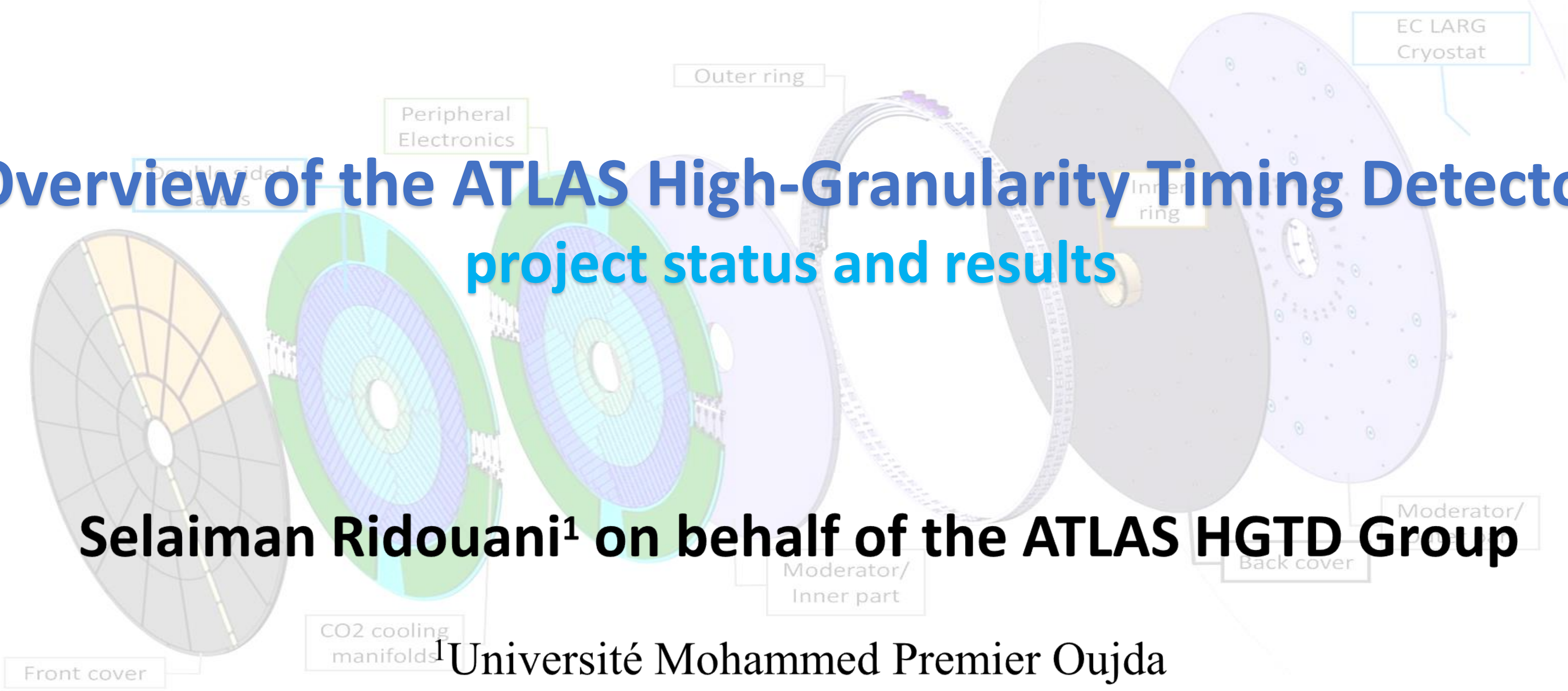
XII International Conference on New Frontiers in Physics

10-23 July 2023, OAC, Kolymbari, Crete, Greece

Overview of the ATLAS High-Granularity Timing Detector

project status and results



Selaiman Ridouani[1] on behalf of the ATLAS HGTD Group

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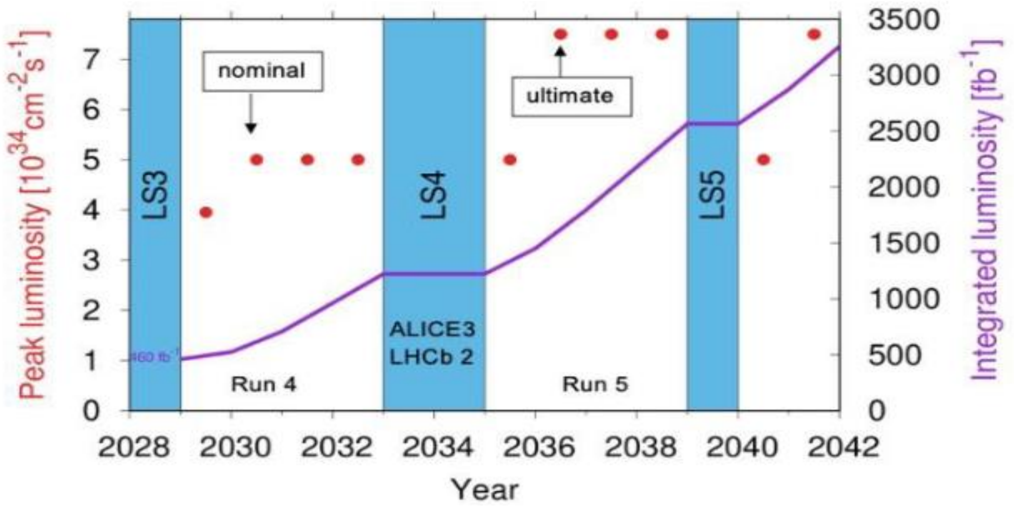
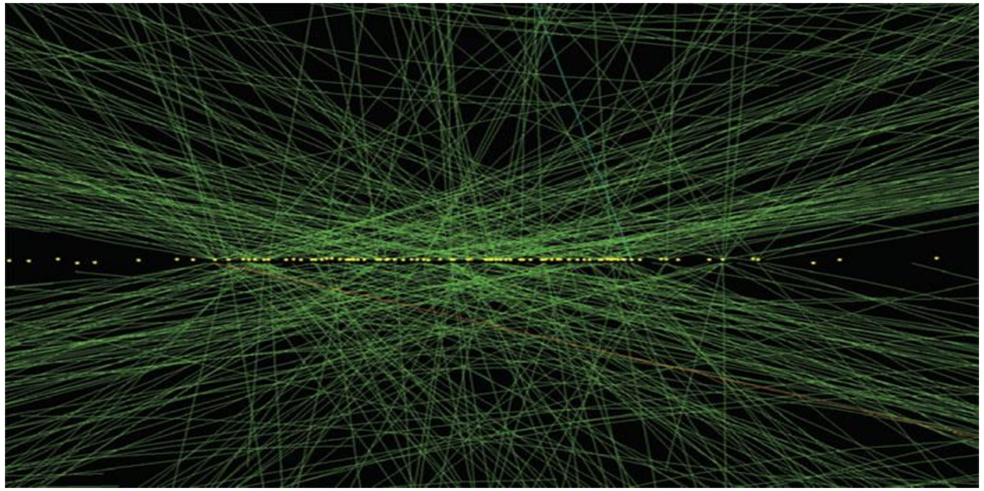
High-Luminosity LHC: 2029 and beyond

- The peak instantaneous luminosities: L ~ $7.5 \times 10^{34}\ cm^{-2}\ s^{-1}$
- Collecting 10 times the data sample than the Run3 in the long term
- ~ 10 Times more interactions per proton bunch crossing
  - High pile-up density => increasing reconstruction complexity
- Harsh radiation environment up to 2 x 10^{15} n_{eq} cm^{-2}
  - impact on detector technologies, electronics, and materials



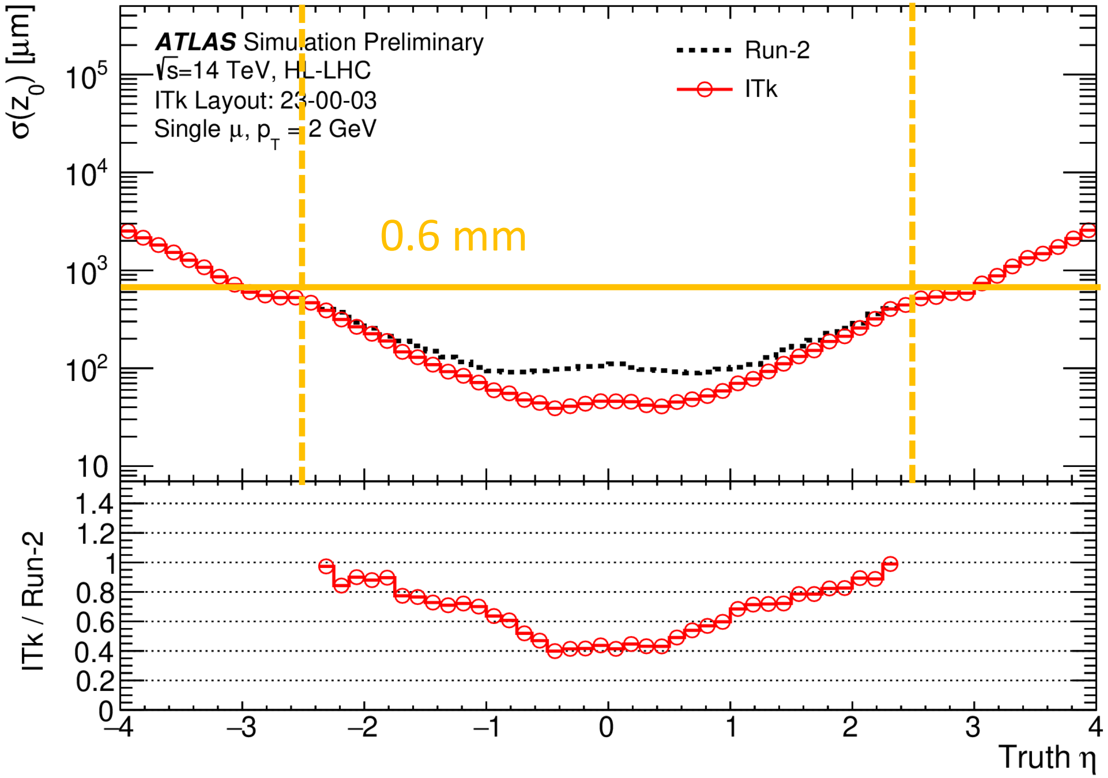


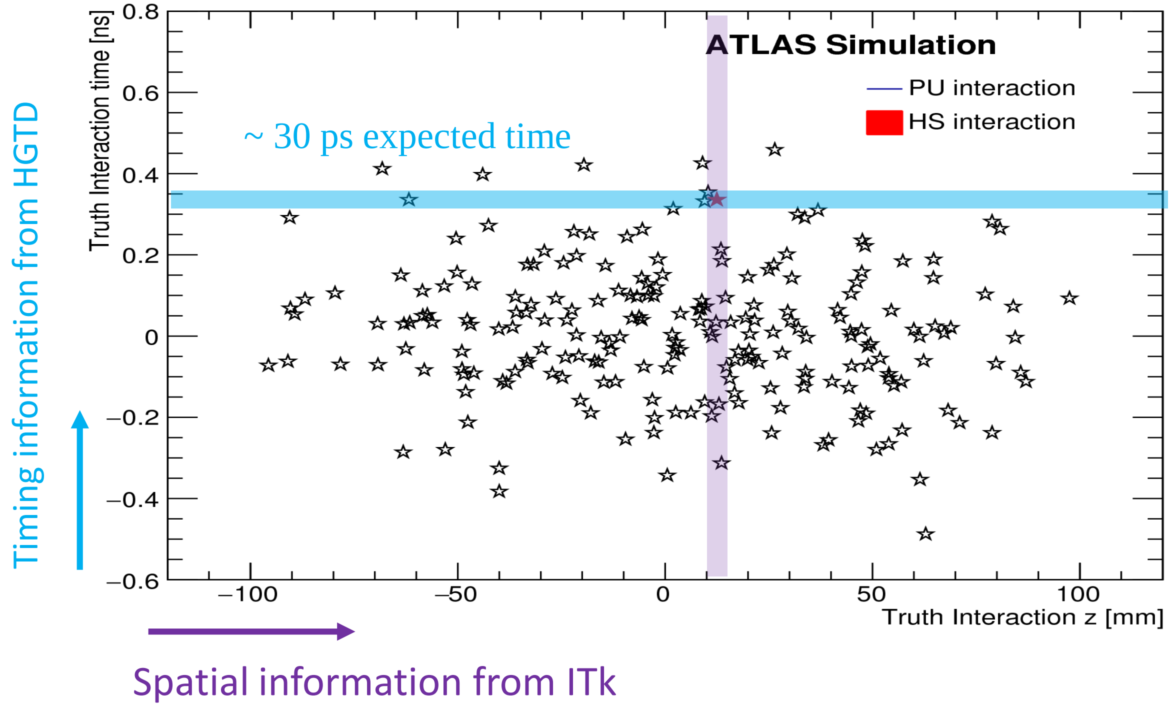
ATLAS Inner Tracker Performance

- Pile-up of ~ 200 spread in ~ 45 mm along the beam axis
  - 1.6 vertices/mm on average
- Inner Tracker (ITk) is designed to cope with high pile-up density, but still challenging in the forward region
  - σ_{z0} should be significantly better than the inverse of the average pile-up density (~ 0.6mm)

✓ **Exploit the time dimension of the beam spot**

- Discriminating tracks from pile-up vertices with the same z but different time
- With the expected time resolution => pile-up suppression by **a factor of ~ 6**

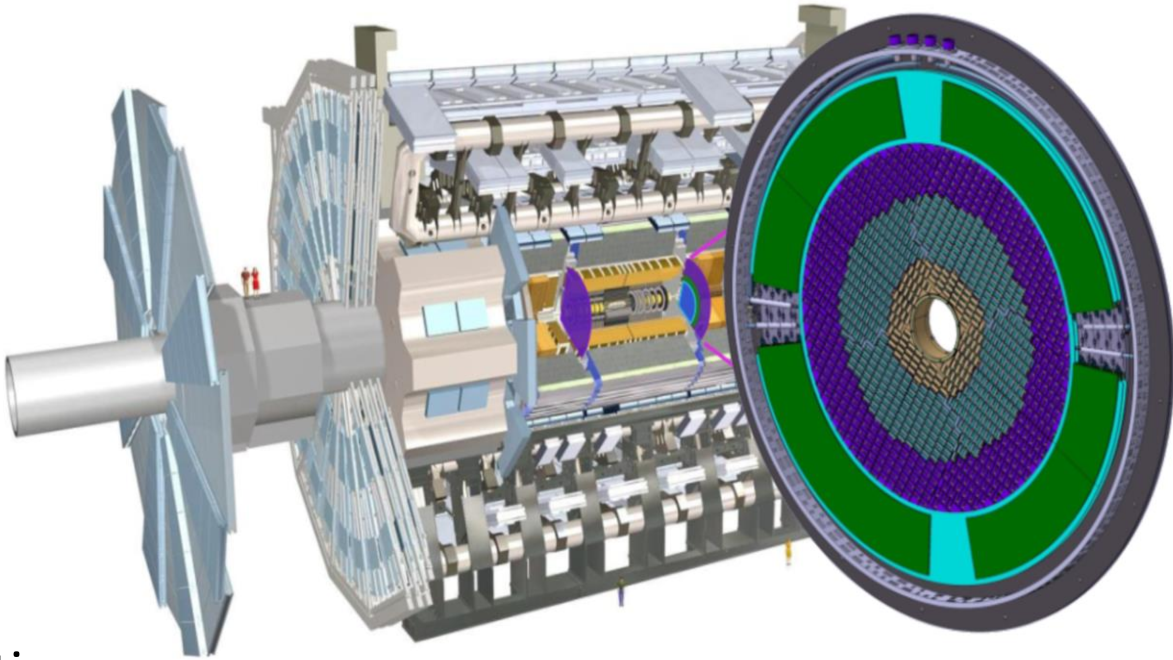




High Granularity Timing Detector

ATLAS EXPERIMENT

The HGTD located at z = ± 3.5 m, between ITk and the end-cap calorimeter



Requirements

- Time resolution:
  - per track: 30 ps (start) and 50 ps (end of lifetime)
  - per hit: 35 ps (start) and 70 ps (end of lifetime)
- Radiation hardness:
  - Maximum n_{eq} fluences: 2.5×10^{15} n_{eq} cm^{-2}
  - Total Ionising Dose (TID): 2 MGy at 4000 fb^{-1}
- Collected charge per hit > 4 fC
- Hit efficiencies: 97% (95%) at the start (end) of their lifetime

Technology

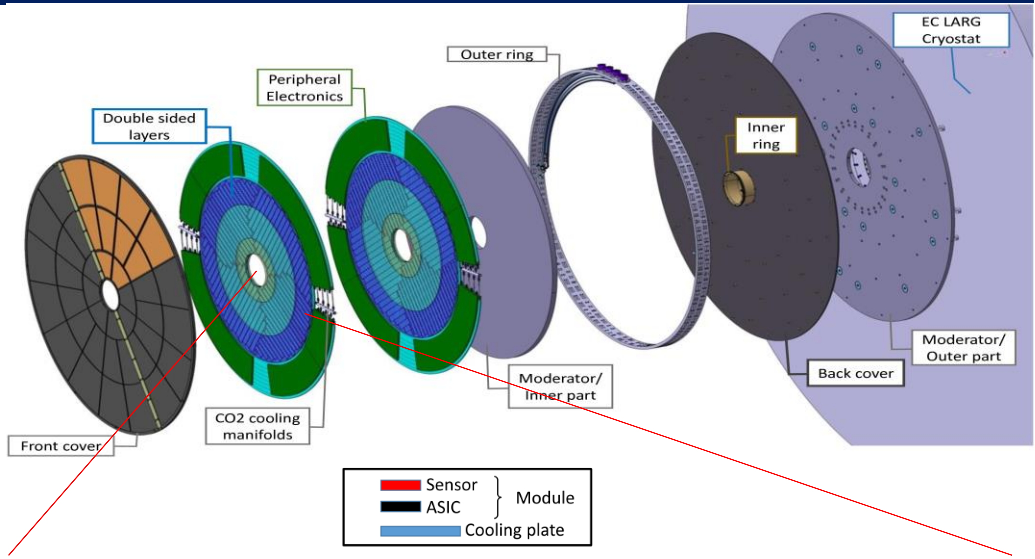
- **Sensor**: Low Gain Avalanche Detector (LGAD)
- **Front-end electronics**: ATLAS LGAD Timing ReadOut Chip (ALTIROC)

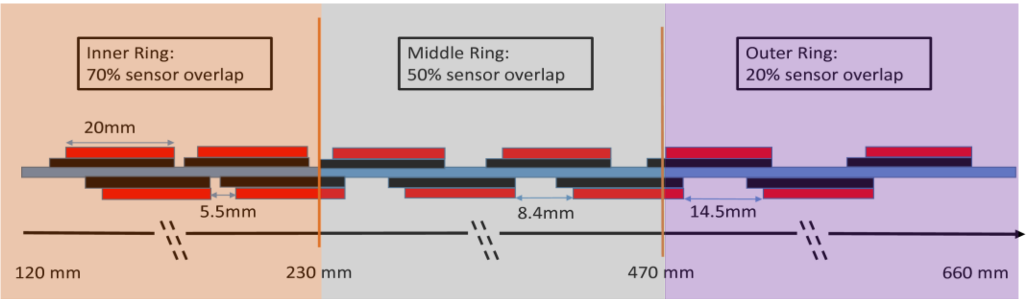
High Granularity Timing Detector

ATLAS EXPERIMENT

Detector Design

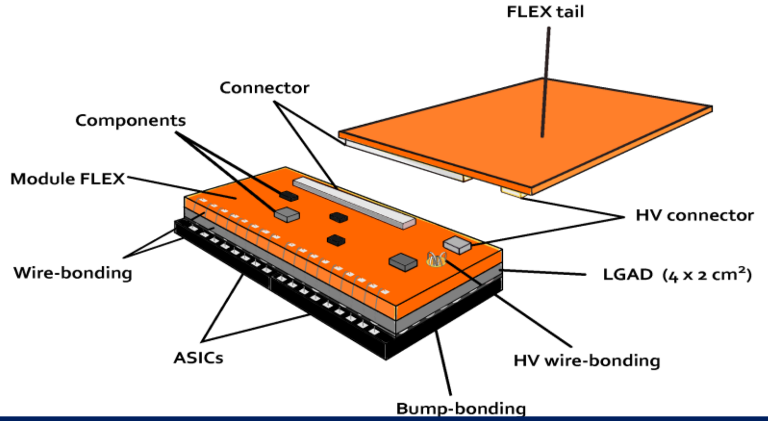
- Maximum thickness in $z = 125\ mm$
- Active area $6.4\ m^2$, radius $120\ mm < R < 640\ mm$ corresponding to $2.4 < |\eta| < 4$
- Two double-side layers mounted on the cooling disk
- Three rings layout with different active sensors overlap **70%, 50%, 20%**
  - Inner ring replaced every 1000 fb^{-1}
  - Middle ring replaced after 2000 fb^{-1}
  - Outer ring never replaced





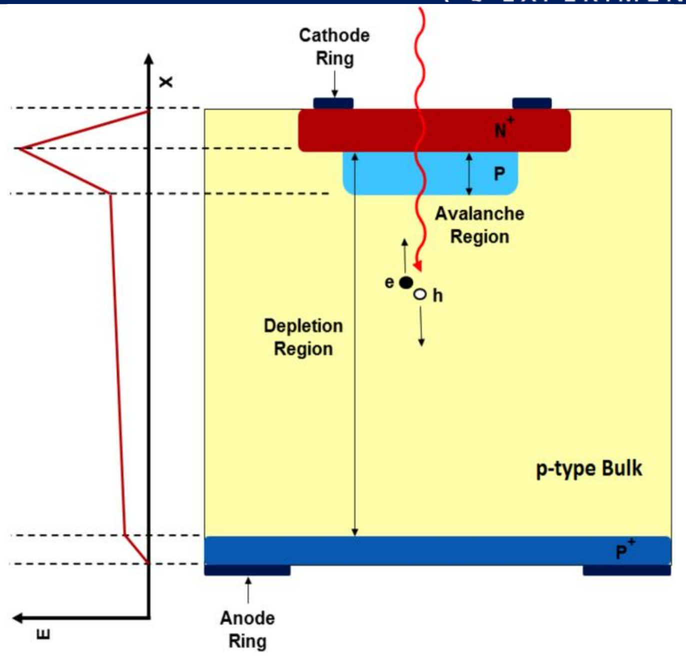
HGTD Module

- 2 LGADs (15x15 pads) + 2 ASICs (15x15 channel) + flex
- Flex cable carrying all connections between the ASIC and the peripheral electronics (it also provides HV for the sensor)
- 8032 modules with 3.6 M channels operating at -30°C

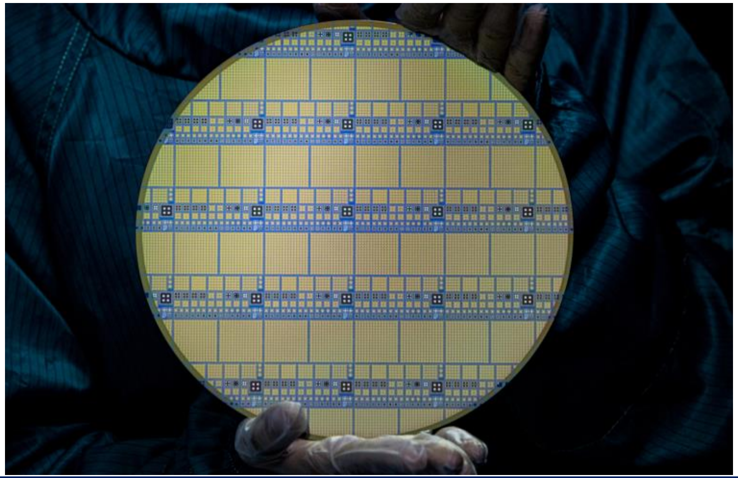


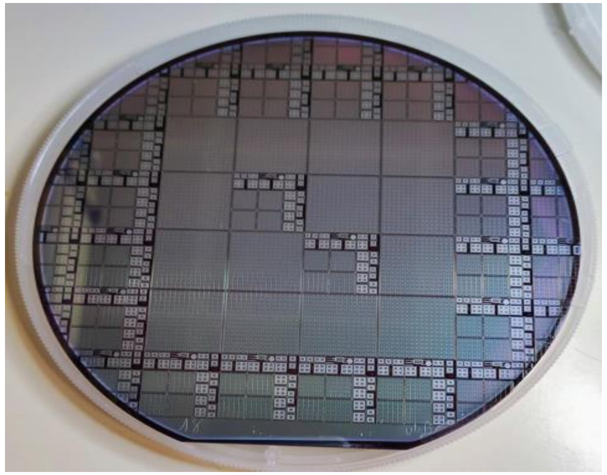
Low Gain Avalanche Detector

- LGAD: silicon detector with an extra thin p-layer (<5 µm) highly doped below the junction p-n
  - Creating high E-field ➞ internal gain 20 (start), 8 (end of lifetime)
- Excellent time resolution (30 ps before irradiation)
- Pad size: 1.3 x 1.3 mm^2
- Thin sensor 50 μm
  - Faster rise time ~ 0.5 ns
  - Good radiation tolerance
- Several prototypes of LGADs
  - CNM (Spain), HPK (Japan), FBK (Italy), USTC/IHEP-IME (China), NDL (China)



IHEP-IMEv2 LGAD wafer with full size (15 x 15)





FBK UFSD4.0

LGAD Performance Studies at CERN SPS and DESY test beam

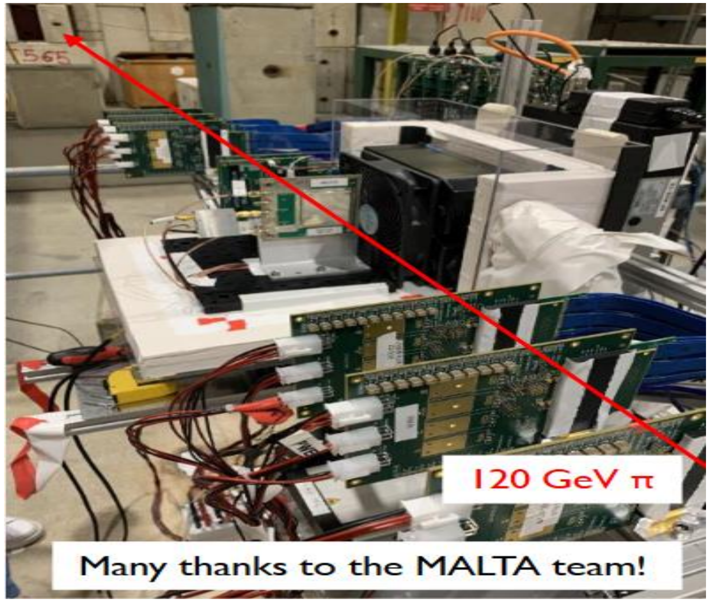
Evaluation of the performance of sensors at test beam 2021-2022 campaigns:

- Determine safe bias voltages to avoid "single event burnout" (SEB)
- Qualify carbon-enriched LGADs performance:
  - collected charge, time resolution, and efficiency

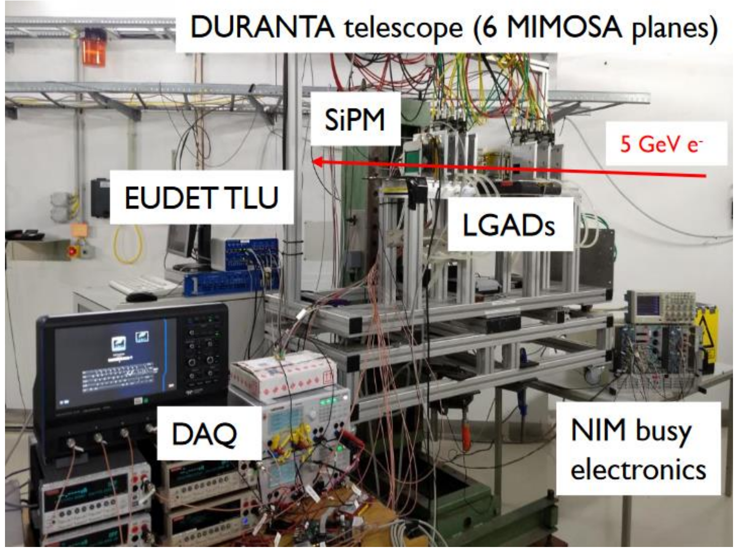
List of sensors

Device name	Vendor	Sensor ID	Implant	Irradiation type	Fluence [n_{eq} /cm²]	Tested at
CNM-0	CNM	W9LGA35	boron	unirradiated	–	DESY/CERN
FBK-1.5	FBK	UFSD3.2 W19	boron + carbon	neutrons	$1.5\text{x}10^{15}$	DESY/CERN
FBK-2.5	FBK	UFSD3.2 W19	boron + carbon	neutrons	$2.5\text{x}10^{15}$	DESY/CERN
USTC-1.5	USTC-IME	v2.1 W17	boron + carbon	neutrons	$1.5\text{x}10^{15}$	DESY
USTC-2.5	USTC-IME	v2.1 W17	boron + carbon	neutrons	$2.5\text{x}10^{15}$	DESY
IHEP-1.5	IHEP-IME	v2 W7 Q2	boron + carbon	neutrons	$1.5\text{x}10^{15}$	DESY/CERN
IHEP-2.5	IHEP-IME	v2 W7 Q2	boron + carbon	neutrons	$2.5\text{x}10^{15}$	CERN

- 3 vendors FBK, USTC-IME and IHEP-IME
- Sensors irradiated at 1.5×10^{15} n_{eq} cm^{-2} and 2.5×10^{15} n_{eq} cm^{-2} at the TRIGA reactor in Ljubljana, Slovenia with fast neutrons



CERN North Area SPS H6A beamline (120 GeV pion beam)

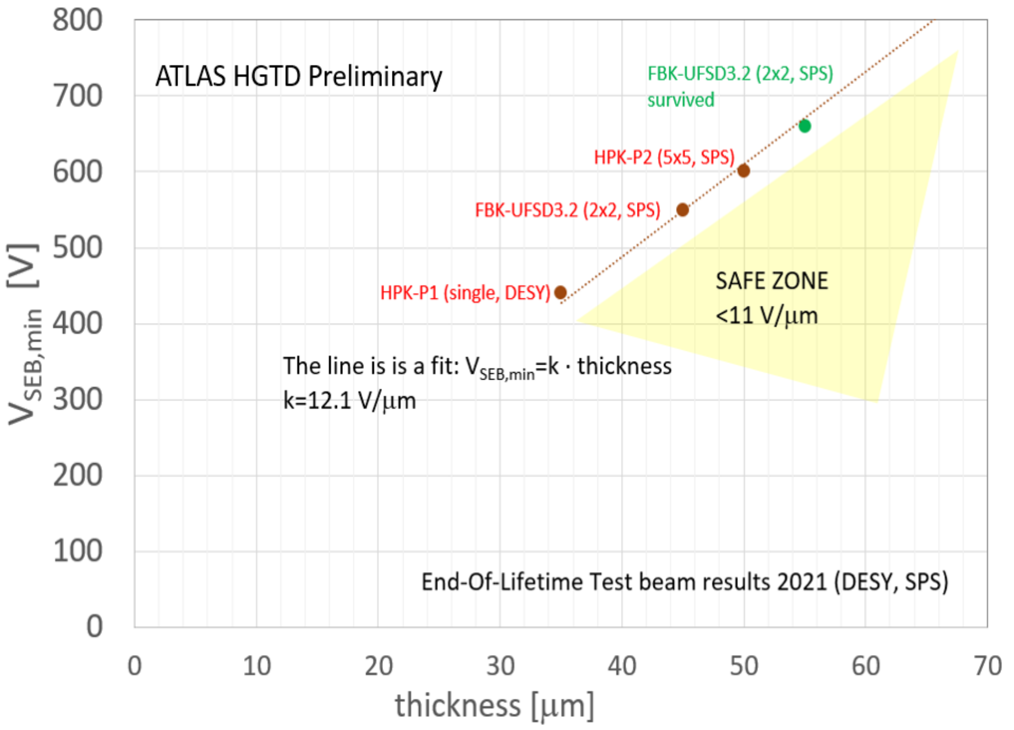


DESY T22 beamline (5 GeV e- beam)

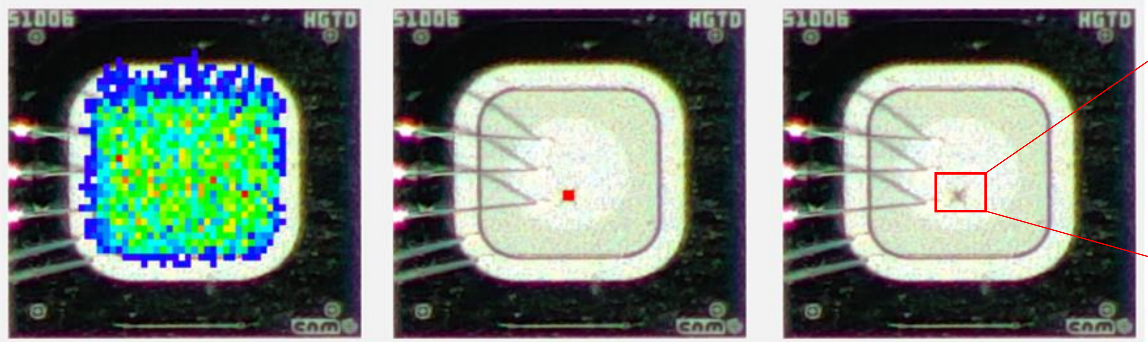
ATLAS EXPERIMENT

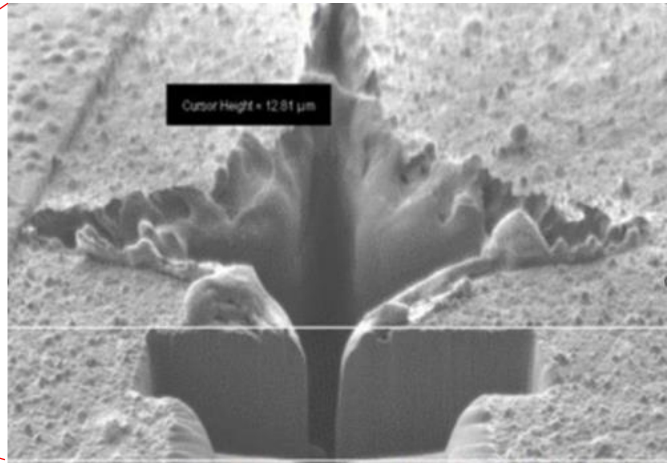
Single Event Burnout (SEB)

- Single Event Burnout (SEB) has been observed in several test beam campaigns
  - After irradiation timing performance degrades due to loss of gain
  - Increasing the bias voltage to recover → Irreversible breakdown while operating in these conditions
  - Observed by CMS/ATLAS/RD50 teams
- A safe zone has been defined
  - Safe zone <11 V/µm our case LGAD 50 µm → max voltage is 550 V



ATLAS HGTD Preliminary

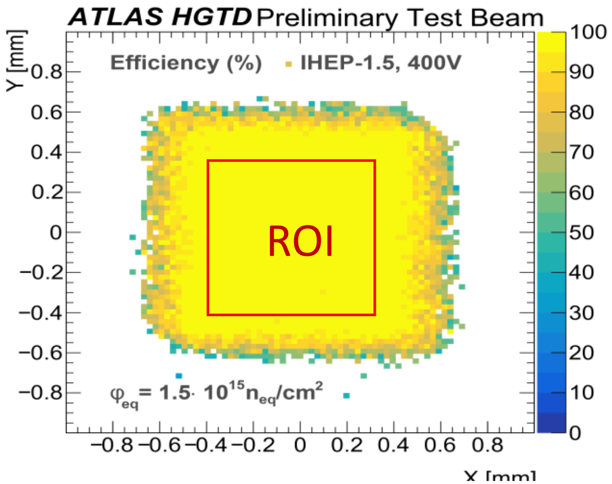


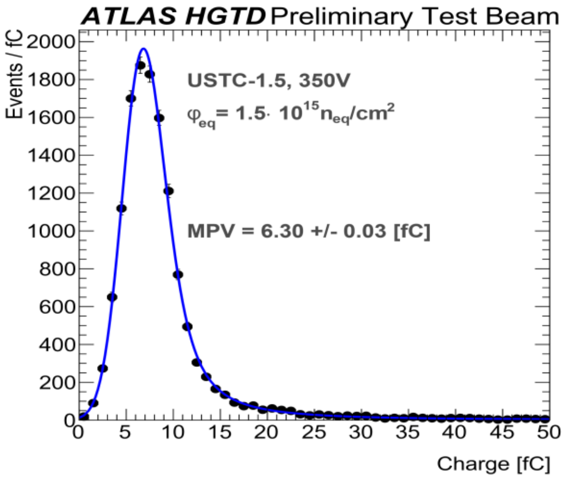


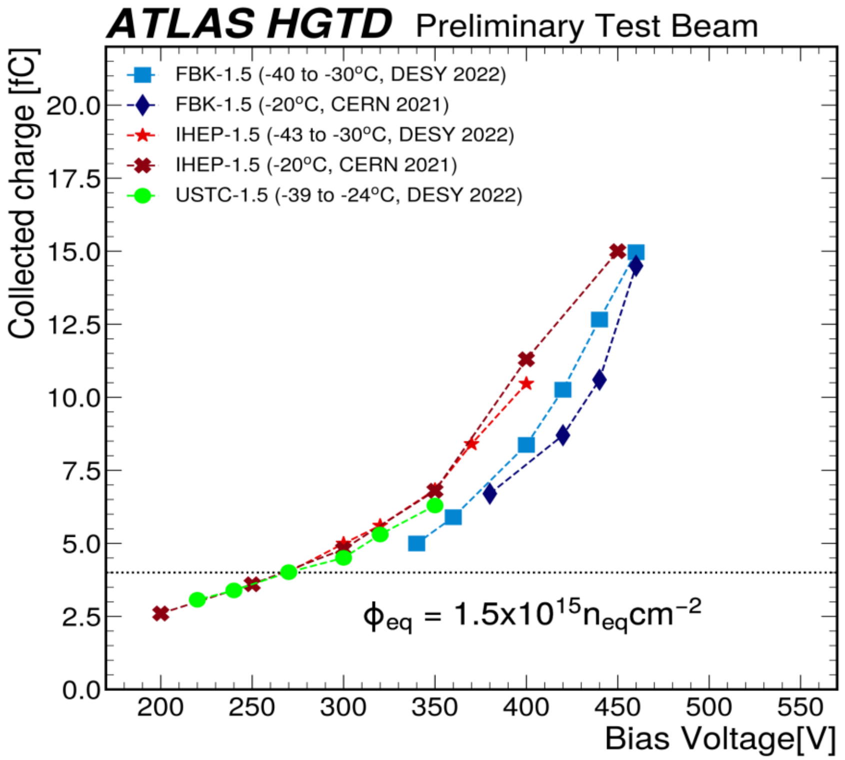
Collected Charge

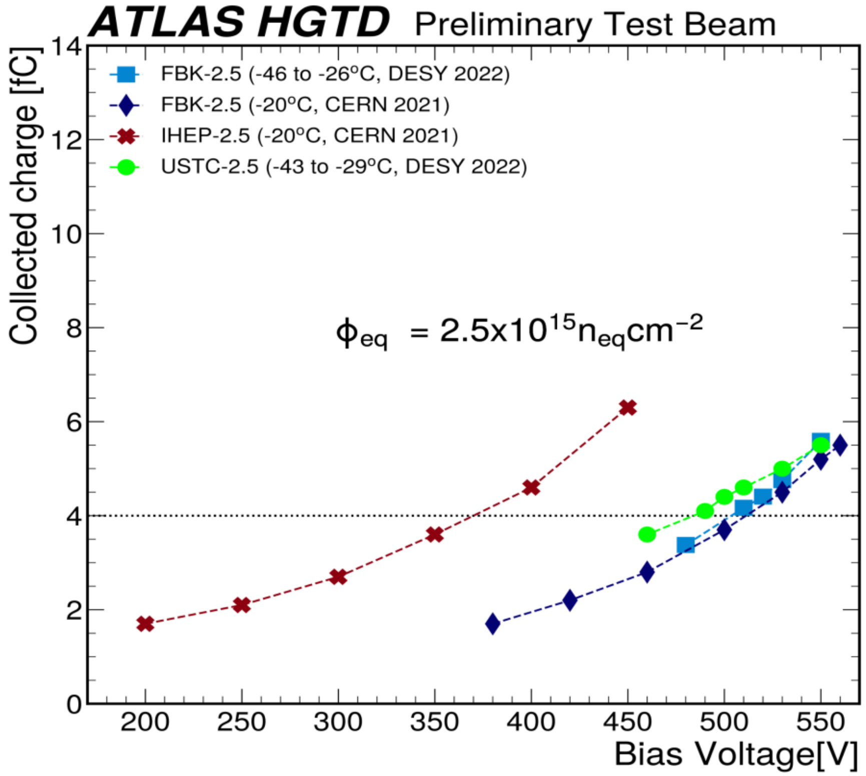
arxiv:2303.07728

- Fitting the Region Of Interest (ROI) with a Landau-Gaussian convoluted function
- Collected Charge is defined as the Most Probable Value (MPV) from fit



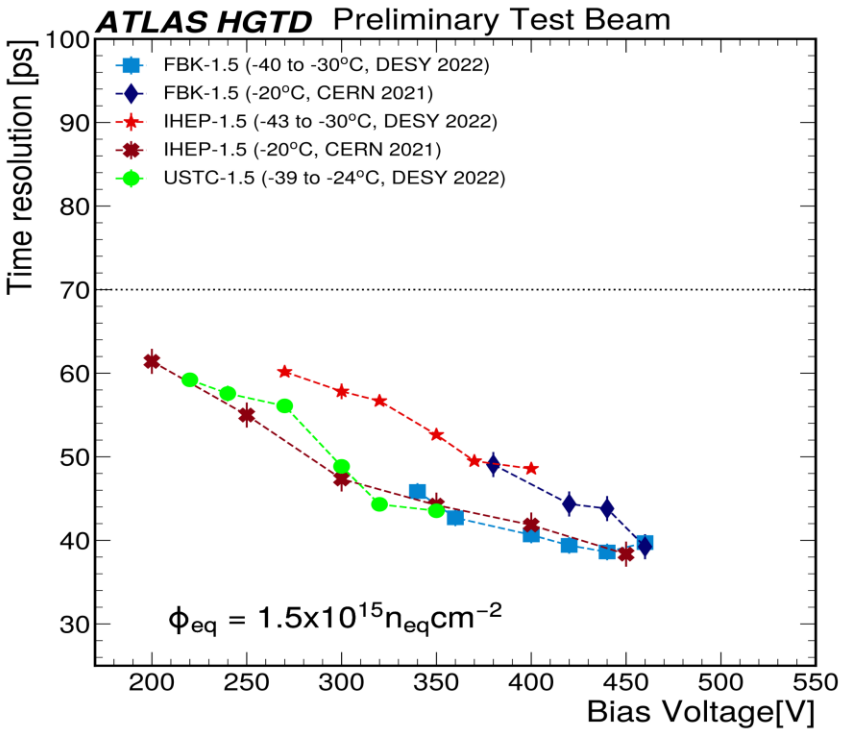


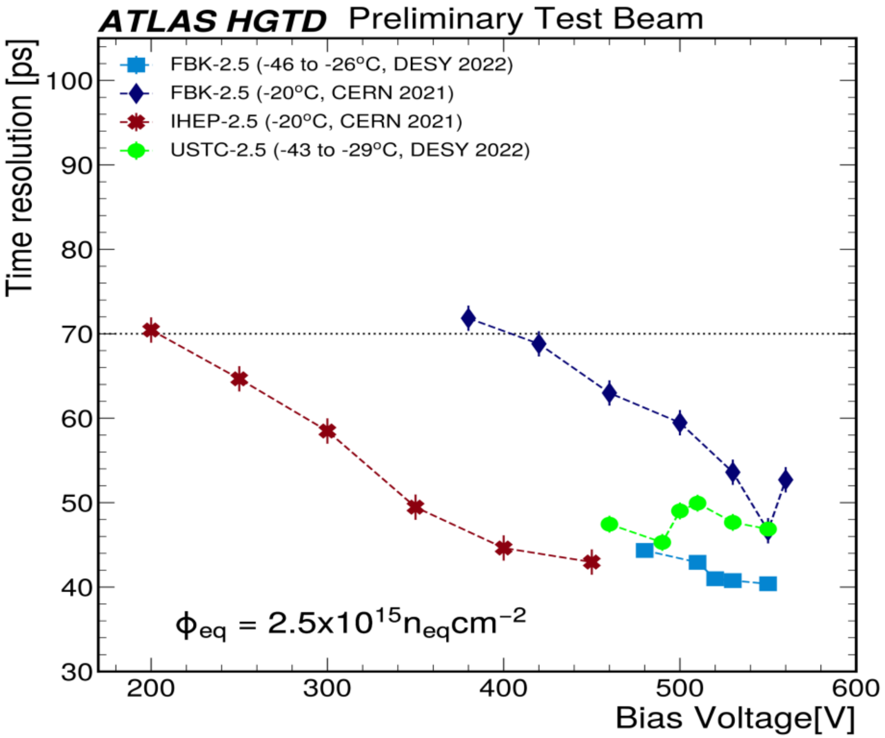




Time resolution

- To extract the LGADs' time resolutions, the distributions of the difference between the TOA of the LGAD and that of the time reference device (σ_{SiPM} = 62.6 ps, σ_{CNM} = 54.8 ps) were fitted with a Gaussian function, each of them giving a width σ_{ij}
- Three devices in these setups, the resolution of each one is calculated as: $\sigma_i = \sqrt{\dfrac{\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2}{2}}$

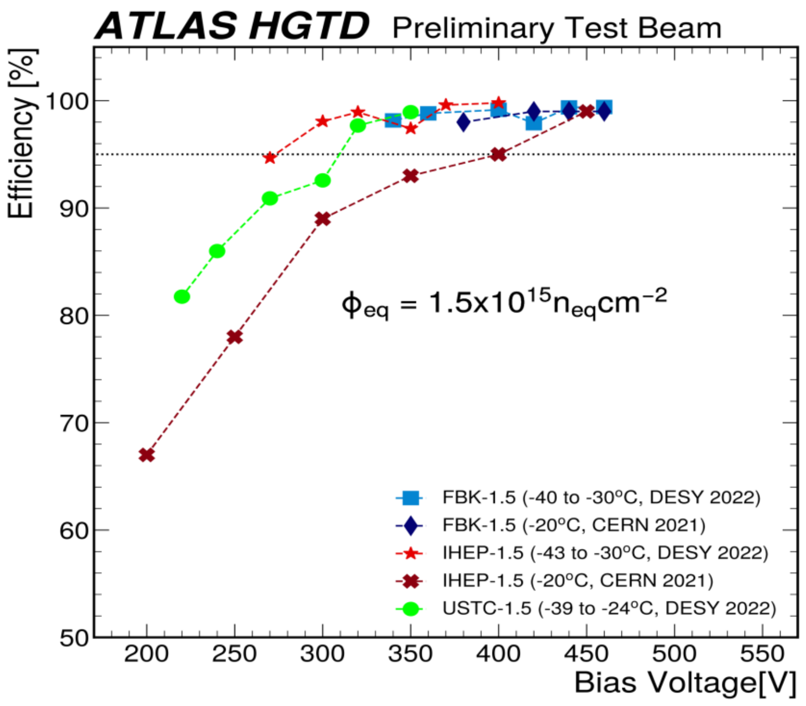


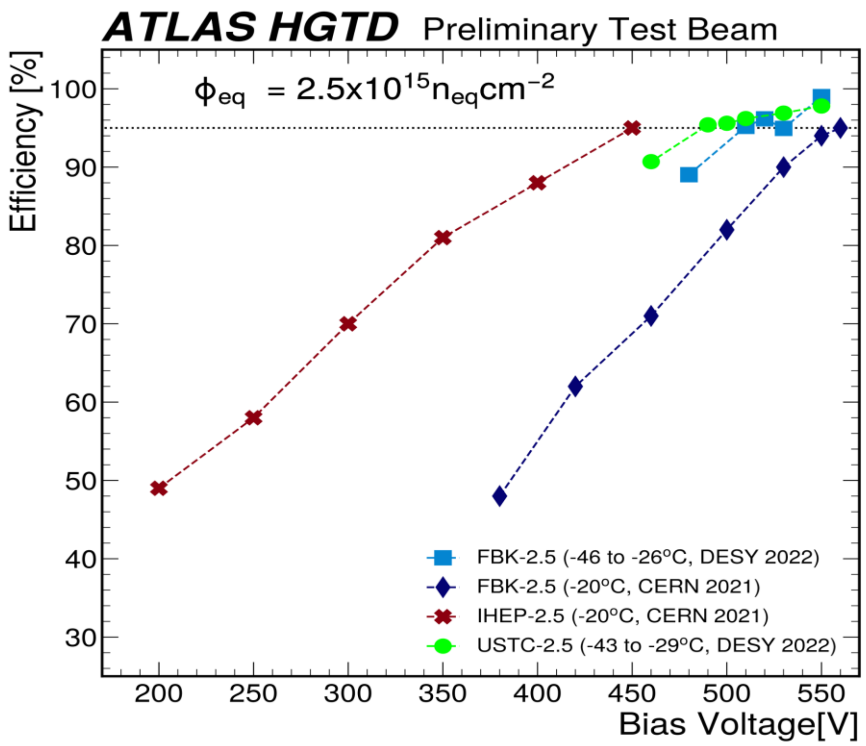


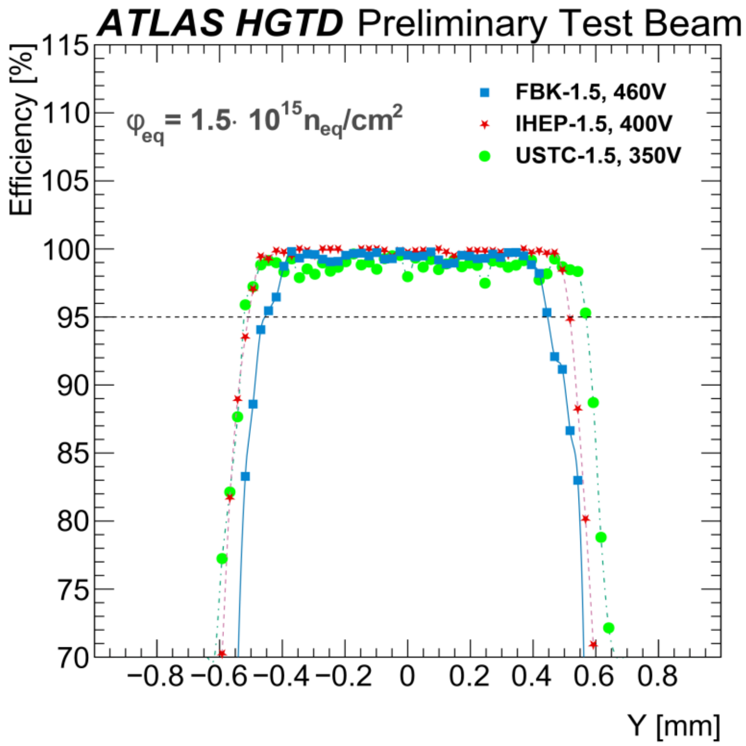
Hit Efficiency

$$\text{Hit Efficiency} = \frac{\text{Reconstructed tracks with } q > Q_{\text{cut}}}{\text{Total reconstructed tracks}}$$

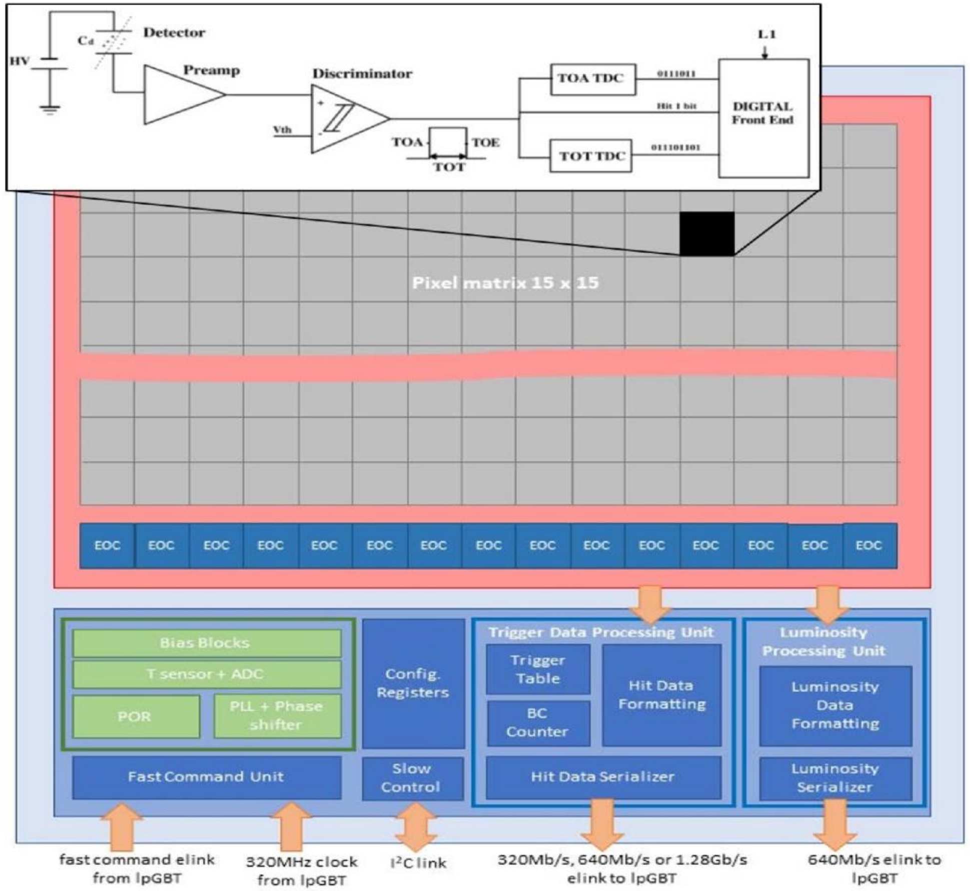
- Setting Q_{cut} = 2 fC => minimum value of the discriminator of the future ALTIROC

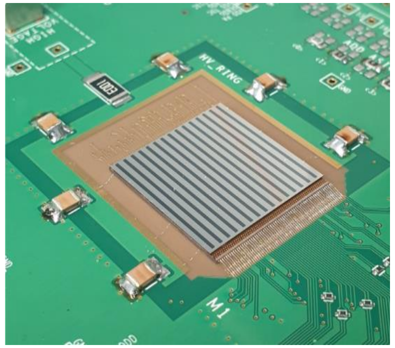






- **ALTIROC (TSMC 130 nm CMOS)**
  - Reads the signal from each LGAD sensor
  - 225(15x15) Channels → Each single-channel readout fits within the sensor pad (1.3mm)
  - Providing the Time Of Arrival (TOA), Time Over Threshold (TOT) for time walk correction
- **Requirements**
  - Providing strict jitter
    - Jitter < 25 ps @ 10 fC and <65 ps @ 4 fC
  - Discriminator threshold minimum of 2 fC
- **ALTIROC prototypes**
  - **ALTIROC1:** 25 (5x5) channels prototype, with all analog functionality
  - **ALTIROC2**: 225 (15x15) channels full prototype, including all functionalities
  - **ALTIROC3**: Radiation hard version of ALTIROC2 (under test)



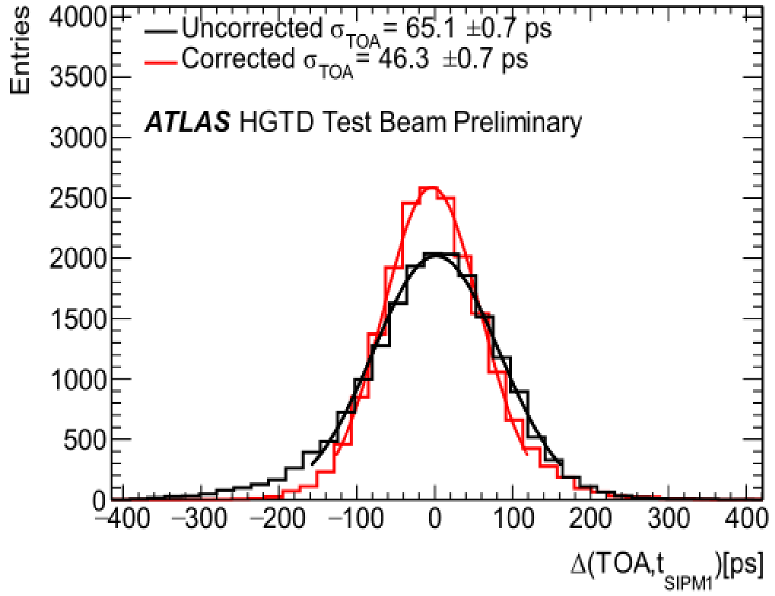


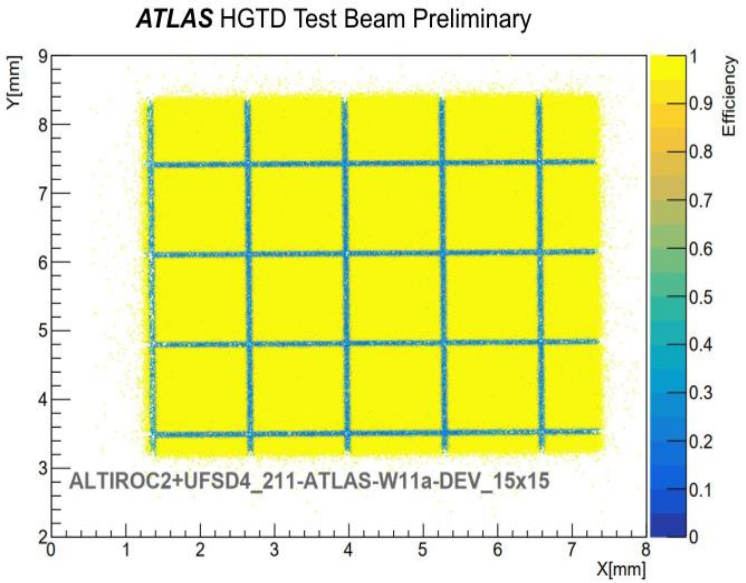
ALTIROC2 + HPK 15x15 LGAD

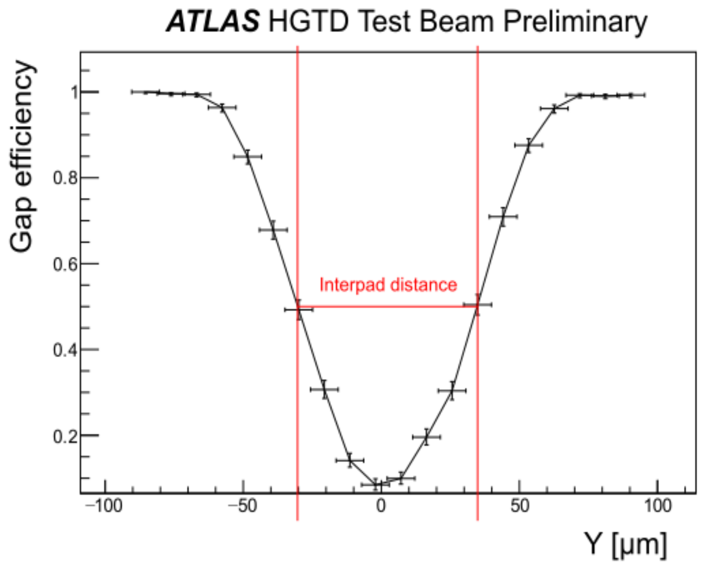
arxiv:2306.08949

Test beam measurement

- **ALTIROC1**
  - Focus on the performance of analogue electronics
  - Fit of TOA variation as a function of the TOT is used to calculate time-walk corrections
  - Estimated resolution of ~ 46 ps after time-walk correction
  - Estimated jitter contribution: ~ 39 ps



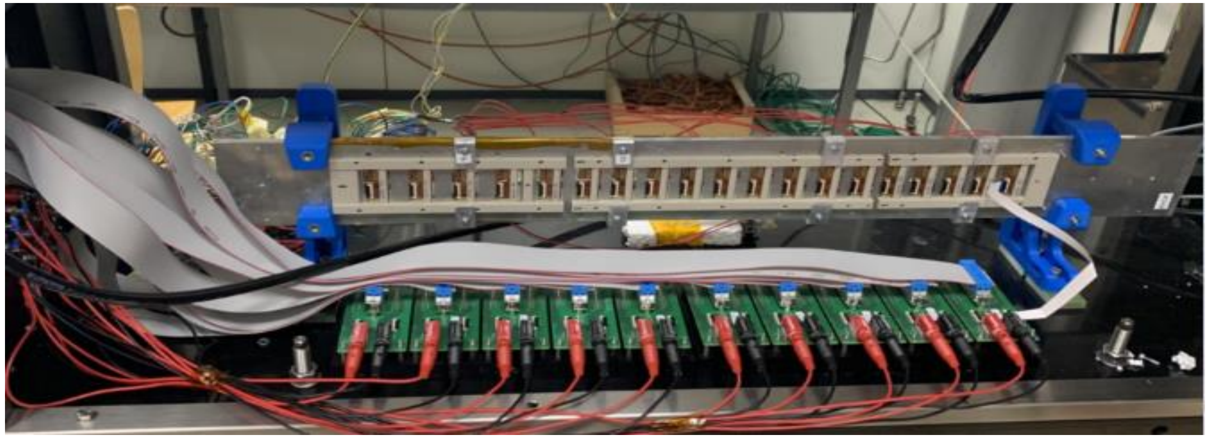




- **ALTIROC2**
- 100% efficiency for each pixel
  - Hit Efficiency = $\frac{\text{the reconstructed tracks with a hit seen by ALTIROC}}{\text{all reconstructed tracks that hit module area}}$
- Efficiency measured in the interpad region
  - interpad region size at 50% - 50% of efficiency is 65.3 +/- 0.2 μm.

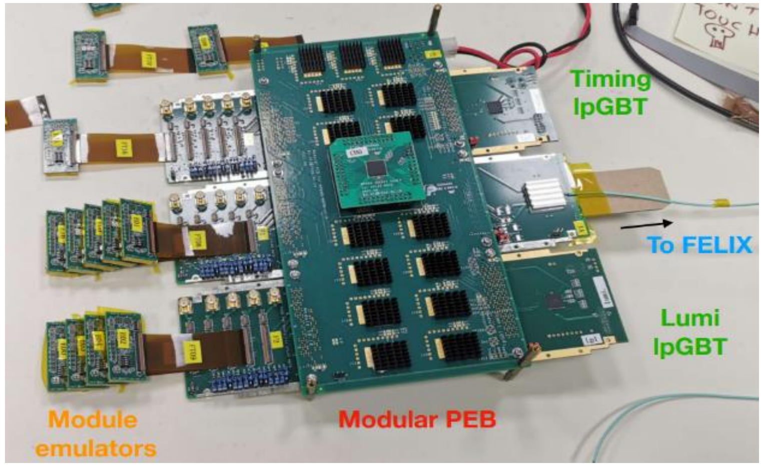
Demonstrator project

The purpose of the demonstrator project is to validate different components of the overall HGTD project



Heater Demonstrator

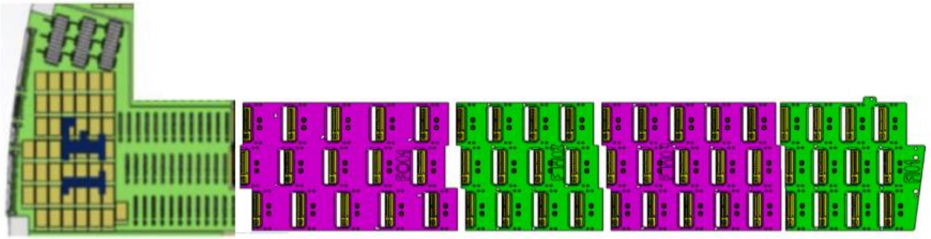
- Verify the CO_2 cooling capabilities and identify the best thermal media between modules and the cooling plate
  - Using silicon heaters to model the thermal properties of modules



DAQ Demonstrator

- Construct a complete DAQ chain to test the communication link between module emulators and a backend server

A full demonstrator under preparation with 55 modules connected to a peripheral electronic board (PEB) prototype



Conclusion

- Timing information will play a crucial role to mitigate the impact of pile-up in the challenging environment of the HL-LHC

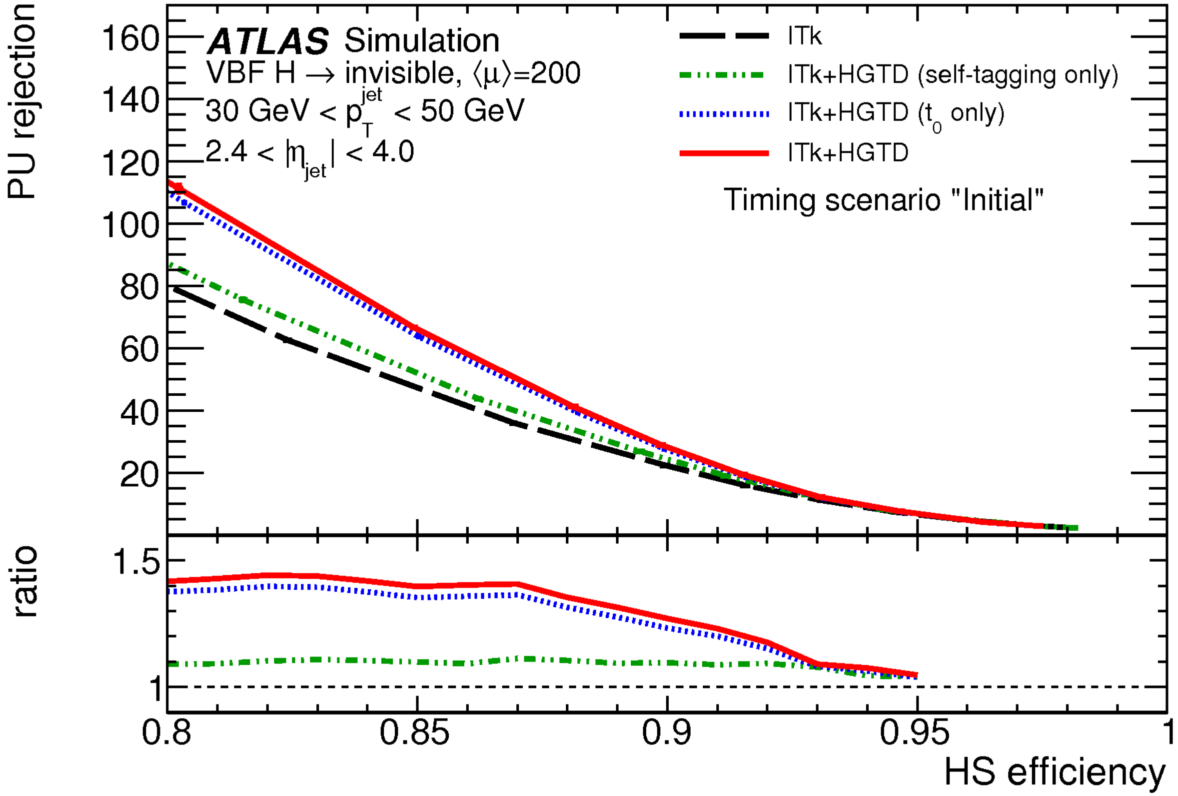
- The High Granularity Timing Detector will provide the timing information using the LGAD technology to improve the ATLAS performance in the forward region

- Carbon-enriched LGADs meet the requirements up to the highest fluence and safely below SEB threshold
  - Collected charge, time resolution, and efficiency

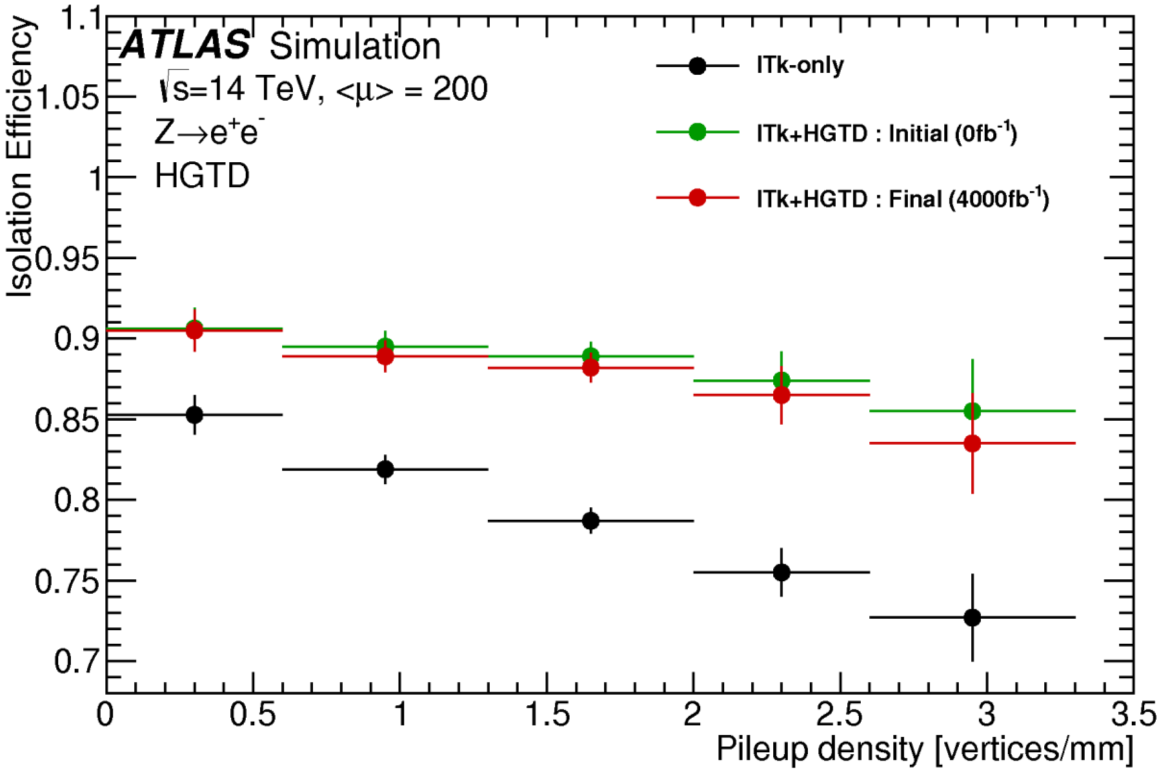
- Readout electronics are still under test (V3 - irradiation resistant)
  - Test beam scheduled in September

Back up

Physics performance

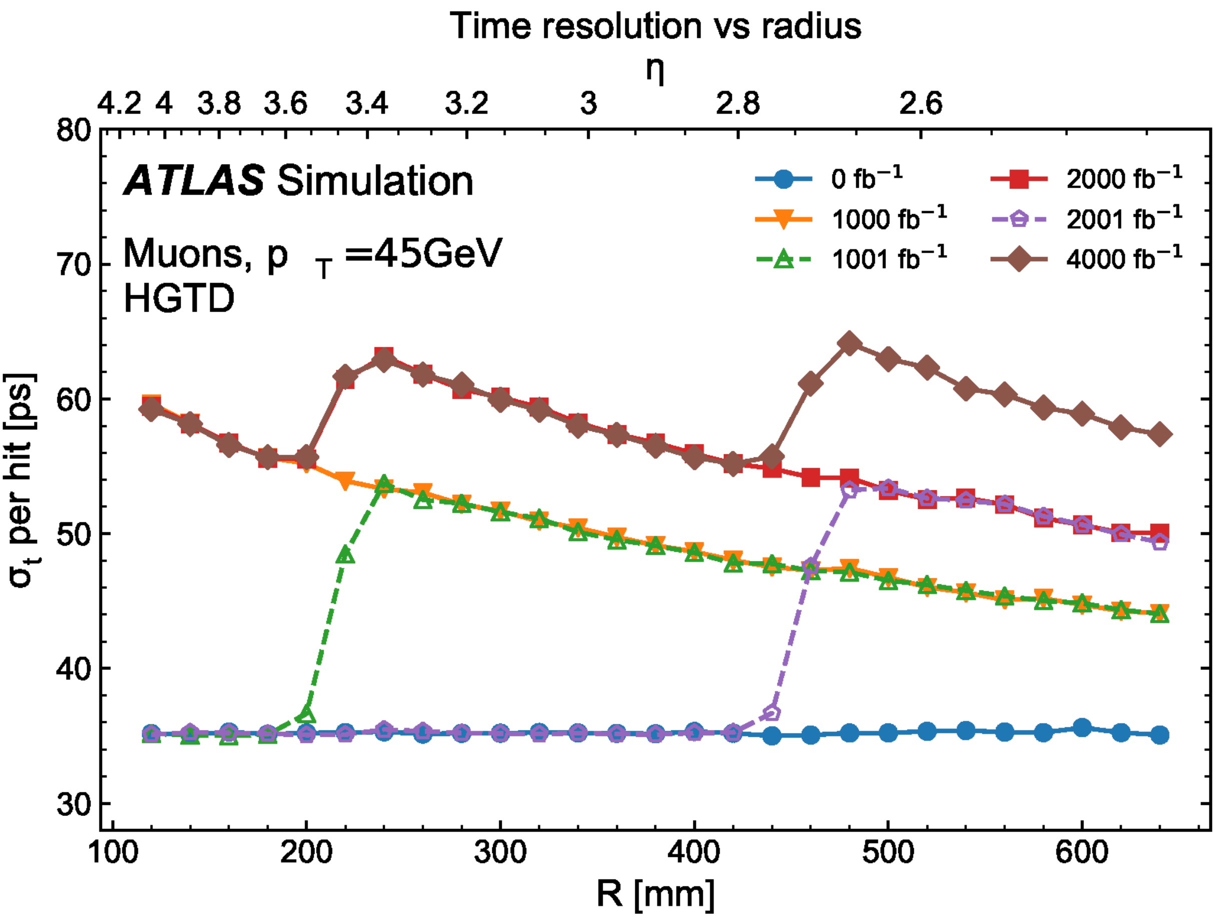


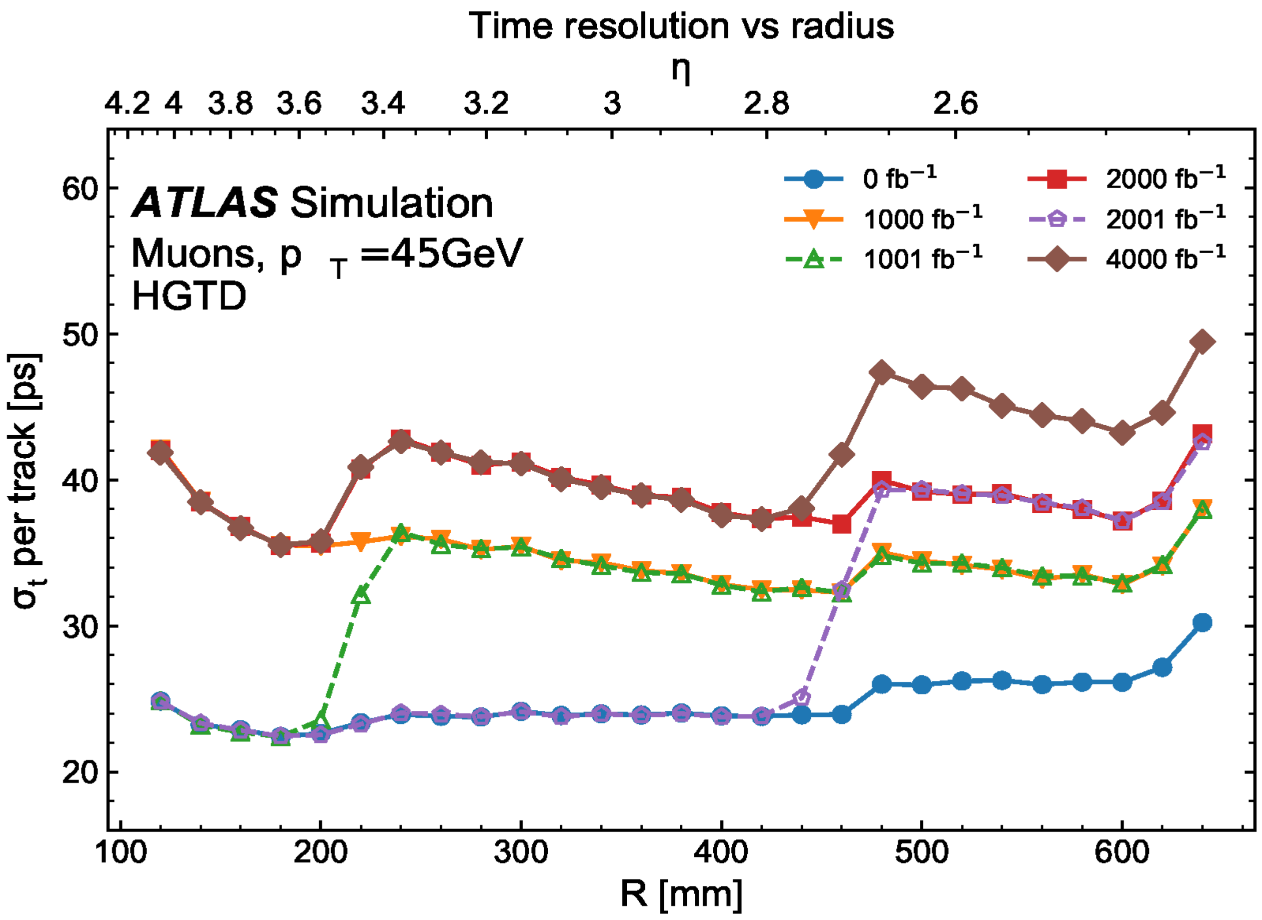
Suppression of pile-up jets



Efficiency of track isolation requirement for forward e^-

Timing resolution per-hit and per-track



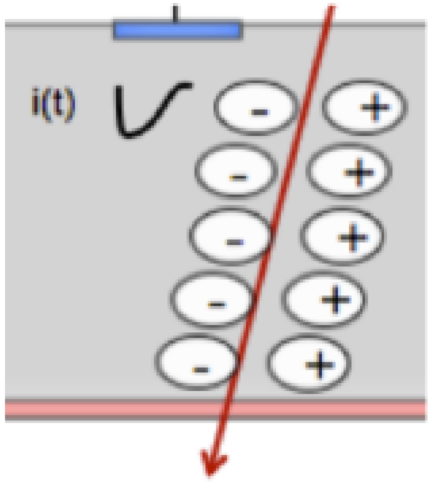


Contributions to the time resolution

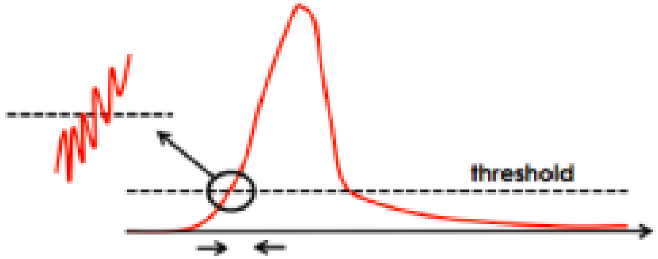
overview of contributions to the time resolution:

$$\sigma^2_{hit} = \sigma^2_{Landau} + \sigma^2_{jitter} + \sigma^2_{time-walk} + \sigma^2_{TDC} + \sigma^2_{clock}$$

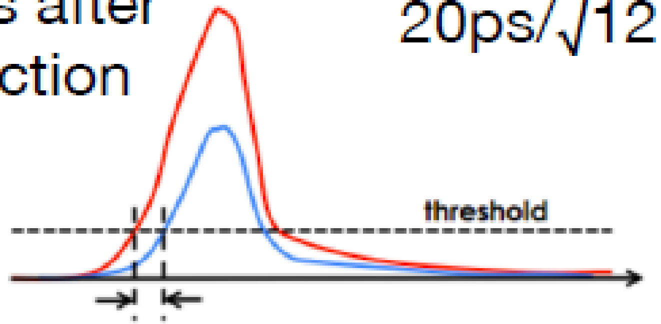
~25 ps
(thin sensor)



<25 ps at
large gain



<10 ps after
correction



bin width,
20ps/√12

from clock
distribution, <10ps