Characterization of front-end electronics for the High Granularity Timing Detector of the ATLAS experiment

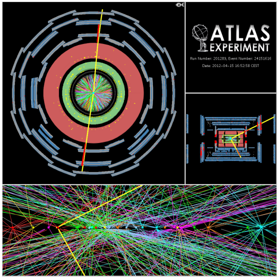
Christina Agapopoulou - LAL

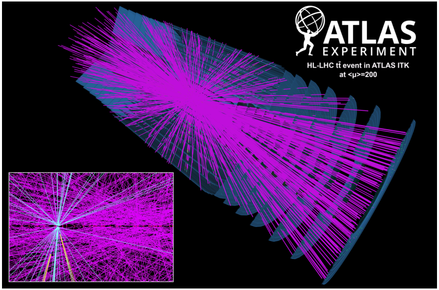
May 28, 2019

The High Luminosity LHC

HL-LHC:

- Scheduled to start at 2026
- $\times$ 5-7 increase in instantaneous luminosity
- One of the main challenges of the HL-LHC will be **pile-up** interactions





Pile-up: all interactions happening around the interaction of interest

- Now: 60 PU interactions/crossing
- HL-LHC: 200!

the ATLAS experiment has to maintain tracking and vertexing performance under these harsh conditions!

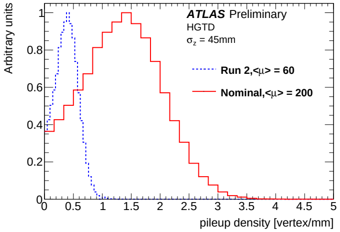
Motivation for time measurement

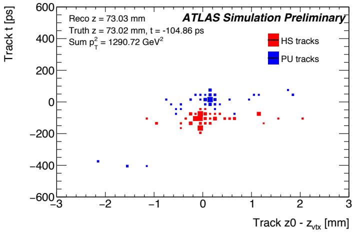
At the HL-LHC:

- x3 more PU interactions/event → vertex density up to 4 vert./mm
- merged vertices → ambiguites in the track to vertex association
- object reconstruction performance degrades

Time omplementary to space information. It can be used to:

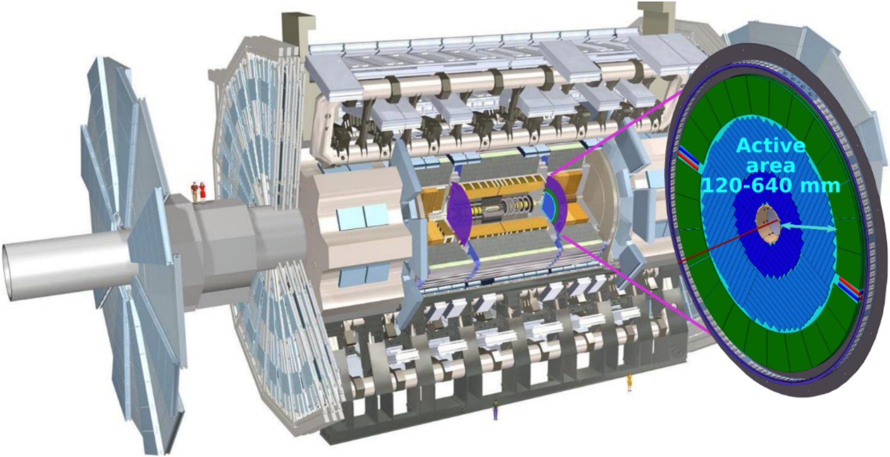
- mitigate pile-up by rejecting out-of-time tracks
- Improve jet reconstruction, lepton isolation, b-tagging, Vertex ID and track to vertex association





At HL-LHC: vertex spread in time ∼ **180 ps**. Time resolution of **30 ps** can greatly help disentangle merged-in-space vertices

What is the HGTD?



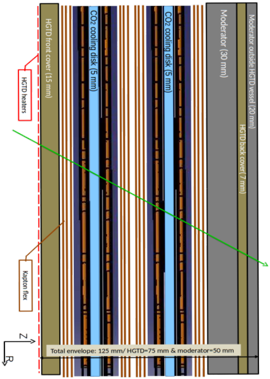
High Granularity Timnig Detector: planar, disk-like detector that provides timing information for forward objects

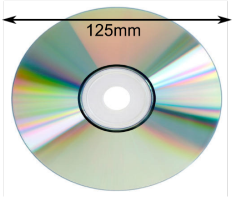
Detector overview

- Parameters
  - $2.4 < |\eta| < 4$
  - thickness in z = 125mm
  - 354M channels

- Requirements
  - **Time resolution = 30 ps**
  - Withstand radiation up to 4.5 10^{15} n_{eq}/cm^2 and 4.5 MGy
  - Occupancy < 10%
  - operation at -30^{o}C

- Design:
  - 4 Si sensor layers based on each side of 2 cooling plates
  - 2-3 hits per particle
  - 1.3×1.3 mm^2 silicon pixels to minimize occupancy and detector capacitance





And what about the time resolution?

$$\boxed{\sigma_t^2 = \sigma_{sensor}^2 + \sigma_{electronics}^2}$$

- **Sensor**:
  - Landau fluctuations due to non-uniformity in the energy deposition
  - Signal variation due to spatial non-uniformity of the field
  - Landau term is dominant in our case

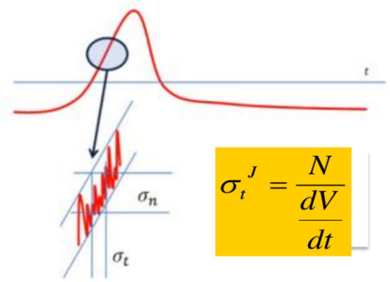
Electronics contribution to the time resolution

Contributions of the electronics to the time resolution:

$$\sigma^2_{elec} = \sigma^2_{jitter} + \sigma^2_{TimeWalk} + \sigma^2_{digitization}$$

- **Jitter**: Noise contribution to the signal - proportional to:
  - Detector Capacitance
  - Noise
  - Rise time

$$\sigma_{jitter} = \frac{N}{\frac{dV}{dt}} \sim \frac{t_{rise}}{\frac{S}{N}}$$

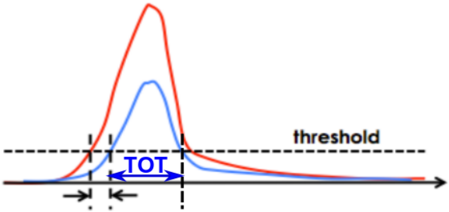


Jitter effect

Electronics contribution to the time resolution

- **Time Walk**: large signals cross a constant threshold faster than small ones biasing the time measurement
  - can be corrected with a Time Over Threshold (TOT) measurement (offline).
  - Expecting < 10ps contribution after correction

$$\sigma_{TW} = \left[\frac{V_{th}}{\frac{S}{t_{rise}}}\right]_{RMS}$$



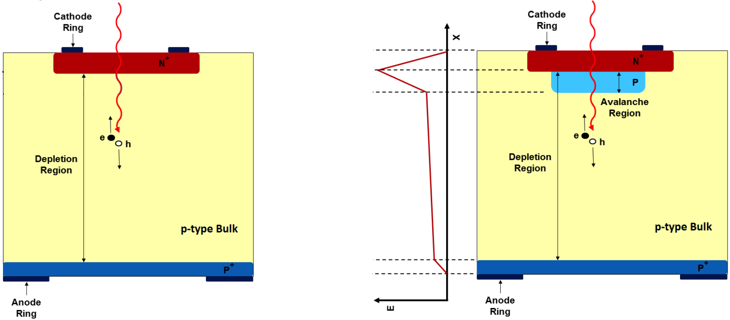
- **Digitization**: Error due to the binning of the measurement digitization
  - Fine digitization 20-40 ps
  - negligible contribution

Sensor technology: Low Gain Avalanche Detectors

Low Gain Avalanche Detector (LGAD): n-on-p Si detector with extra doped p-layer

Standard p-n Diode Sensor

LGAD Sensor



Gain = Charge in LGAD / Charge in p-n diode without amplification layer

- Internal amplififcation
- Low gain $\approx$ (10-50)
- Increased S/N ratio
- Excellent timing

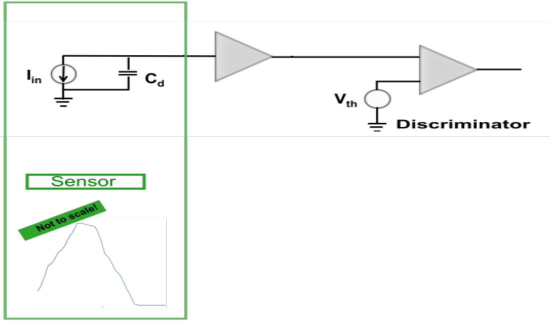
Electronics for the HGTD

- Requirements:
  - Keep excellent LGAD **time resolution**
  - Radiation hardness
  - Operation in cold temperature
  - low power consumption
  - cope with HL-LHC bunch crossing and trigger rate

- Design:
  - LGAD time information is first measured and digitized by the **"front-end"** on-sensor electronics
  - Digital information is transfered to the periphery of the detector and later to the ATLAS central DAQ system (back-end)

Front End Electronics

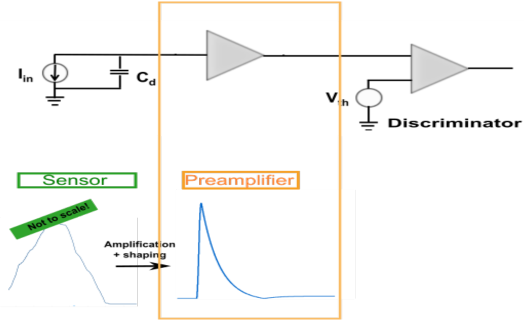
A timing detector from the electronics point of view



- **Sensor**: seen as a current source in parallel with a "detector capacitance"
  - C_d crucial to the electronics timing performance
  - Should be as small as possible

Front End Electronics

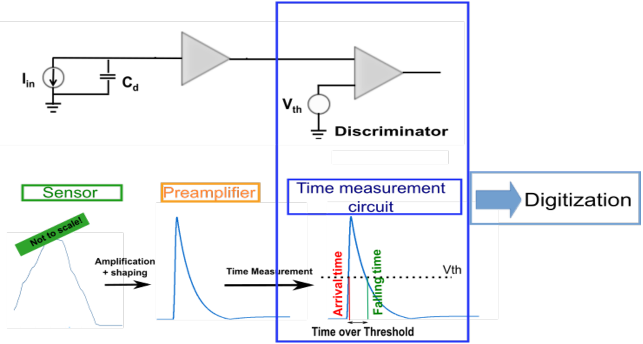
A timing detector from the electronics point of view



- **Preamplifier**: amplifies and shapes the sensor signal
  - the preamplifier design impacts the rise time and S/N

Front End Electronics

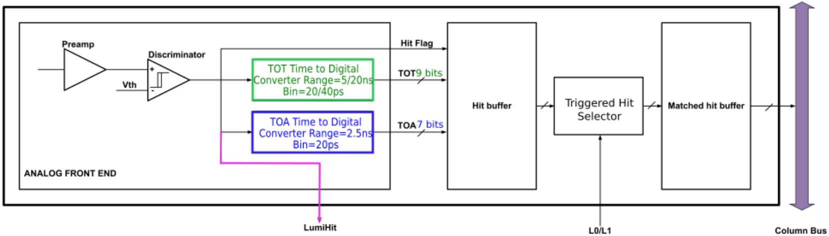
A timing detector from the electronics point of view



- **Constant threshold discriminator**
  - Measures the time the signal crosses a constant threshold
  - Time of Arrival (TOA), Falling time (TOE), Time over Threshold (TOT)
- **Signal digitization and sampling**

ALTIROC ASIC

ALTIROC: 225 channel 2x2cm^2 ASIC to convert the LGAD signal into a time measurement

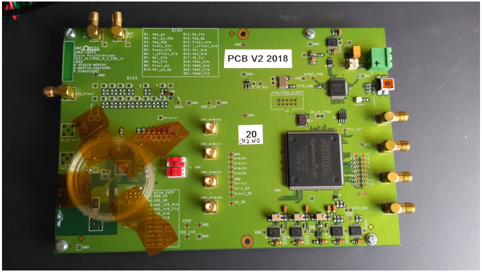


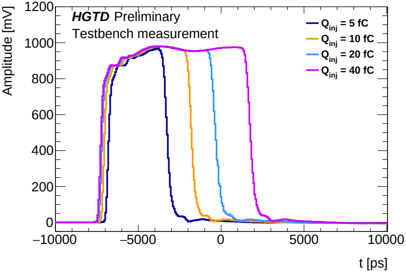
- Main analog components:
  - Preamplifier for signal amplification
  - Discriminator for the time measurement
- Main digital components:
  - Time-to-digital converters for digitization of the TOA and TOT signals
  - Buffers for signal storage until trigger reception

ALTIROC0: an analog prototype

Simplified version of the final chip

- only analog part (preamplifier + discriminator)
- 4 channels
- 2 design iterations
- ASIC alone or with a sensor
- calibration/testbeam



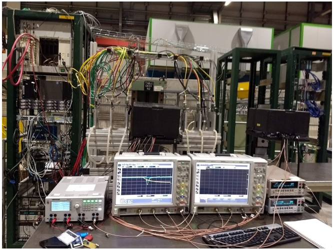


Testbeam measurements with ALTIROC0

Testbeam: performance under realistic conditions!

- beam of 120 GeV pions from SPS @ CERN
- ALTIROC0 ASIC bump-bonded to an un-irradiated 2x2 mm^2 sensor array
- time reference from a SiPM
- tracking from a beam telescope

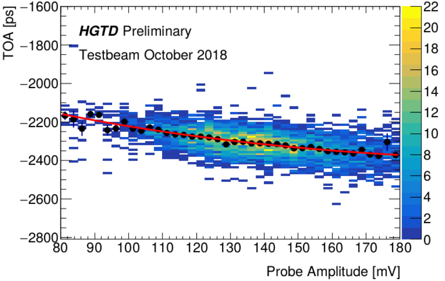
Lot's of cables and fun!



Testbeam measurements with ALTIROC0

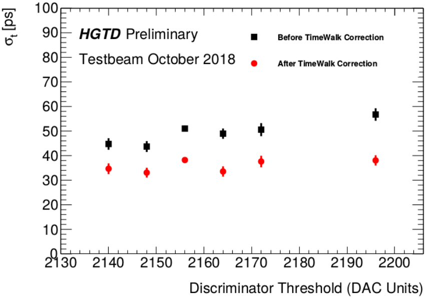
Time Walk correction:

- need to correct for the time walk effect
- used amplitude of preamplifier probe
- correction extracted from polynomial fit



Time resolution calculation

- σ of the TOA distribution - subtracting SiPM resolution
- time walk correction improves performance by $\sim$ 30%
- time resolution flat with the threshold!

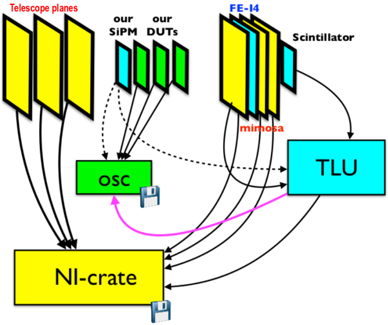


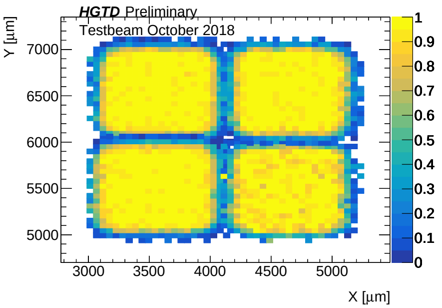
Best achieved time resolution $\sim$ 35 ps

Testbeam measurements with ALTIROC0

$$\text{efficiency} = \frac{\text{Number of tracks with LGAD response}}{\text{Total number of tracks}}$$

- uniform among channels
- above **95%** in the bulk of the pad





Conclusions

- The **HGTD** is a timing detector that can significantly improve the reconstruction of all physics objects and the selection of events of interest by mitigating **pile-up** interactions

- Its requirements to be radiation hard, compact and highly granular are well met with Si sensors, while the **LGAD** technology meets the time resolution requirements

- the **ALTIROC ASIC** integrates electronic components designed to measure time while keeping the excellent LGAD timing resolution
  - A first analog prototype has been fabricated
  - Testbeam campaigns with electronics+sensors for realistic performance tests
  - high efficiency, good uniformity among channels

Testbeam results show good performance of analog part

$\sim$ **35 ps time resolution!**