# A High-Granularity Timing Detector for the Phase-II upgrade of the ATLAS Calorimeter system:

## detector concept, description and R&D and beam test results

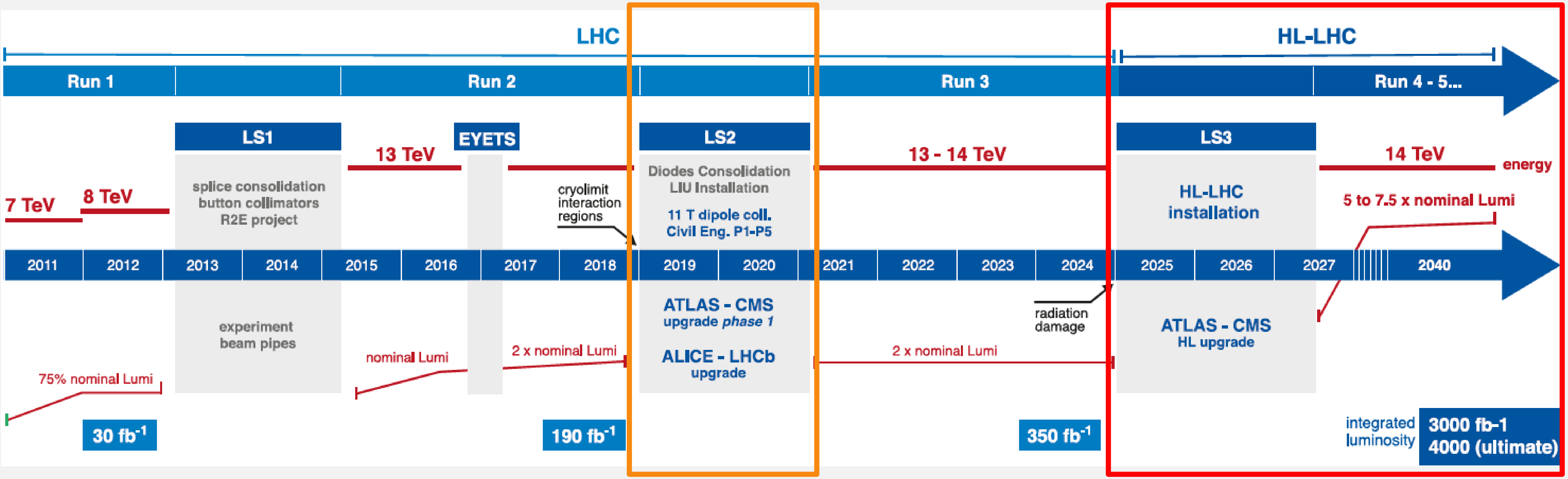
Lucía Castillo García on behalf of the ATLAS HGTD group - 26th February 2020

# Overview

- Motivation: HL-LHC
- High Granularity Timing Detector (HGTD)
  - Overview and requirements
  - Layout
  - Hybrid module
    - Low Gain Avalanche Detectors (LGADs)
    - ATLAS LGAD Timing ReadOut Chip (ALTIROC)
  - Radiation hardness
- R&D program
  - Laboratory measurements
  - Test beam campaigns
- Summary and outlook

# LHC Timeline

Currently we are in Long Shutdown 2 (LS2)

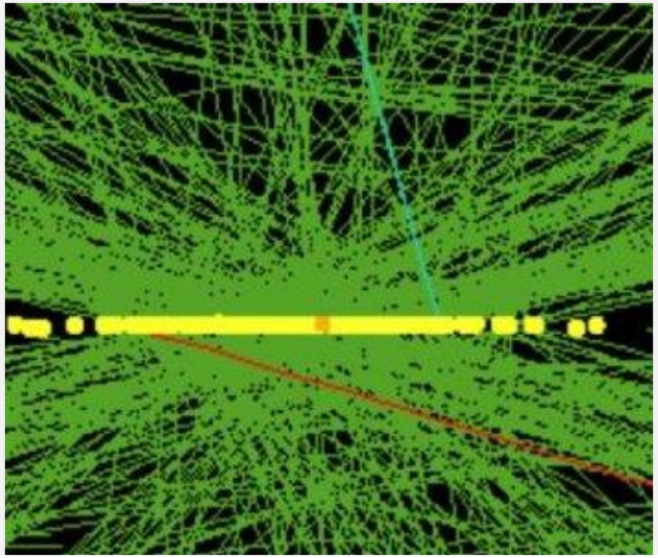


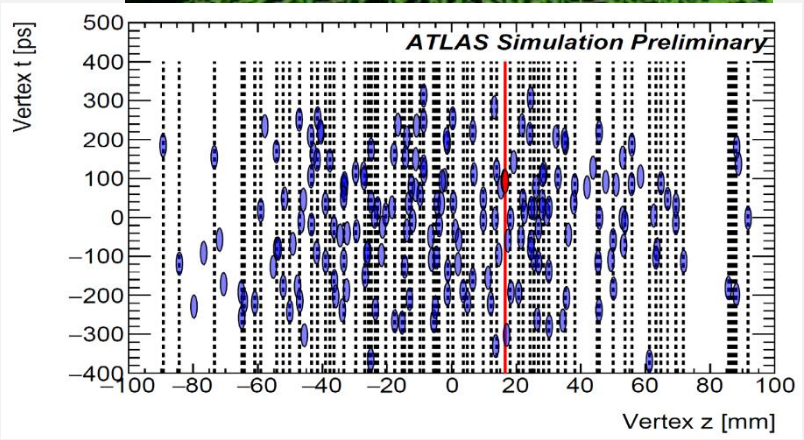

- In LS2, experiments will be upgraded for Run 3 that will start during 2021
- After Run 3, LS3 for a new experiment upgrade phase
- HL-LHC will start running in ~2027 with 5-7.5 times the nominal luminosity

High Luminosity phase will result in much more interactions per bunch crossing

# Why timing is needed in HL-LHC?

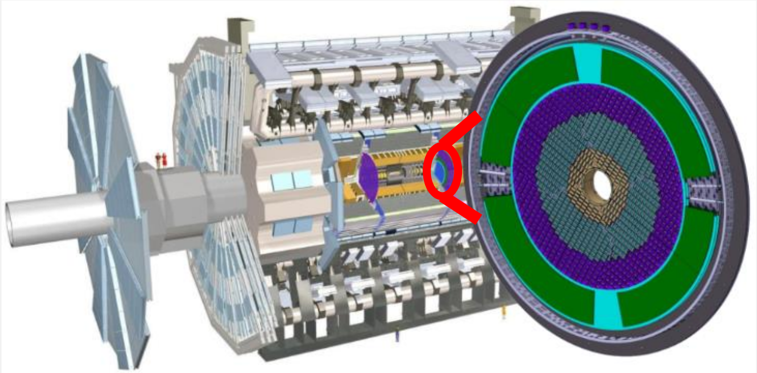
- **High-Luminosity phase of LHC (HL-LHC)**
  - Instantaneous luminosities up to L $\simeq 7.5\times10^{34}$ cm$^{-2}$ s$^{-1}$ (×5 current $L_{inst}$)
  - Pile-up challenge
    - $<\mu>$ = 200 interactions per bunch crossing → 1.8 vertices/mm on average
    - efficiently reconstruct charged particles
    - correct primary vertex association
  - Vertex reconstruction and physics objects performance in ATLAS experiment will be significantly degraded in the forward region where compared to the central region
    - Liquid Argon based electromagnetic calorimeter has coarser granularity
    - Inner tracker has poorer momentum resolution
- **High Granularity Timing Detector (HGTD)**
  - Proposed in front of the Liquid Argon end-cap calorimeters for pile-up mitigation
  - Improve performance in the forward region by combining
    - HGTD high-precision time measurement
    - ITk (new ATLAS tracker) position information (vertices longitudinal impact parameter)





# HGTD overview and requirements

- HGTD designed for operation with $<\mu>$ = 200 and 4000 fb$^{-1}$
- Located in the gap region between the barrel and the end-cap calorimeters
- Silicon-based timing detector technology chosen due to the space limitations
- Two instrumented double-sided layers mounted in two cooling/support disks per end-cap

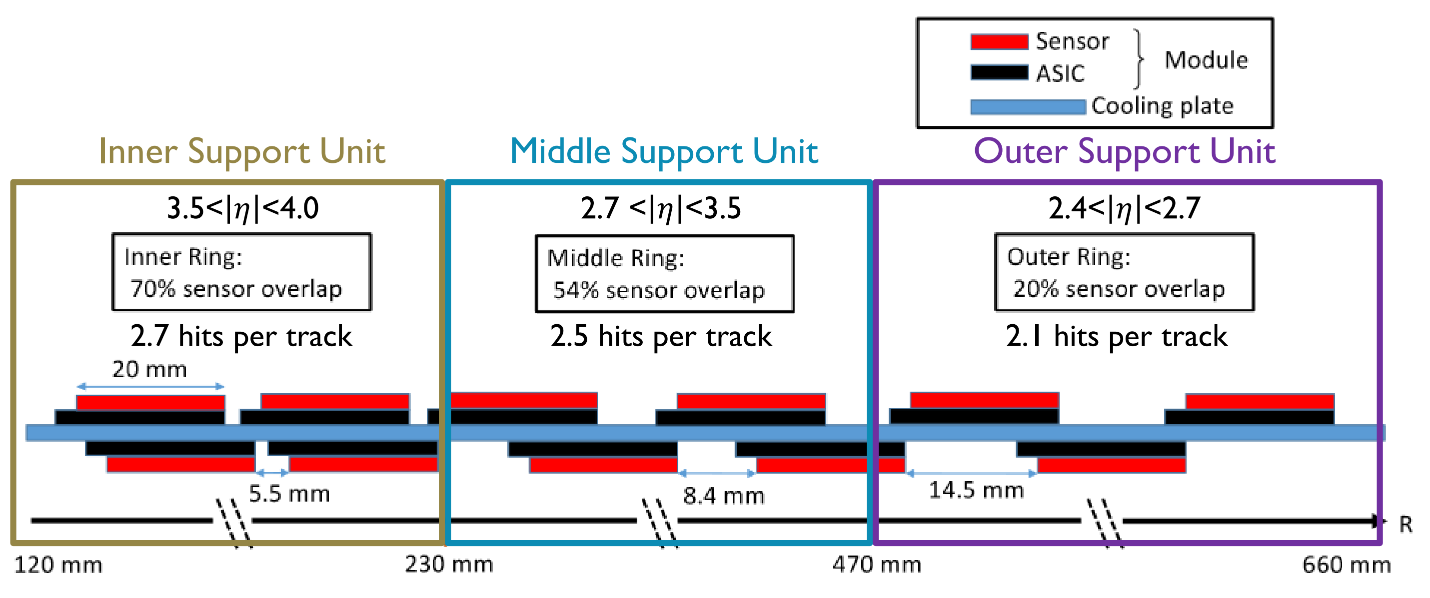


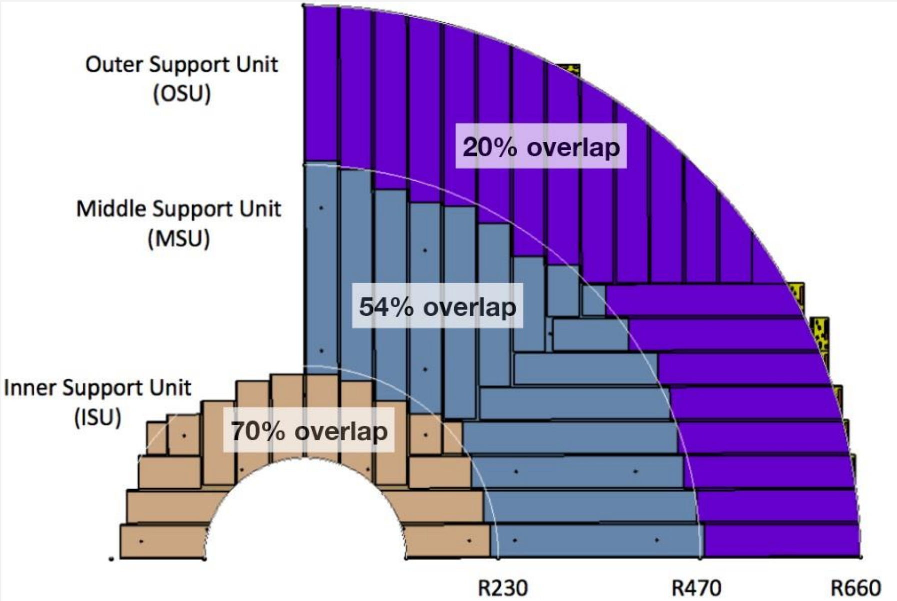
| | |
|---|---|
| Pseudo-rapidity coverage | $2.4 < \|\eta\| < 4.0$ |
| Thickness in $z$ | 75 mm (+50 mm moderator) |
| Position of active layers in $z$ | $z = \pm 3.5$ m |
| Weight per end-cap | 350 kg |
| Radial extension: | |
| Total | 110 mm $< r <$ 1000 mm |
| Active area | 120 mm $< r <$ 640 mm |
| Pad size | 1.3 mm $\times$ 1.3 mm |
| Active sensor thickness | 50 µm |
| Number of channels | 3.6 M |
| Active area | 6.4 m$^2$ |
| Module size | 30 x 15 pads (4 cm $\times$ 2 cm) |
| Modules | 8032 |
| Collected charge per hit | $>$ 4.0 fC |
| Average time resolution per hit (start and end of operational lifetime) $2.4 < \|\eta\| < 4.0$ | $\approx$ 35 ps (start) $\approx$ 70 ps (end) |
| Average time resolution per track (start and end of operational lifetime) | $\approx$ 30 ps (start) $\approx$ 50 ps (end) |

- Sensors (LGADs)
  - Configurable in arrays
  - Provide the required timing resolution in harsh radiation environments
  - Pad size of 1.3×1.3 mm$^2$ ensures
    - Occupancy <10% at lowest radius (120 mm)
    - Small dead areas between pads
    - Low sensor capacitance
  - Operated at -30 °C to mitigate impact of irradiation
- Custom ASIC (ALTIROC)
  - To meet time resolution and radiation hardness requirements
  - Provide functionality to count the number of hits registered in the sensor to allow bunch-by-bunch luminosity measurement

# HGTD layout

- Three rings layout optimised for timing performance and cost
- Coverage
  - Module overlap between layer sides optimised for uniformity
  - Average number of hits per track for the active regions
  - Disk rotation in opposite direction (15-20) to avoid gaps and maximize the hit efficiency
- Support structure
  - Each cooling/support disk is physically separated in two half circular disks
  - Support unit made of carbon fibre ensures exact module position and alignment of x and y readout row



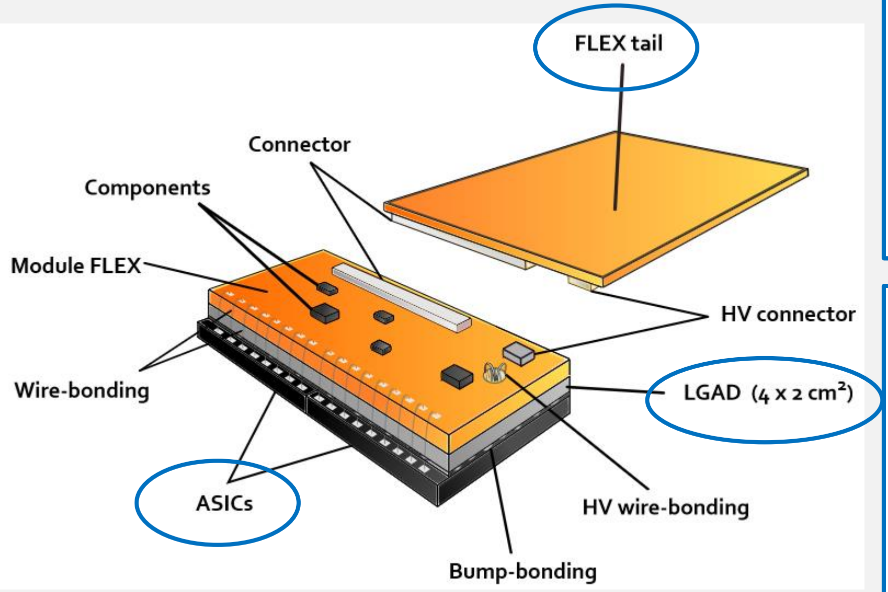



# HGTD hybrid module

- Low Gain Avalanche Detectors (LGADs) read out by dedicated front-end electronics ASICs (ALTIROC)
  - Connected through flip-chip bump bonding process (hybridization)
  - Total amount of bare modules: 8032
  - Layout defined by maximising the coverage and minimising the effect of non-instrumented regions

- **Flexible printed circuit board**
  - Made of two pieces
  - Bare module glued to small flex
  - Routing all connections between ASIC and peripheral on-detector electronics
  - Signal lines of ASIC wire bonded on it
  - Bias voltage of sensor provided to the back-side through a hole
  - 2 layer design with 220 µm thickness

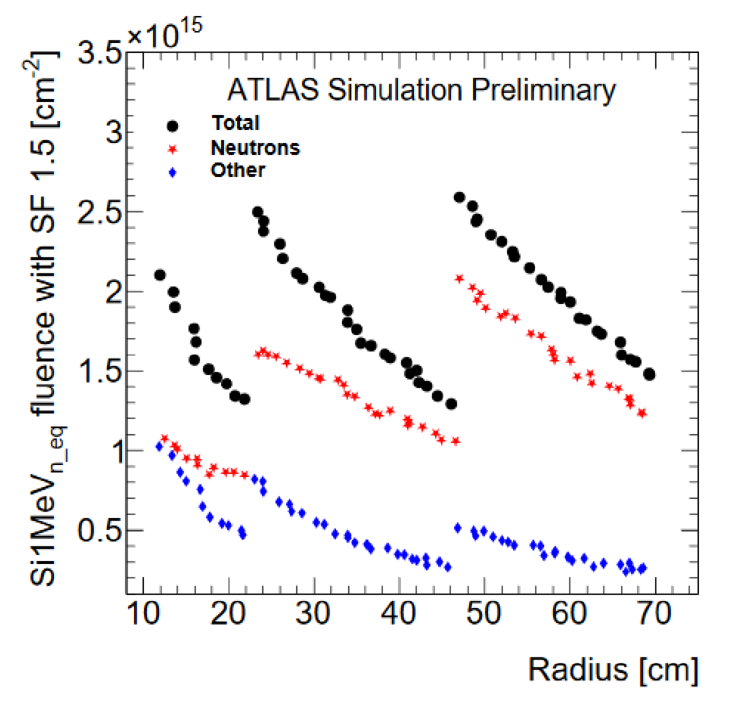
- **ALTIROC ASIC**
  - Minimize noise and power consumption
  - Provide **T**ime **O**f **A**rrival (TOA) and **T**ime **O**ver **T**hreshold (TOT) measurements
  - Target time resolution <25 ps
  - Developed in various phases
    - ALTIROC0: single-pixel analog readout (pre-amp + discriminator)
    - ALTIROC1: full single-pixel readout (analog + digital) in 5×5 arrays
    - ALTIROC2: final 15×15 pads version total size of 20×22 $mm^2$
  - Discriminator threshold of about 2 fC




- **LGAD**
  - n-p silicon planar detector + multiplication layer to amplify the signal
  - High E field, moderate internal gain (10-50), typical rise time 0.5 ns
  - Excellent time resolution <30 ps before irradiation
  - Pad size of 1.3×1.3 $mm^2$
  - 15×30 pads, for a total area of 4×2 $cm^2$

# Radiation hardness

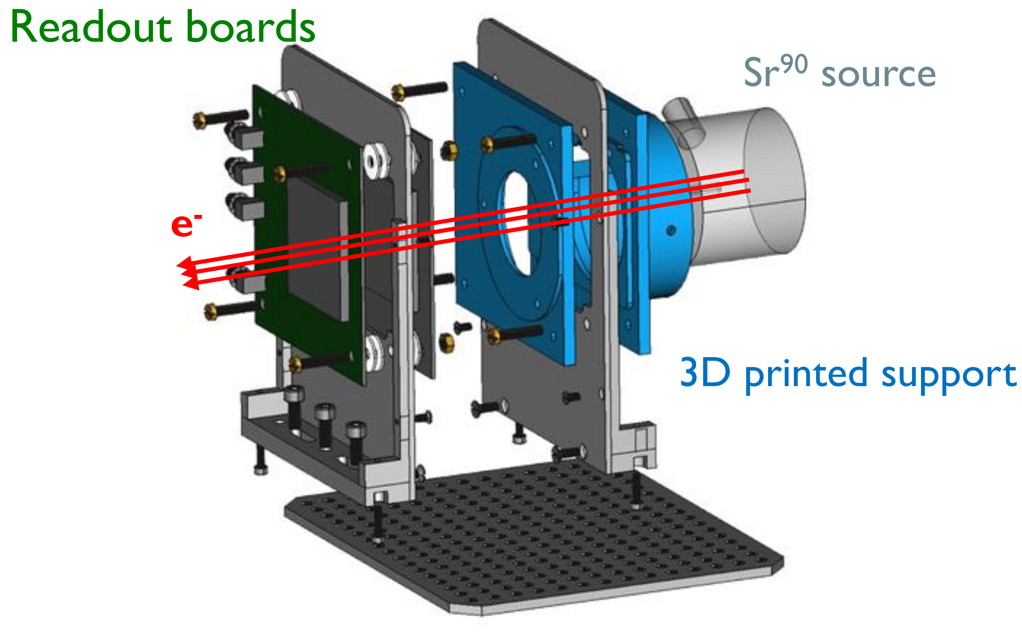
- It is crucial that the detector can withstand the lifetime of the HL-LHC running
- Maximum $n_{eq}$ fluences **$2.5\times10^{15}$ $n_{eq}/cm^2$** and Total Ionising Dose (TID) **2 MGy** at the end of HL-LHC (4000 $fb^{-1}$)
  - Replacement of sensors and electronics (~52%)
    - Innermost ring → 3 times (after each 1000 $fb^{-1}$)
    - Middle ring → once (at half lifetime 2000 $fb^{-1}$)
  - Account for uncertainties in the simulation and low dose rate effects on the electronics
    - a safety factor of 1.5 for the sensors → more sensitive to the particle fluence
    - a safety factor of 2.25 for the electronics → more sensitive to the TID
- Expected radiation levels in HGTD
  - Using Fluka simulations
  - Inner ring → similar contribution from neutrons and charged particles
  - Middle and outer rings → dominant effect comes from neutrons



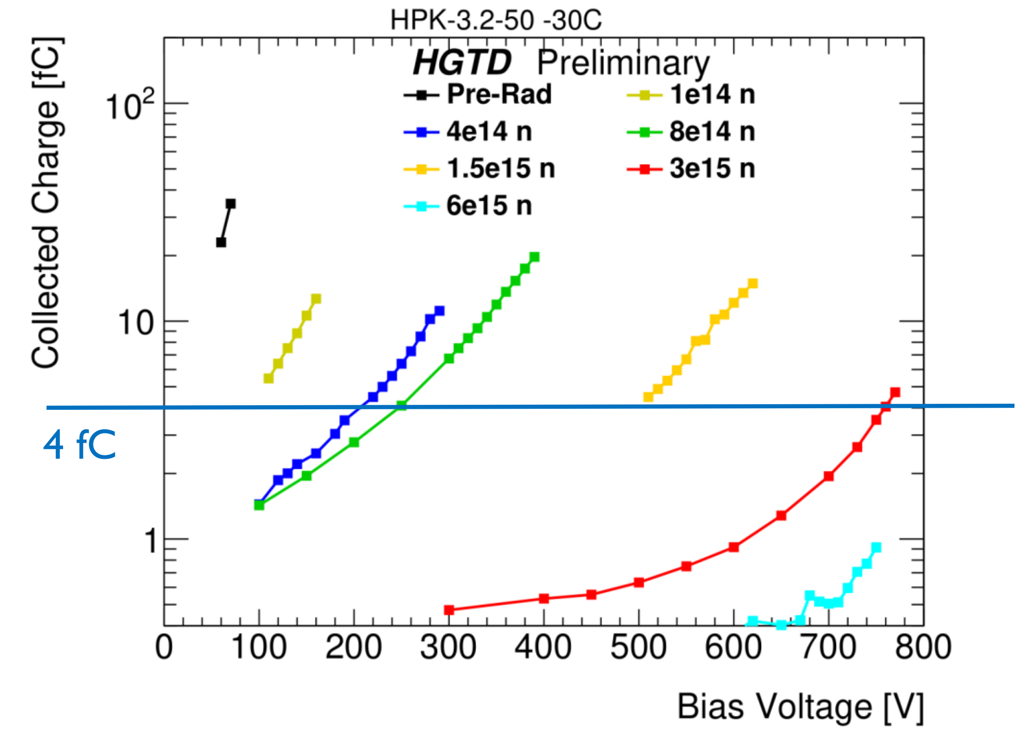

- Radial transition between the three rings to be tuned for the final detector layout with updated FLUKA simulations

# Laboratory measurements

- Setup
  - Use $Sr^{90}$ source and commercial readout
  - Temperature control with climate chamber
  - Avoid condensation by providing dry air

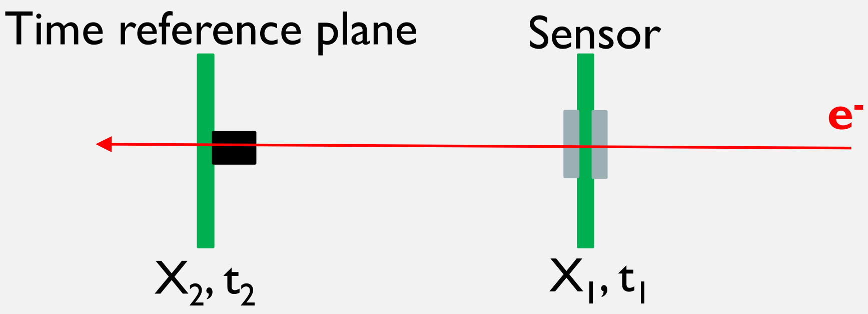


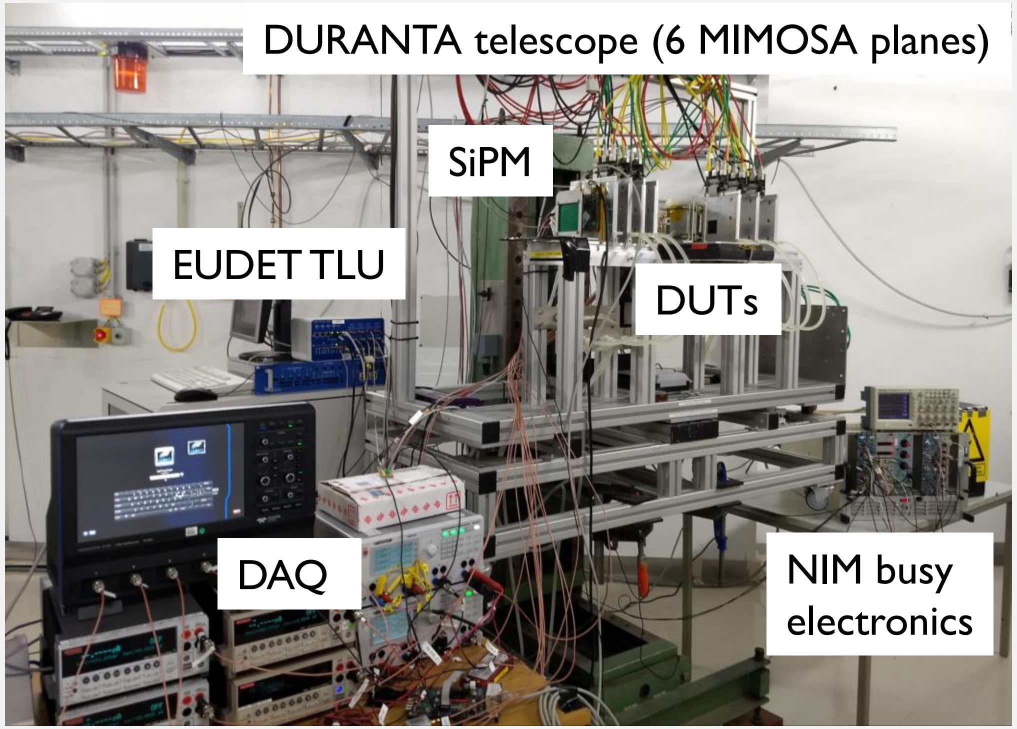

- Collected charge as a function of bias voltage
  - Different fluences for HPK-3.2-50 sensors after n irradiation
  - Measurements were performed at -30 °C

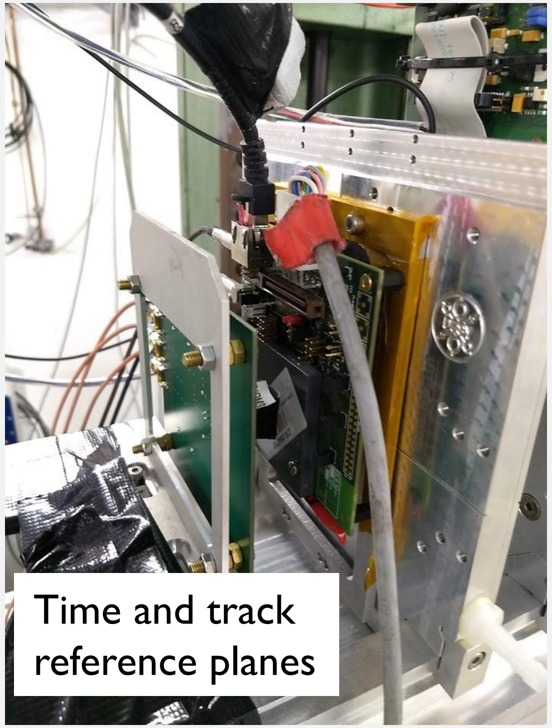


# Test beam campaigns

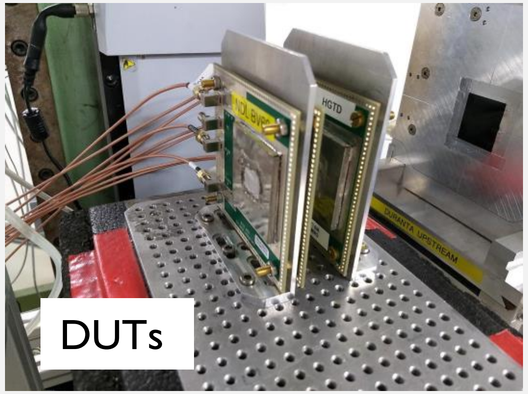
- Different facilities:
  - CERN North Area SPS H6A & B beamlines (120 GeV pion beam)
  - DESY T22 beamline (5 GeV $e^-$ beam)
  - Use of silicon sensor based telescope for tracking (EUDET-type)



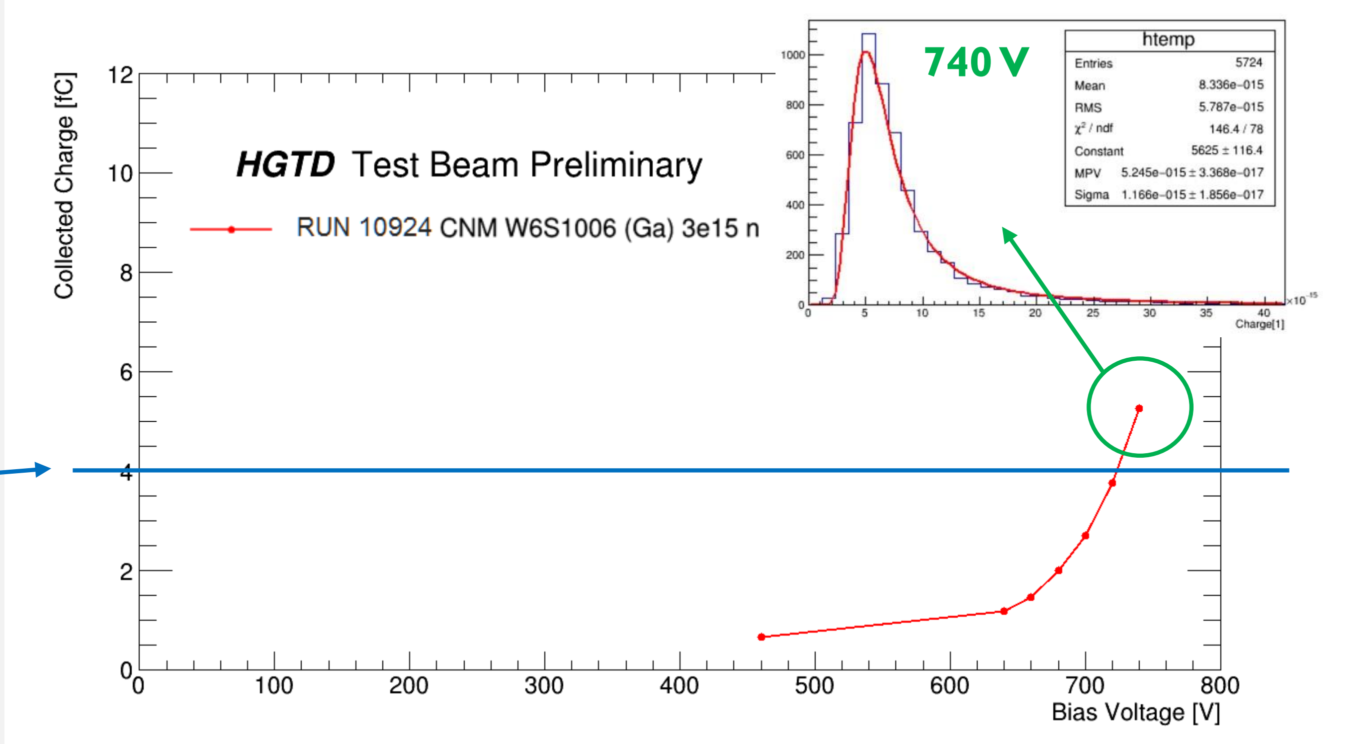




- Performance
  - LGADs
    - Un-irradiated and irradiated
    - Different geometries and vendors
  - Electronics and HGTD module
- Contributions to timing ($\sigma_{\Delta t=t1-t2}$)



# LGAD collected charge

- Charge calculated as the integral of the signal area for each recorded waveform after pedestal substraction
- At each voltage point the collected charge is given by the MPV value of the Landau-Gauss fit of the events charge distribution
- Performance of a CNM Gallium doped W6S1006 irradiated to $3\times10^{15}$ $n_{eq}/cm^2$
- Collected charge as a function of bias voltage
  - Bias voltage range from 460 to 740 V
  - 2 fC at 680 V
  - Reaches 4 fC for optimal ALTIROC performance at bias voltage >720 V
  - At **740 V** collected charge is **5.3 fC**

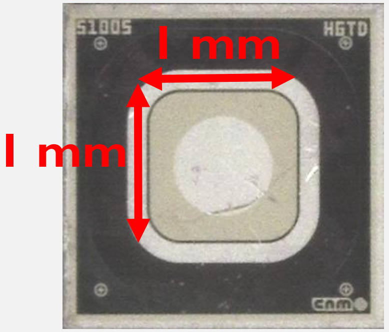


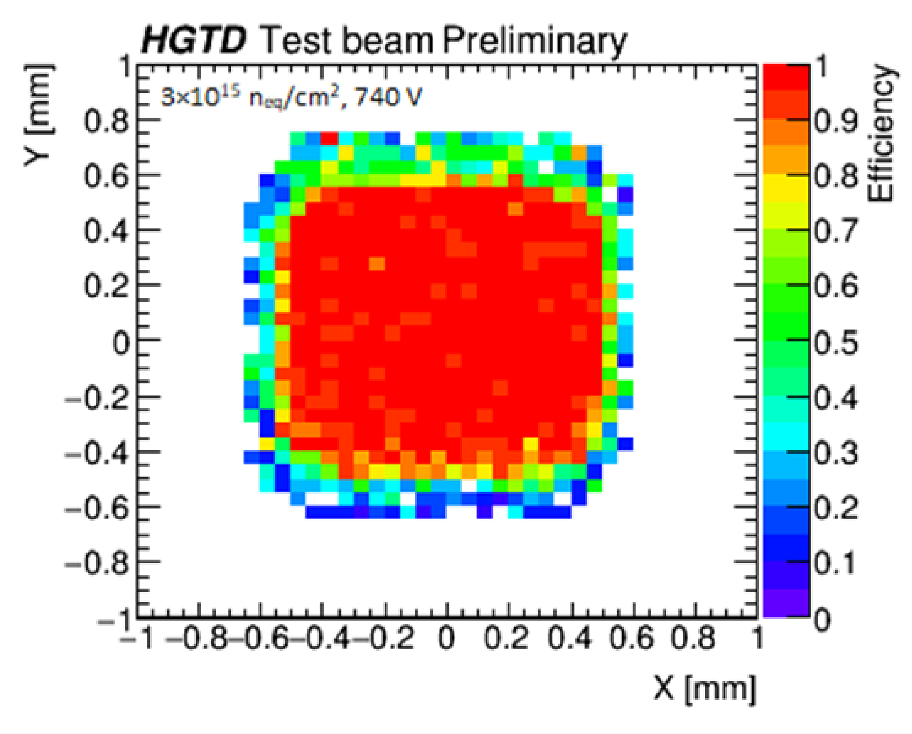
# LGAD 2D efficiency map

- Efficiency as a function of the reconstructed position of particles for CNM W6S1006 $3\times10^{15}$ $n_{eq}/cm^2$ at bias voltage **740 V** (5 °C difference from start and end of batch / ~0.1 mm/°C)

- Efficiency is defined as

$$\varepsilon = \frac{Tracks\ with\ \text{charge} > 2\ fC}{Total\ number\ of\ Tracks}$$




- A 2 fC threshold corresponds to ~15 mV for this voltage point

- ALTIROC expected to start to be efficient for charges >2 fC

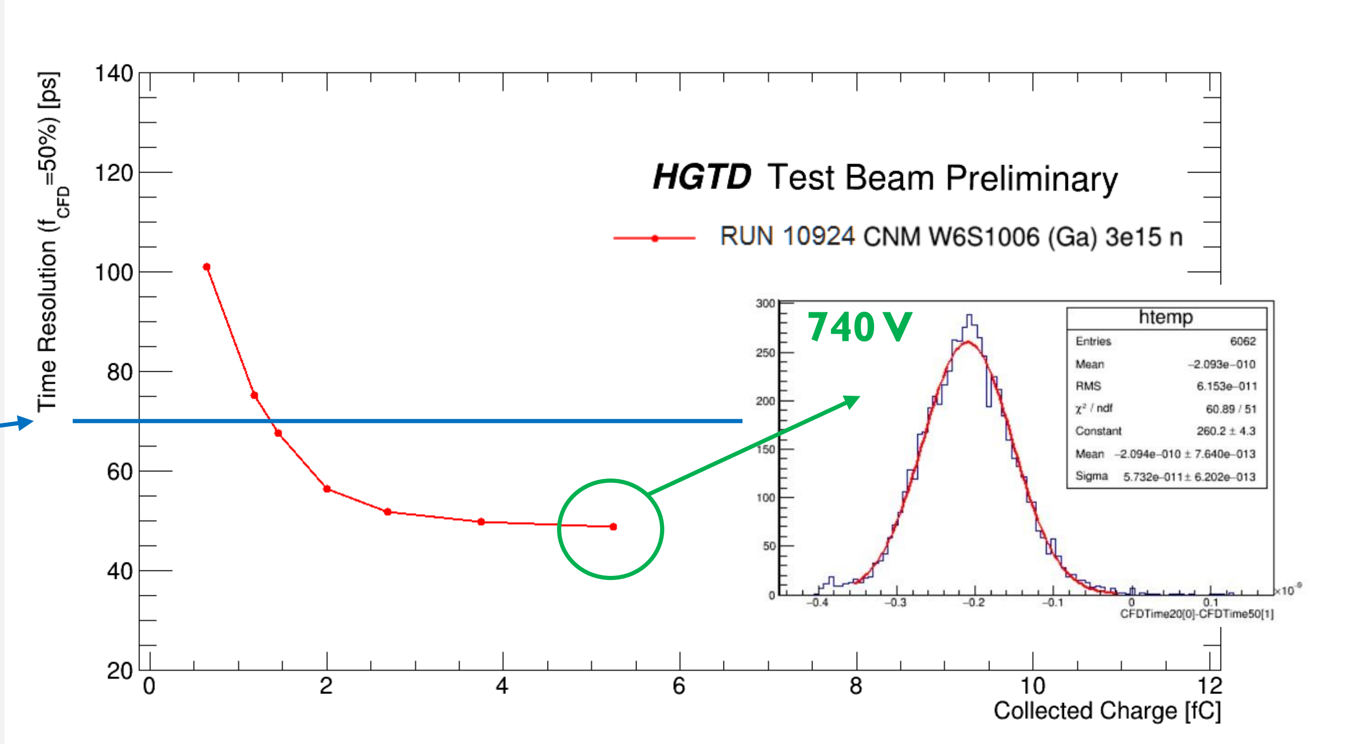
- **Average efficiency** in the central 0.5×0.5 mm² area: **99,1%**

# LGAD time resolution

- Timing distribution calculated as the difference between the time at $f_{CFD}$=50% for DUT and the time at $f_{CFD}$=20% for the un-irradiated reference sensor

$$\Delta t = t_{DUT(f_{CFD}=50\%)} - t_{LGA35(f_{CFD}=20\%)}$$

  - Fraction defined by the dominant contribution
    - Un-irradiated sensor → Landau fluctuations
    - Irradiated sensor → jitter (higher threshold)
- The time difference distribution is fitted with a Gaussian with the time resolution of the system defined as the $\sigma$ of the Gaussian
- At **740 V**
  - **Time resolution** is **48 ps** (<70 ps requirement)
  - The contribution of the reference sensor is subtracted (29.7 ps at -28 °C)

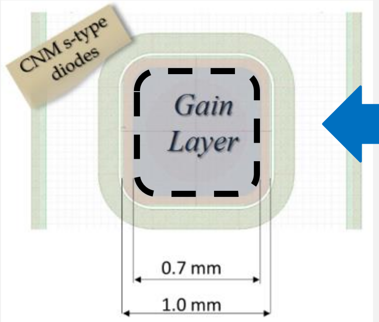


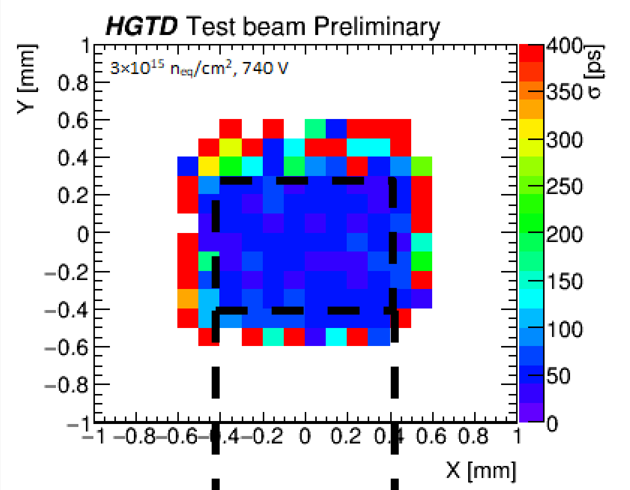
# LGAD 2D timing map

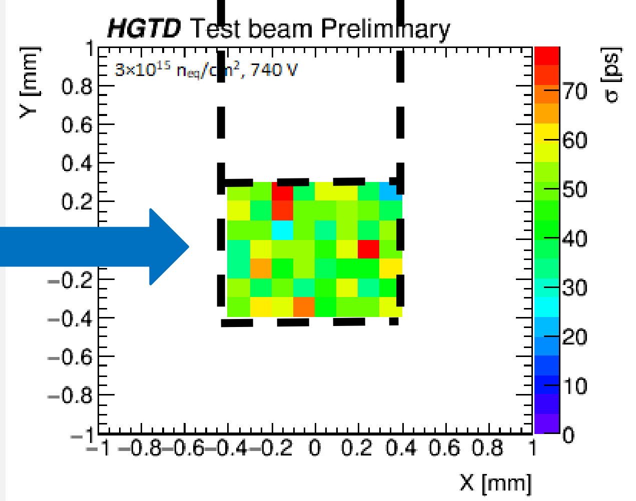
- Time resolution as a function of the reconstructed position of particles for **CNM W6S1006 $3\times10^{15}$ $n_{eq}/cm^2$** at **740 V**
- Time difference distribution for each bin calculated as:

$$\Delta t = t_{DUT(f_{CFD}=50\%)} - t_{LGA35(f_{CFD}=20\%)}$$

- A 2 fC threshold is applied
- Bin size of $100\times100$ µm$^2$ to ensure sufficient statistics
- Time resolution
  - Degrades at the sensor edges which also suffer from low statistics
  - Quite homogeneous at the central area (**~55 ps**)
  - The contribution of the reference sensor (29.7 ps) is already subtracted
- Pad region
  - $0.7\times0.7$ mm$^2$ (gain layer implantation)
- Edge region
  - $0.15\times0.15$ mm$^2$

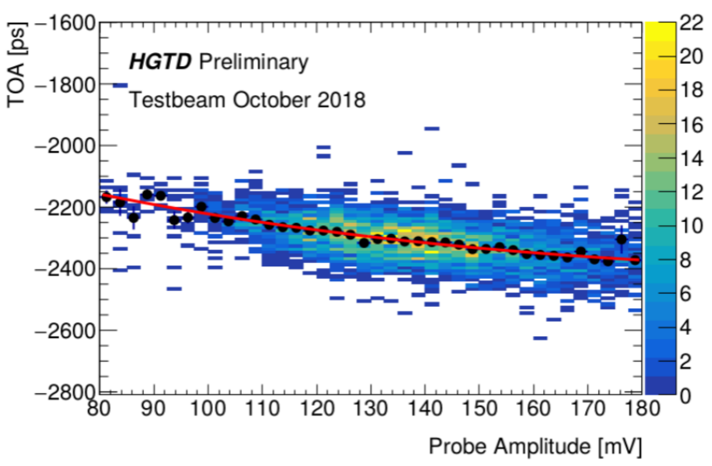


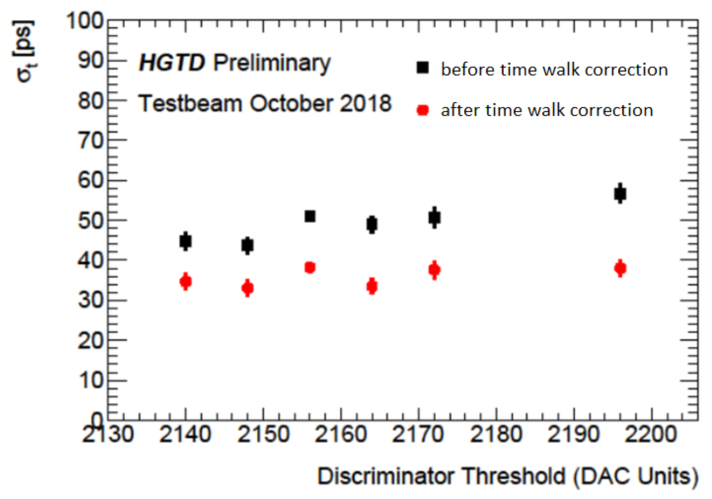



# 2×2 LGAD + ALTIROC results

- ALTIROC0v2 bump bonded to a un-irradiated CNM 2×2 LGAD array
- October 2018 test beam at CERN SPS beam line with 120 GeV pions
- TOA of signal corrected for time walk effects
  - TOA vs amplitude of pre-amplifier probe signal
  - Black points correspond to profile of 2D distribution
  - Red line corresponds to polynomial fit use to correct for time walk effects
- Best achieved **time resolution 35 ps** after time walk correction
  - Time resolution vs discriminator threshold (in DAC units) **before** and **after** time walk correction
  - Amplitude of pre-amplifier probe use to correct for time walk
  - 30% improvement
  - A SIPM is used as time reference where its 40 ps contribution is subtracted



# Summary and outlook

- The HGTD is proposed to mitigate pile-up effects and improve the performance in the ATLAS forward region
  - Challenging requirements to perform track-to-vertex association
  - Technical proposal was approved by LHCC [link to HGTD Technical Proposal]
  - HGTD community working to deliver Technical Design Report in April 2020
- Parameters as collected charge, time resolution and efficiency are studied and are close to the HGTD requirements
  - An extensive list of LGAD prototypes have been tested from different technologies and manufacturers and exploring new doping materials
  - CNM Gallium doped LGAD irradiated to $3\times10^{15}$ $n_{eq}/cm^2$ performance at 740 V is highlighted
    - LGAD reaches 4 fC for optimal ALTIROC performance
    - Efficiency in the bulk is 99.1% with a 2 fC threshold
    - Achieves a time resolution of 48 ps for ${f_{CFD}}_{DUT}$ 50% and ${f_{CFD}}_{LGA35}$ 20% (reference sensor contribution subtracted)
  - ALTIROC+LGAD results are promising

# THANK YOU FOR YOUR ATTENTION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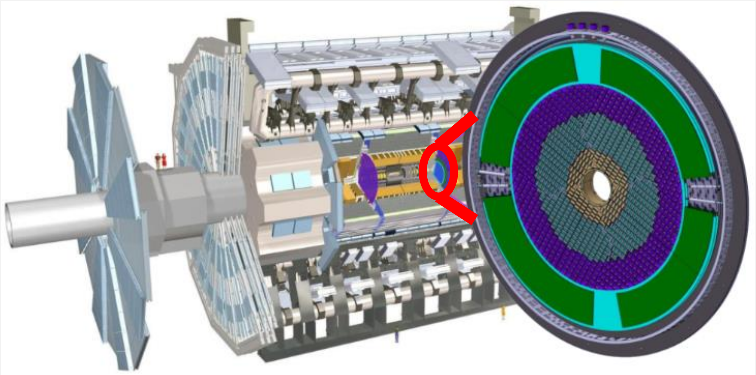
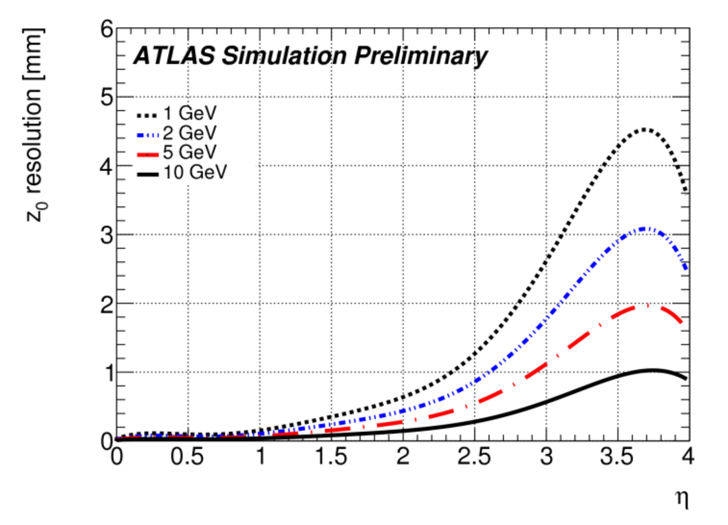
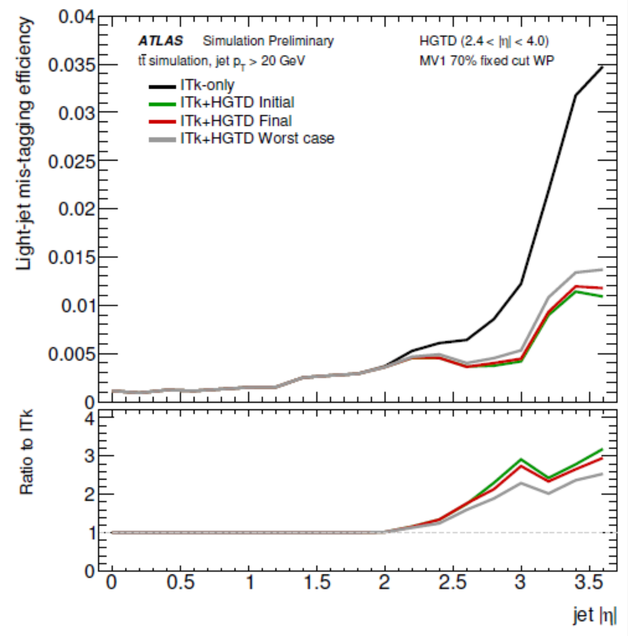
# HGTD requirements



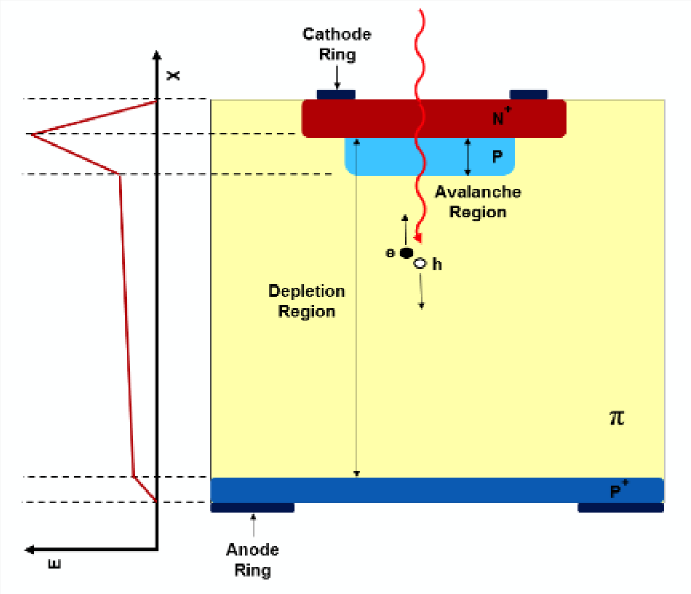
- Detector quite constrained by the space available and the harsh environment
- Time resolution better than 30 ps per track (50 ps per hit in a 2 layer geometry)
  - Recovers electron ID, track & jet reconstruction and b-tagging
- **L**ow **G**ain **A**valanche **D**etectors (LGAD) technology has been chosen
  - It provides an internal gain good enough while providing a large S/N ratio
- Design optimized for <10% occupancy

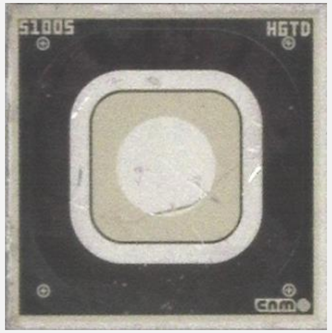


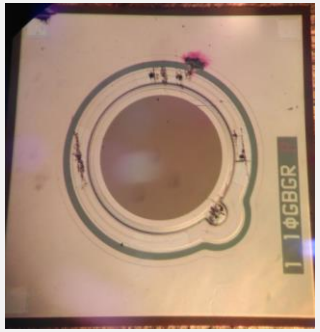
# Detection technology: LGAD

- **L**ow **G**ain **A**valanche **D**etectors (LGADs) originally developed by CNM
  - n-p silicon planar detector + multiplication layer that amplifies the signal
  - High E field
  - Moderate internal gain (10-50)
  - Typical rise time 0.5 ns
  - Excellent time resolution <30 ps before irradiation
- R&D programme to deliver thin sensors to provide the required time resolution (30 ps per track), fine segmentation, radiation hardness
  - New doping materials, substrates and new geometries
  - Prototypes tested from CNM, HPK, BNL, FBK



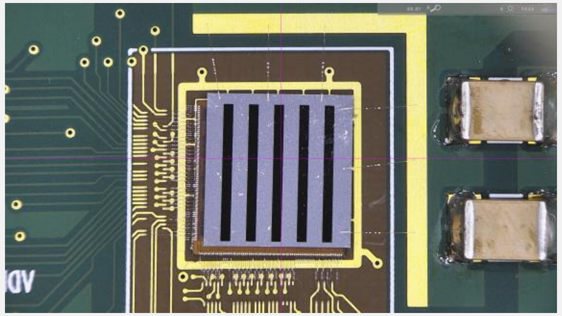
CNM LGAD for HGTD



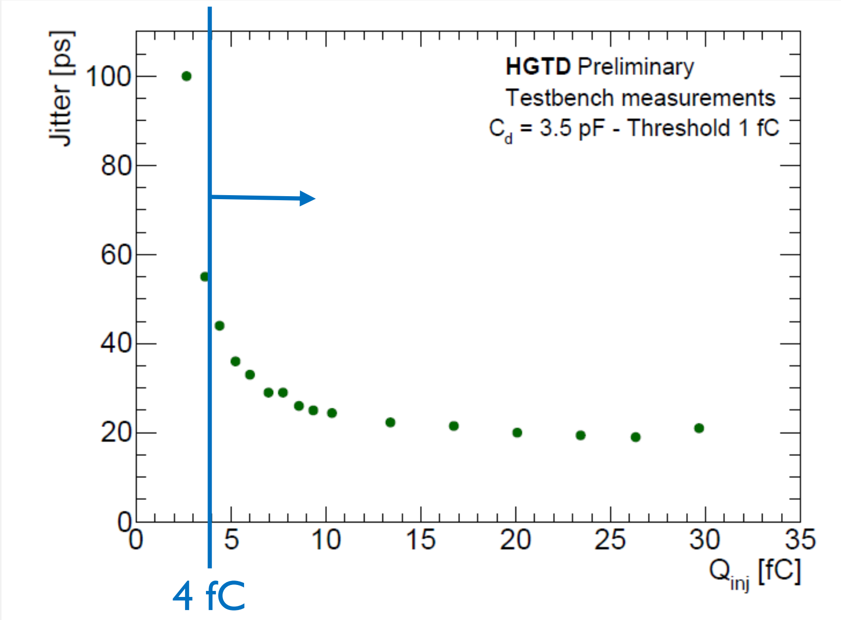
HPK LGAD for HGTD

# Readout electronics: ALTIROC ASIC

- **A**TLAS **LGAD** **T**iming **I**ntegrated **R**ead**O**ut **C**hip (ALTIROC)
  - Minimize noise and power consumption
  - Provide **T**ime **O**f **A**rrival (TOA) and **T**ime **O**ver **T**hreshold (TOT) measurements
  - Target time resolution <25 ps
  - Developed in various phases
    - ALTIROC0: single-pixel analog readout (pre-amplifier + discriminator)
      - Test bench measurements satisfactory
      - Beam tests → see next slides
    - ALTIROC1: full single-pixel analog readout (analog + digital) in 5×5 arrays
      - Test bench measurements on-going
      - Irradiation campaigns and beam tests in Q1 2019
    - ALTIROC2: final 15×15 version
      - Submission expected end of 2019



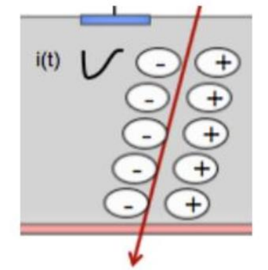
5×5 HPK LGAD bumb-bonded to ALTIROC1_v2

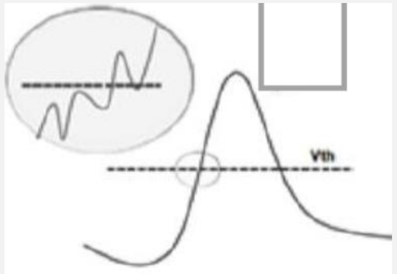


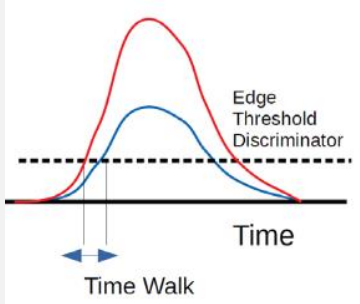
# Contributions to timing

- **Time resolution:**
  - Landau term <25 ps
    - Reduce for thin sensors: 35-50 $\mu$m
  - Jitter term <15 ps and time walk term <10 ps
    - Low noise and fast signals
  - Digitization granularity ~5 ps
  - Clock distribution <15 ps

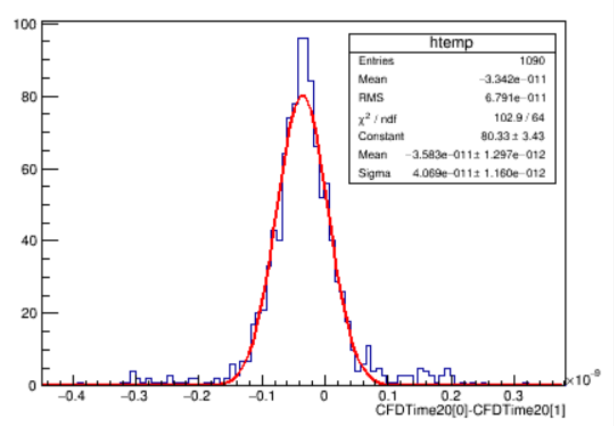
$$\sigma_{tot}^2 = \sigma_{Landau}^2 + \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2 + \left(\frac{\mathrm{TDC}_{bin}}{\sqrt{12}}\right)^2 + \sigma_{clock}^2$$

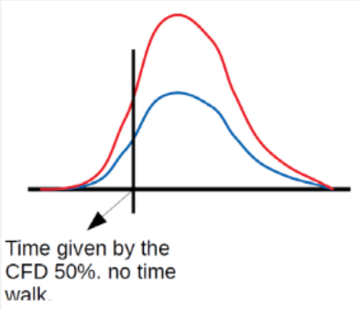


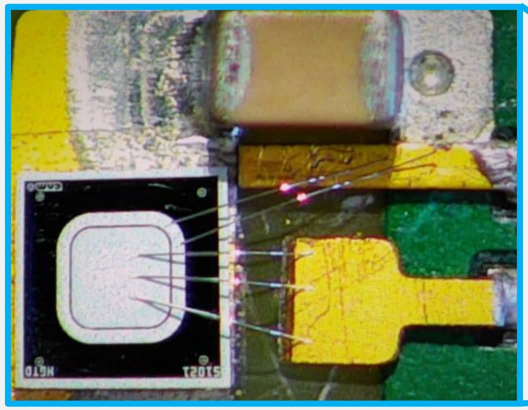

- Time walk corrections on beam test data using the **C**onstant **F**raction **D**iscriminator (CFD) technique
  - Considering the time at a fraction of 50% of the amplitude (typical fraction is 20%)

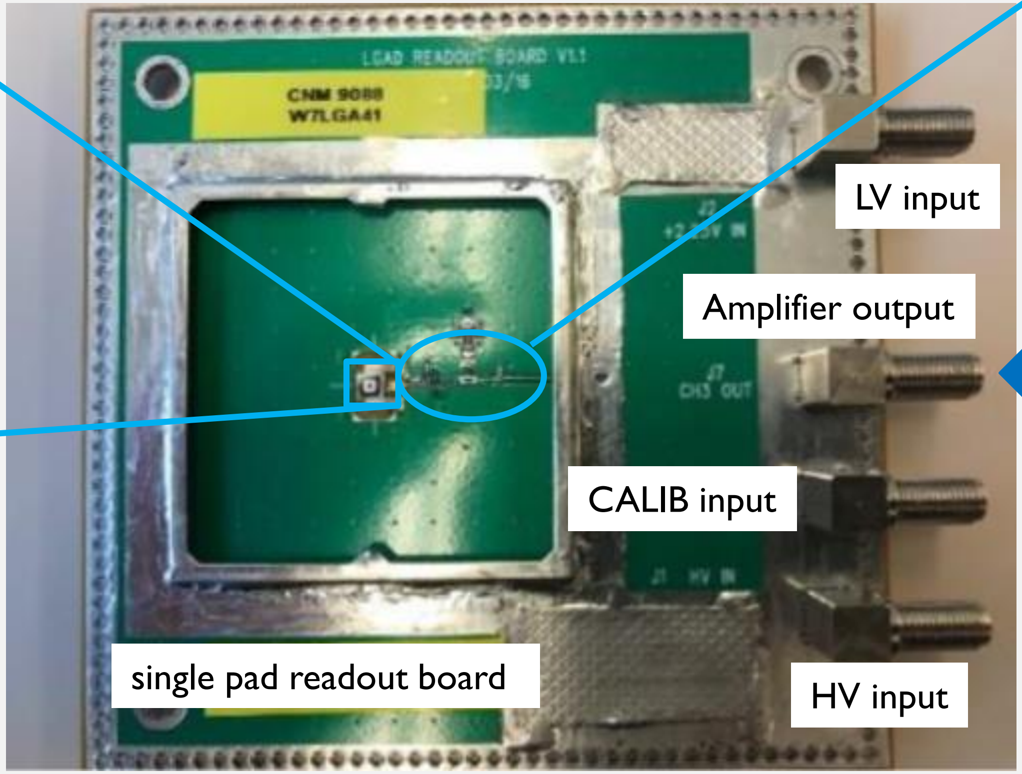


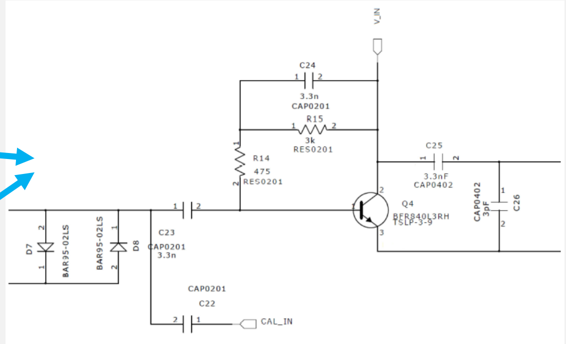



# Assembly Sensor + Readout board

- 50 sensors (un-irradiated, p- and n-irradiated) tested so far
- LGAD readout boards with trans-impedance first stage amplifier
- Voltage second stage amplifiers with hermetic E/B cover design





- Sensor attached to board using double-sided conductive tape
- Amplifier input coupled to metallization layer via wire bonds
- Guard ring grounded

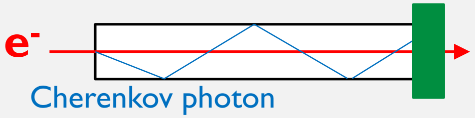

Second stage amplifier output to oscilloscope

- Gain of ~10
- 2 GHz Bandwidth

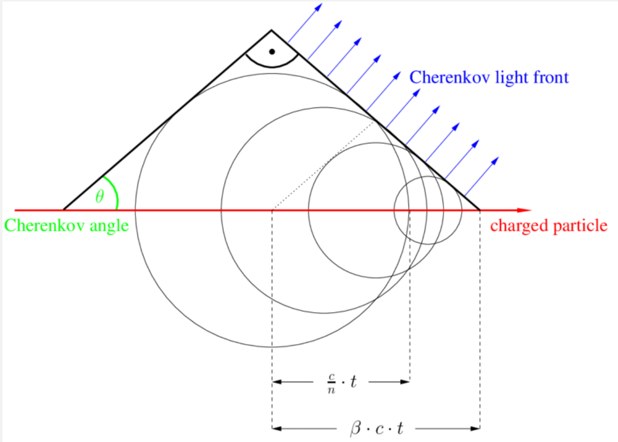
# Development of a timing reference system

- Cherenkov effect
  - Speed of particle $(\beta c)$ is higher than the speed of light in the medium $(cn)$

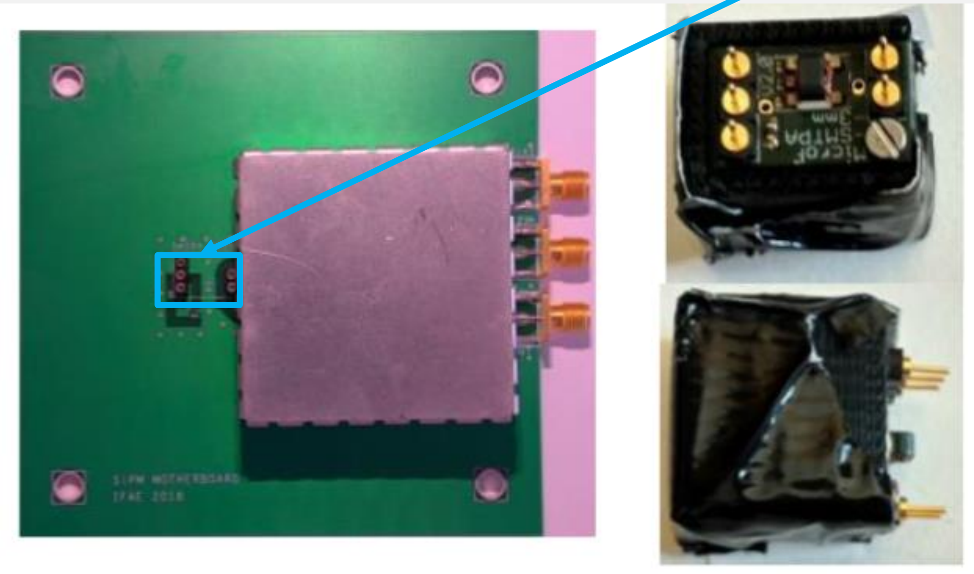
$$\cos\theta = 1/\beta n$$

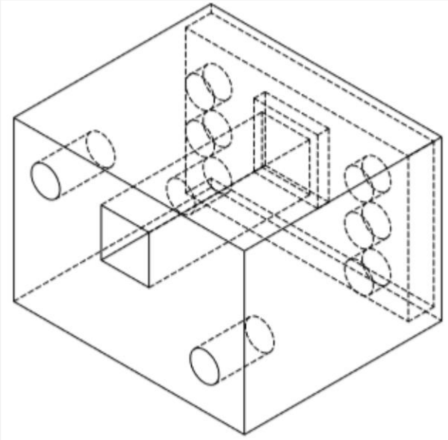



SIPM detects Cherenkov photons generated by charged pions in quartz

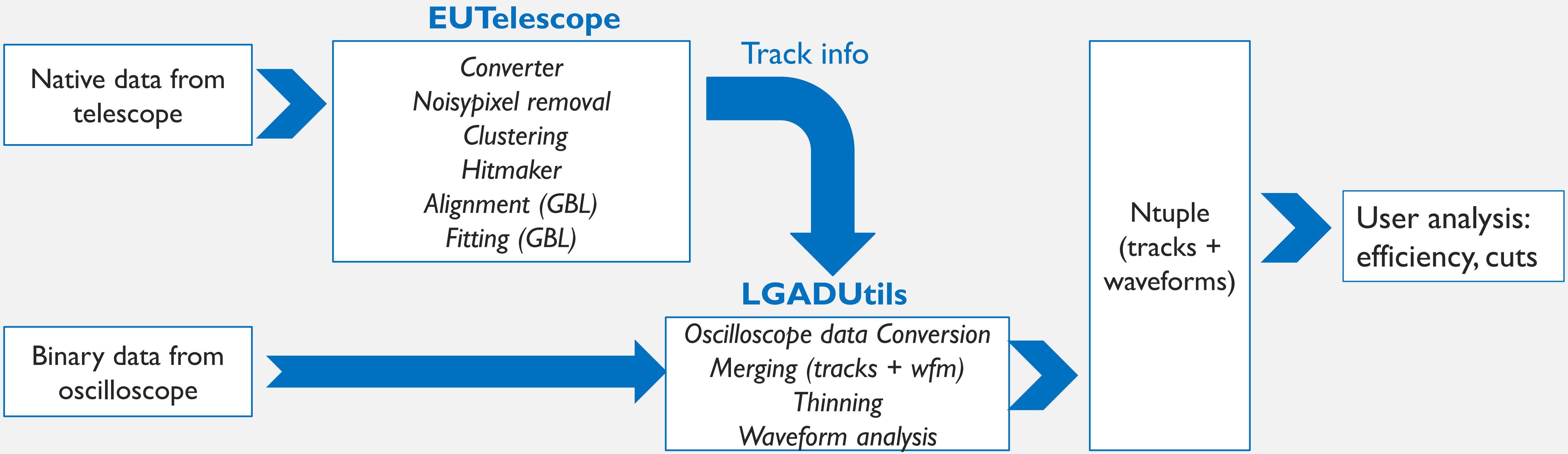



- Quartz bar
  - 3×3×10 mm$^3$
- Translucent optical grease
- Single channel SIPM from SensL
  - 4×4 mm$^2$ base
- SIPM readout and amplification boards
- 3D printed quartz light-tight enclosure



# Data analysis tools




- Track reconstruction performed with **EUTelescope software v01-19-02 using GBL algorithm**
  - Requiring one hit in FE-I4 plane → resulting in ~30% of total events with an average FE-I4 efficiency of 99.6%
- Waveform processing performed with **LGADUtils framework v1.0 (C++ based)** developed at IFAE by V. Gkougkousis (https://indico.cern.ch/event/782573/#preview:2889703 )
  - Match event information between telescope and oscilloscope discarding events without FE-I4 hits

# LGADUtils framework

- Steps:
  - Conversion oscilloscope binary data to Root ntuple with raw waveform information
  - Merging with track ntuple from EUTelescope
  - Waveform analysis
    - Determination of pulse polarity, signal start and stop, determine if the pulse is noise or signal
    - Calculate noise level and pedestal using Gaussian fit, pedestal subtraction, re-calculation of start and stop of the signal
    - Compute charge, rise time, time at different CFD fractions, …
  - User analysis
    - Efficiency
    - Timing