The High-Granularity Timing Detector for ATLAS at HL-LHC

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on behalf of ATLAS HGTD group

XIII International Conference on New Frontiers in Physics

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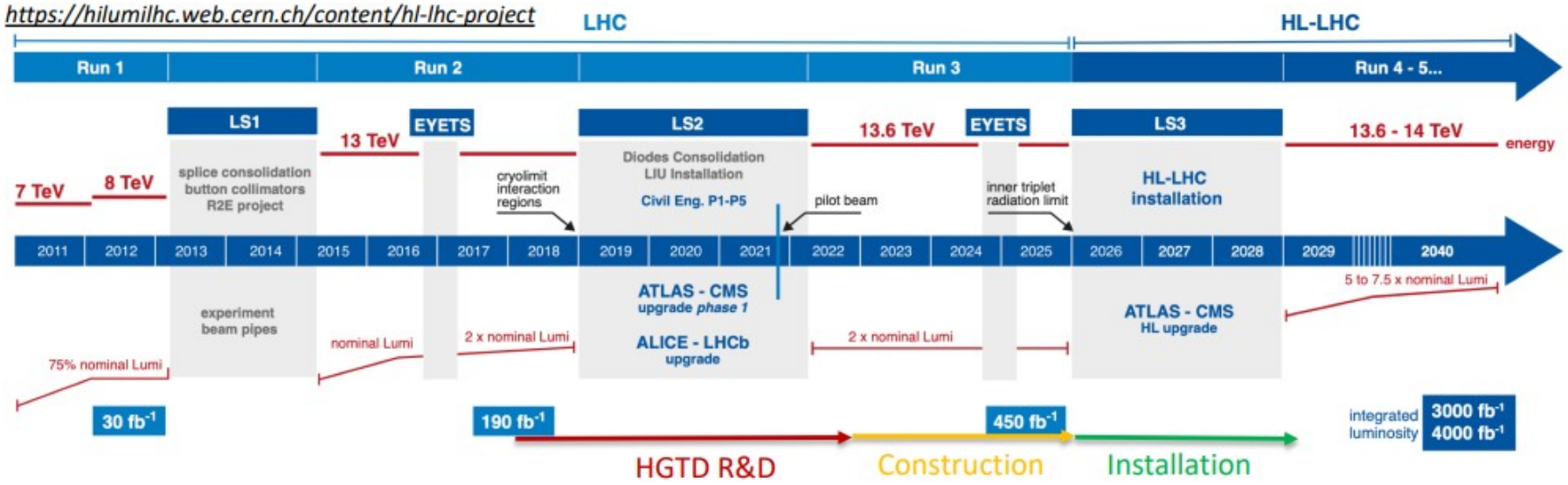
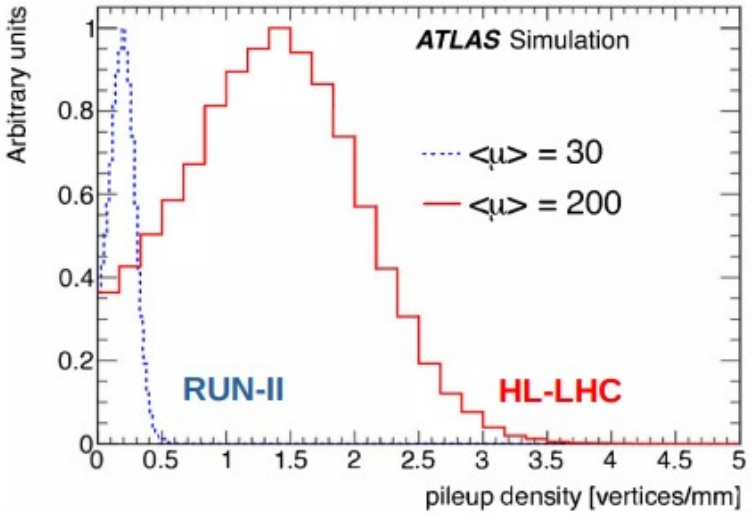
LHC Upgrade

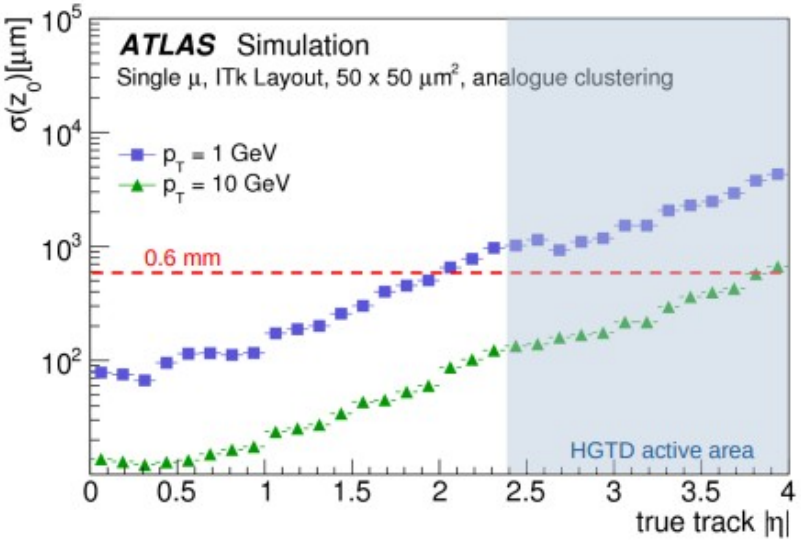


- The new HL-LHC environment:
  - 7.5× Nominal luminosity
  - Integrated luminosity up to 4000 fb^{-1}
  - 140 to 200 collisions per Bunch Crossing (BC)
  - 1.5 vertex/mm on average

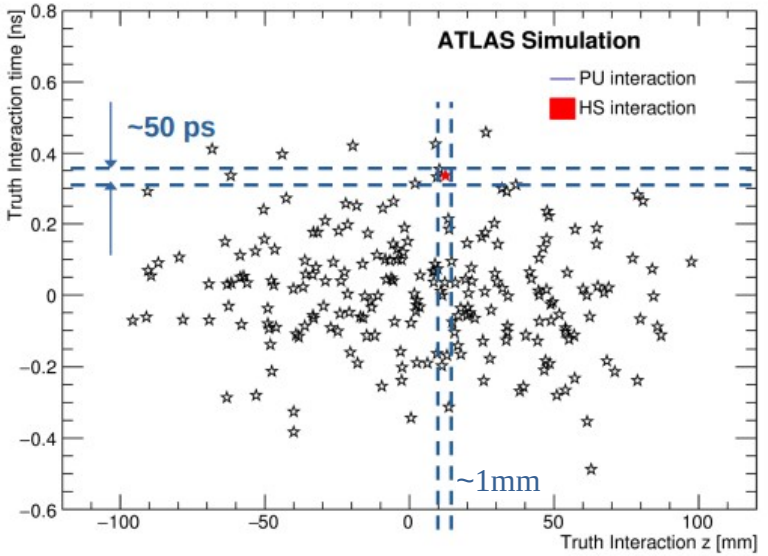


Motivation for HGTD

- The new Inner Tracker (ITk) extends the tracking down to $|\eta| \leq 4$, but it is very challenging to associate tracks at such high rapidity to the primary vertex using only spatial information
- Need z_0 resolution < 0.6 mm

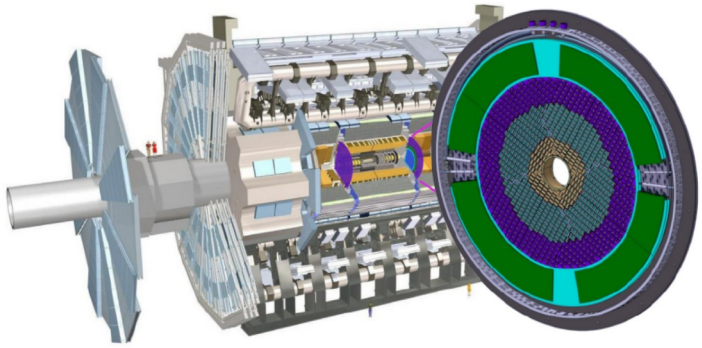


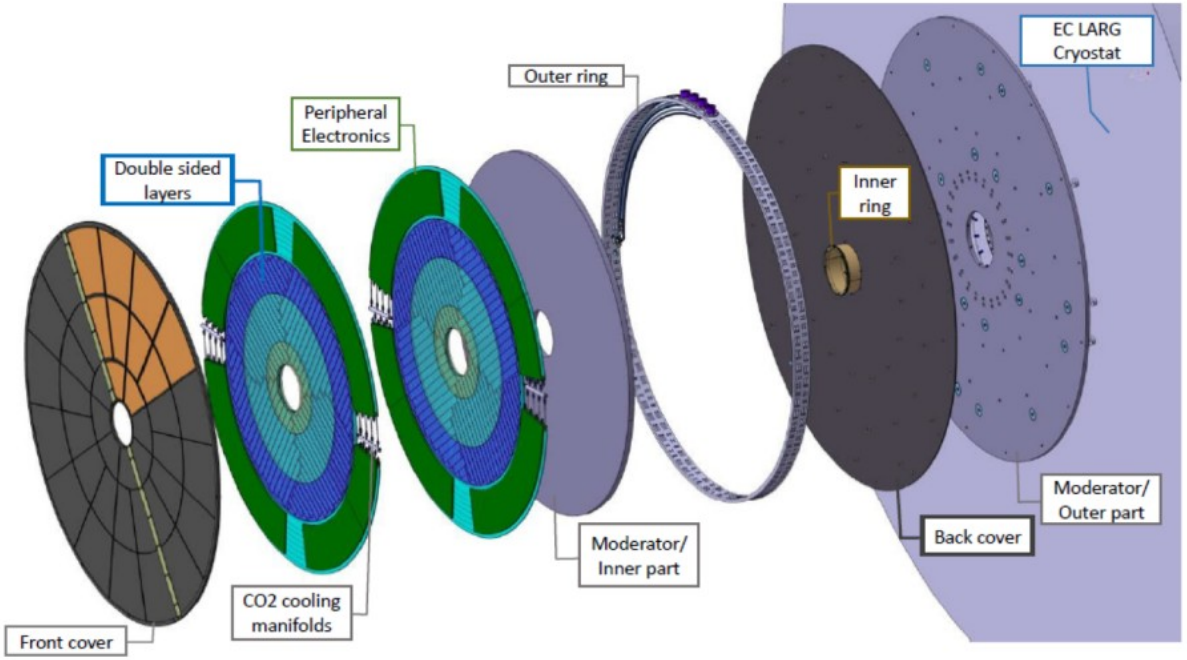
- High Granularity Timing Detector (HGTD)
  - Placed in front of the endcap calorimeter for pile-up mitigation ($2.4 < |\eta| < 4$)
  - Add time information to be combined with ITk position to improve pile-up rejection
  - Provide a 1% luminosity measurement in each BC



Overview of HGTD

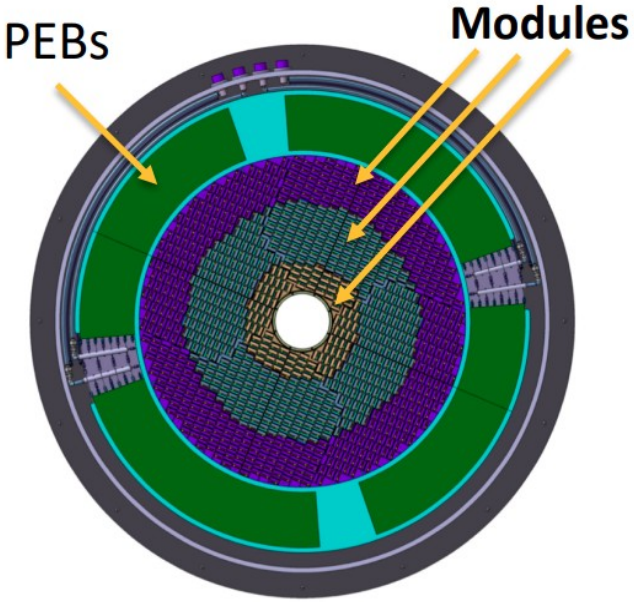
- Two endcaps located between the barrel and the endcap calorimeters
  - Two double-sided disks per endcap
  - Located at ± 3.5 m from the interaction point
  - Active radius 120 mm to 640 mm
  - Total radius 1100 mm

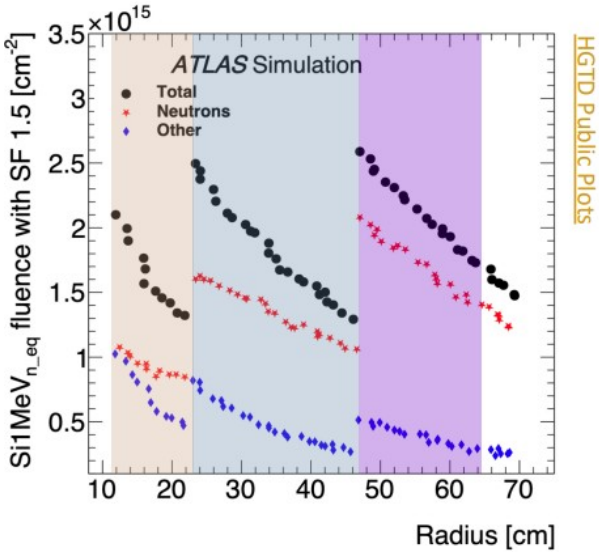


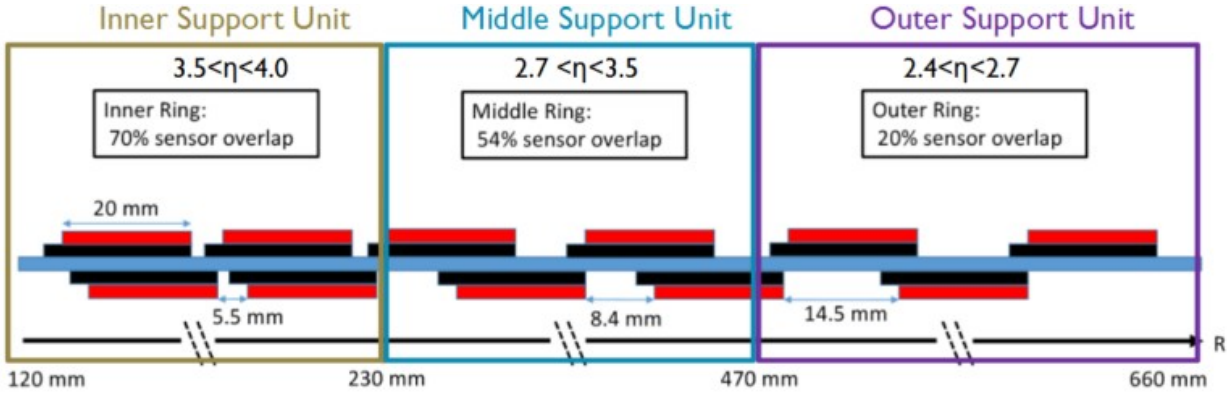


Radiation hardness

- Detector segmented into three independently replaceable rings:





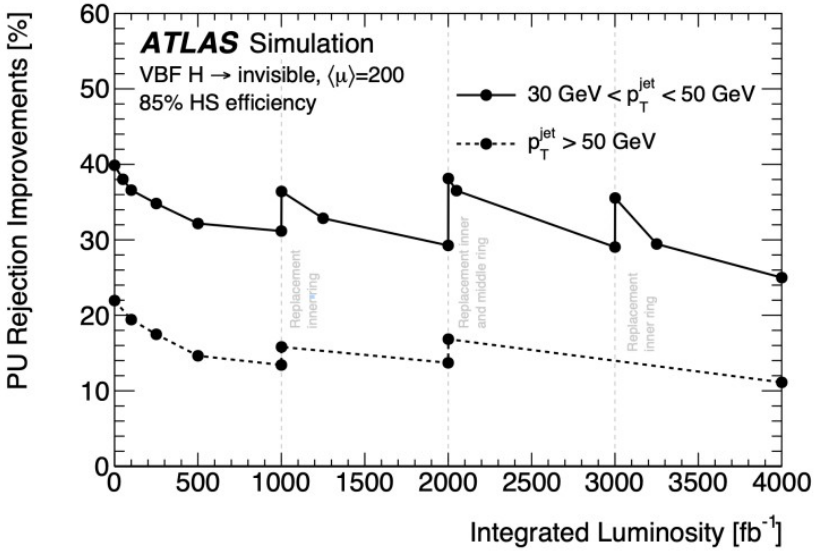


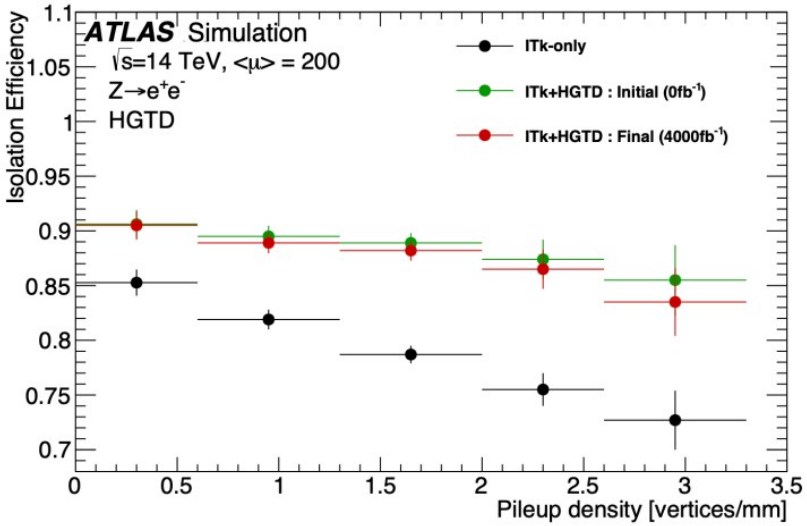
Replaced every 1000 fb^{-1} | Replaced every 2000 fb^{-1} | Can stand the 4000 fb^{-1}

Maximum fluence **2.5 x10¹⁵ n_{eq}/cm²** and **2 MGy** at the end of HL-LHC (after 4000 fb^{-1})

Performance improvement with HGTD

- HGTD time information will allow to recover the performance in the forward region where the impact parameter resolution is lower:
  - Pile-up jet rejection
  - Lepton isolation



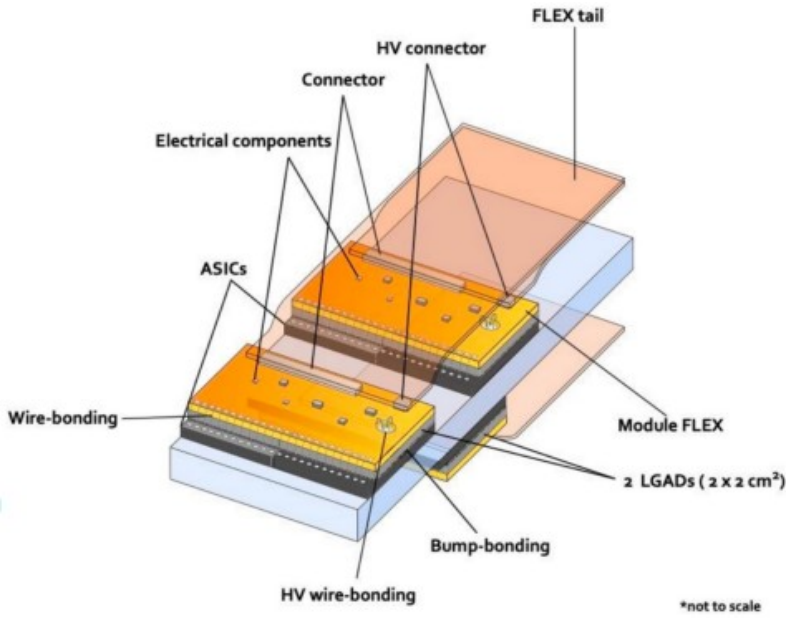


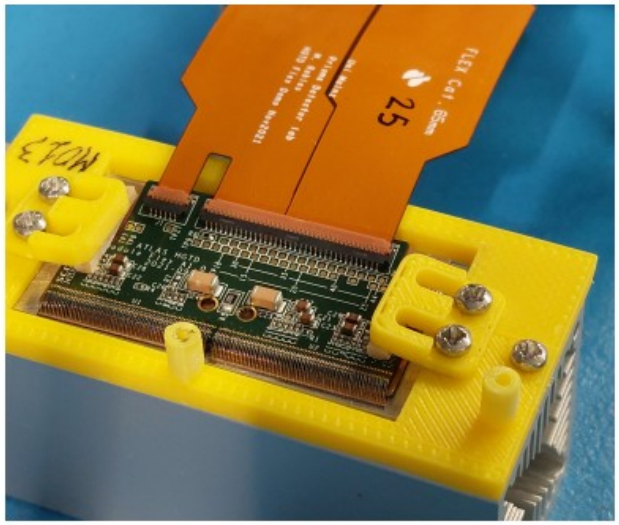
A. Leopold, KTH, ICHEP, 2024

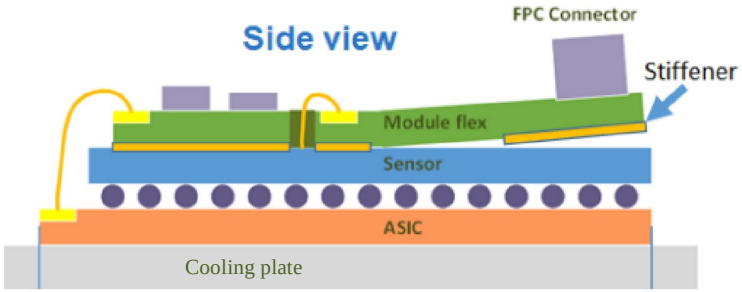
HGTD Modules

HGTD Modules:

- 8032 Modules with 3.6M channels in total
- Two hybrids glued to the flex PCB
  - ALTIROC ASIC
  - LGAD silicon sensor
- 1.3 × 1.3 mm² pixels, 15 × 15 pixels per ASIC
- 2 × 4 cm² modules, 15 × 30 pixels per module
- ASIC contacting the cooling plate and wire bonded to the flex PCB



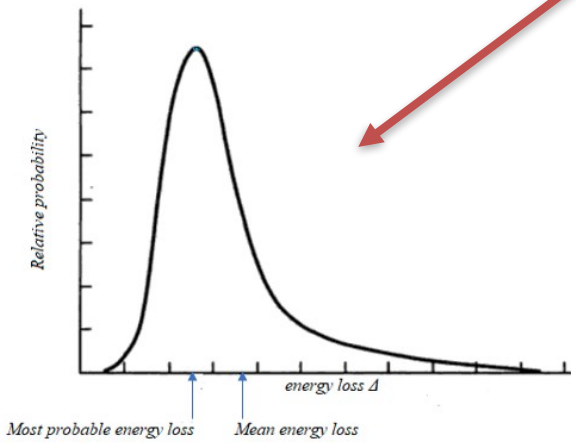




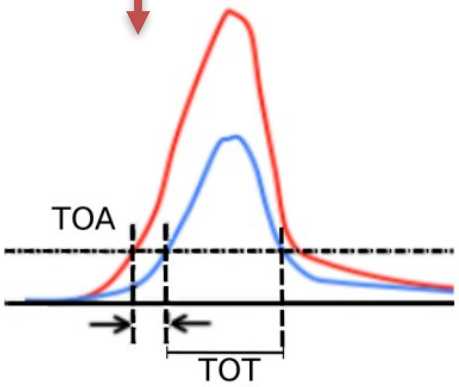
Time resolution

Main contributions to the time resolution on HGTD timing measurement:

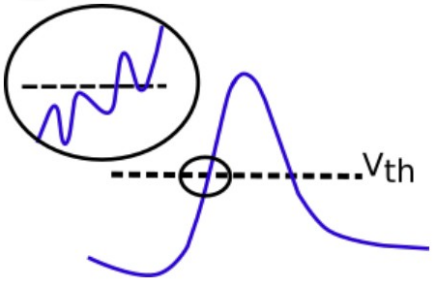
$$\sigma^2_{T_{hit}} = \sigma^2_{Landau} + \sigma^2_{jitter} + \sigma^2_{TW} + \sigma^2_{clock} + \sigma^2_{TDC}$$



Non-uniform energy deposit along the path on silicon by a charged particle



Time Walk affecting the TOA measurement



Sensor signal jitter before the discriminator

S. Sacerdoti, LAL, LLR seminar

- Clock jitter expected <15 ps
- TDC contribution expected to be negligible (<6 ps)

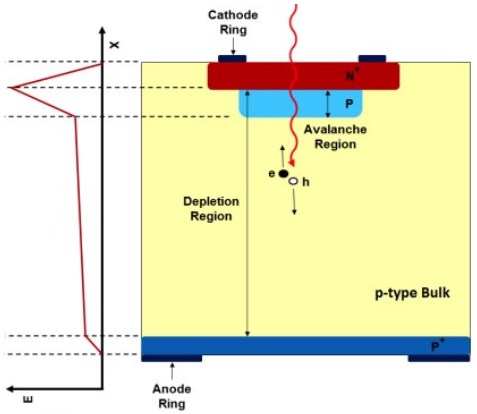
LGAD requirements for HGTD

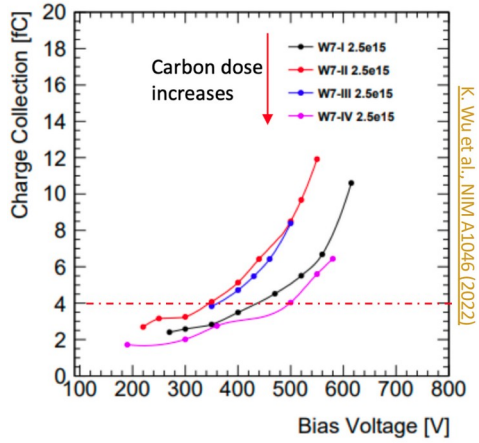
	Start	End	
Maximum Fluence	-	2.5×10^{15}	[n_{eq}/cm^2]
Time Res. / hit	35	70	[ps]
Time Res. / track	30	50	[ps]
Collected Charge	10	4	[fC]
Hit Efficiency	97	95	[%]

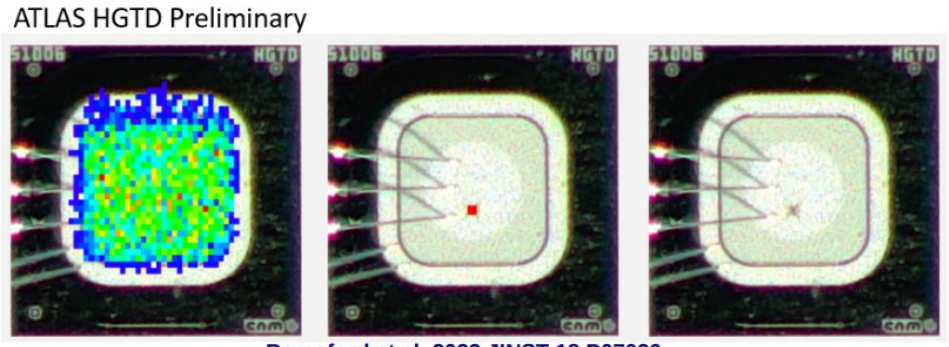
LGAD sensors

Low Gain Avalanche Diodes (LGAD):

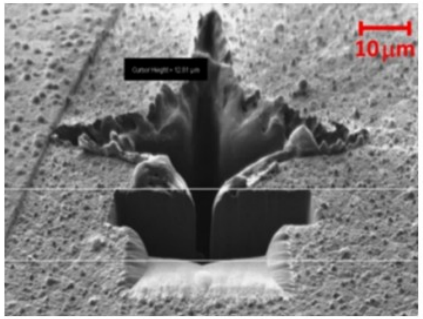
- **N-on-p** silicon sensors with p-type multiplication layer
- **50 µm** thin active substrates, to reduce the landau contribution on the time resolution
- **Gain at operational point ~10**, to reduce noise and keep signal proportionality
- **High Voltage bias limited to 550 V** (E>11 V/µm) to avoid damaging the sensor
- **Carbon-enriched** sensors diminish the effect of gain loss due to irradiation (acceptor removal)







Beresford et al, 2023 JINST 18 P07030



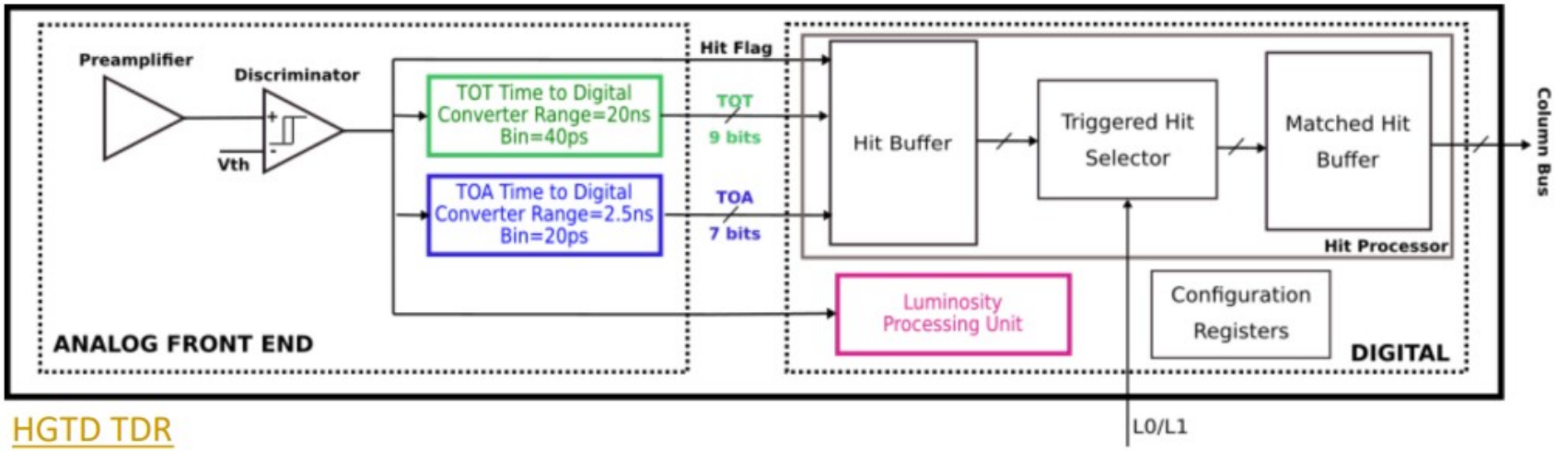
Burn mark on a CNM sensor after proton beam irradiation in Fermilab in 2018 (picture produced by CNM)

ALTIROC

ATLAS LGAD Timing Integrated ReadOut Chip (ALTIROC):

- 130 nm node CMOS technology from TSMC
- 225 channels (**15 × 15**) readout providing Time of Arrival (**ToA**) and Time over Threshold (**ToT**)
- Luminosity measurement per Bunch Crossing
- Has to **withstand 2MGy**
- Minimum discriminator threshold of 2 fC
- Jitter < 25 ps for 10 fC (< 70 ps at 4 fC)

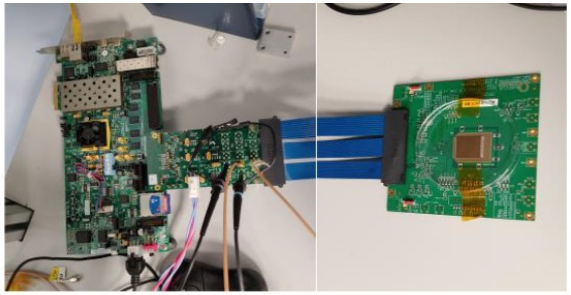
ALTIROC0: 1st prototype
ALTIROC1: 5 x 5 pixel
ALTIROC2: VPA/TZ preamplifiers, 15 x15 pixel
ALTIROC3: Rad hard prototype, TZ only
ALTIROCA: Preproduction ASIC

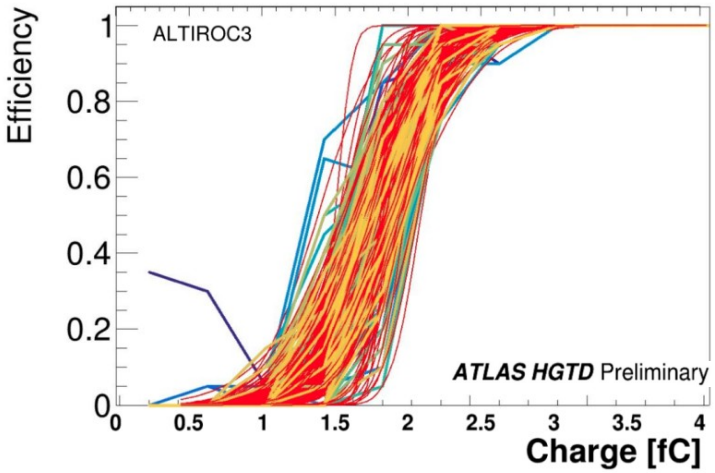


Hybrid performance

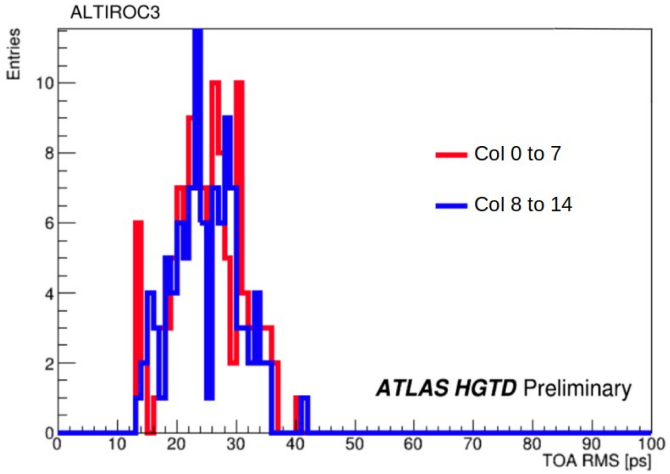
- Testbench measurement performed by AlVin (IFAE) and FADA (IJClab) readout
  - Characterization of ASIC, sensor and module flex
  - Quality Control (QC) on modules
    - IV curves
    - Lower threshold
    - Bump connectivity before/after thermal cycling
    - Jitter

Measurement setup for test PCBs



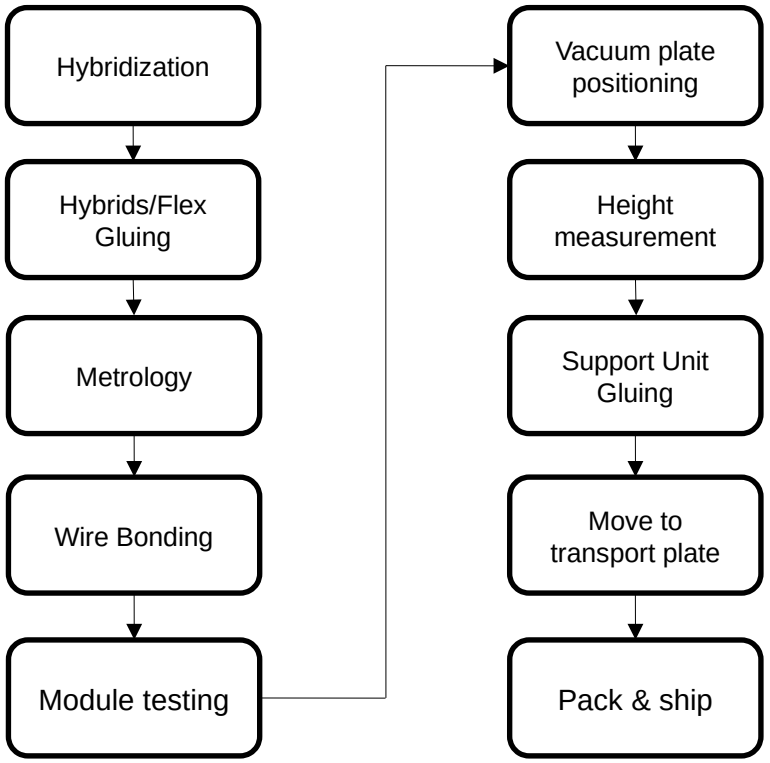


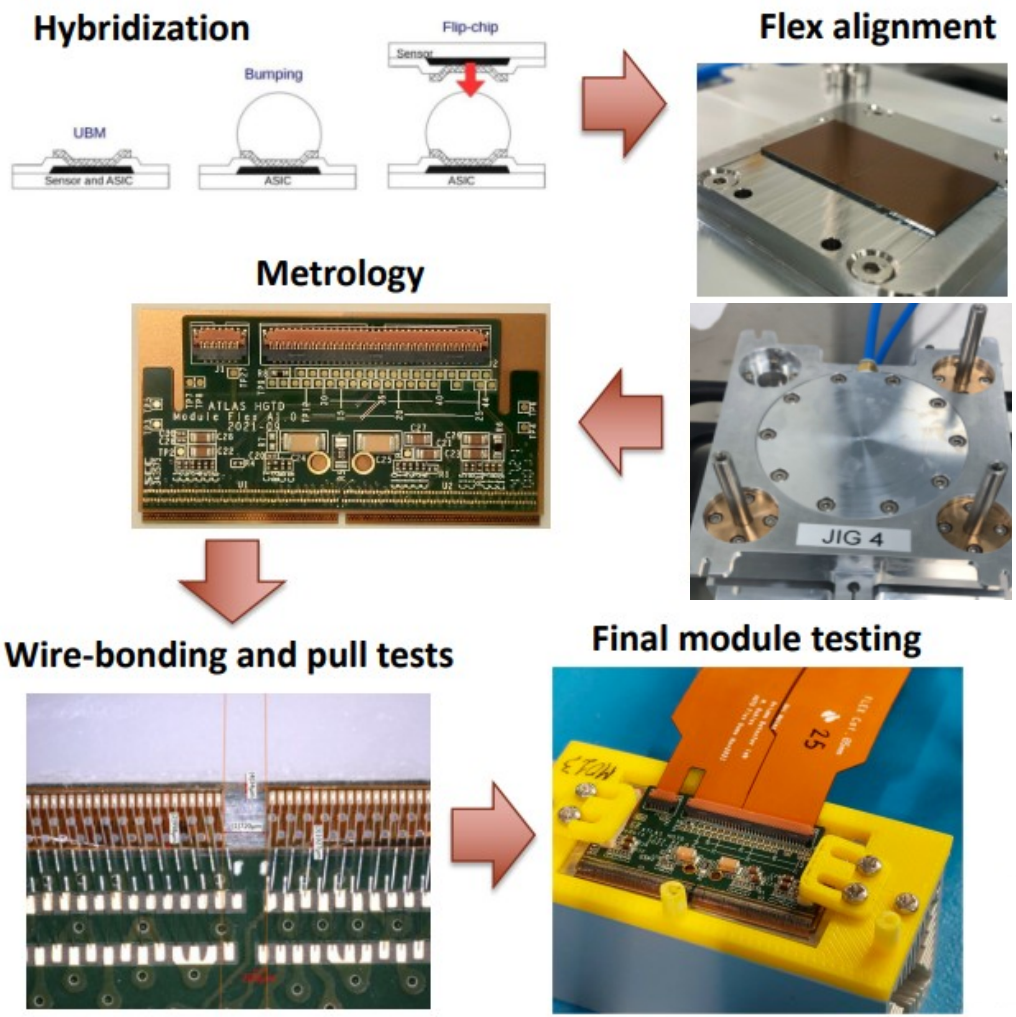
Threshold defined at 50%
efficiency from internal injection



Jitter measurement with 10fC internal injection

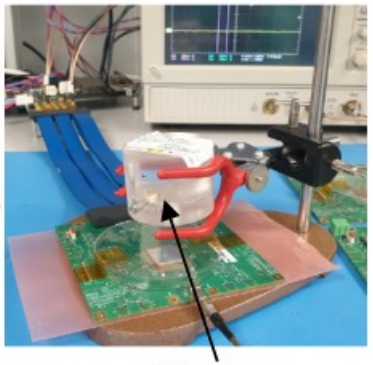
HGTD module assembly



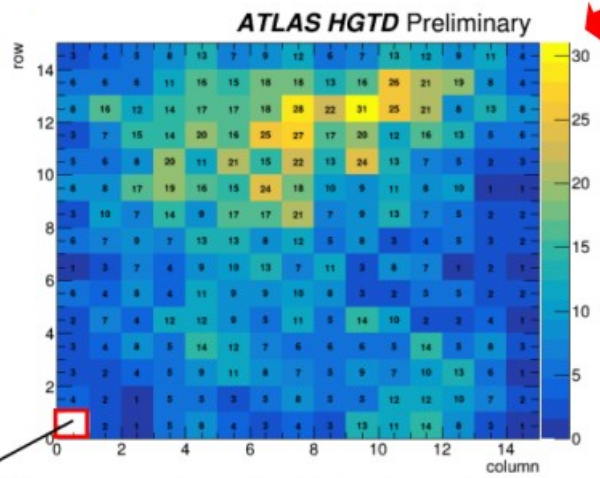


Bump connectivity

- Robust performance at single hybrid and module level
  - Thermal cycling on the climate chamber
    - Temperature range: -45 to 40 ºC
    - Testing for module operation
    - Testing occupancy with ^{90}Sr

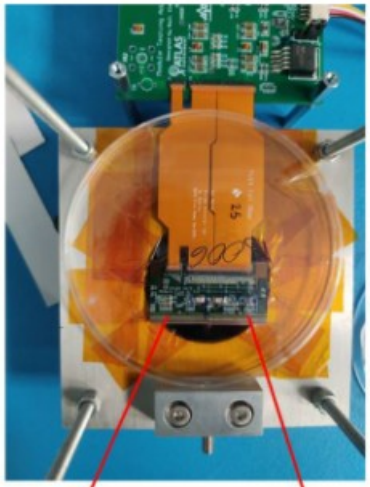


Tests on single hybrid

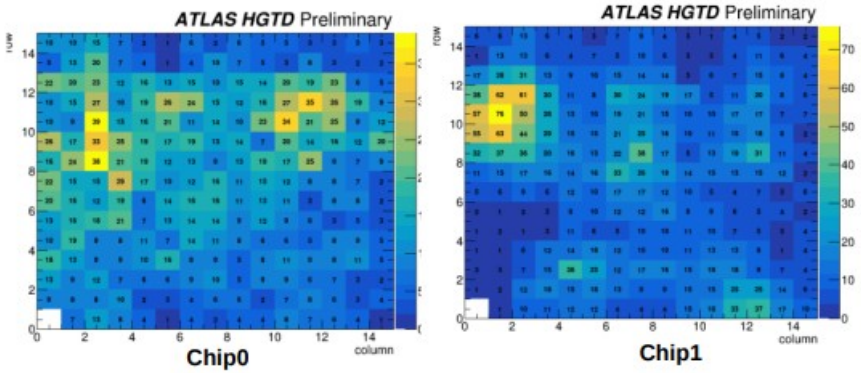


Occupancy map with Sr-90 source. Sensor biased at = HV 90 V.

Threshold = 8 fC



Tests on full HGTD modules

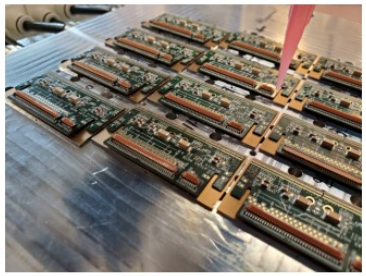


- Sr90 source scans shows 100% bump connectivity

P. Fernández-Martínez, IFAE, EPS-HEP 2023

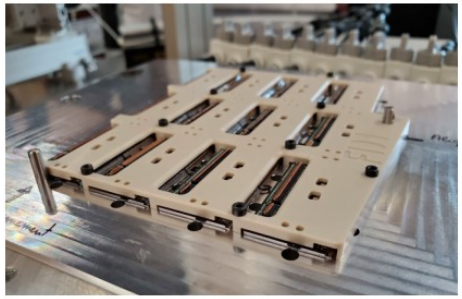
Detector Units, Flex tails and PEB

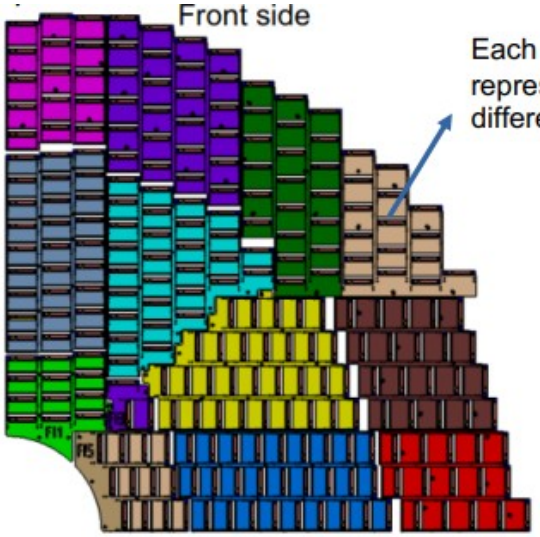
- HGTD disks are comprised of four identical quadrants
  - Each quadrant has different Detector Units (DU)
  - Each module in the detector unit connects through a flex tail to the Peripheral Electronics Board (PEB)



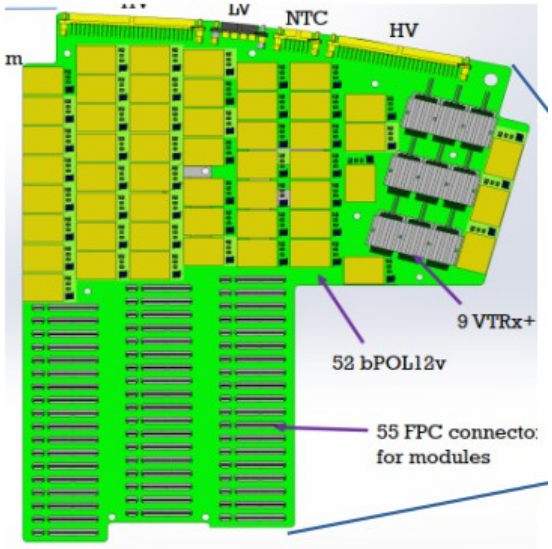
Gluing

Loading



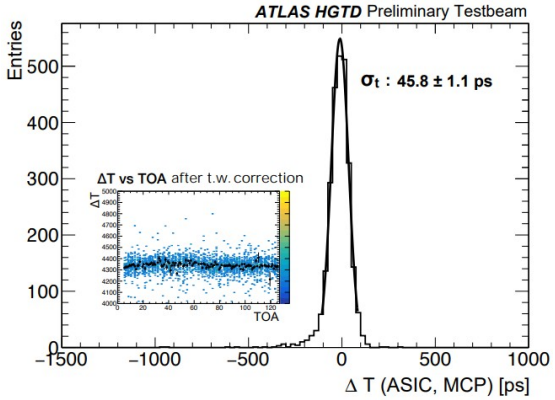


- The PEBs are located after the active radius of the detector
  - Merge and translate copper-based lpGBT data transmission from various ASICs to optic lines interfacing FELIX readout card
  - Provide ASIC power through a Point of Load DC/DC
  - Monitor ASICs power and temperature

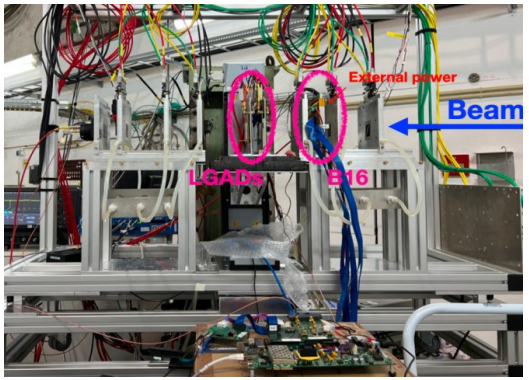


Test beam measurements

- Test beam measurements performed with AlVin on hybrids and sensors at SPS and DESY
- Tracking with MIMOSA telescope and Micro-Channel Plate (MCP) for time reference
- First results of efficiency and time resolution with ALTIROC3 (more on next talk by Salah)

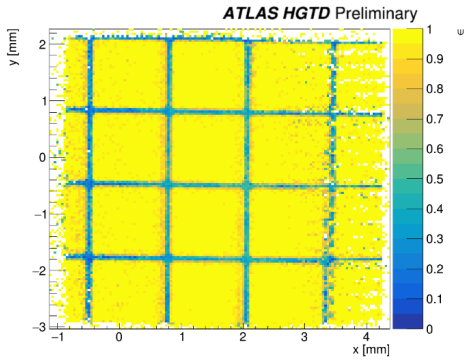


Time resolution on TestPCB

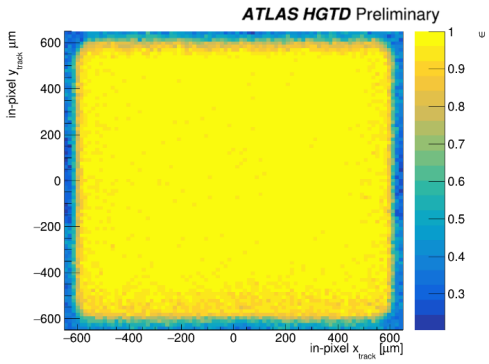


Test beam setup

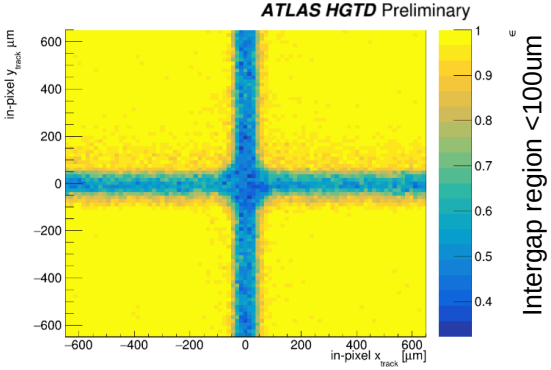
Global efficency



Single pixel efficiency



XY half-pitch shifted single pixel efficiency



Intergap region <100um

Tracking with Corryvreckan of a preproduction sensor with ALTIROC3

X. Yang, CERN, 42nd ICHEP, Prague

Summary

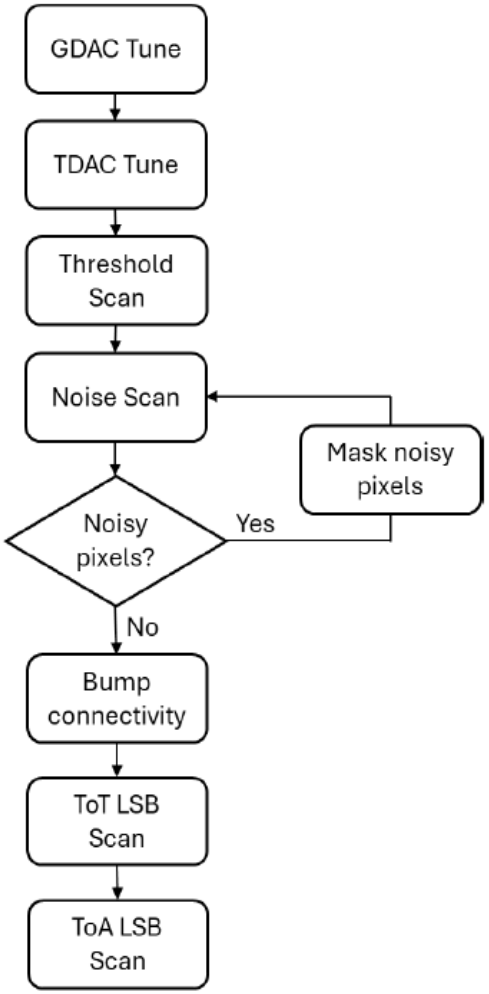
- HGTD aims to **reduce the effects of pile-up**

- LGAD:
  - Time resolution per hit of 35 ps and 70 ps after 2.5×10^{15} n_{eq}/cm^2 irradiation
  - Pre-production started

- Module assembly procedure stablished with ALTIROC3
  - Hybridisation validation ongoing (bump connectivity)
  - Moving to ALTIROCA

- Hybrid measurements:
  - First promising results with ALTIROC3
  - First ALTIROCA and irradiated hybrids are being charaterized at test beam
  - Full module testing coming soon

Backup



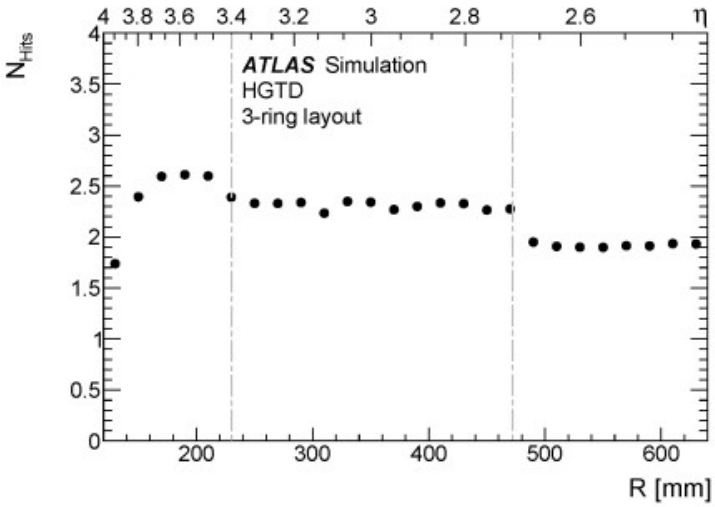
Module testing procedure

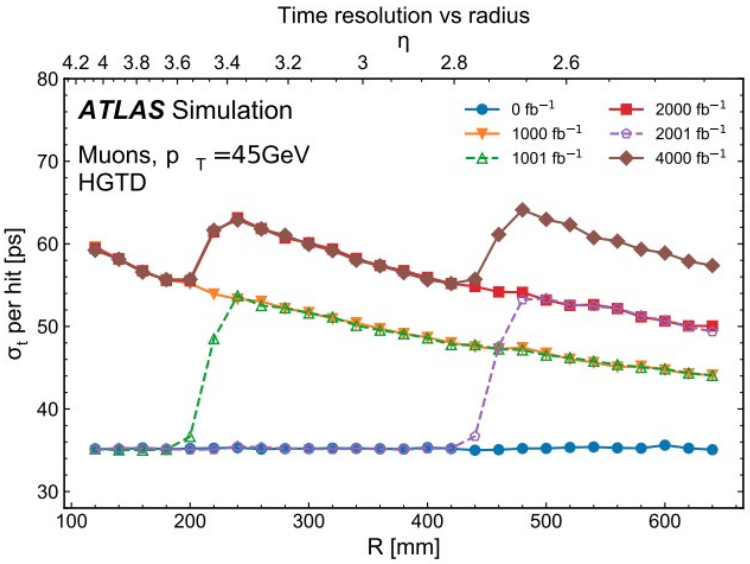
Backup - Time resolution

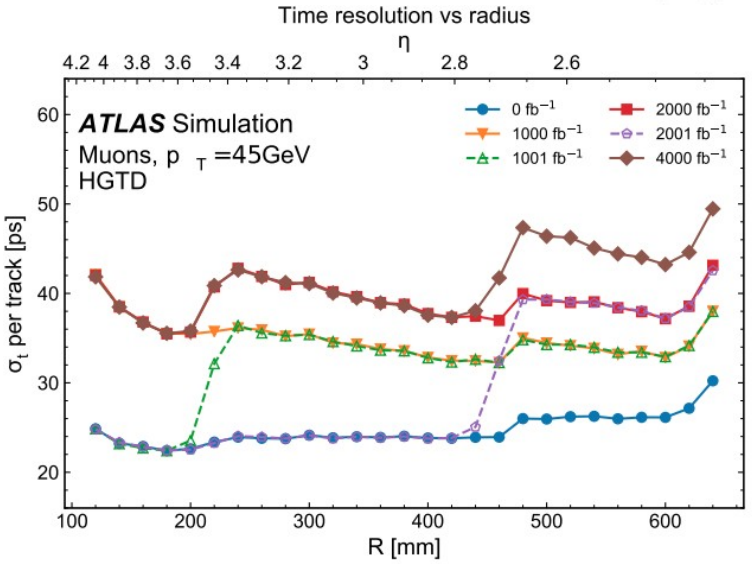
$$\sigma^2_{T_{hit}} = \sigma^2_{Landau} + \sigma^2_{jitter} + \sigma^2_{TW} + \sigma^2_{clock} + \sigma^2_{TDC}$$

- Time resolution per track:

$$\sigma_{T_{track}} = \frac{\sigma_{T_{hit}}}{\sqrt{N_{hits}}}$$



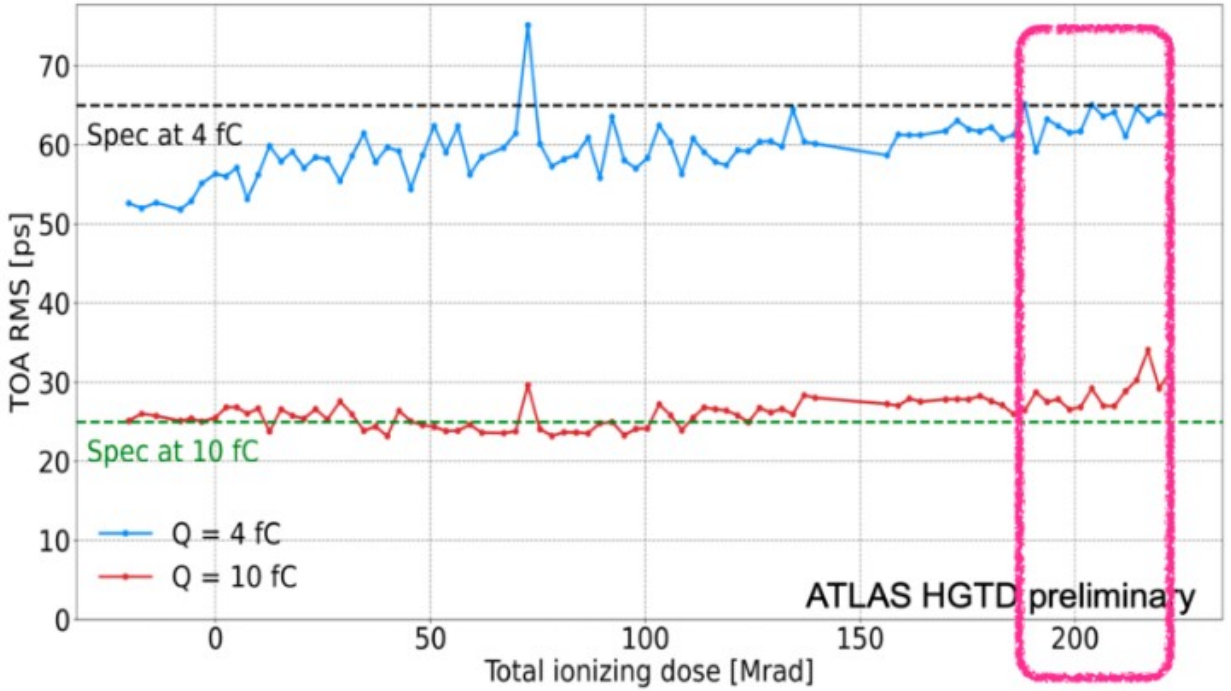




Backup – ALTIROC2 irradiation studies

- Study of the effects of irradiation
  - Up to TID 220 Mrad
  - 3 Mrad/h
  - Temperature 22 ºC

- Jitter stays stable with the increasing Total Ionising Dose (TID):



S. Terzo, IFAE, VERTEX 2023