12th International Conference on POSITION SENSITIVE DETECTORS

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A High-Granularity Timing Detector for the ATLAS Phase-II upgrade

PSD (2021, Birmingham)

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on behalf of the ATLAS HGTD group

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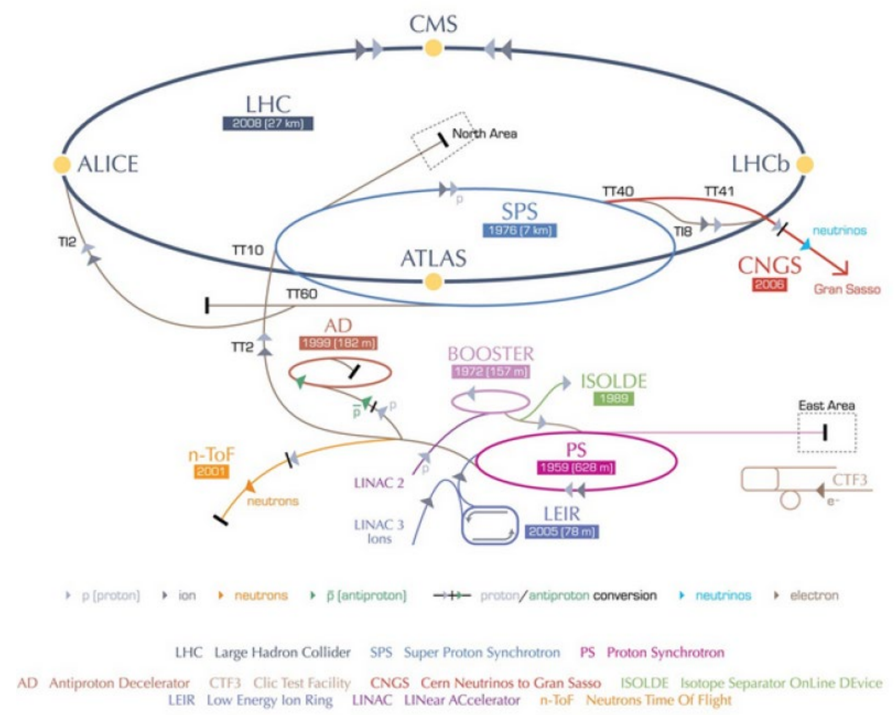
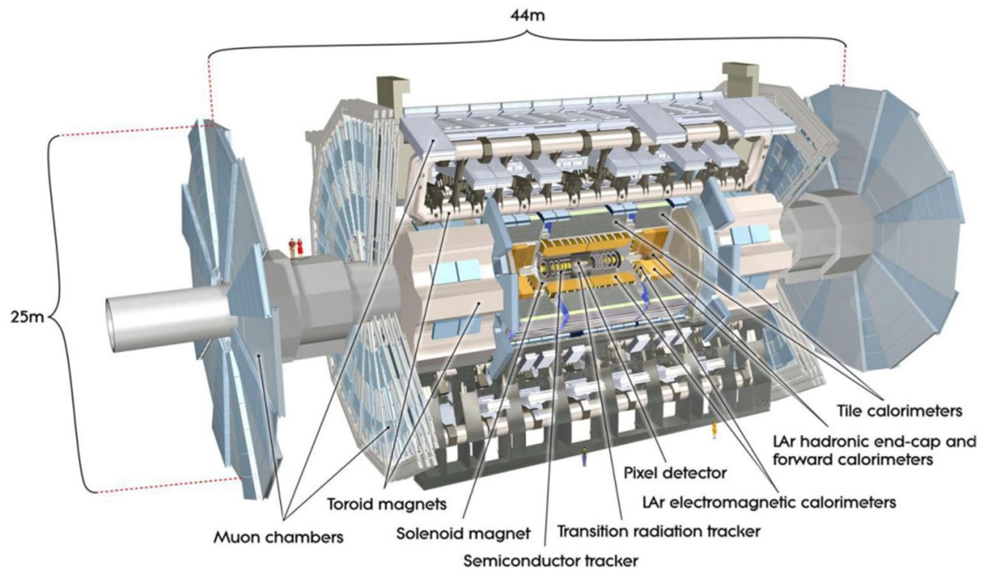
ATLAS EXPERIMENT

LHC high luminosity and ATLAS

- **LHC** had very successful runs since the start of collisions in 2010
  - Discovery of the Higgs boson, SM measurements, search for SUSY and exotic particles
- It will be upgraded in 2027 to High Luminosity LHC (HL-LHC)
  - Instantaneous luminosity will be ~3 times past run conditions
  - From L = 2.5E34 $cm^{-2}s^{-1}$ to L = 7.5E34 $cm^{-2}s^{-1}$

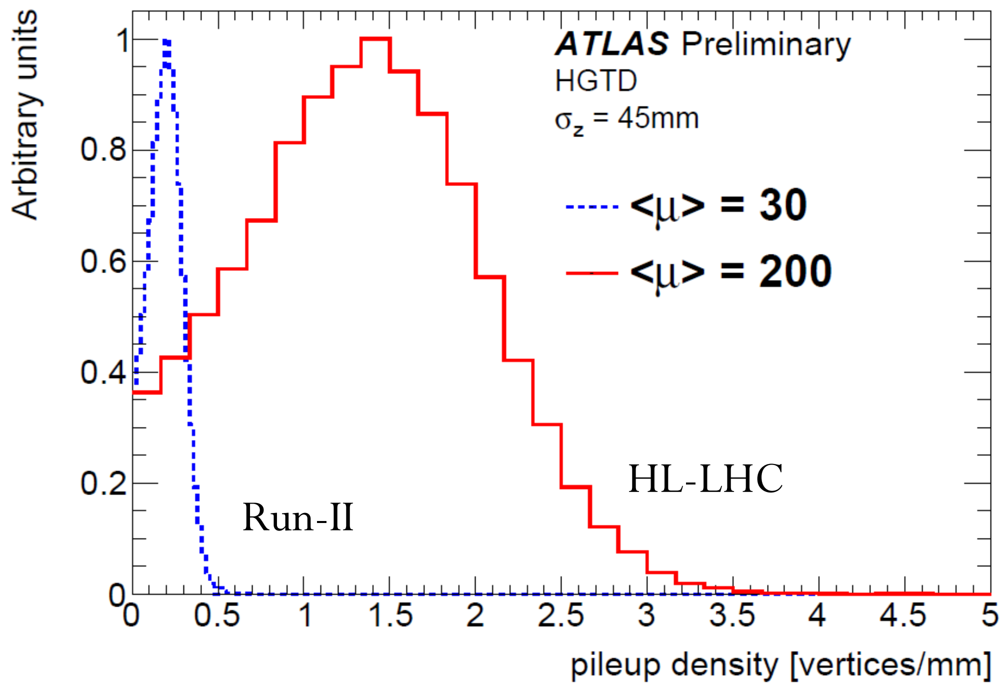


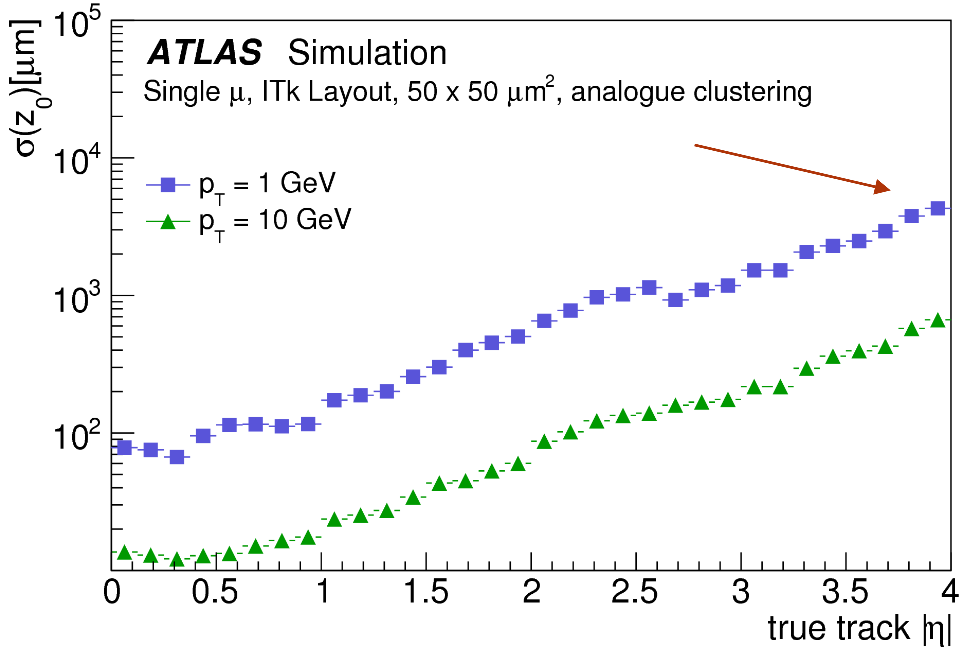
- To maintain performance the ATLAS detector will be upgraded (phase-II upgrade) for HL-LHC
  - The inner detector will be replaced (ITk project)
  - New readout electronics for EM and Hadronic calorimeters
  - Upgraded muon spectrometer
  - TDAQ system will be completely re-worked
- **New end-cap pixel timing detector**
  - High granularity timing detector, **HGTD**
  - HGTD TDR



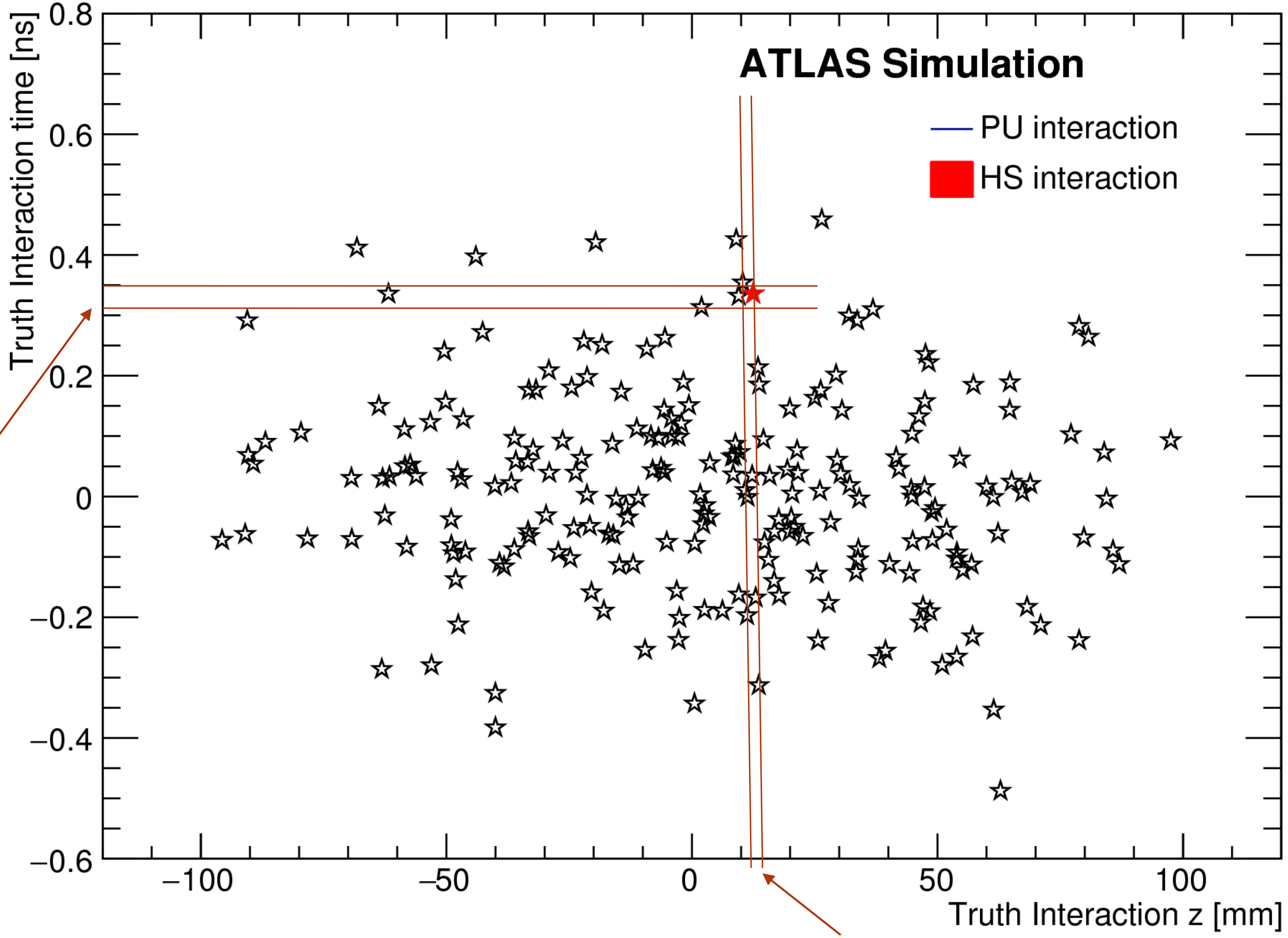
HGTD motivation

- With increased instantaneous luminosity the biggest challenge will be the **Pileup**
  - Beam profile σ_z = 50 mm, σ_t = 180 ps, 1.44 vertex/mm
  - Pileup will be ~6 times higher than current pileup
  - Especially troublesome in the forward region
- The new ITk tracker will have a better position resolution and extended pseudo-rapidity
  - However Z0 (impact parameter) resolution for end-cap tracks at η > 3 is order of ~mm
- **With timing information** from HGTD the **pileup effects can be further reduced** (see next slide)





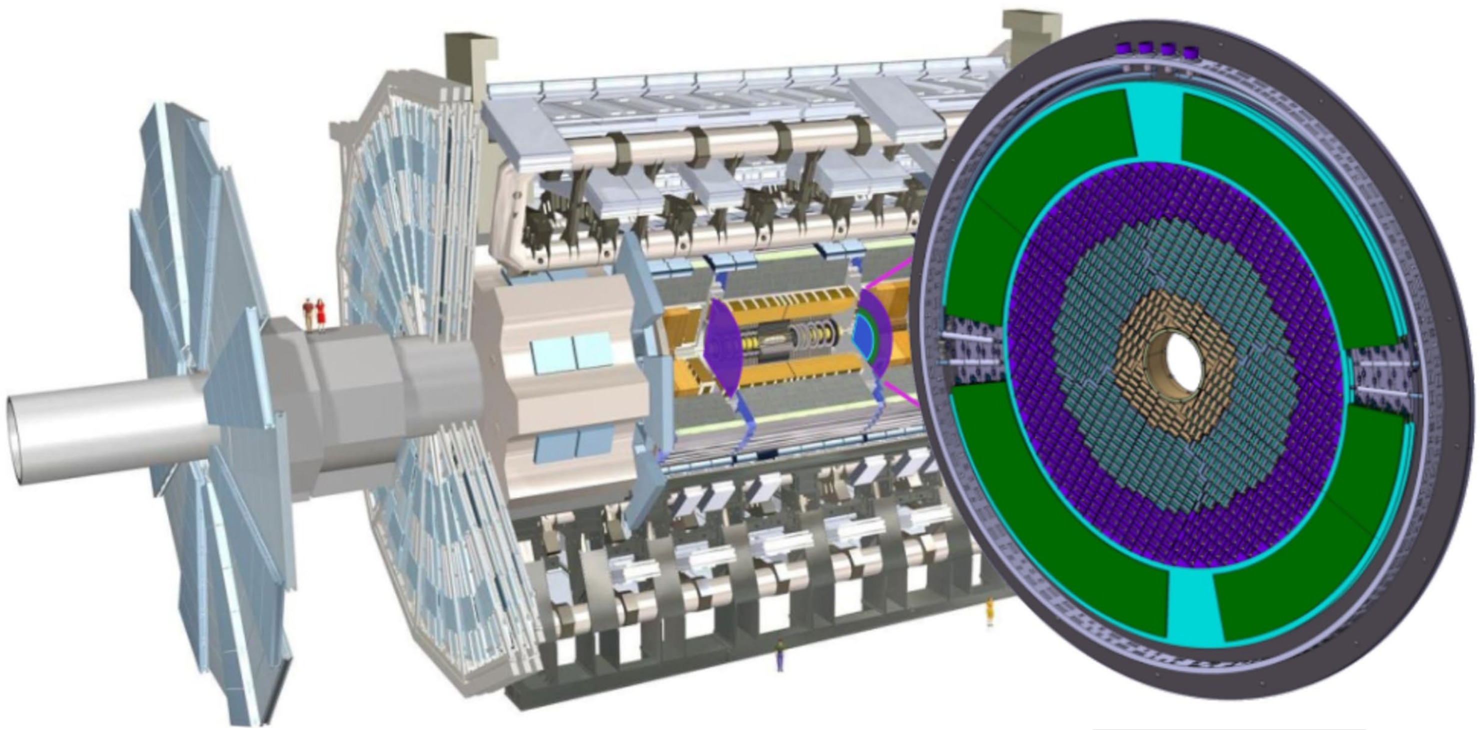
ATLAS HGTD TDR

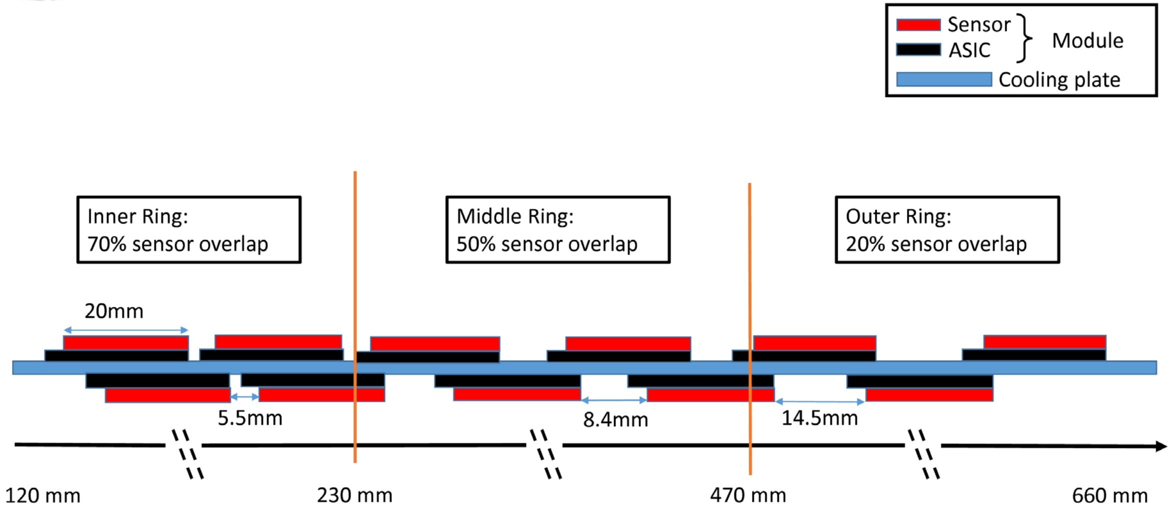


With the timing information the HS interaction is easier to identify

Several pileup events overlap with the HS event if only the position is used

HGTD layout





Structure

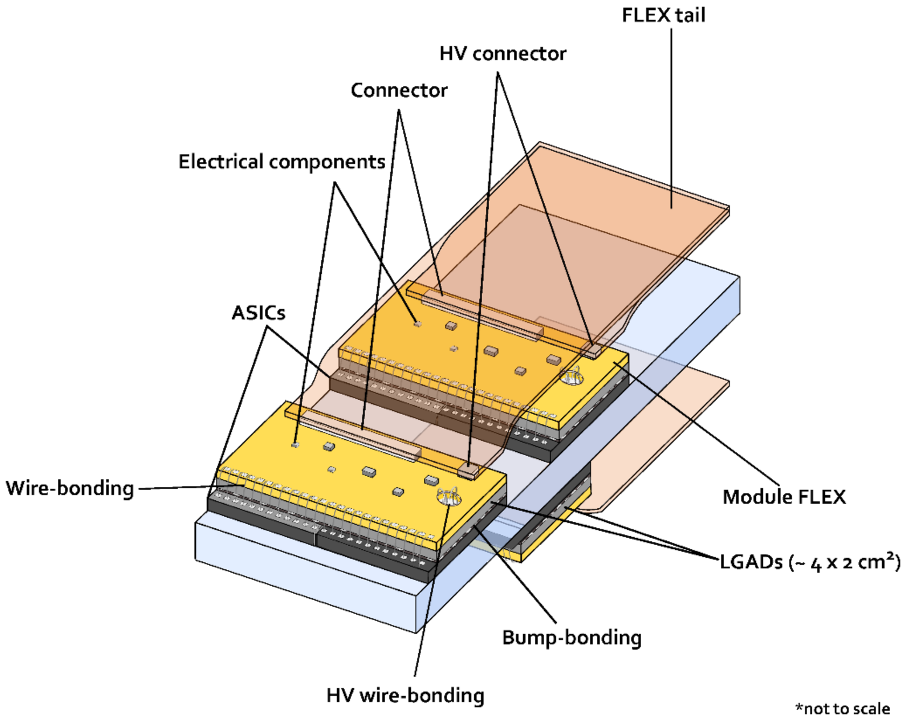
- Two double-instrumented disks in the end-cap
- Rotated by 15° in opposite directions to avoid gaps
- $2.4 < |\eta| < 4$, $120\text{ mm} < r < 640\text{ mm}$
- Structure is divided in concentric 3 rings with different active sensor overlap (70%, 50%, 20%)
- Number of hits per tracks: 2.6, 2.4, 2

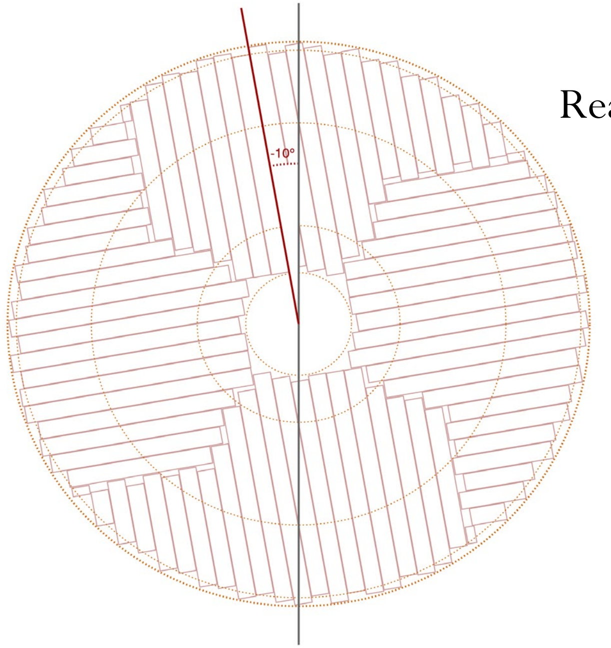
Requirements

- Time resolution < 30-50 ps per track, < 35-70 ps per hit (start-finish)
- Occupancy < 10%
- Fill factor > 85%
- Total power dissipation < 500 $^{mW}/_{cm^2}$
  - <100 $^{mW}/_{cm^2}$ sensor-only
- Radiation damage: 2.5E15 N_{eq}/cm^2 and 2 MGy

HGTD modules and readout

- 8032 modules to be installed (sensor + chip)
  - Two 15x15 LGAD sensors with pads of 1.3x1.3 mm^2
  - Bump bonded to two 15x15 ASIC
- Modules arranged in readout staves
- Modules are glued to flex that provides LV (ASIC), HV (sensor) and module readout
  - ASIC output wire-bonded to the flex
- Flex cable goes to periphery electronics
  - Then sent off detector to USA15 service cavern with optical link
- HV brought separately for each module
  - To adjust the voltage for radiation damage at different radii
- CO_2 cooling system will keep the sensors at -30 °C
  - Power consumption constrained by cooling power

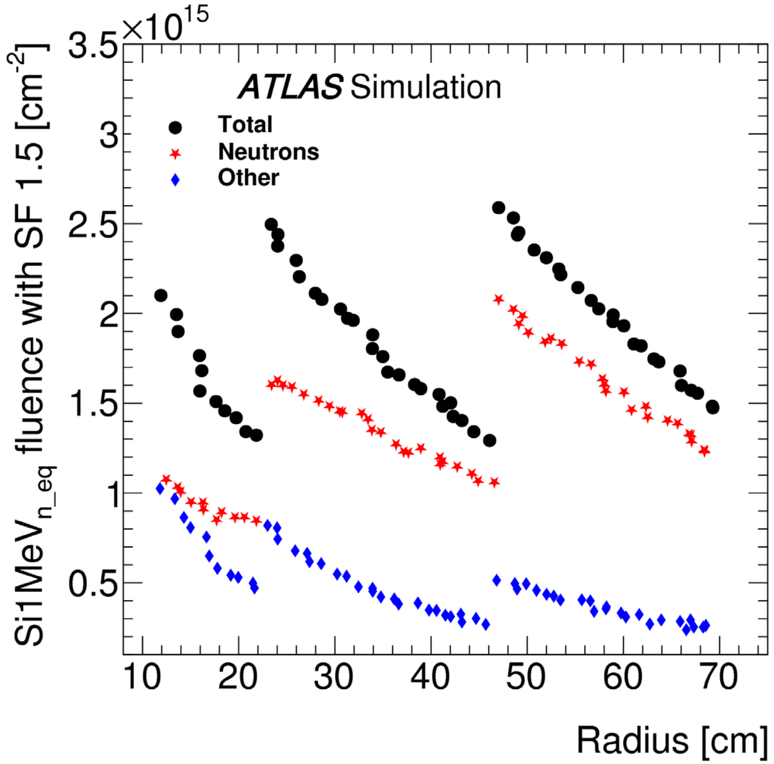


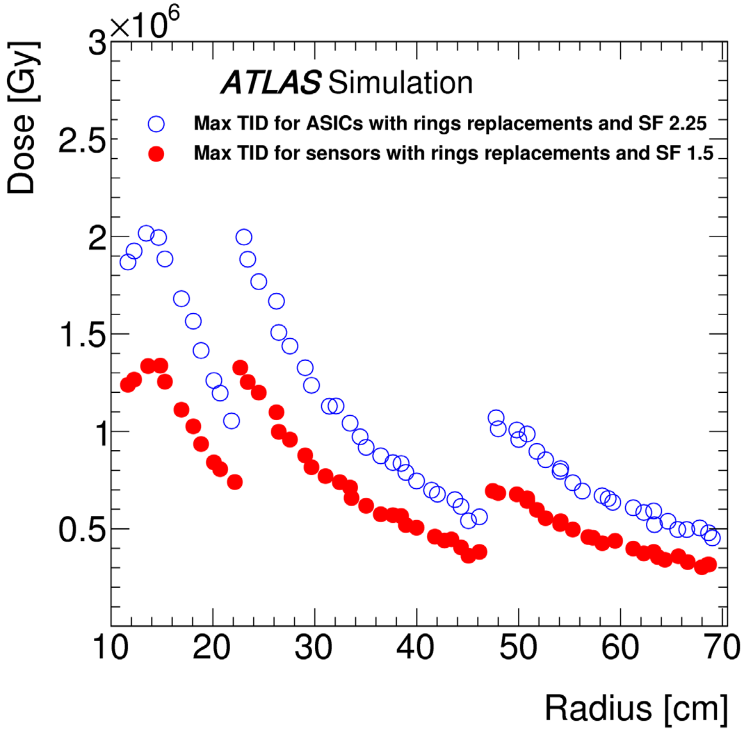


Readout staves structure

Radiation damage sustained

- Total fluence for HGTD is
  - ~1E16 N_{eq}/cm^2 at 10 cm radius (central region).
  - ~2E15 N_{eq}/cm^2 at 32 cm radius.
  - Values are taking into account a ~2 safety factor.
- **Inner and middle rings are substituted at intermediate points in the HL-LHC run** (4000 fb^{-1})
  - Inner ring every 1000 fb^{-1} (3 times)
  - Middle ring at 2000 fb^{-1} (once)
- Total radiation damage < 2.5E15 N_{eq}/cm^2 and < 2 MGy
- Part of radiation damage is from neutrons, part from charged particles
  - In the innermost ring 1E15 Neq from neutrons and 1E15 Neq from other particles

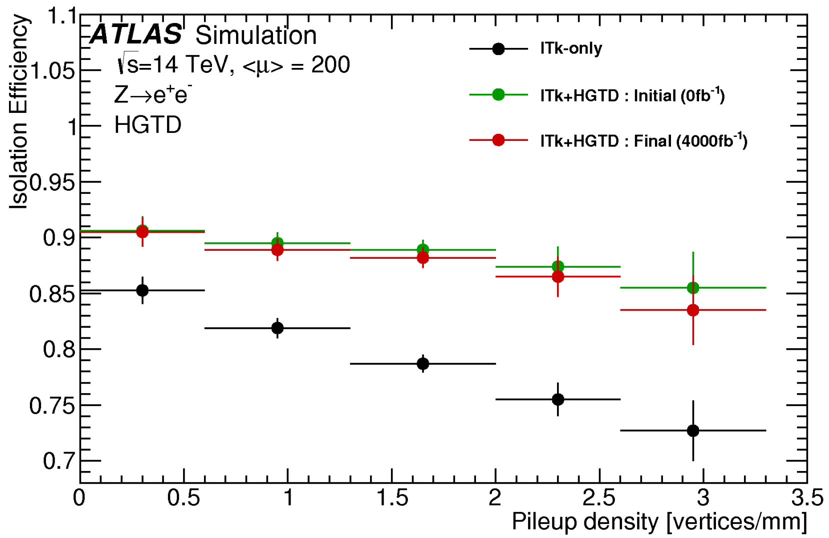


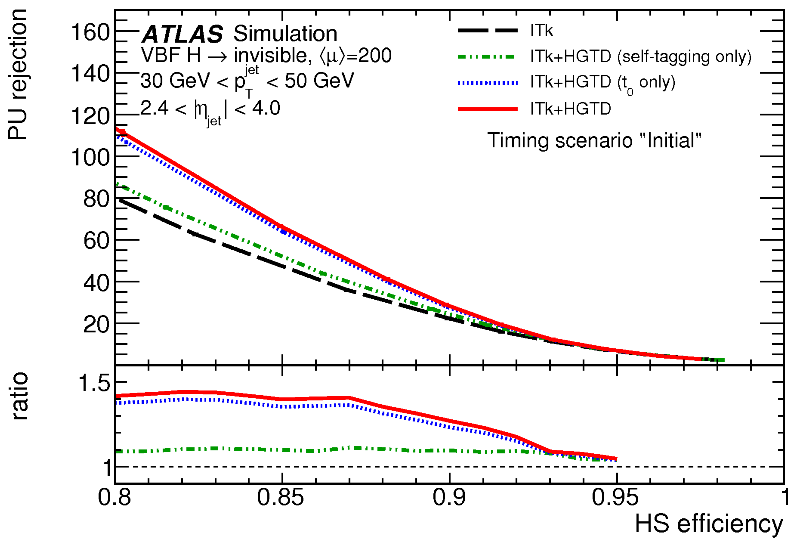


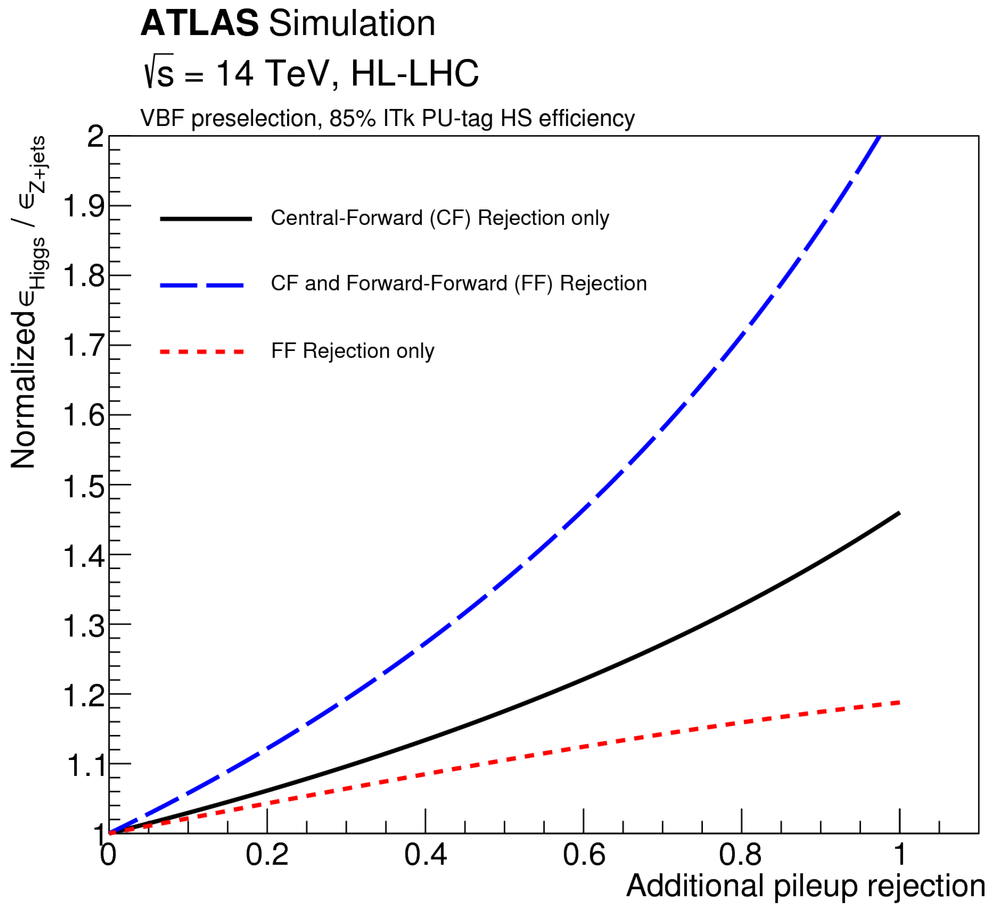
ATLAS HGTD TDR

HGTD physics enhancement

- Increased pileup rejection and better track to vertex association will allow for increased physics performance
  - Lepton isolation efficiency increased up to 25%
  - Jet pileup rejection increases by a factor 1.4 (for 85% efficiency)
- With better jet PU rejection the S/N increases for analyses subject to pileup background (e.g. VBF H→ invisible)



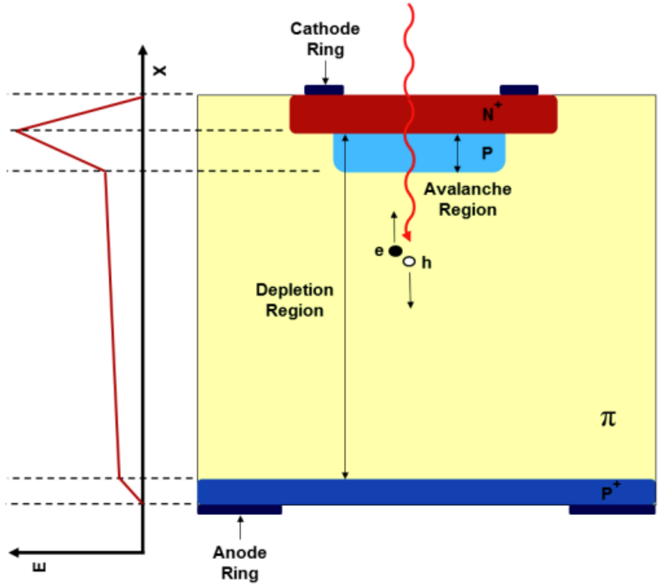


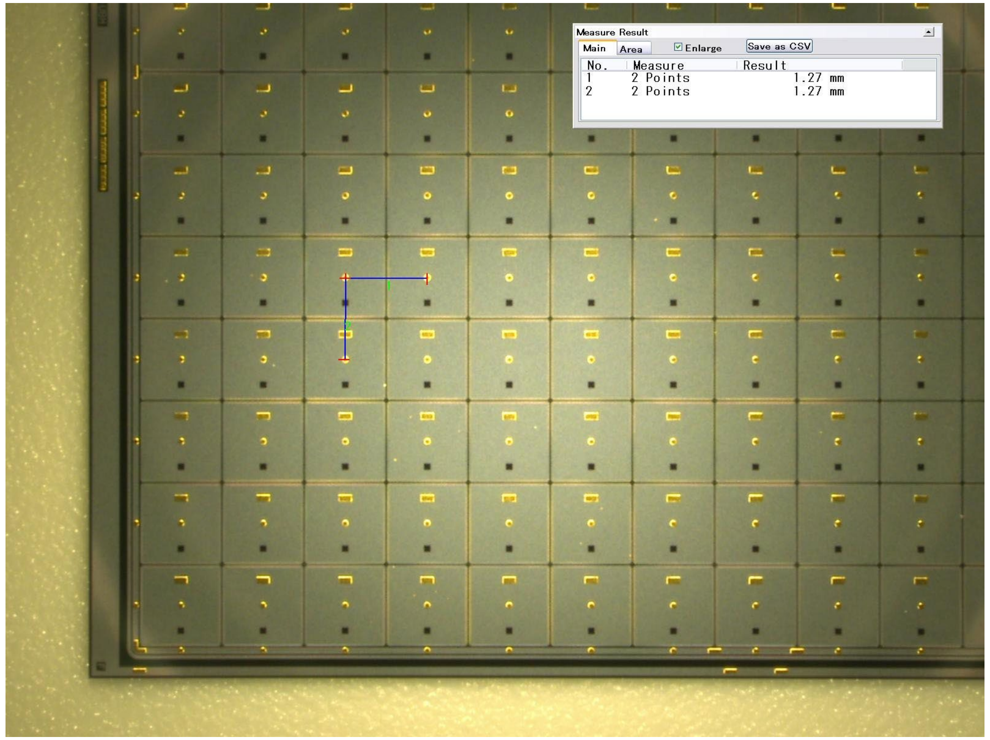


HGTD sensors - LGADs

- Chosen technology for ATLAS HGTD is **Low Gain Avalanche Diode (LGAD)**
- Silicon detector with a thin (< 5 µm) and highly doped (~10^{16}) multiplication layer
  - High electric field in the multiplication layer
- LGADs have intrinsic modest internal gain (10-50)
  - $G = \frac{Q_{LGAD}}{Q_{PiN}}$ (collected charge of LGAD vs same size PiN)
- **~50 µm active thickness detectors**
  - Thinner detectors have shorter rise time and less Landau fluctuations
  - Gain allows for great signal to noise ratio even in thin substrate
- Good radiation resistance (up to a few 1E15 Neq)
- **Time resolution < 30 ps**
- More details: LGADs for HGTD poster at PSD12

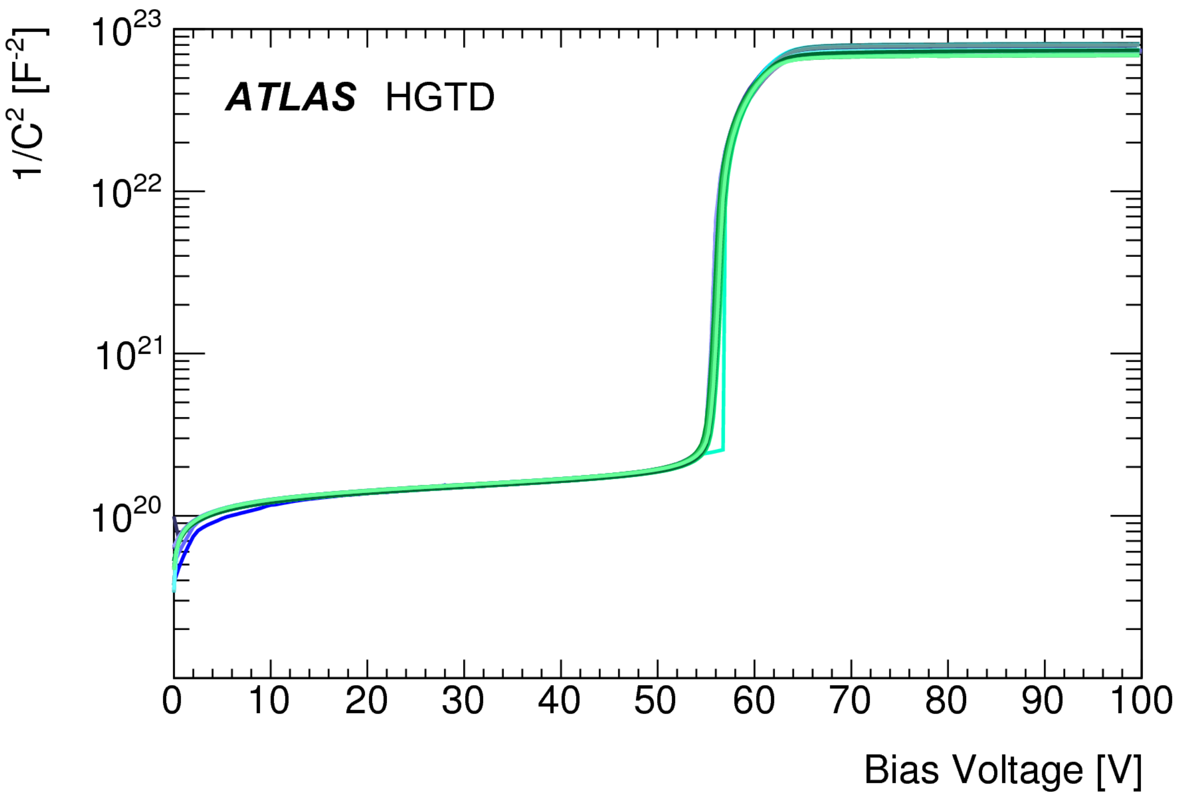
- HGTD working with several vendors of thin LGADs
  - CNM (Spain), HPK (Japan), FBK (Italy), BNL (USA), NDL/IMEI (China)

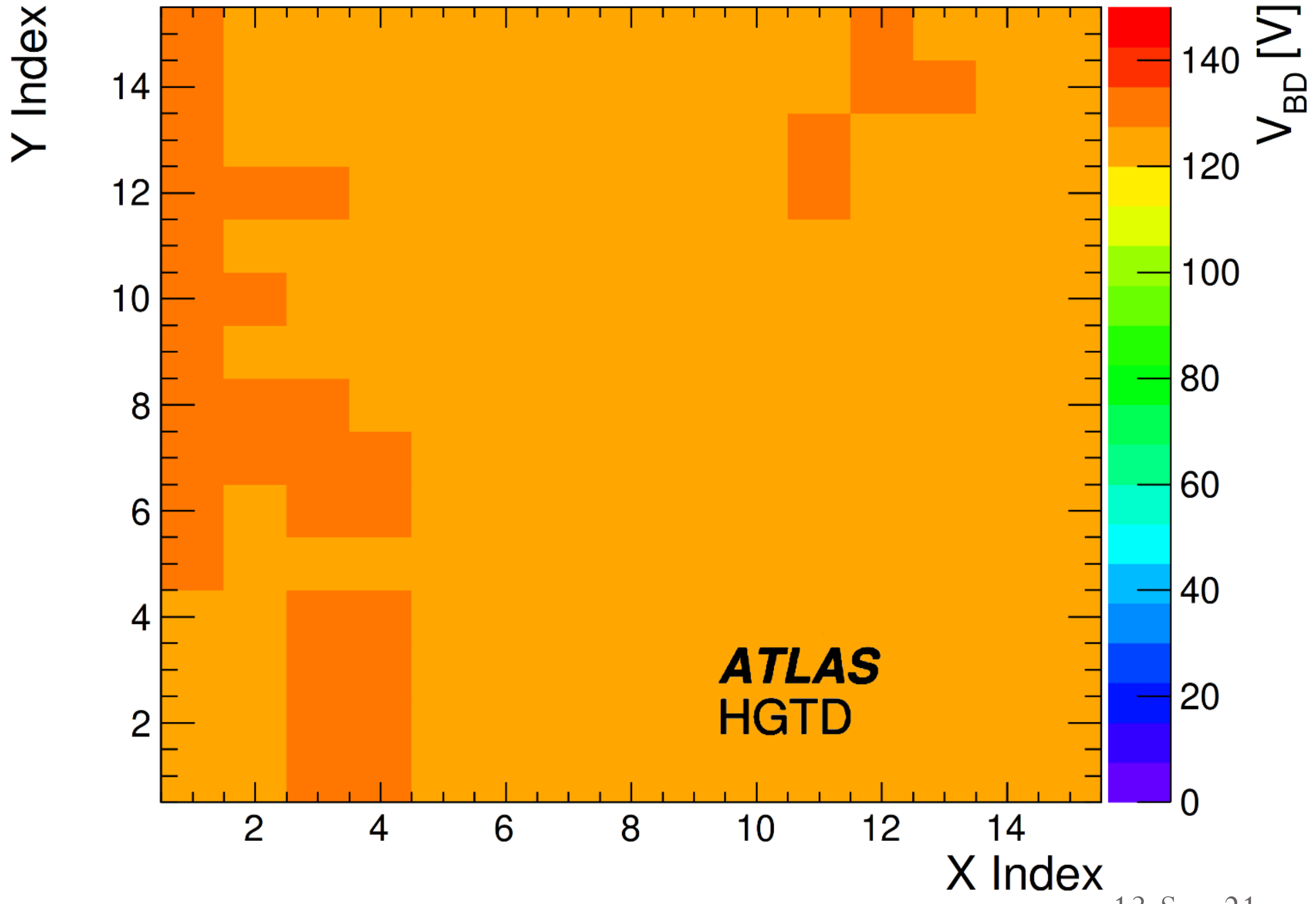




LGAD production stability

- LGAD production was proven to be very stable and consistent
  - Prototypes of final sensor arrays (15x15) produced and tested to be working
- Left: $1/C^2$ plot of several HPK-3.2 sensors show a very stable "foot" (flat part before full depletion, proportional to gain layer doping)
- Right: breakdown voltage is stable for each pad in a 15x15 array (HPK-3.2)

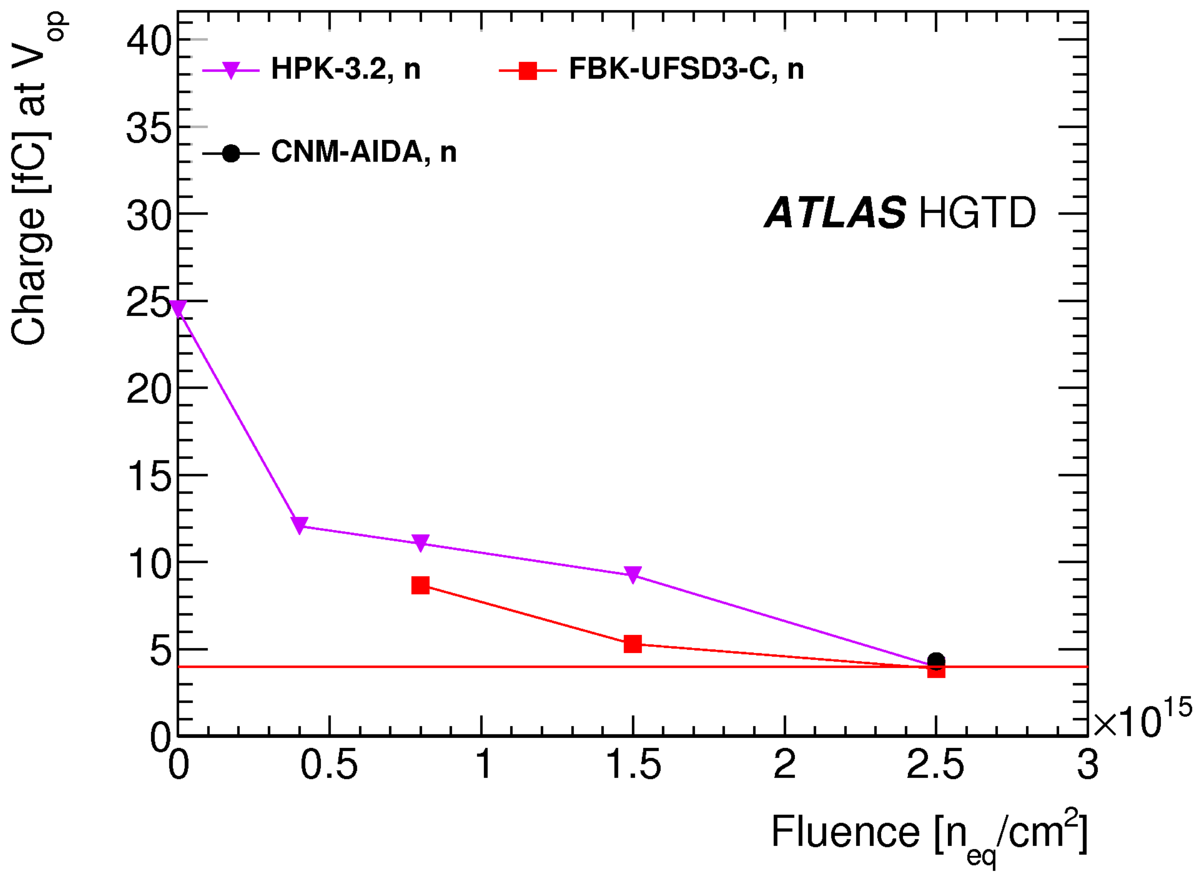


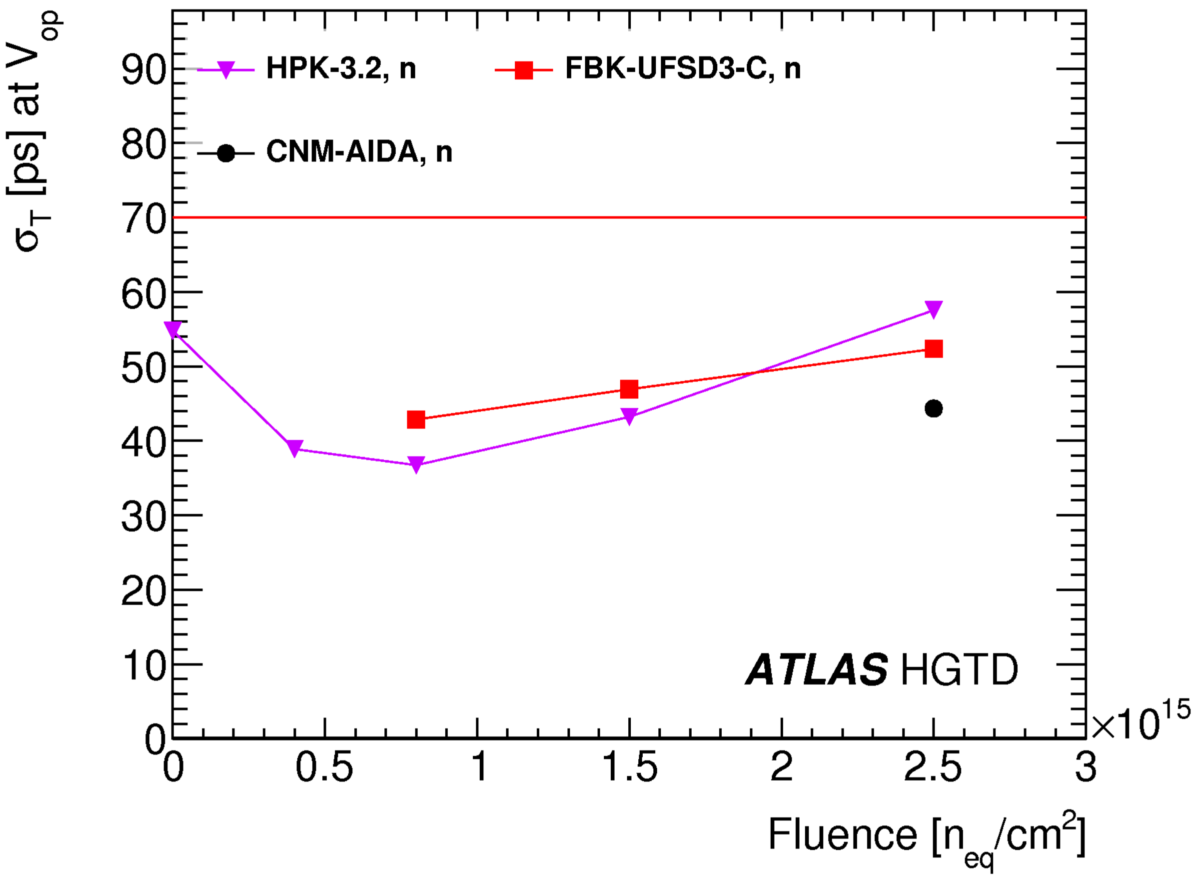


ATLAS HGTD TDR

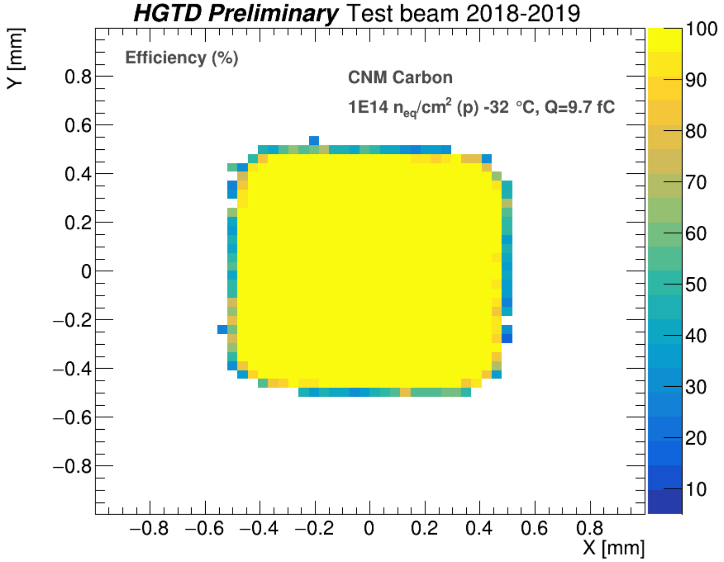
LGAD performance with radiation damage

- Performance of LGADs at Vop during the lifetime of HGTD (based on laboratory Sr90 measurements)
  - Vop: operating voltage chosen at every fluence to satisfy requirements
- 4 fC requirement (for the electronics to work properly) reached at the max fluence by 3 vendors
- Time resolution < 60 ps for the entire life time
- **New LGAD productions** from HPK and FBK **show even better performance** (results at PSD12 here)
- For CNM AIDA run plus Bo-Ga and Carbon infused LGADs results at PSD12 see here

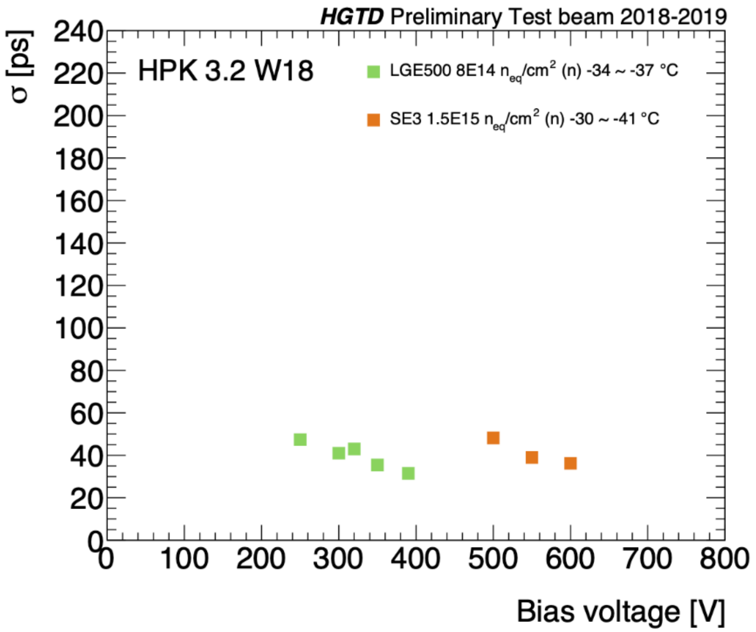




Test beam – DESY 5 GeV electron facility



- DESY test-beam with 5 GeV electrons
  - DURANTA tracking telescope provides hit position
  - SiPM coupled to Cherenkov light emitting quartz bars provide timing reference
  - Sensors mounted in fast electronics board (2 GHz bandwidth) and digitized by a fast scope

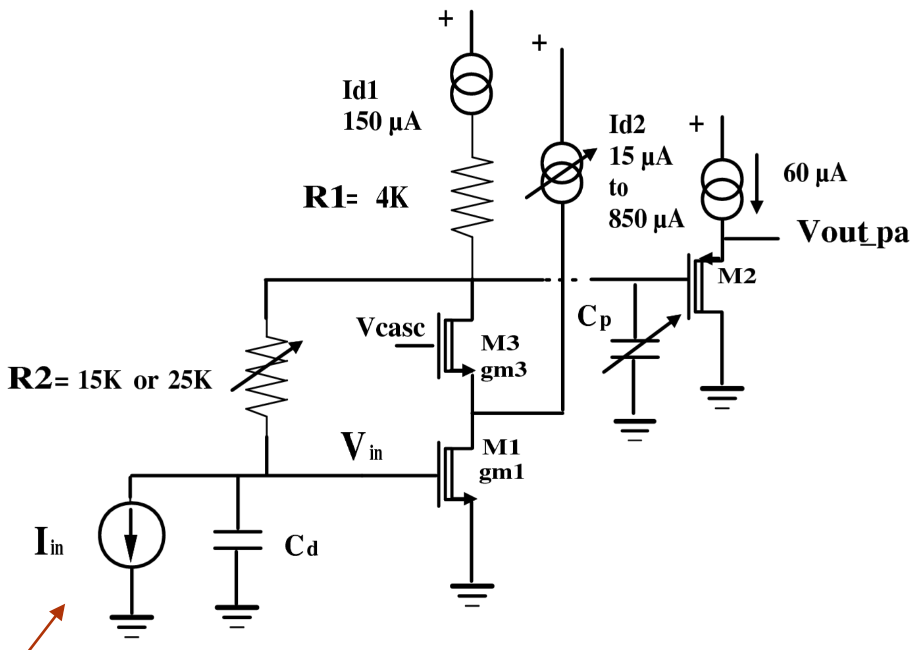


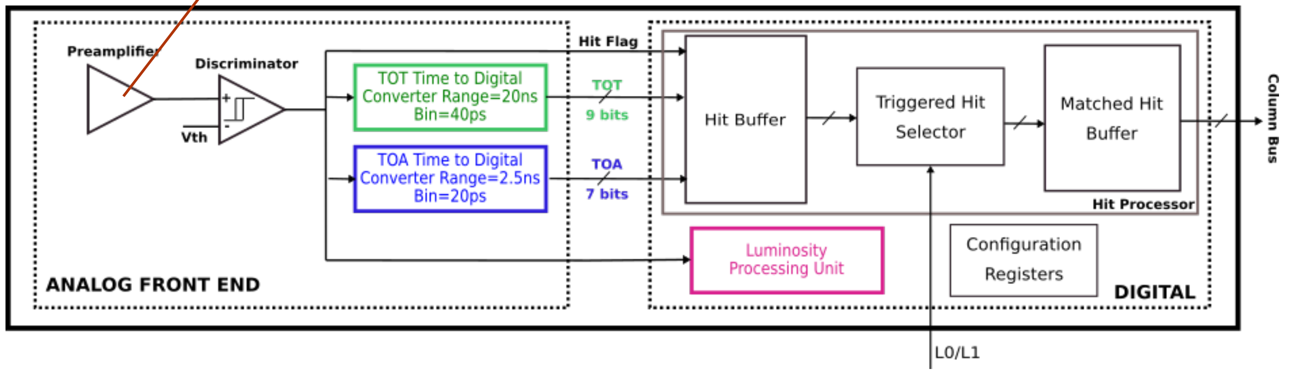
- CNM sensor irradiated to a fluence of 1E14 Neq
  - Hit efficiency is ~100% in the active area
  - Defined as hits on sensor with > 2 fC response
- Time resolution for HPK 3.2 sensors irradiated at 8E14 Neq and 1.5E15 Neq
  - Time resolution < 40 ps

ATLAS LGAD Timing Integrated ReadOut Chip (ALTIROC)

- HGTD ALTIROC integrated chip for LGAD readout
- Preamplifier: fast broad band amplifier
  - Rise time ~0.5-1 ns (as the sensor)
- **TOA (Time of Arrival) of the signal is corrected with TOT (Time over threshold)**
  - ToA and ToT TDCs with slow and fast delay line with 20ps (ToA) and 40ps (TOT) time measurement bins
  - **ToT correction minimizes the time walk contribution to the time resolution**
- Bunch by bunch luminosity measurement capability
  - Sums of hits in two time windows to evaluate the background bunch by bunch
- ALTIROC has to withstand 2 MGy (max dose)

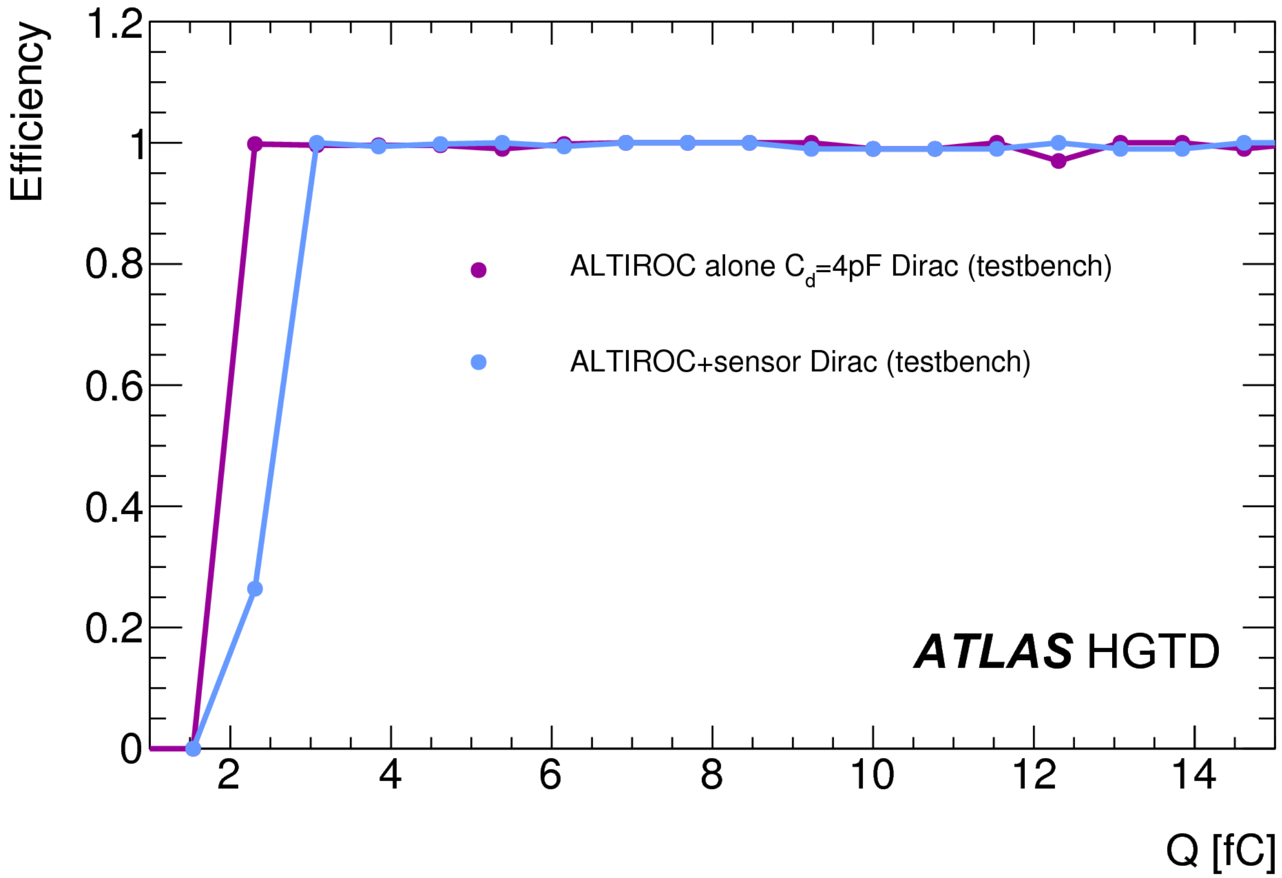
- ALTIROC1 produced and tested (2018)
  - 5x5 channels amplification and TOT correction with digital components
  - Performance in the next slides
- Next: ALTIROC2
  - 15x15 channels, all functionalities of the final ASIC

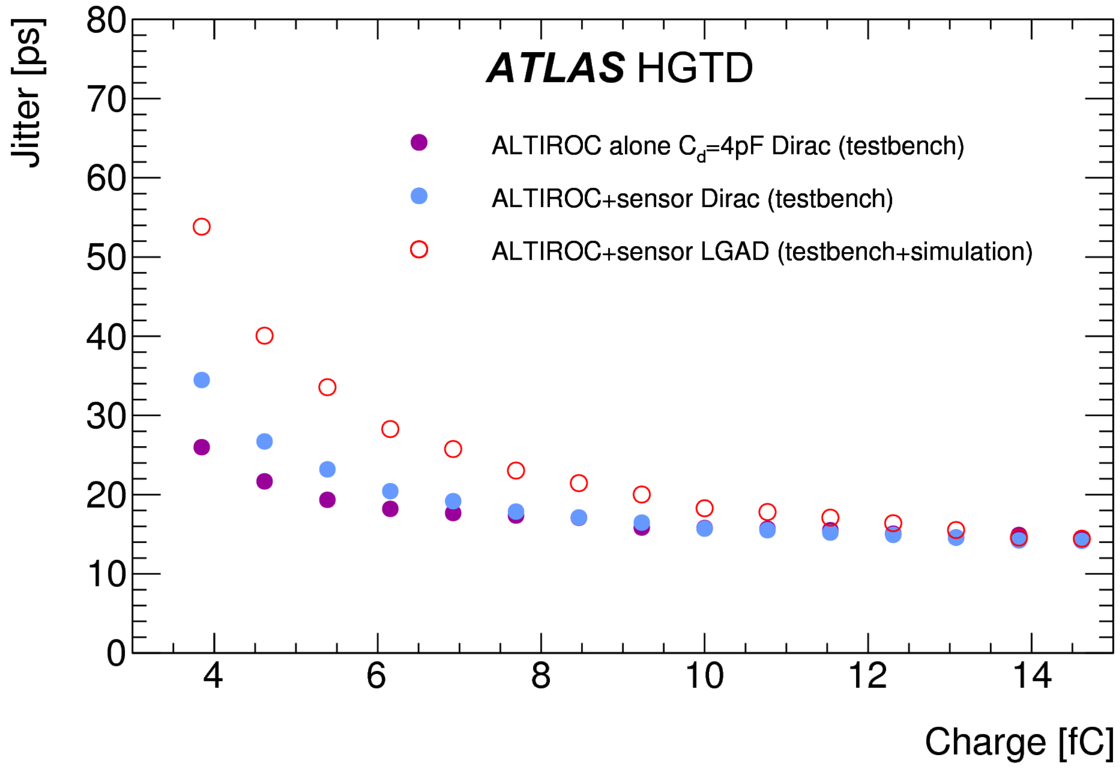




ALTIROC1 performance (test-bench)

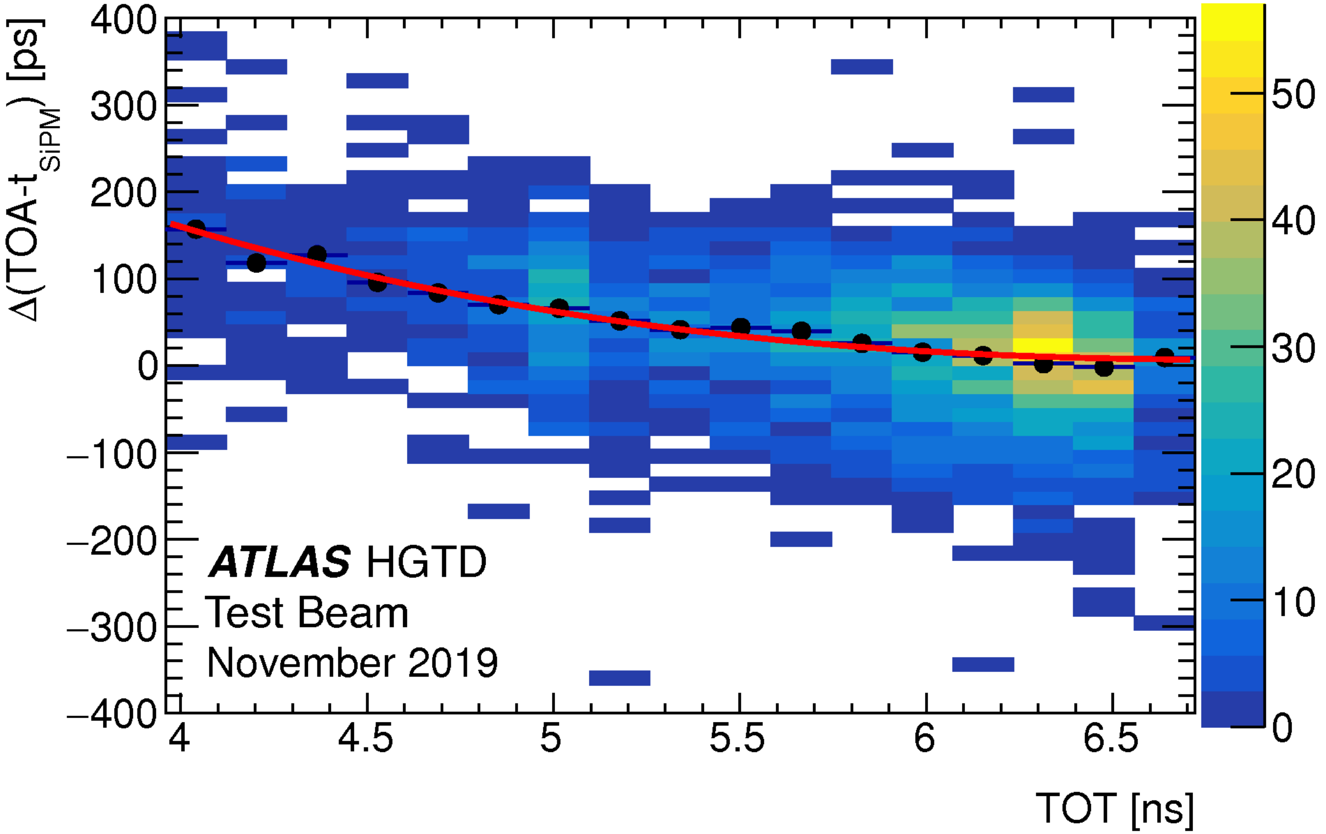
- ALTIROC1 shows 100% hit efficiency for collected charge > 2.5 fC (lab tests)
- ~55 ps jitter for collected charge > 4 fC (lab test with sensor simulation)
  - Reason for LGAD requirement of > 4 fC
- Irradiation tests show a negligible amplitude loss and a 10-15% increase in Jitter for 2 MGy of dose

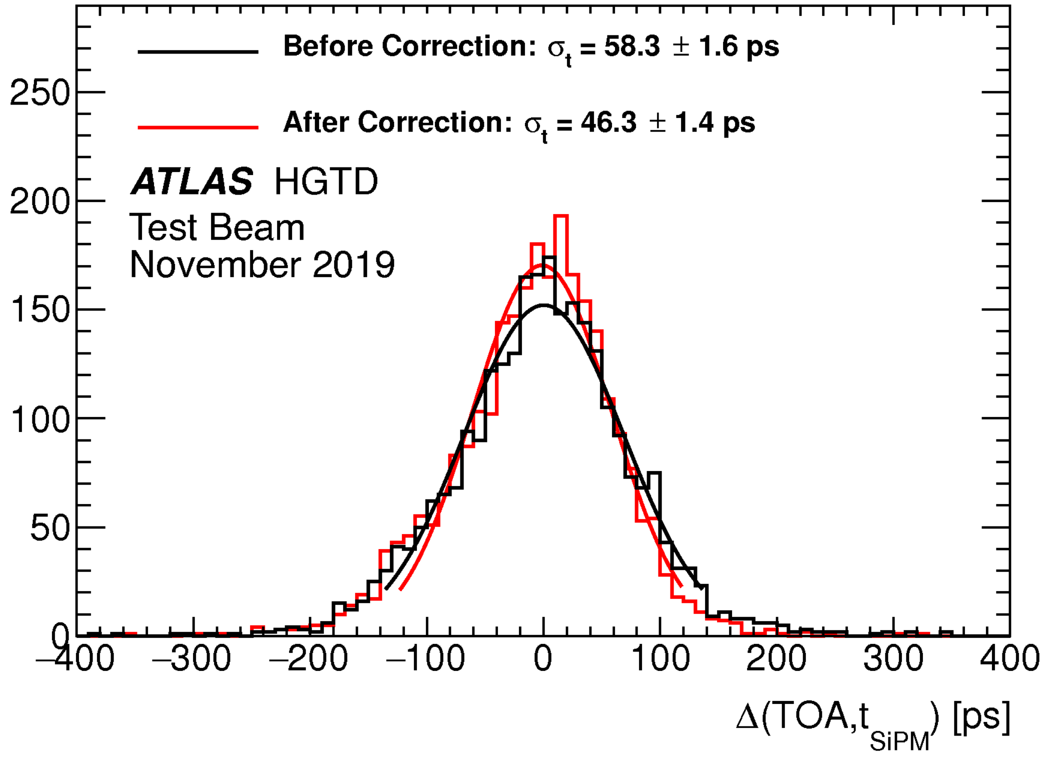




Mini-module performance in test beam

- ALTIROC 1v2 bump bonded to HPK 3.1 LGAD performance at DESY test beam
- ToA correction as a function of ToT is applied (fitted red line)
- Before corrections the time resolution is ~58 ps, after correction is ~46 ps (39 ps Jitter)
  - Worse performance than expected (26 ps Jitter) was observed due to increased noise in TB conditions





Conclusions

Run 3 starting soon

HGTD Production

Installation

Data taking

- **HGTD is going forward as scheduled**
  - Expected to enter production in 2023 and installation in 2025
  - Ready for data taking in 2027
- **First large-scale application of LGAD technology**
- It will be a powerful new tool to reduce the pileup contribution in the ATLAS end-cap
  - Providing track time resolution of 35-50 ps for the entire HL-LHC run time
- Preliminary simulations show good object reconstruction and **physics performance enhancement**

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This work was partially performed within the CERN RD50 collaboration.

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Abstract

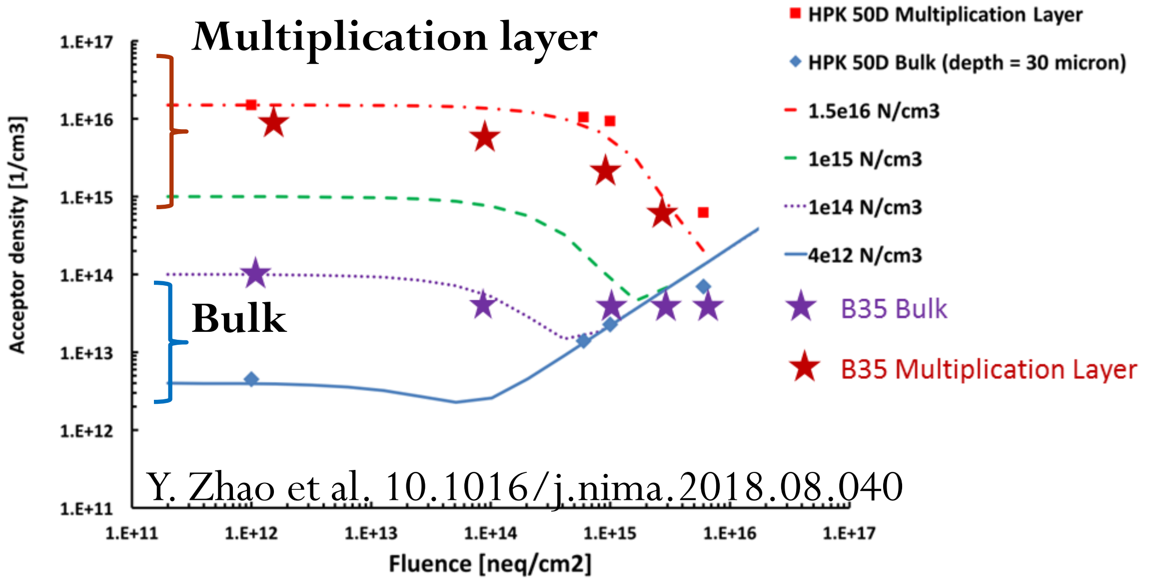
The increase of the particle flux (pile-up) at the HL-LHC with instantaneous luminosities up to L ≃ 7.5 × 10 34 cm-2s-1 will have a severe impact on the ATLAS detector reconstruction and trigger performance. The end-cap and forward region where the liquid Argon calorimeter has coarser granularity and the inner tracker has poorer momentum resolution will be particularly affected. A High Granularity Timing Detector (HGTD) will be installed in front of the LAr end-cap calorimeters for pile-up mitigation and luminosity measurement.

The HGTD is a novel detector introduced to augment the new all-silicon Inner Tracker in the pseudo-rapidity range from 2.4 to 4.0, adding the capability to measure charged-particle trajectories in time as well as space. Two silicon-sensor double-sided layers will provide precision timing information for minimum-ionising particles with a resolution as good as 30 ps per track in order to assign each particle to the correct vertex. Readout cells have a size of 1.3 mm × 1.3 mm, leading to a highly granular detector with 3.7 million channels. Low Gain Avalanche Detectors (LGAD) technology has been chosen as it provides enough gain to reach the large signal over noise ratio needed.

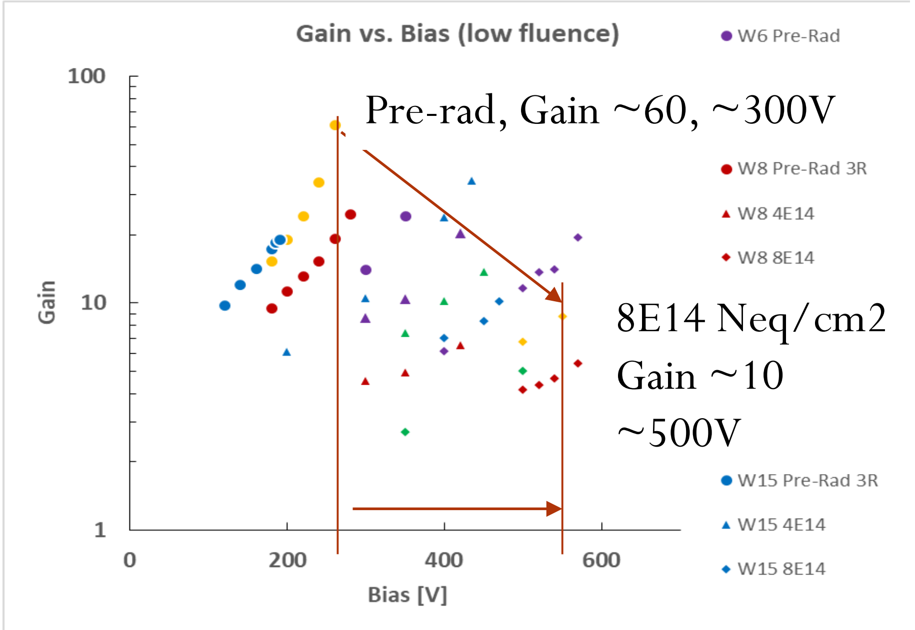
The requirements and overall specifications of the HGTD will be presented as well as the technical design and the project status. The on-going R&D effort carried out to study the sensors, the readout ASIC, and the other components, supported by laboratory and test beam results, will also be presented.

Radiation damage on LGADs

- Most widely accepted radiation damage explanation for LGADs is **acceptor removal**
  - M. Ferrero et al. arXiv:1802.01745, G. Kramberger et al. JINST **10** (2015) P07006
- Radiation damage for LGADs can be parameterized
  - $N_A(\phi) = g_{eff}\phi + N_A(\phi=0)e^{-c\phi}$
- Acceptor creation: $g_{eff}\phi$
  - By creation of deep traps
- Initial acceptor removal mechanism: $N_A(\phi=0)e^{-c\phi}$
  - Ionizing radiation produces interstitial Si atoms
  - Interstitials inactivate the doping elements (Boron) via kick-out reactions that produce ion-acceptor complexes
  - **Reduction of gain**



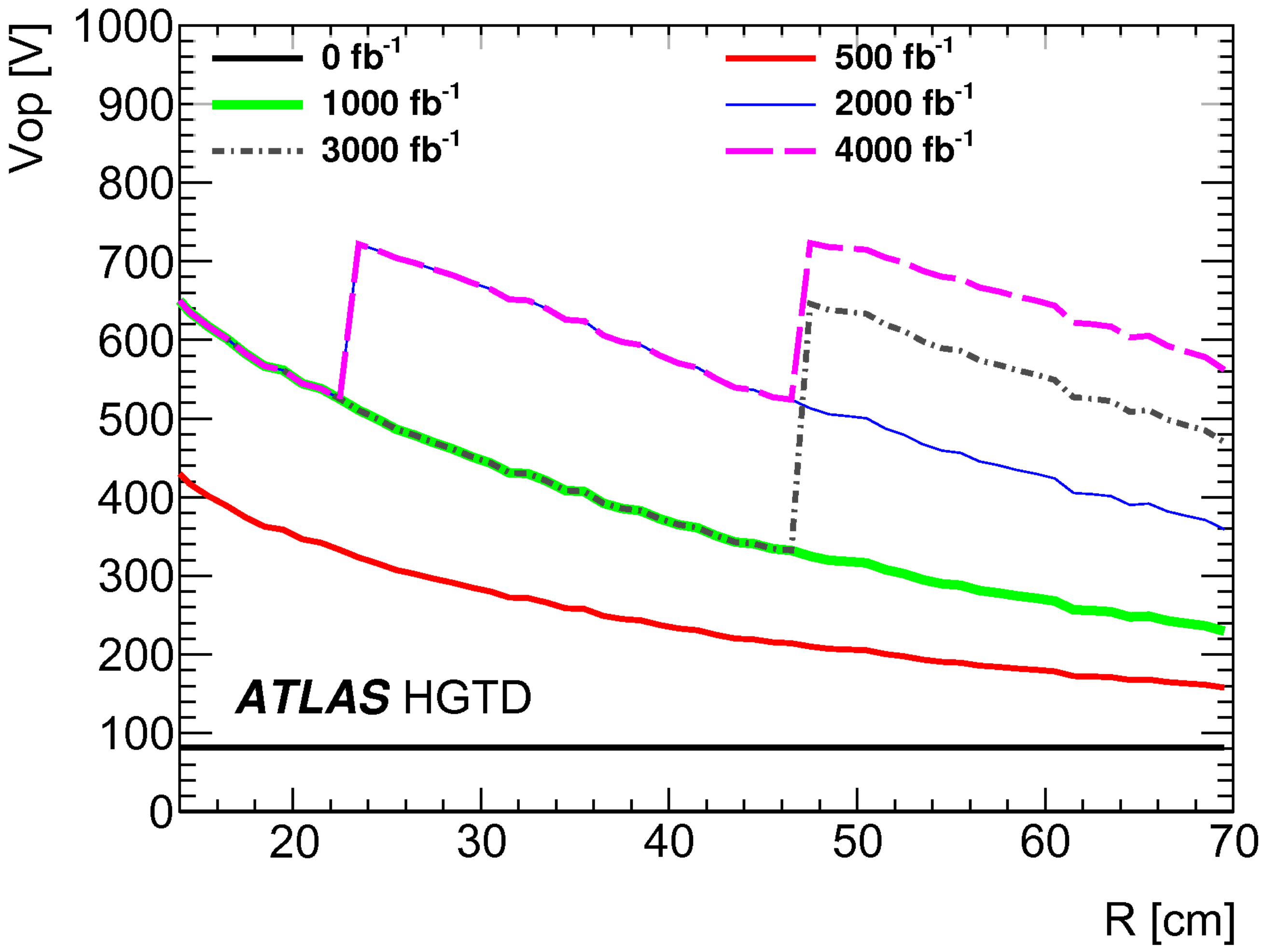
Y. Zhao et al. 10.1016/j.nima.2018.08.040



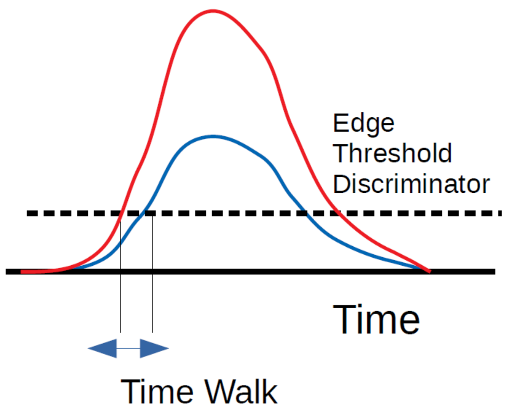
S.M. Mazza et al. arXiv:1804.05449

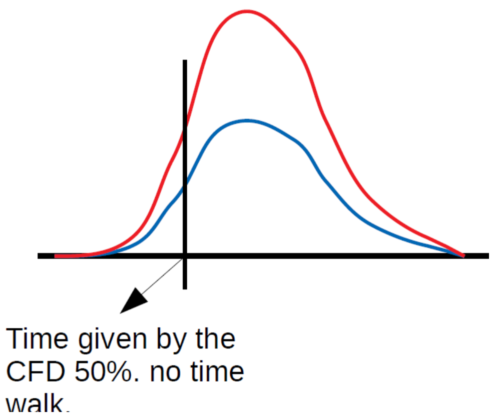
Bias voltage increase during run

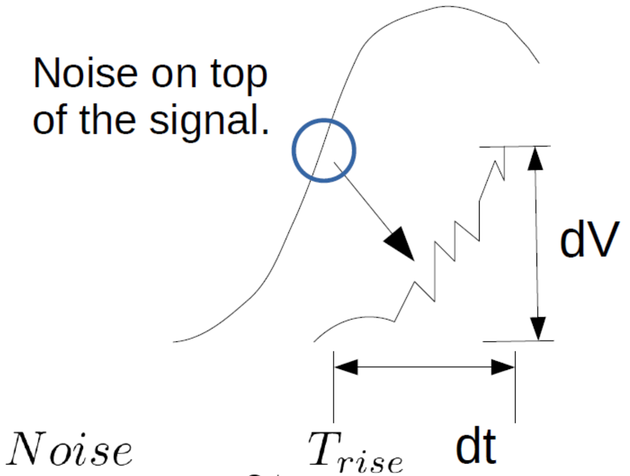
- The applied bias voltage in each HGTD section has to be increased accordingly to compensate for the radiation damage
- The dissipated power is less than $100\ ^{mW}/_{cm^2}$ until max fluence



LGADs timing resolution







$$\sigma_{Jitter} = \frac{Noise}{dV/dt[CFD\%]} \approx \frac{T_{rise}}{SNR}$$

Sensor time resolution main terms

$$\sigma^2_{timing} = \sigma^2_{time\,walk} + \sigma^2_{Landau\,noise} + \sigma^2_{Jitter} + \sigma^2_{TDC}$$

- Time walk:
  - Minimized by using for time reference the % CFD (constant fraction discriminator) instead of time over threshold
- Landau term:
  - Reduced for **thinner sensors** (50,35 μm)
- Jitter:
  - Proportional to $^1/_{\frac{dV}{dt}}$
  - Reduced by increasing S/N ratio with gain

Neutron vs proton irradiation