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

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on behalf of the ATLAS HGTD collaboration

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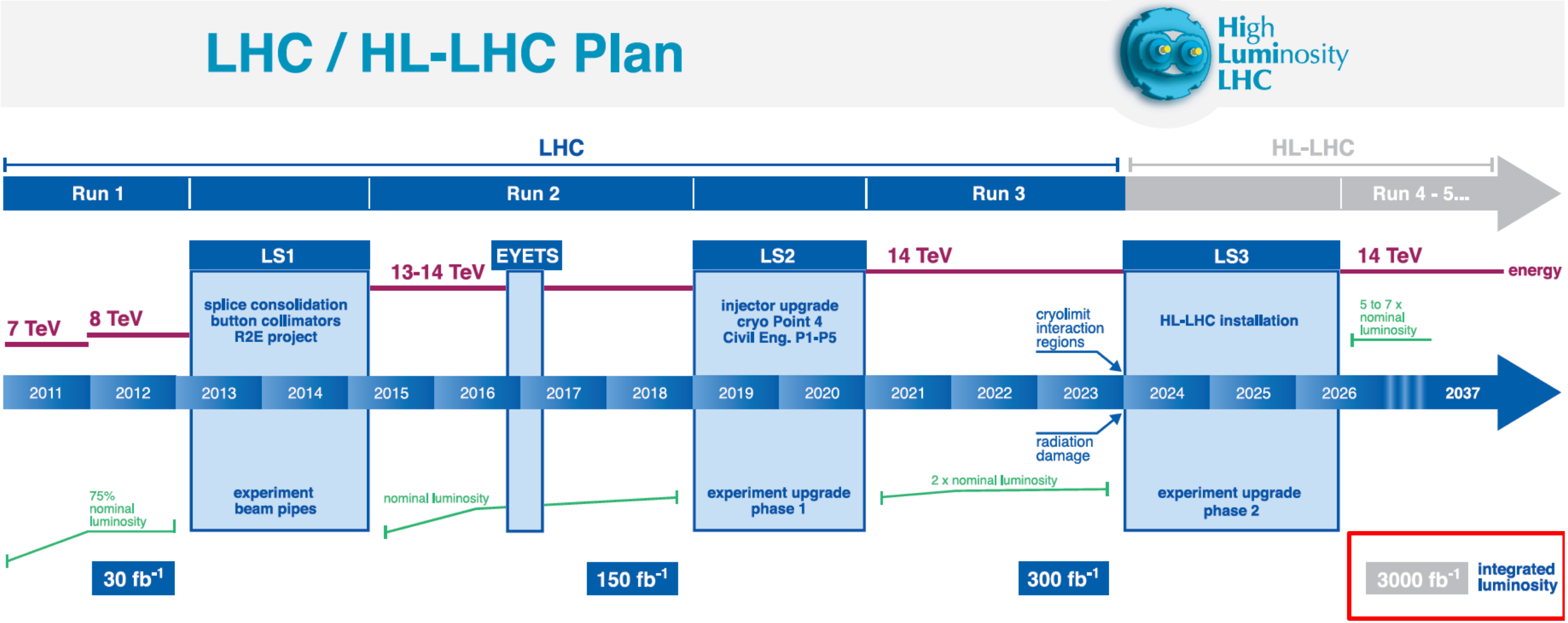
The High Luminosity LHC Upgrade

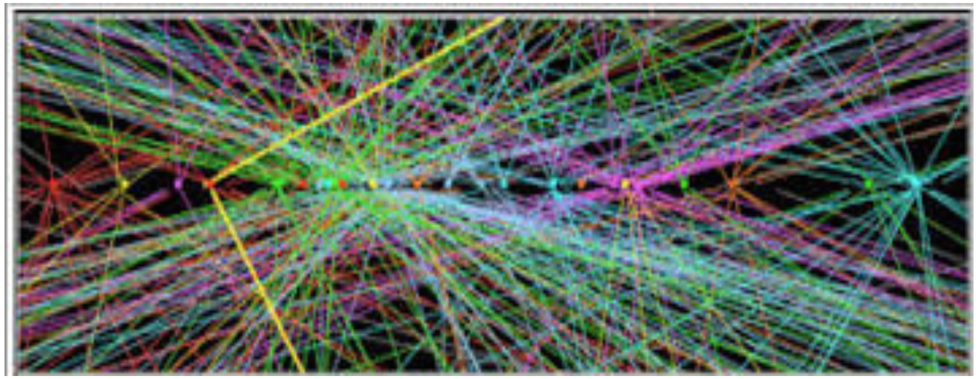


- Luminosity up to 7.5×10^{34} cm^{-2}s^{-1}, pileup $<\mu>$ ~200, irradiation level TID ~2MGy
- L1 trigger rate of 1 MHz. Additional 15 years of operation and maintenance.

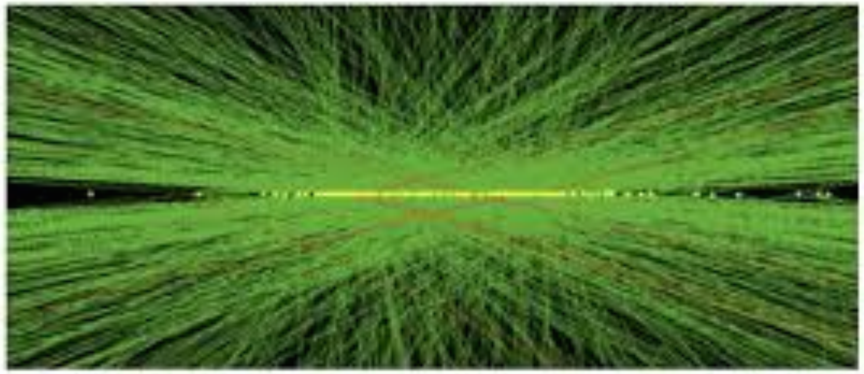
The High Luminosity LHC Challenges

Unprecedented opportunities with great challenges

- **Peak luminosity** could be $\mathbf{7.5 \times 10^{34}\ cm^{-2}s^{-1}}$
- **Statistics** enlarged **one order of magnitude** wrt Run 1 - 3 sample.
- Up to **200 p-p interactions** per bunch crossing!



Current LHC: mu ~40

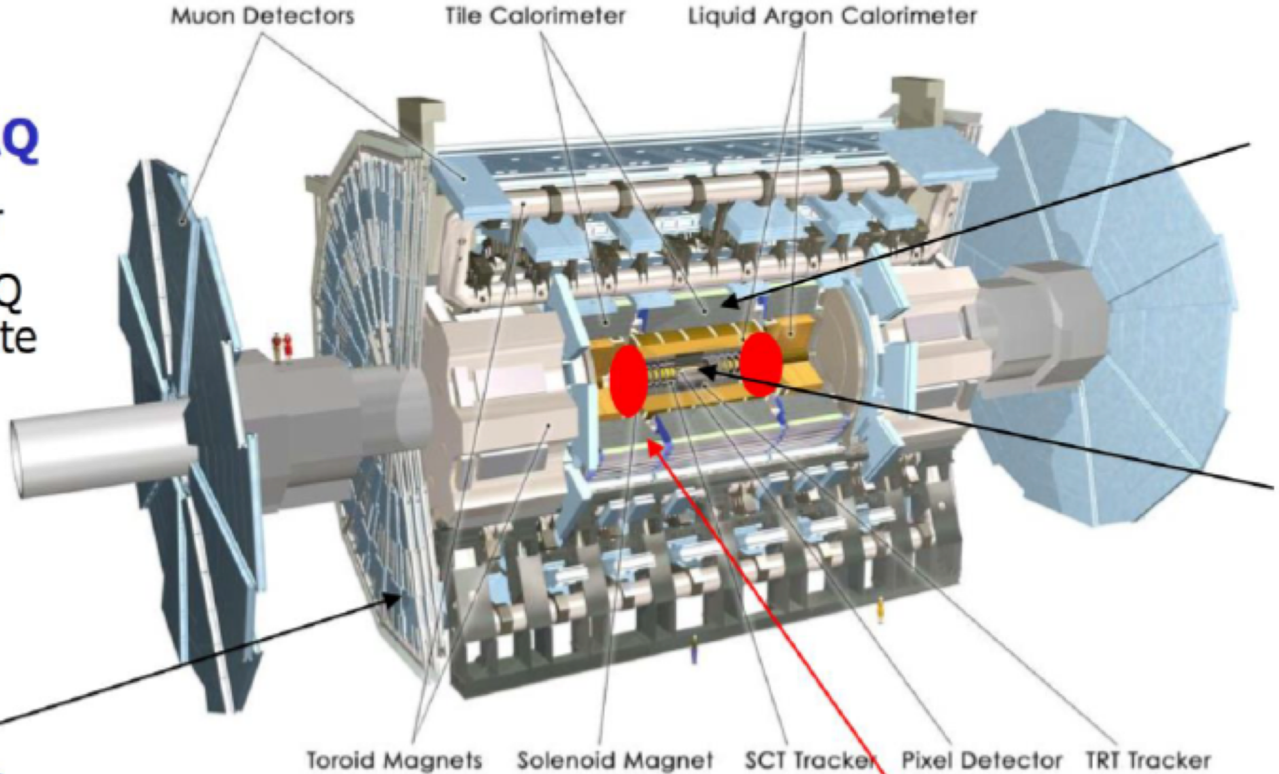


HL-LHC: mu~140-200

ATLAS Upgrade

Trigger + DAQ

- Track trigger
- Upgrade DAQ for higher rate



Calorimeters

- Upgrade electronics

Inner Tracker

- Full replacement: all-Si extended to $|\eta|=4$

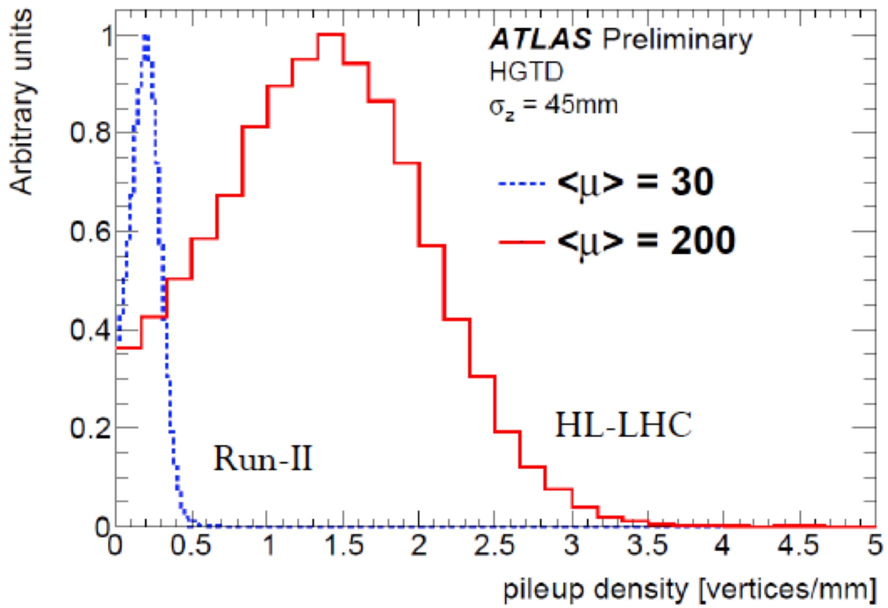
Muon System

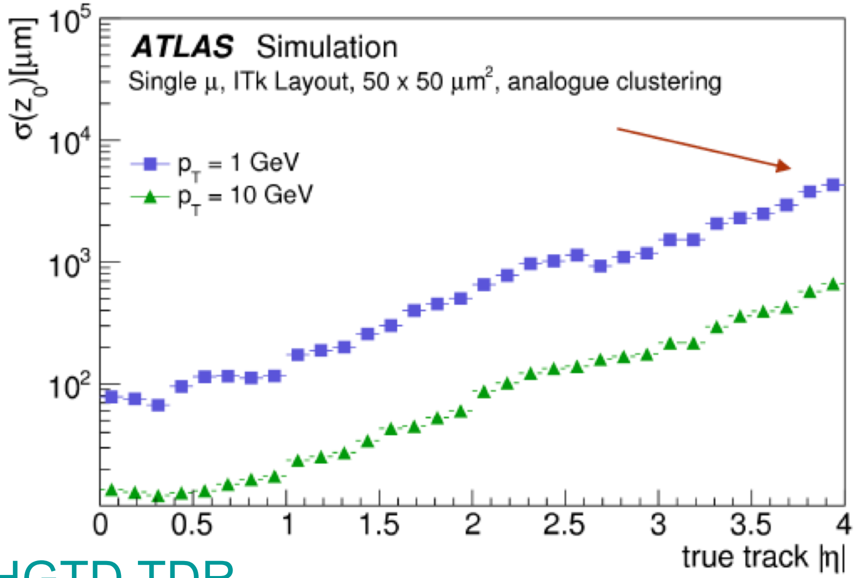
- New trigger chambers in barrel

- High Granularity Timing Detector
- Silicon-based novel detector

Motivation for HGTD

- For L= 7.5×10^{34} $cm^{-2}s^{-1}$, big **Pileup**.
  - Beam profile: σ_z = 50 mm, σ_t = 180 ps, 1.44 vertex/mm.
  - Especially problematic for low pT tracks in forward region.
- ITk tracker will provide better σ_z and extended coverage.
  - For η > 3, resolution is ~mm.
- HGTD can mitigate pileup effects with timing information (next slide).

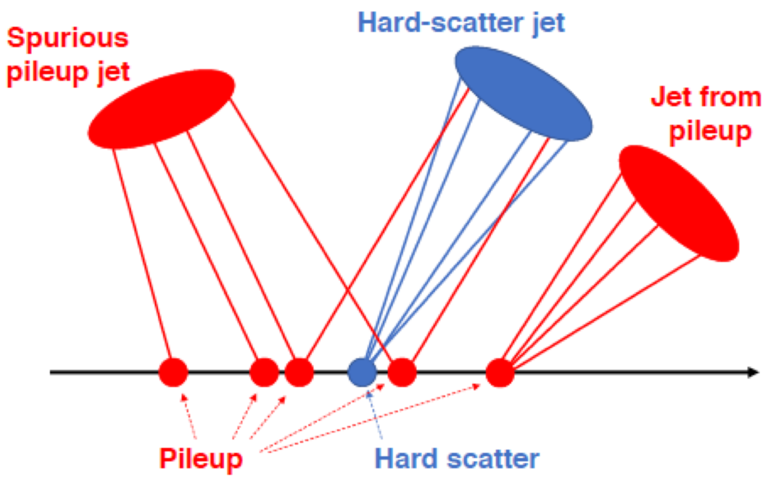


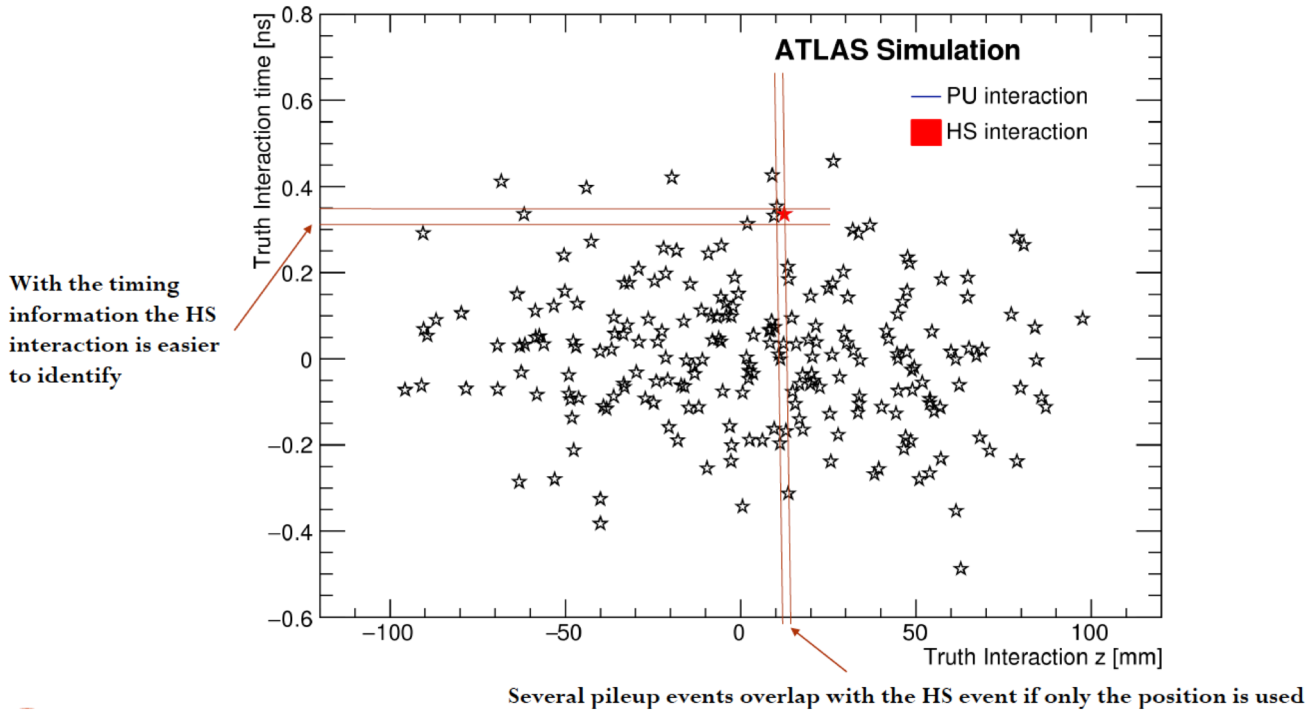


ATLAS HGTD TDR

Motivation for HGTD

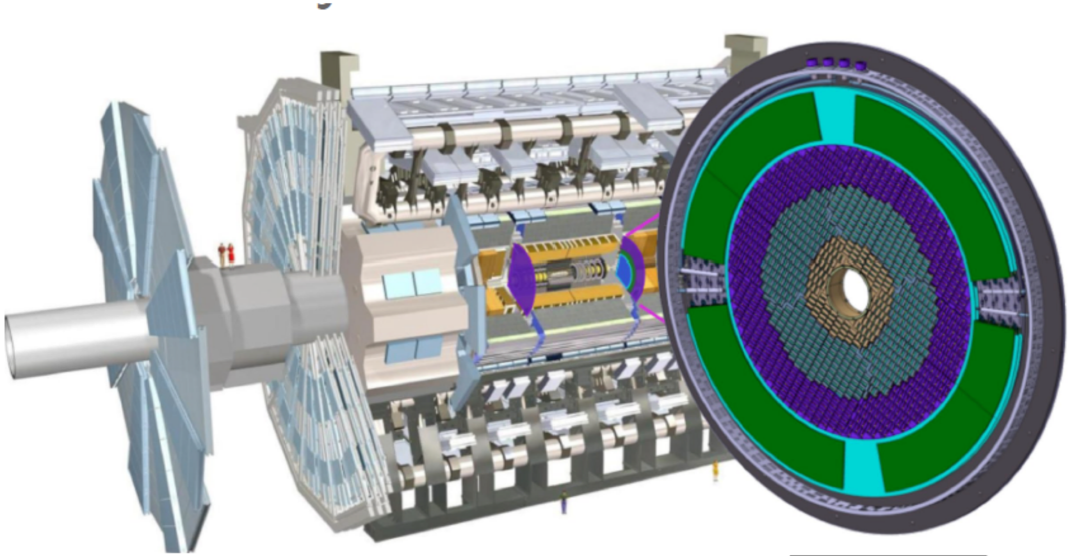
ATLAS HGTD TDR

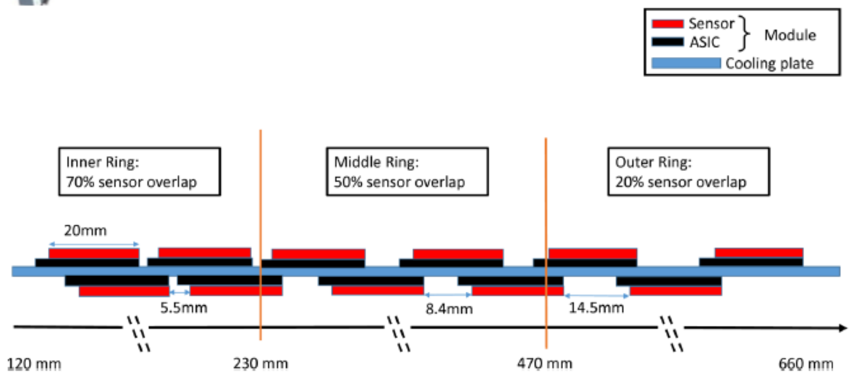




- With 1.44 vertices/mm ⟹ < 0.5 mm ITk resolution
- ITk will only perform up to |η| ~2-2.7
- HGTD can assign time to each track 2.7 < |η| <4.0
- 30-50 ps time resolution per track will give ~x6 pile-up rejection

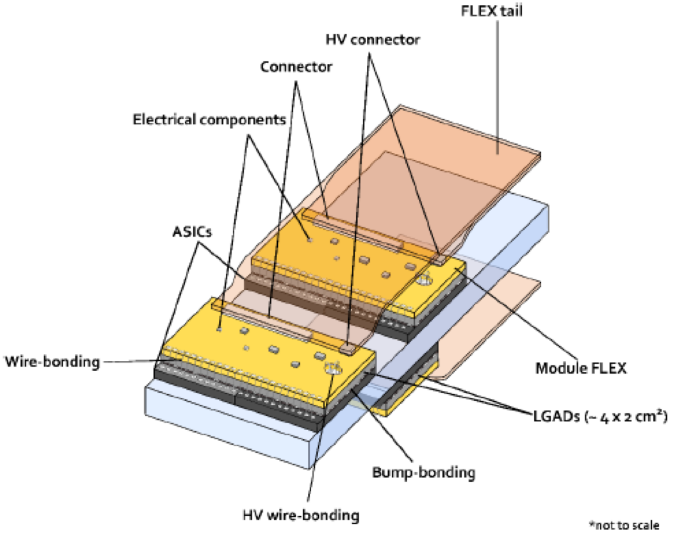
HGTD detector

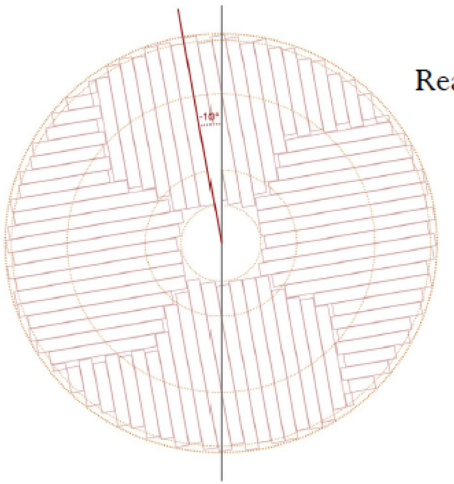




- Layout
  - Two double-instrumented disks per end-cap
  - $2.4 < |\eta| < 4$, 120 mm < r < 640 mm
  - 3.6 M channels operating at -30ºC.
- Requirements
  - σt < 30-50 ps per track.
  - Occupancy < 10%
  - Total power dissipation < 500 mW /cm^2
  - Radiation tolerance: 2.5 E15 N_{eq}/cm2 and 2 MGy

HGTD modules and readout

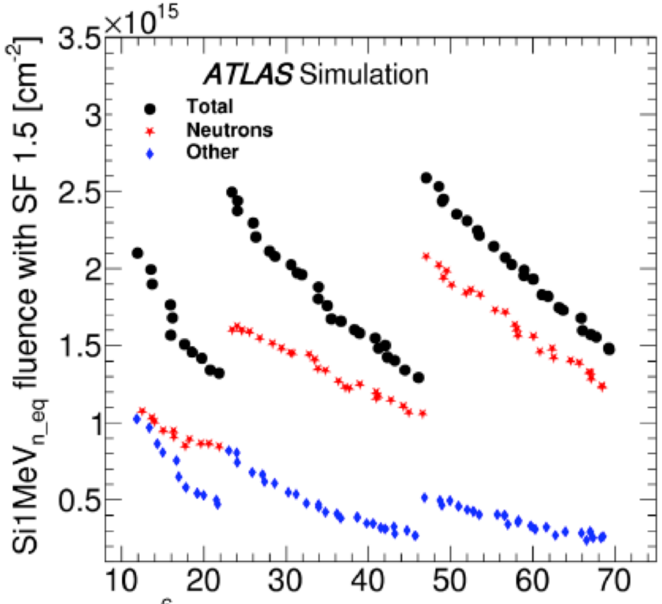


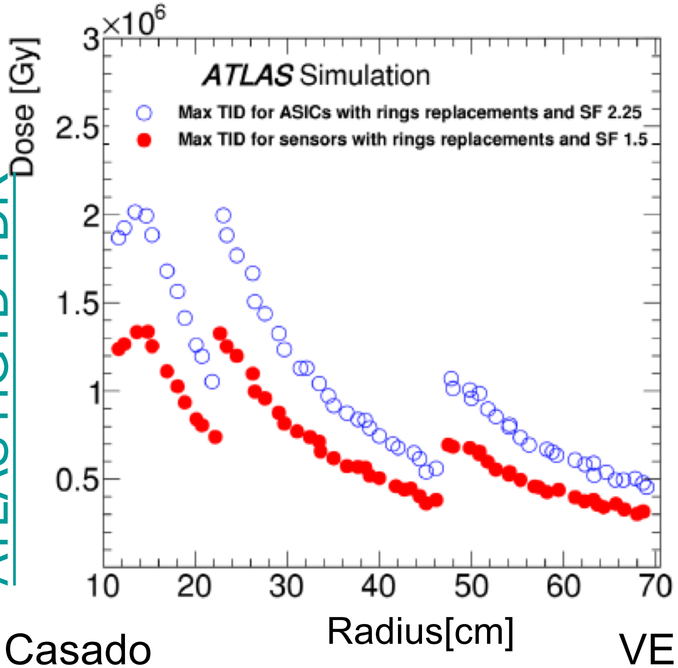


Readout staves structure

- 8032 modules to be installed (sensor + chip)
  - Two 15x15 LGAD sensors withd pads of 1.3x1.3 mm^2
  - Bump bonded to two 15x15 ASIC
- Modules arranged in readout staves
- Modules are connected to flex that provides LV, HV and module readout
- Flex cable goes to periphery electronics
- HV brought separately for each module
- CO2 cooling system to keep sensors at -30ºC
  - Power consumption constrained by cooling power

Radiation damage torelance





ATLAS HGTD TDR

- Maximum fluence 2.5E15 N_{eq}/cm2
- Maximum TID 2 MGy

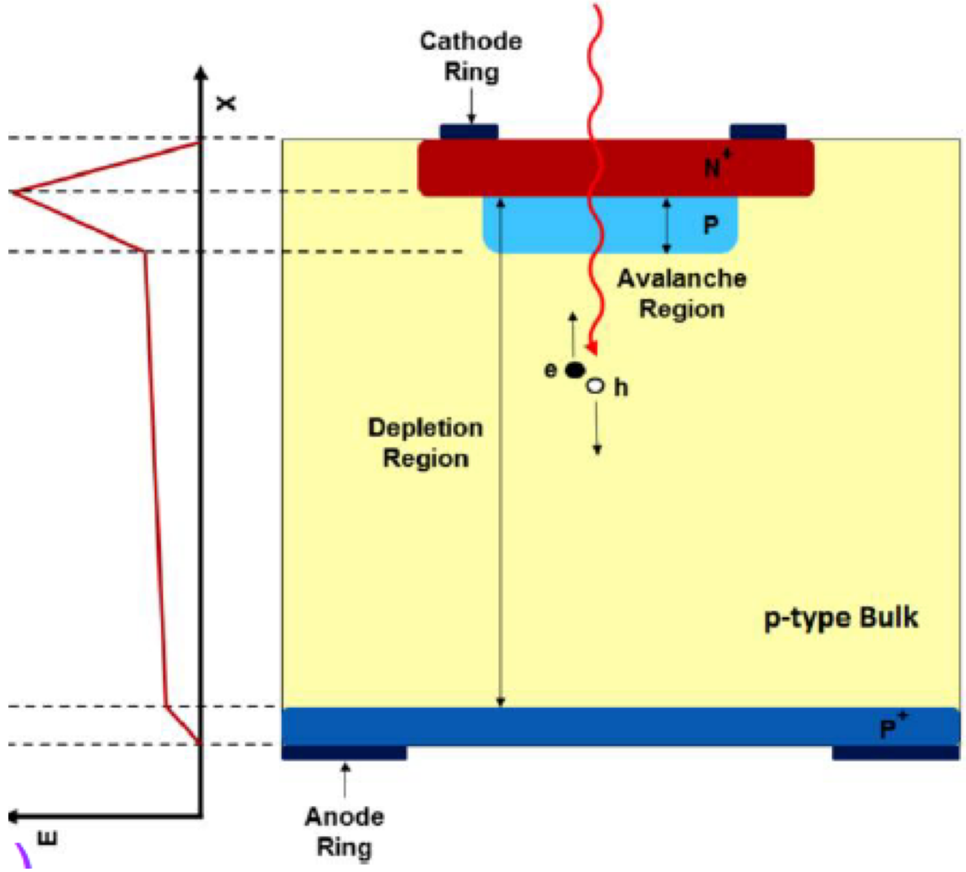
  (Values are taking into account

  ~2 safety factor).
- Part of radiation damage is from neutrons, part from charged particles

- **Inner and middle rings are substituted at intermediate points in HL-LHC run** (3000 fb^{-1})
  - Inner ring (R < 230 mm) every 1000 fb^{-1} (3 times)
  - Middle ring (230mm < R < 470 mm) at 2000 fb^{-1} (once)

LGAD sensors for HGTD

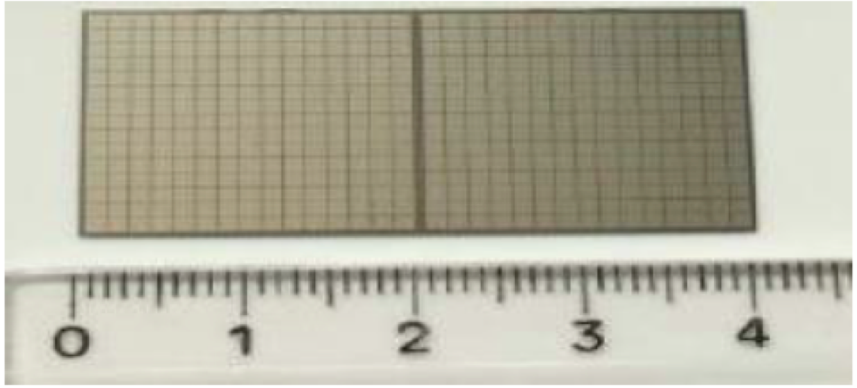
- Low Gain Avalanche Detectors, originally developed in CNM and RD50
- n-p Si detector with an additional p-type doped layer
- High E field. Internal gain (V_{bias}< 800V) > 20 and > 8 after irradiation
- Hit efficiency > 95% at the end of lifetime.



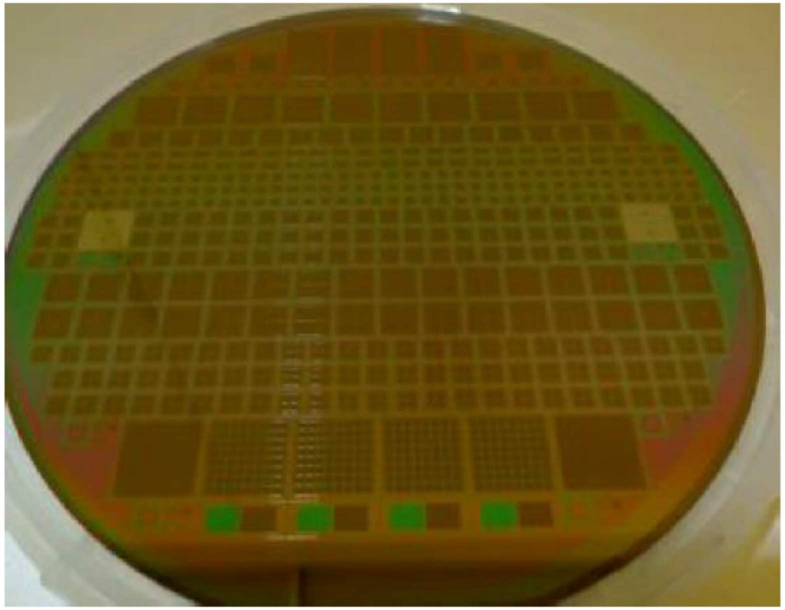
- Several prototypes: CNM (Spain), HPK (Japan), FBK (Italy), IME (China), NDL (China)

LGAD Performance Measurements

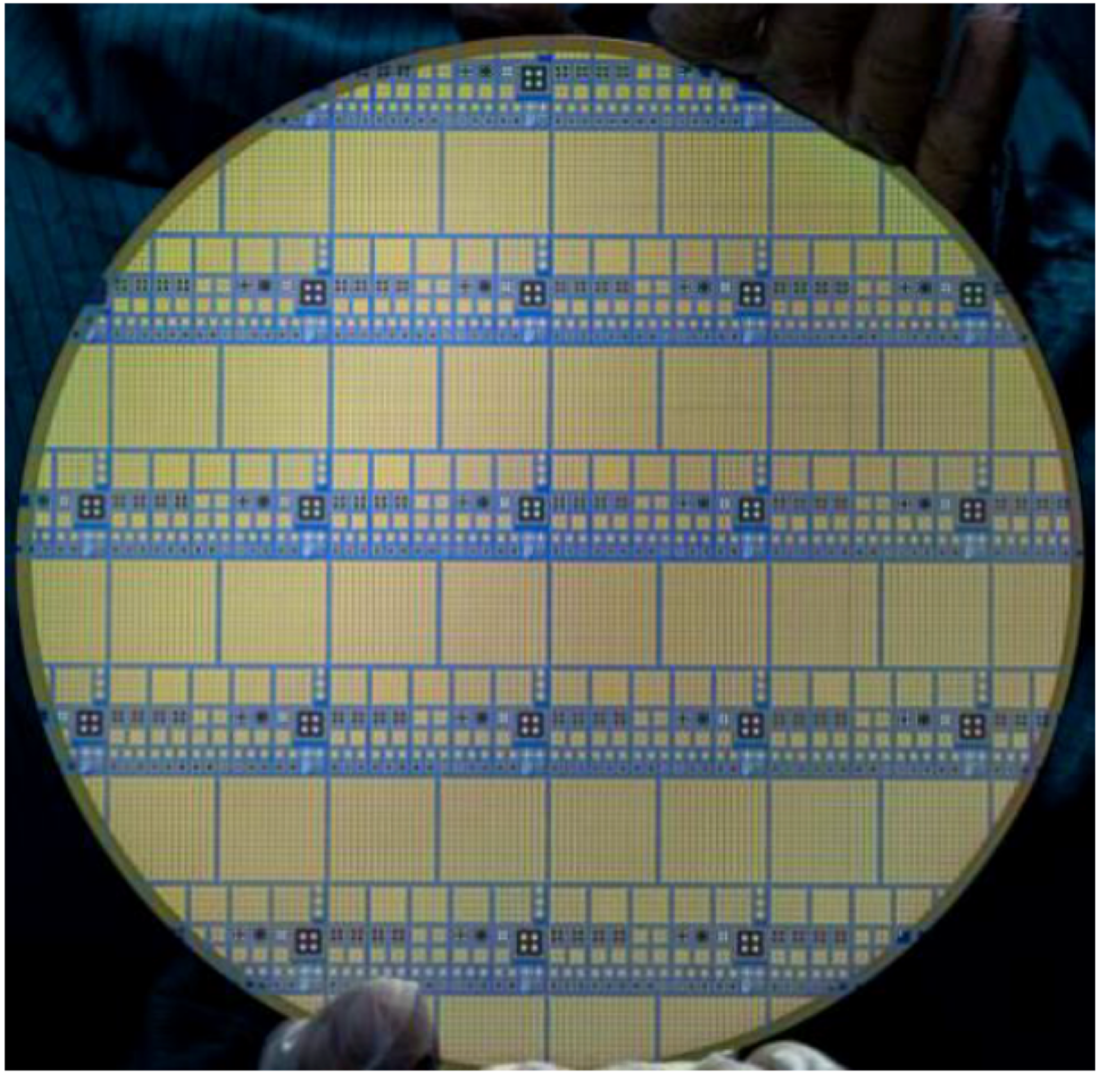
HPK-P2



CNM

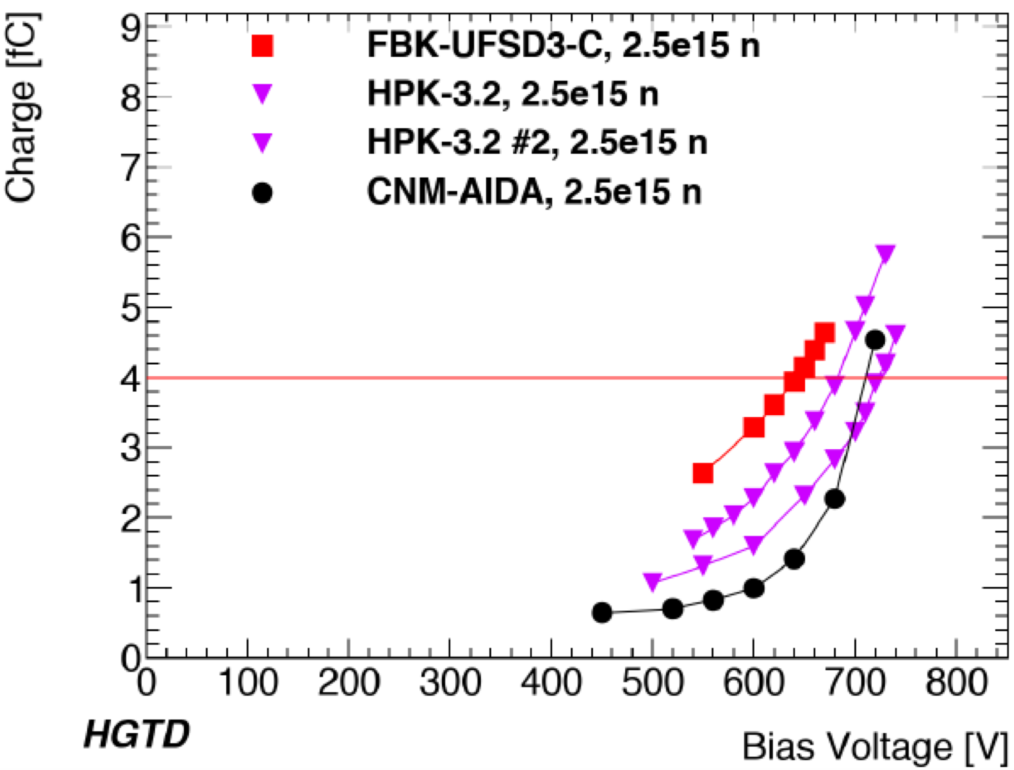


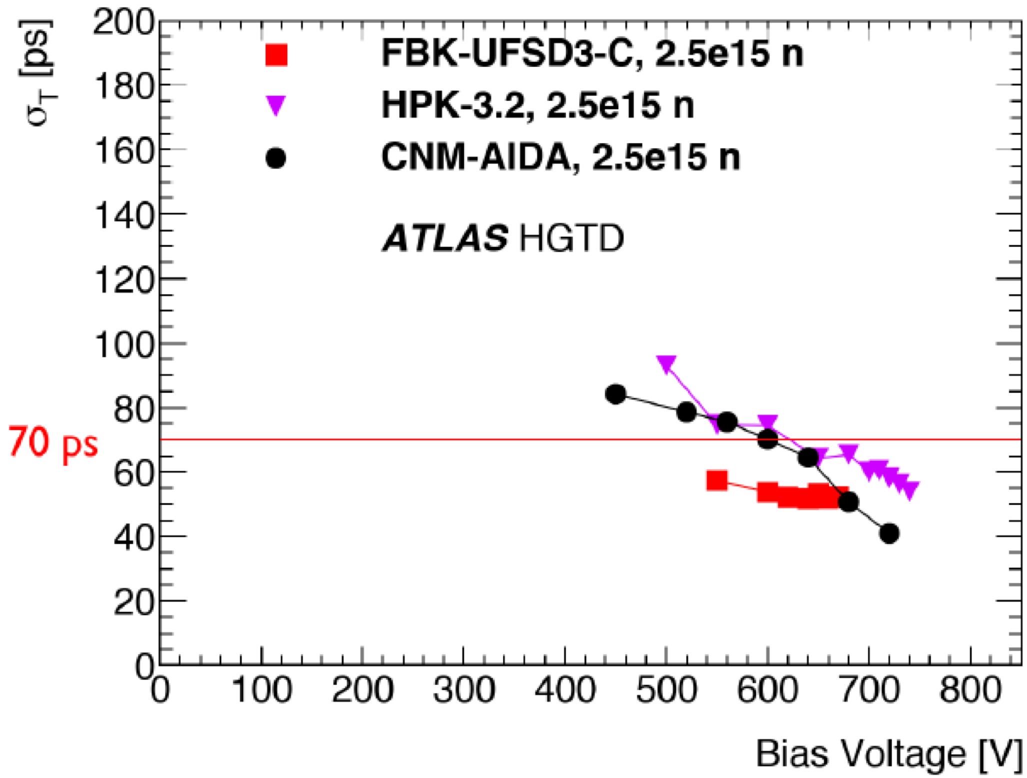
IHEP-IMEv2



LGAD Sensors Laboratory Measurements

- Measure LGAD dynamic performance with ^{90}Sr β.
- Charge and time resolution as a function of V_{bias}.

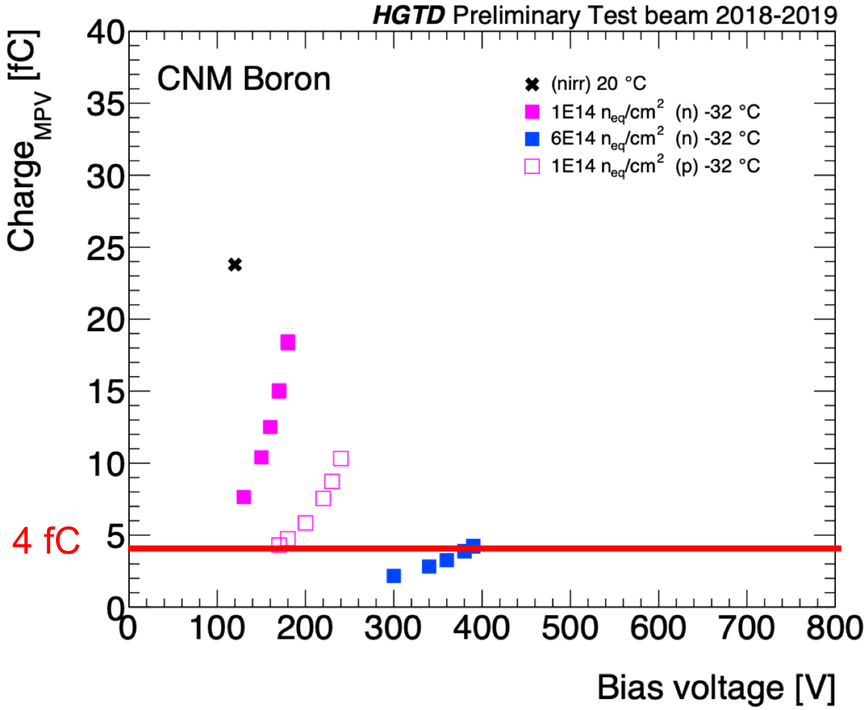




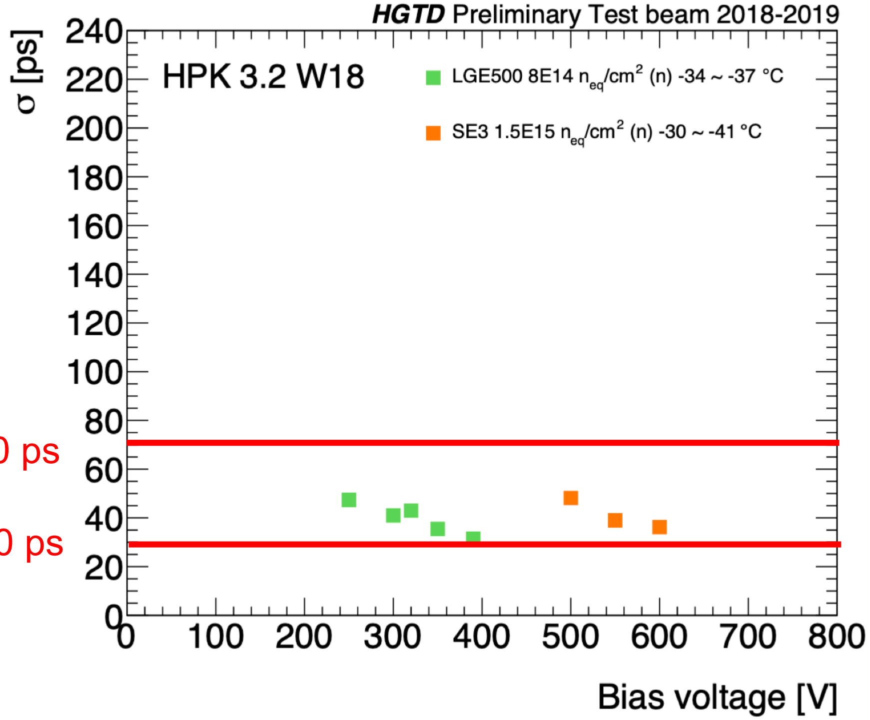
- Various manufacturers.
- Better performance for sensors with C enriched gain layer.

LGAD Sensors Test Beam results

Collected charge



Time resolution

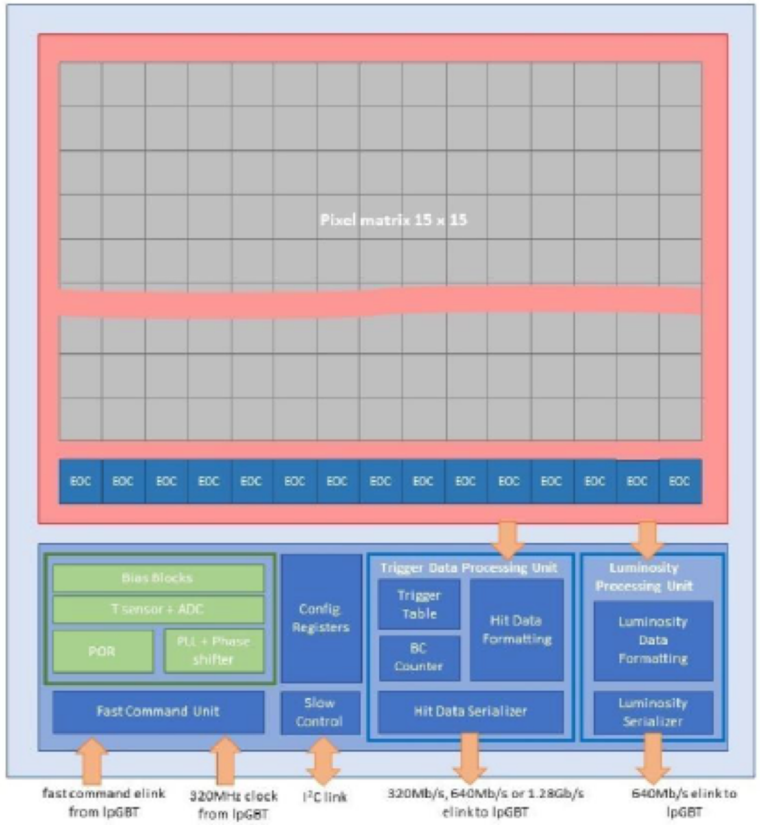


- Collected charge = MPV of Landau-Gaussian fit to charge distribution
- CNM B-doped Q = 4.2 fC (V=390V, $6\times10^{14}\ n_{eq}/cm^2$)

- HPK n-irradiated at $1.5\times10^{15}\ n_{eq}/cm^2$
- σ = 36 ps (600 V and for Q coll = 22.8 fC)
- Tested sensors with Q coll > 4 fC have $\sigma_{time} < 40$ps at high V_{bias}

ATLAS LGAD Timing Integrated ReadOut Chip (ALTIROC)

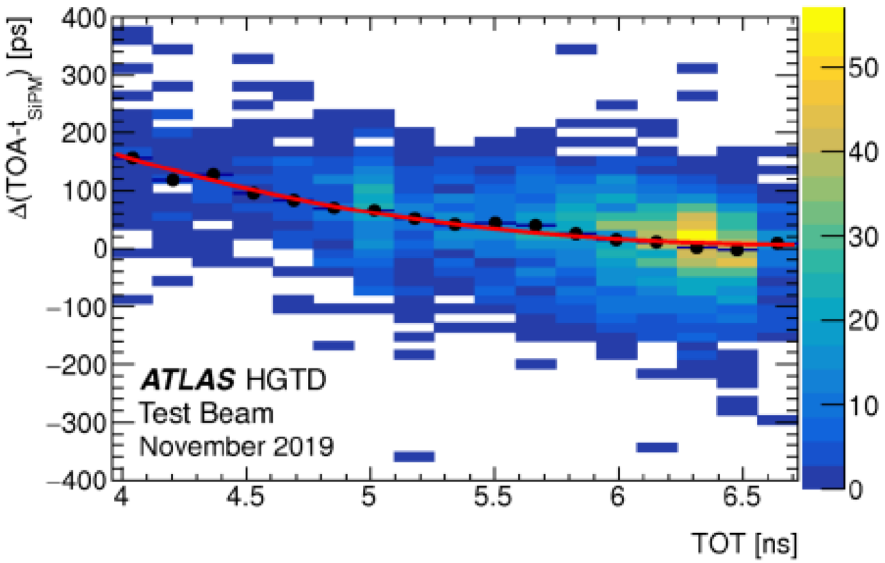
- Chip for LGAD sensor signal reading
- TSMC CMOS 130nm technology. Total of 225 readout channels (15x15).
- Two protypes of ALTIROC produced and tested:
  - ALTIROC0: 2016
    - Four channels in 2x2 array
  - ALTIROC1: 2018
    - 25 channels in 5x5 array
- Ongoing development:
  - ALTIROC2: 2020-2021
    - 225 channels. All functionalitites of final ASIC.
  - ALTIROC3:
    - Radiation hartd version of ALTIROC2.

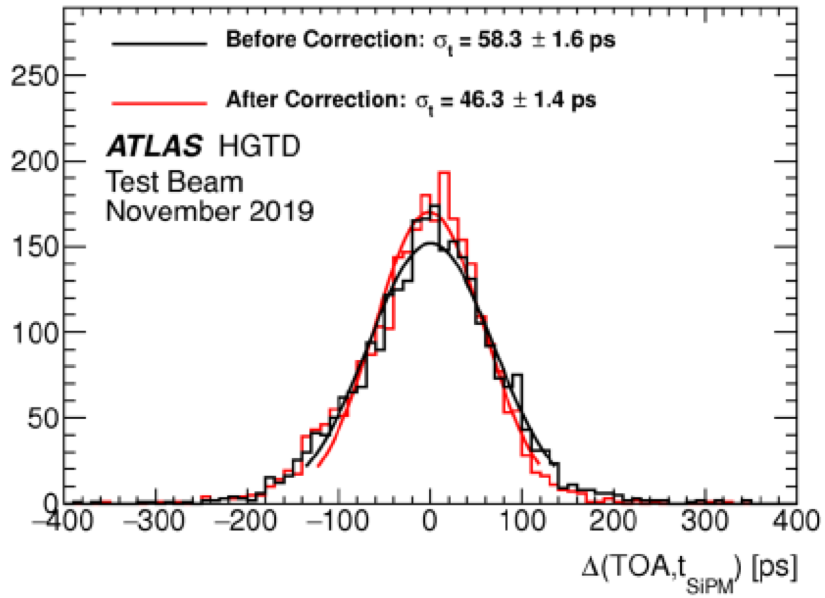


- ALTIROC1 with 4 pF input capacitance can achive ~25ps jitter at 4fC input charge

ALTIROC1 measurements in test beam

- Unirradiated ALTIROC1 from HPK and CNM tested at DESY in 2019.
  - Fit of TOA variation as a function of the TOT is used to calculated time-walk corrections





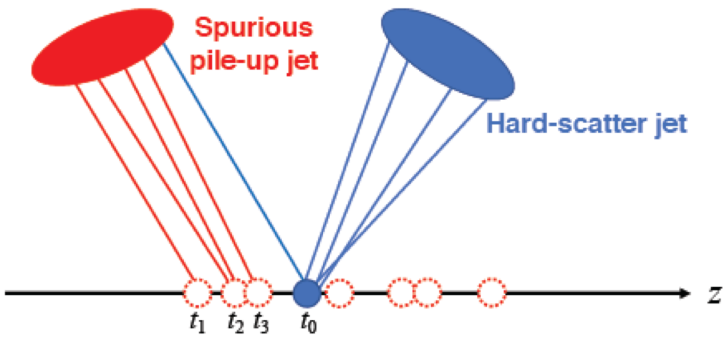
$t_{LGAD+ALTIROC} - t_{Quartz+SiPM}$

- Estimated resolution of **46 ps** after time-walk correction and including Landau contribution (25ps). Estimated jitter contribution: **39 ps**.
- In test beam configuration, improved DAQ (with FPGA) should improve jitter resolution by 35% achieving ~25ps target

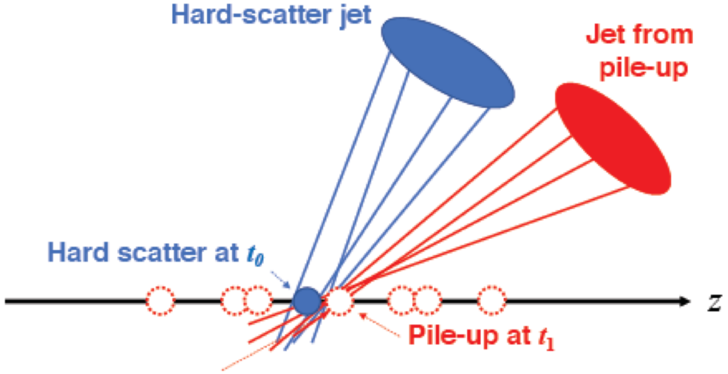
HGTD physics enhancement

Pileup-jet rejection

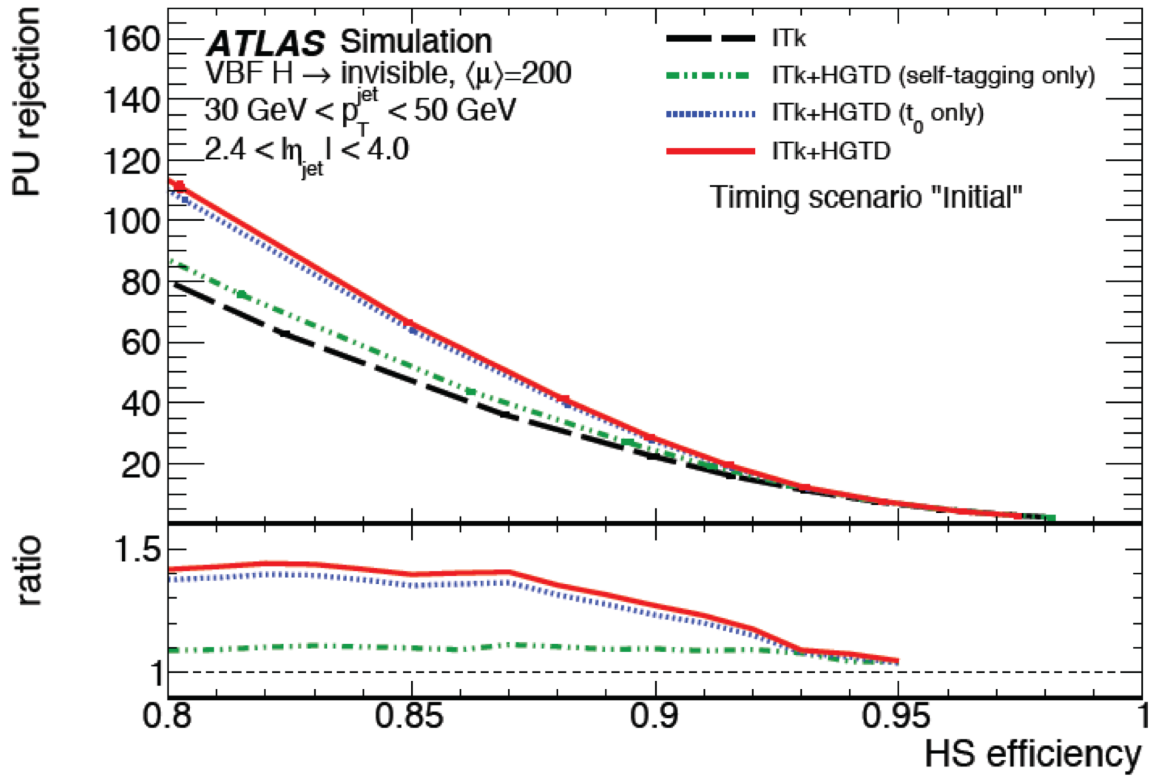
1. "Self-tagging": require consistent times for tracks in jet



2. Require jet time consistent with hard-scatter vertex time (t_0)

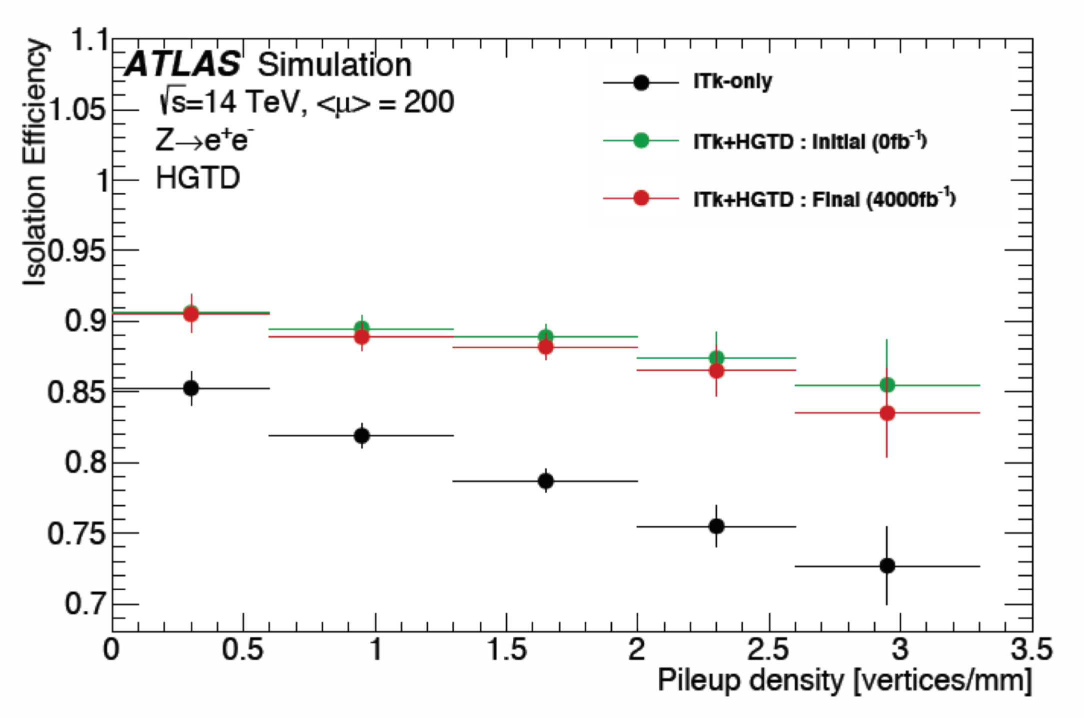


$30\ \text{GeV} < p_T^{\text{jet}} < 50\ \text{GeV}$:



HGTD physics enhancement

Lepton isolation



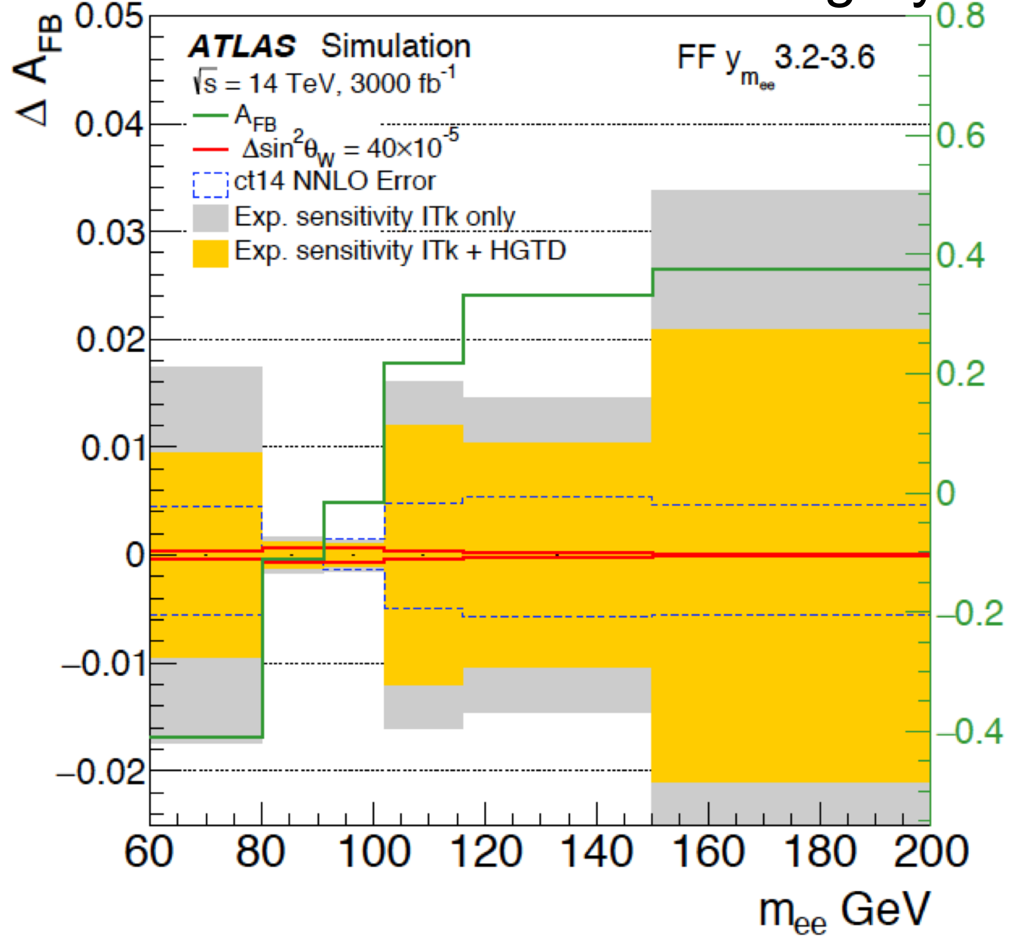
- **Electron isolation** efficiency in $Z \rightarrow ee$ sample as a function of pileup vertex density
- HGTD removes majority of pileup deterioration.

HGTD impact on physics studies

Measurement of weak mixing angle

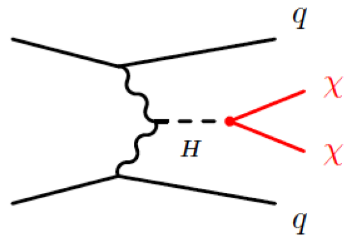
- Precision measurement: determine $\sin^2\theta_W$
- **HGTD gives 11% reduction of total experimental uncertainty**
- Solid red corresponds to variations of $\sin^2\theta_W$, dashed blue indicates CT14 NNLO PDF total error, and green is particle-level AFB prediction.

Z→ee channel, forward-forward category

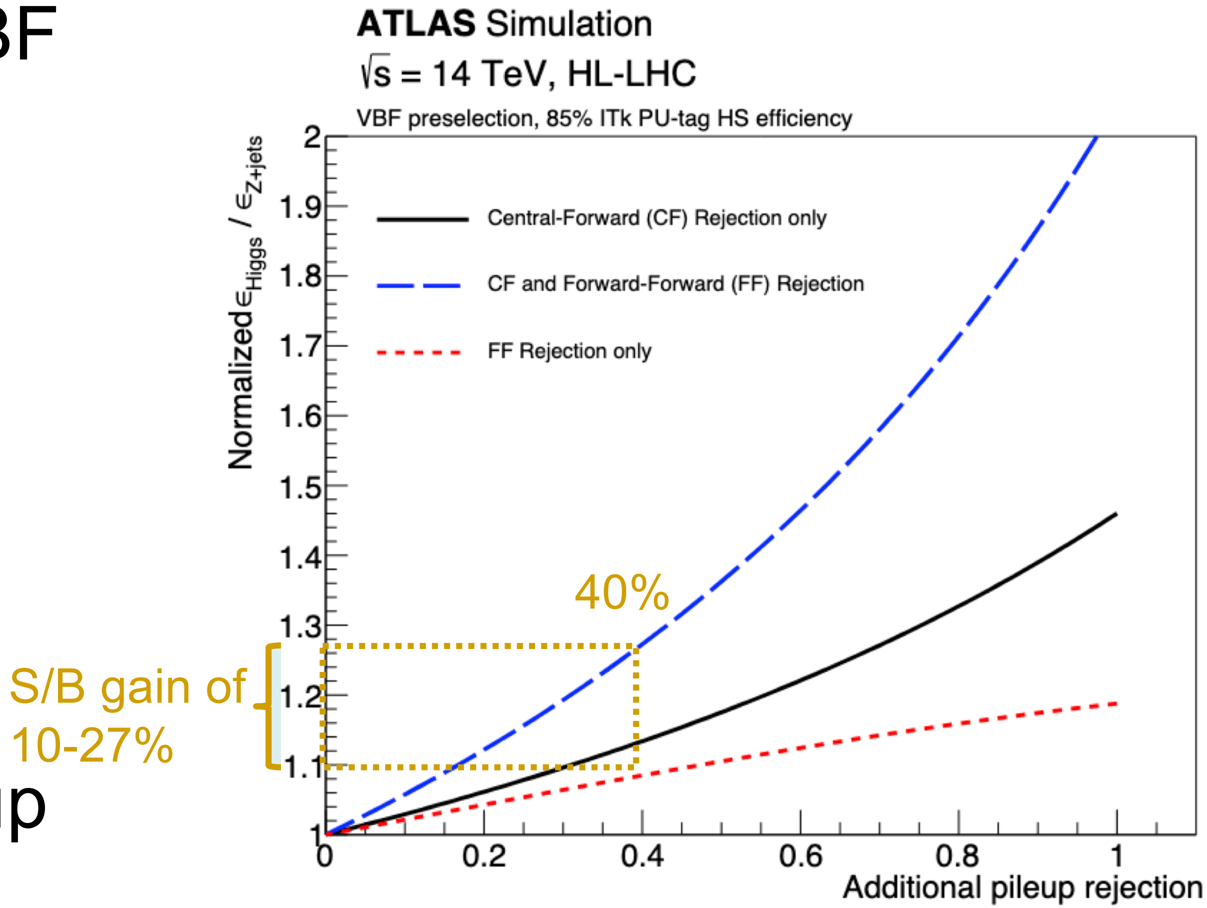


HGTD impact on physics studies

VBF H → invisible



- Background comes from pileup jets mimicking VBF jets.
- Two components:
  - Central-forward(CF)
  - Forward-forward(FF)
- HGTD can help in both cases, **giving improvement of up to 27%** for additional pile-up rejection of 40%.



Normalized to ITk-only performance.

Conclusions

- HGTD will play key role in forward region to mitigate pile-up effect in HL-LHC environment.
- Sensors and layout are optimized for a per-track resolution 30-50 ps up during detector lifetime.
- Diferent manufacturer LGAD sensors comply with required performance in test beams and laboratory measurements.
- New and powerful capability to contribute to luminosity measurement in ATLAS. Overall goal 1% uncertainty.
- Overall design and construction works in progress. Intense R&D to improve radiation hardness. Installation foreseen in 2026-27.