A High Granularity Timing Detector for the Phase II upgrade of the ATLAS detector system

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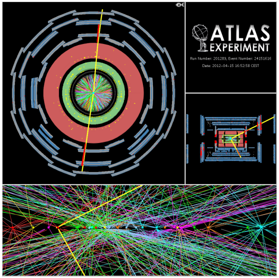
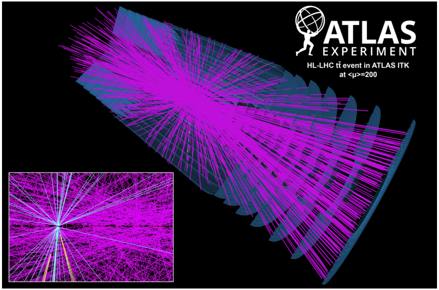
The High Luminosity LHC

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

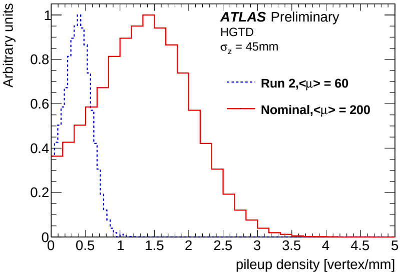
- Now: 60 PU interactions/crossing
- HL-LHC: 200!

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

Motivation for time measurement

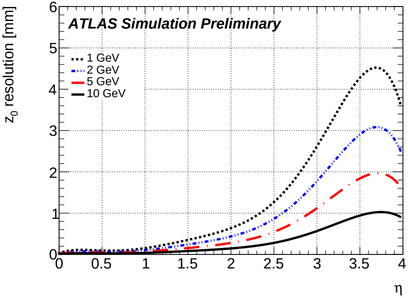
At the HL-LHC:

- x3 more PU interactions/event
- average vertex density increases from 0.4 to 1.5 vertices/mm
- vertex density can reach up to 4 vertices/mm



Tracking performance:

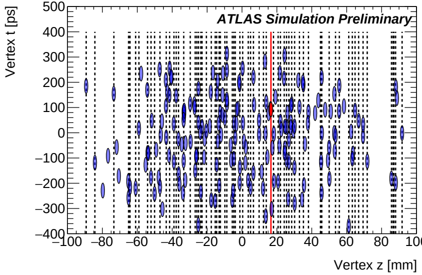
- track matching degrades with η
- merged vertices
- ambiguites in the track to vertex association

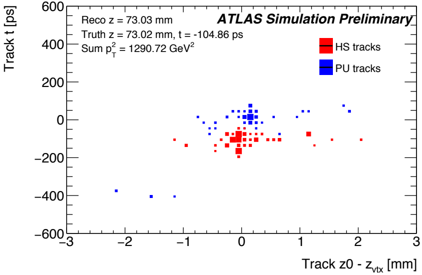


Motivation for time measurement

Time information is complementary to space information. It can be used to:

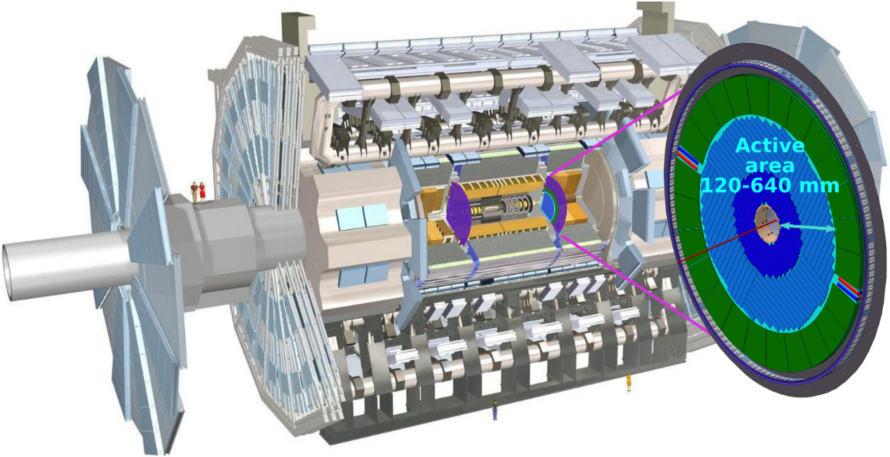
- mitigate pile-up by rejecting out-of-time tracks
- Improve jet reconstruction, lepton isolation, b-tagging, Vertex ID and track to vertex association





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?



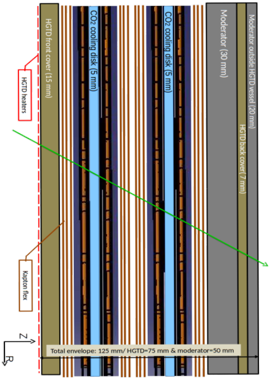
High Granularity Timnig Detector: planar, disk-like detector that provides timing information for forward objects

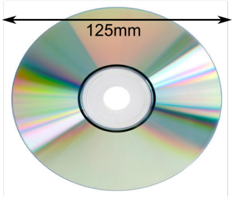
Detector overview

- 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?

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

- **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

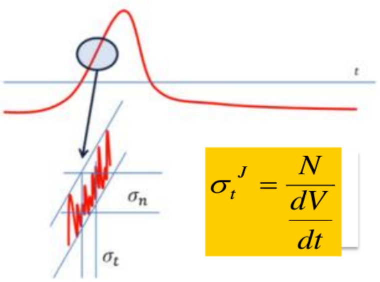
Electronics contribution to the time resolution

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

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

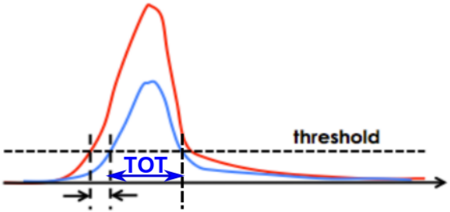


Jitter effect

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

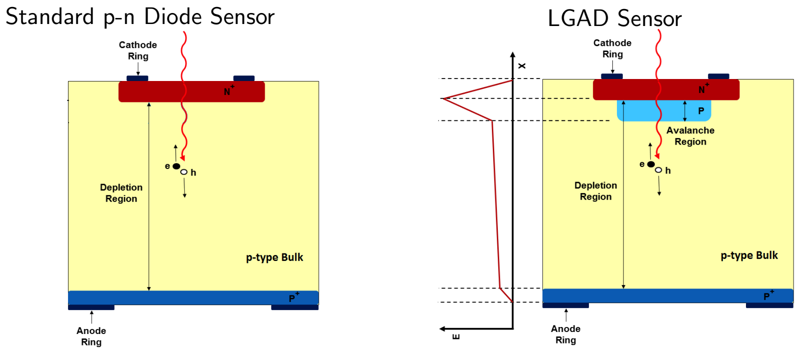
$$\sigma_{TW} = \left[\frac{V_{th}}{\frac{S}{t_{rise}}}\right]_{RMS}$$



- **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



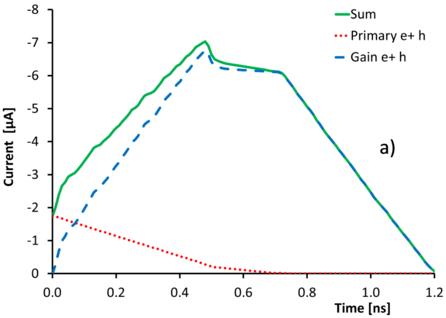
Gain = Charge in LGAD / Charge in p-n diode without amplification layer

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

LGAD signal formation

Signal formation:

- Primary + gain (e,h) pairs
- I_{max} only depends on gain
- rise time $\propto$ sensor thickness



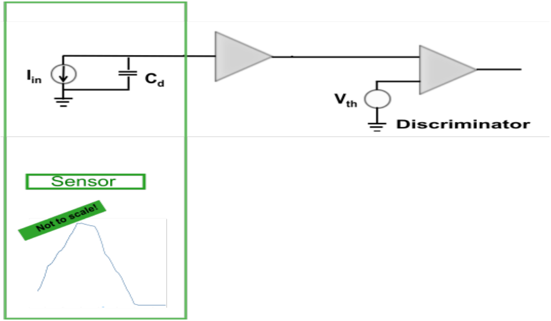
Electronics for the HGTD

- 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

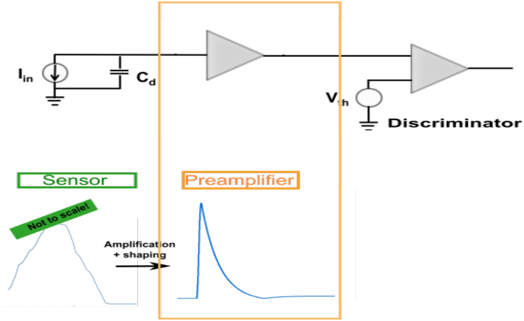
A timing detector from the electronics point of view



- **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

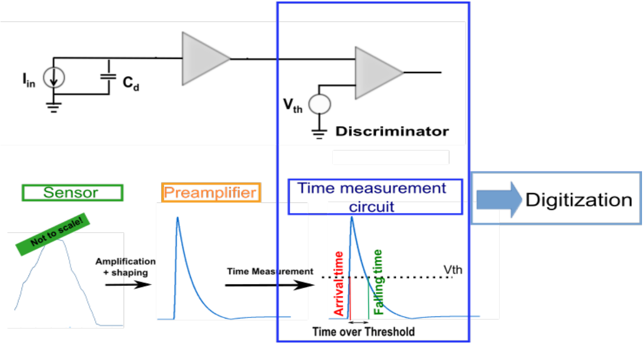
A timing detector from the electronics point of view



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

Front End Electronics

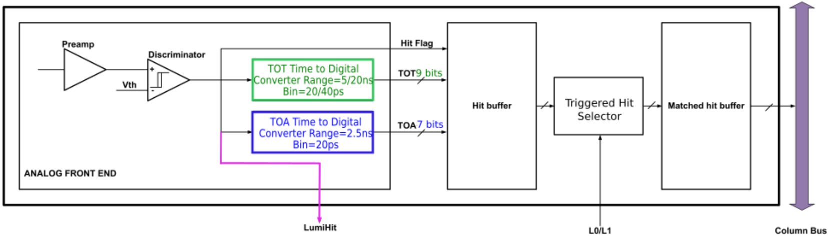
A timing detector from the electronics point of view



- **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

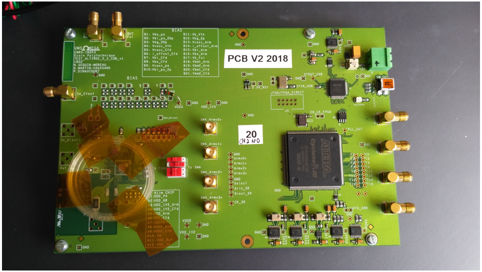


- Main analog components:
  - Preamplifier for signal amplification
  - Discriminator for the time measurement
- Main digital components:
  - Time-to-digital converters for digitization of the TOA and TOT signals
  - Buffers for signal storage until trigger reception

ALTIROC0: an analog prototype

Simplified version of the final ASIC

- only analog part (preamplifier + discriminator)
- 4 channels
- 2 design iterations



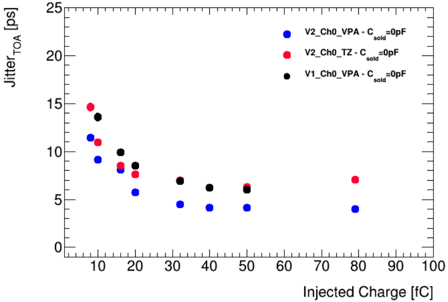
Testing configurations:

- Different preamplifier speeds (V1 and V2)
- Different preamplifier types (Voltage and transimpedance)
- ASIC alone or with a sensor
- calibration/testbeam

ALTIROC0 testing: Preamplifier Jitter

Jitter measurement:

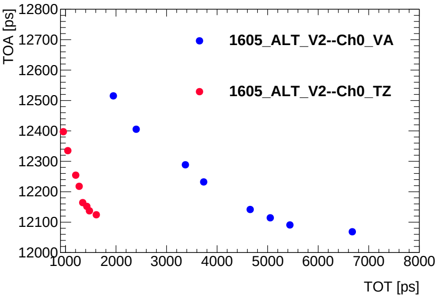
- First iteration of preaplifier (**V1**) found to be too slow
- Second iteration with optimized preamplifier (V2) → 35% improvement
- **TZ** performs slightly worse than **VPA**

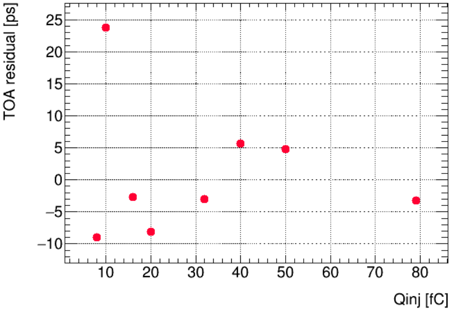


ALTIROC0 testing: Time Walk Correction

Time Walk Correction:

- Time-Over-Threshold (TOT) correction applied to the Time of Arrival (TOA)
- Expected contribution to the time resolution < 10 ps after correction
- Voltage (**VPA**) and transimpedance (**TZ**) were studied





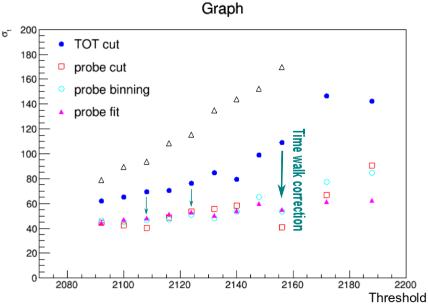
After correction, in both types of preamplifiers $\Delta\text{Residual}_{RMS}$=10ps

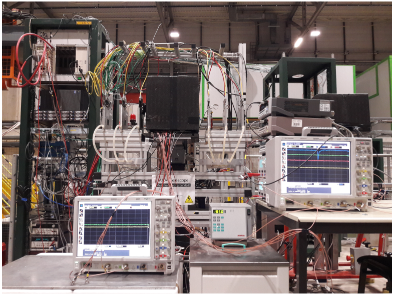
ALTIROC0 testing: Testbeam

Testbeam measurements to estimate performance in more realistic conditions

- September 2017 and June 2018 at CERN
- 120 GeV pions
- Time resolution = convolution of sensor + electronics contributions

$$\sigma_t^2 = \sigma_{sensor}^2 + \sigma_{elec}^2$$





After correcting for the time walk, $\sigma_t \sim$ **40 ps**

Conclusions

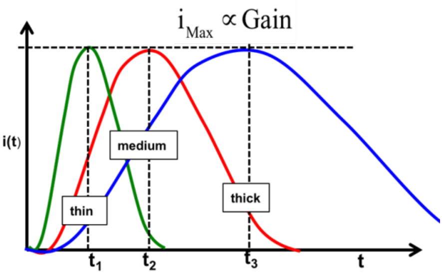
- The **HGTD** is a timing detector that can significantly improve the reconstruction of all physics objects and the selection of events of interest by mitigating **pile-up** interactions
- Its requirements to be radiation hard, compact and highly granular are well met with Si sensors, while the **LGAD** 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
    - Various types of preamplifiers have been tested
    - Tests of the electronics alone show good performance in jitter and time walk correction
    - Testbeam campaigns with electronics+sensors $\rightarrow$ 40 ps time resolution

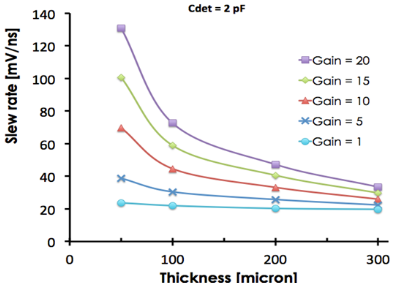
Backup

LGAD characteristics

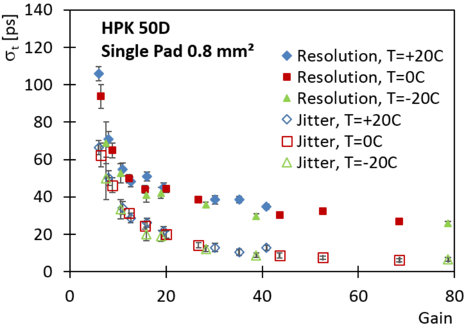
3 key parameters: **rise time**, **signal/noise** and **power**

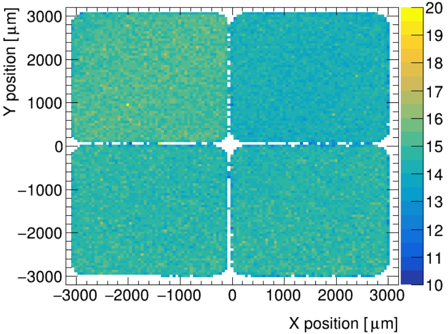
- Gain?
  - low gain $\rightarrow$ less **noise** and **power consumption**
  - high gain $\rightarrow$ higher **signal**
  - **optimized gain $\approx$ 20**
- Sensor thickness?
  - thin sensors $\rightarrow$ faster **rise time** and minimum Landau contributions
  - thin sensors $\rightarrow$ larger detector capacitance
  - **optimized thickness 35-50 μm**





Sensor Testing





- Time resolution decreases with gain
- Time resolution improves for lower temperatures
- Position specific measurements show fairly uniform behaviour

Sensor Testing: after irradiation

Sensors were irradiated by neutrons at the JSI research reactor in Ljubljana up to 6×10^{15} $n_e q/cm^2$ fluence

- Reduction of gain because dopants are removed → need to operate at higher V bias
- Increase of leakage current → need to operate at T=-20-30 C
- electrically active defects in the bulk (area around amplification region) → high fields in the bulk