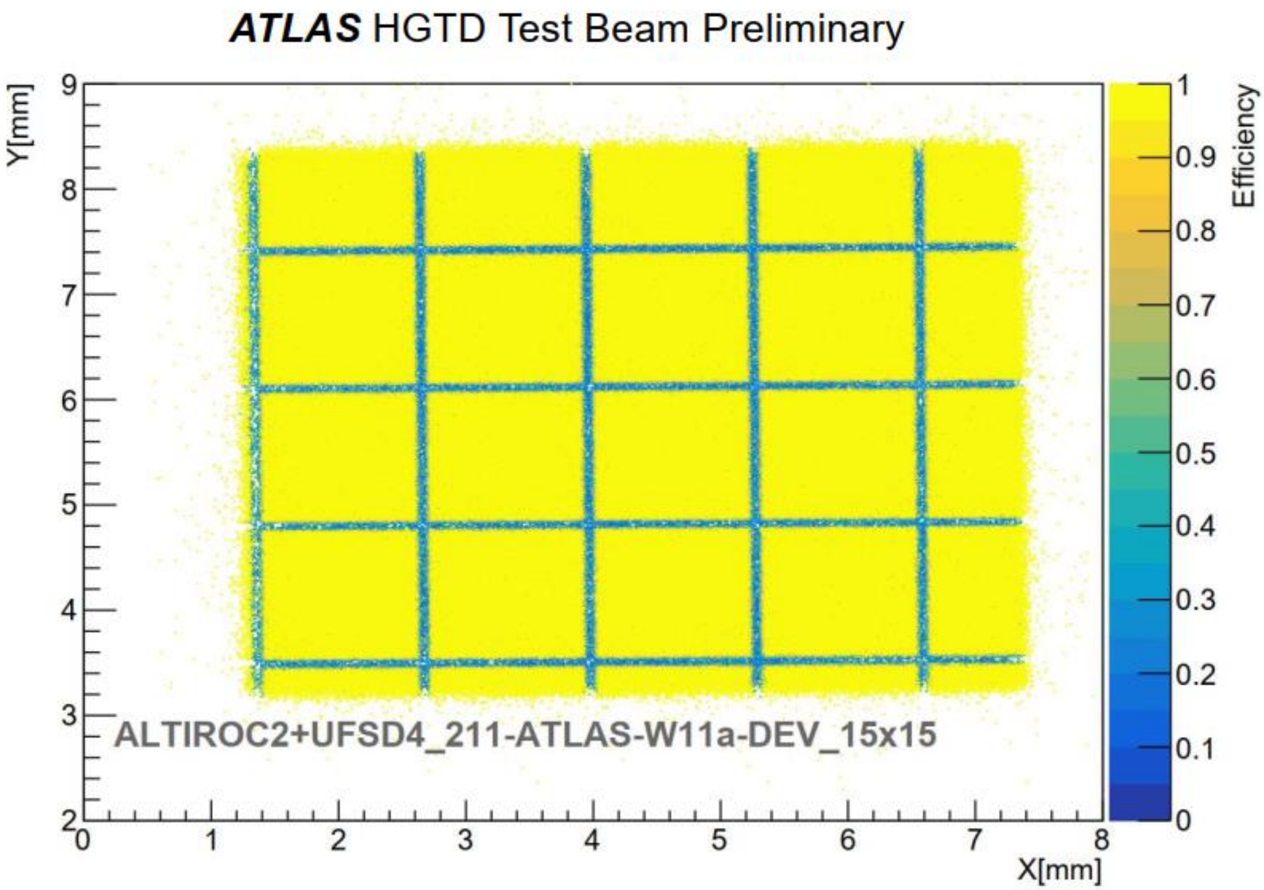
- Where
  - MCP is a reference device, time when it's fired taken wrt to clock because asicTOA is measured wrt to clock
  - asicTOA is *LSB in order to convert from binary to ps



ALTIROC2+LGAD+test board

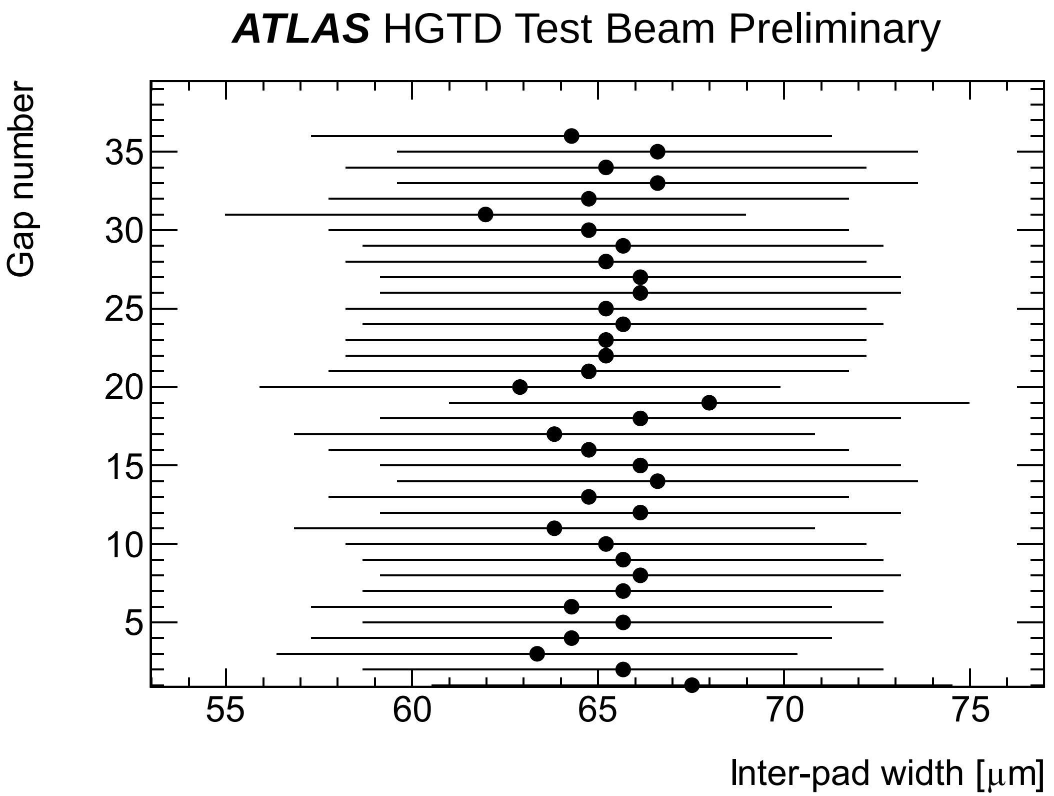
Hit efficiency

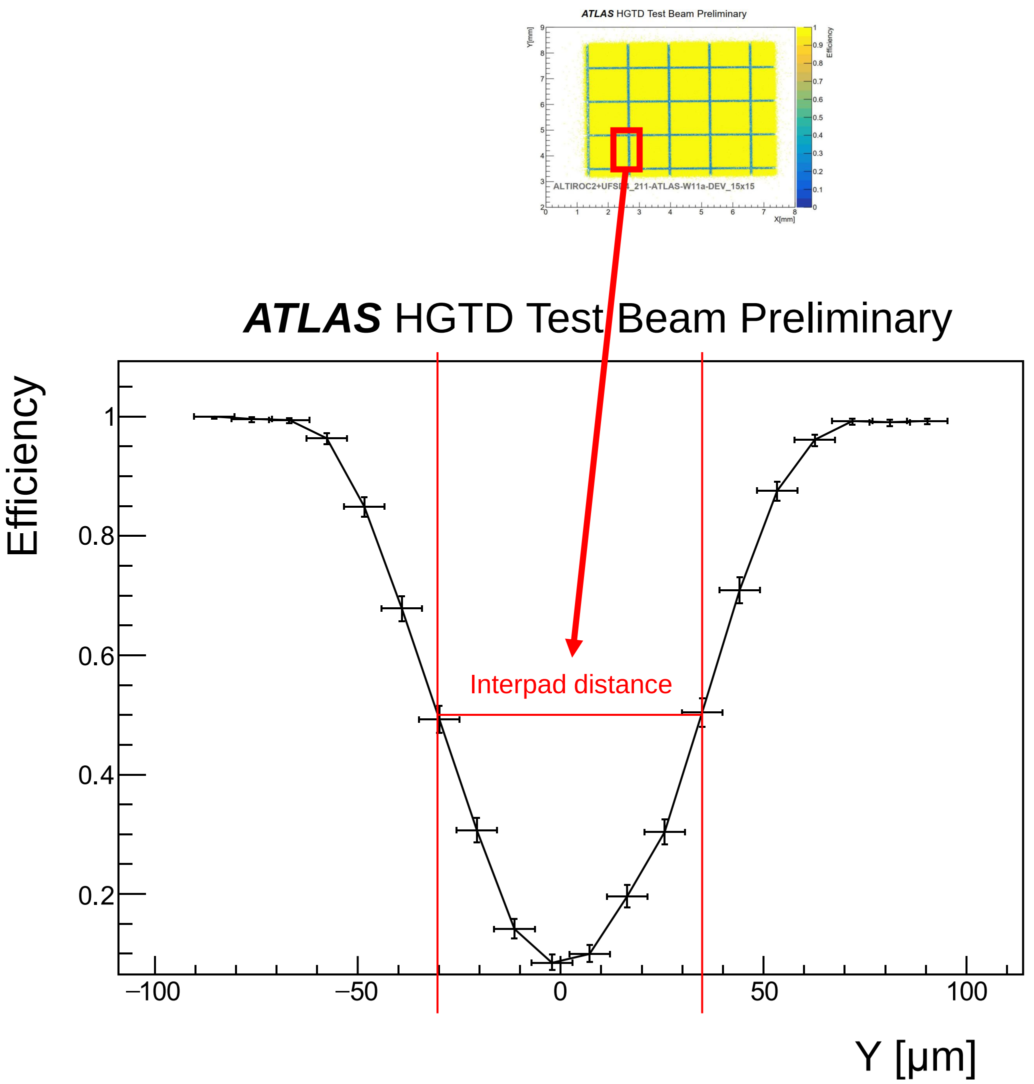
- Setup:
  - Room temperature
  - ~half of ASIC pixels activated
  - Sensor bias voltage is -180 V corresponding to a charge of ~20 fC
  - ASIC threshold 4.8 fC
  - The EUDET telescope is used for track reconstruction
  - Standalone reconstruction software used
- Efficiency map measured as ratio of the reconstructed tracks with a hit seen in ALTIROC to all the reconstructed tracks penetrating the sensor area
- 100% hit efficiency demonstrated for full-size module



Module interpad size from (In)Eff between the pixels

- Zoom into each vertical, horizontal gap
- Take 50 % width as definition of width, get it from linear interpolation
- Sizes of gaps are reasonably uniform
- Nominal is 49 μm





Part 4: Conclusion

- HGTD will be added to ATLAS for HL-LHC to mitigate pile-up via timing measurement
- Radiation tolerant LGADs testbeam performance meets the requirements: charge collected, time resolution, efficiency.

- ALTIROC1+LGAD module (small-size ATLAS HGTD ASIC prototype mounted on the sensor) demonstrated in Test Beam the capability to provide timing information with resolution 40.2 +/- 0.4 ps, which is close to the requirement. However, part of the information not available in the final chip was used. With TDC-only information, the resolution is 46 ps.
- ALTIROC2+LGAD full-size module time resolution is similar. Resolution is better near amplitude peak value, behavior coming from sensor itself and also observed in ALTIROC1.
- ALTIROC2+LGAD showed 100% hit efficiency in Test Beam, as required.
- 50%-50% size of interpad regions is extracted from efficiency maps and equal to 65.3 +/- 0.2 μm.

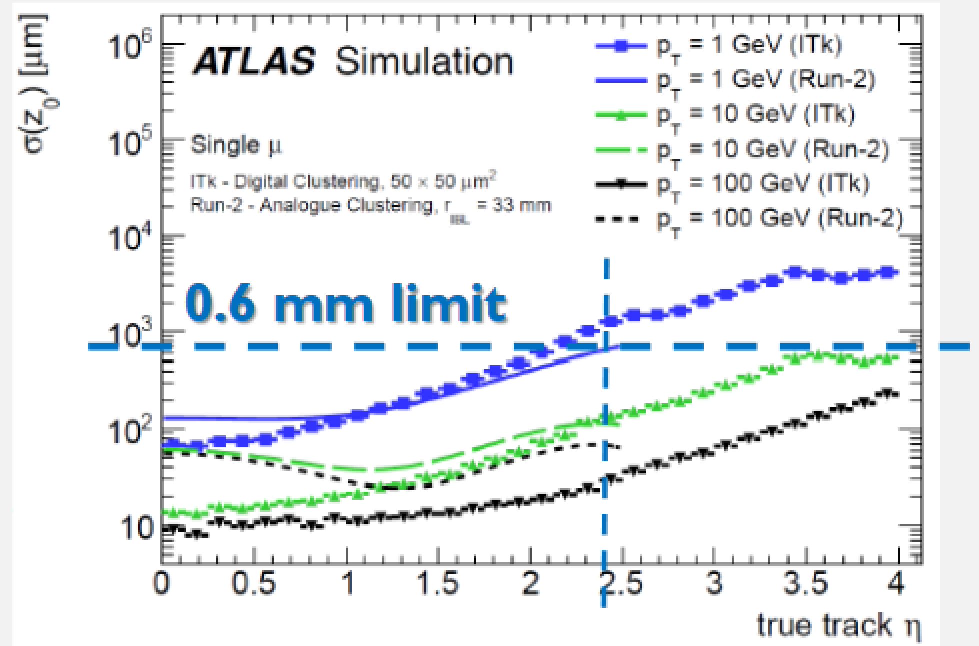
- ALTIROC3 (full-size, fully radiation hard, certain adjustments to design) is available since April, performed first testbeam two weeks ago, another one will happen in two weeks

The End

Backup ↓

Why hgtd only in forward region

- Tracker is good enough
- https://cds.cern.ch/record/2851661/files/ATL-HGTD-SLIDE-2023-015.pdf



Radiation tolerant sensors performance arXiv: 2303.07728

- LGAD R&D is approaching the final design that should be radiation tolerant and meet the performance requirement after irradiation: Q>4 fC, σ_t<70 ps, ε>95 %
- Before unirradiated sensors tested, now radiation tolerance is added by using carbon-enriched LGAD samples. Three vendors considered: FBK, IHEP-IME, USTC-IME
- Sensors were irradiated to 2.5x10^{15} n_{eq}/cm^2 and then put into DESY (electron), SPS (pion) testbeams. Carbon-enriched LGADs from three vendors meet the HGTD requirements
- Tests are done with custom read-out, not the actual HGTD electronics