A new dimension for ATLAS: A High-Granularity Timing Detector

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RAL PPD Seminar
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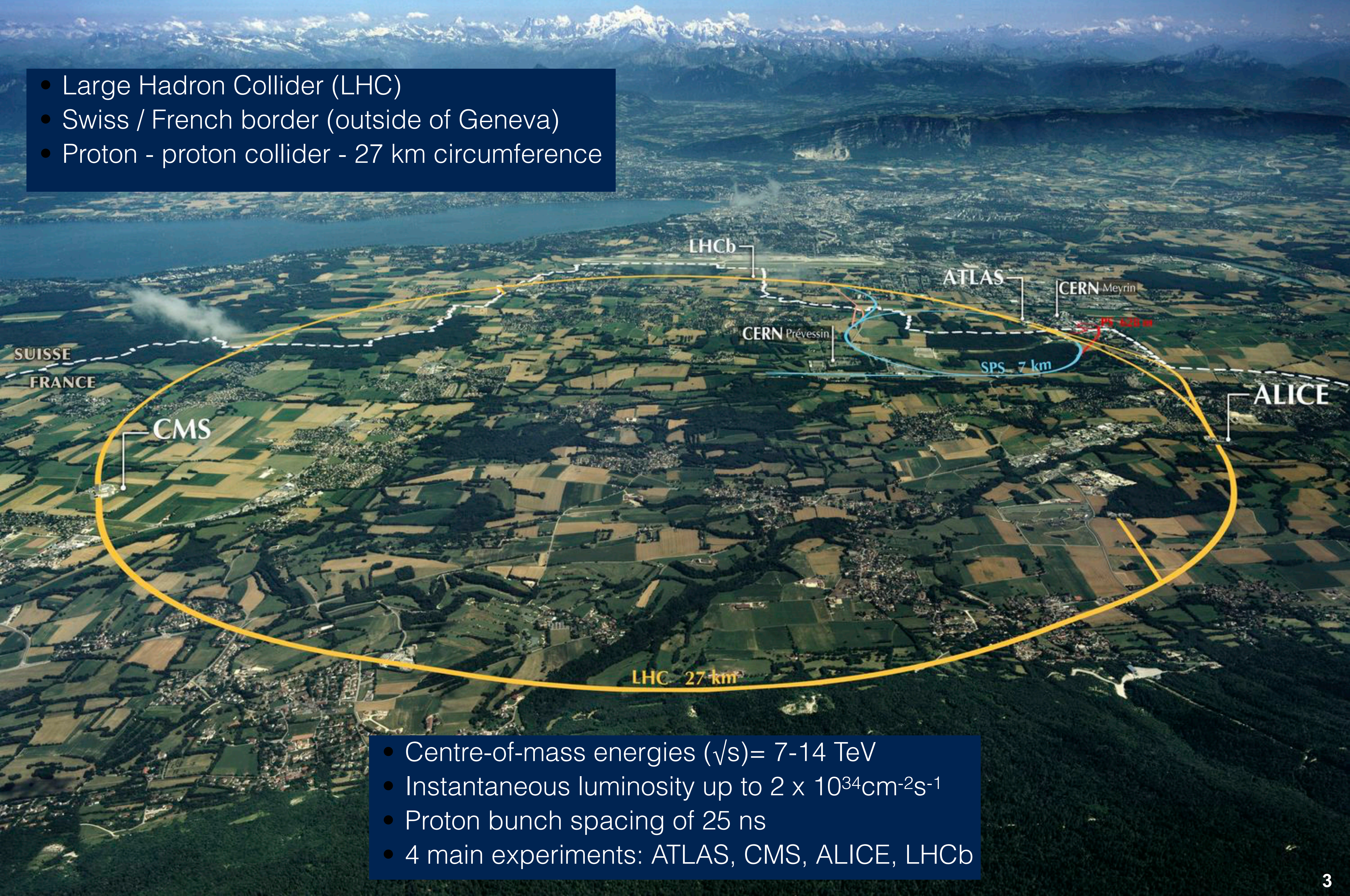
RAL

Overview

- **LHC and the HL-LHC**
- **Upgrades to the ATLAS detector**
- **High Granularity Timing Detector**
  - Motivation and Performance
- **Low Gain Avalanche Detectors (LGADs)**
  - Technology and current performance
  - Challenges and progress
- **Design of the HGTD modules and layout**
- **Conclusions and outlook**

The LHC

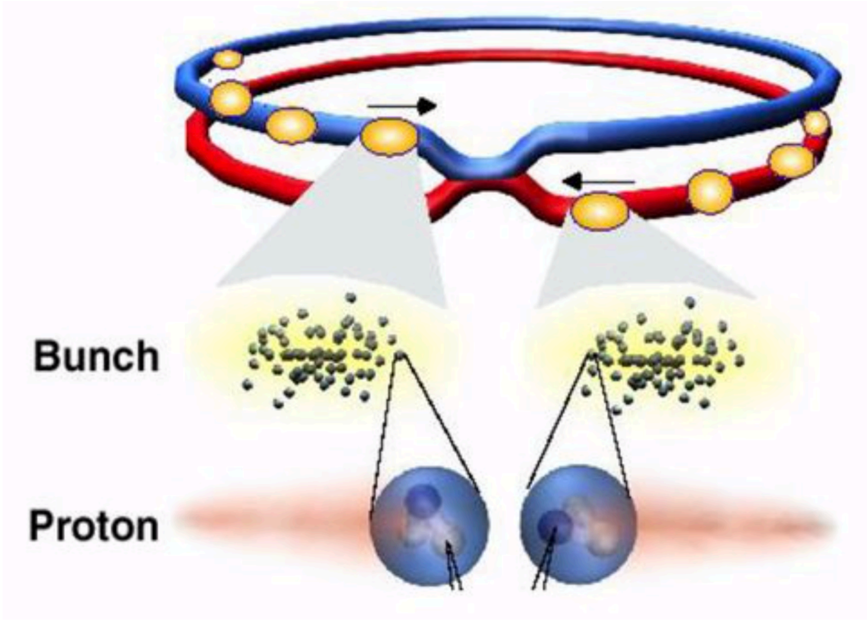
- Large Hadron Collider (LHC)
- Swiss / French border (outside of Geneva)
- Proton - proton collider - 27 km circumference



- Centre-of-mass energies ($\sqrt{s}$)= 7-14 TeV
- Instantaneous luminosity up to 2 x $10^{34} cm^{-2} s^{-1}$
- Proton bunch spacing of 25 ns
- 4 main experiments: ATLAS, CMS, ALICE, LHCb

LHC and ATLAS

- LHC collides ‘bunches’ of protons:
  - **~ 10^{11} protons per bunch**
- Bunches cross every 25ns

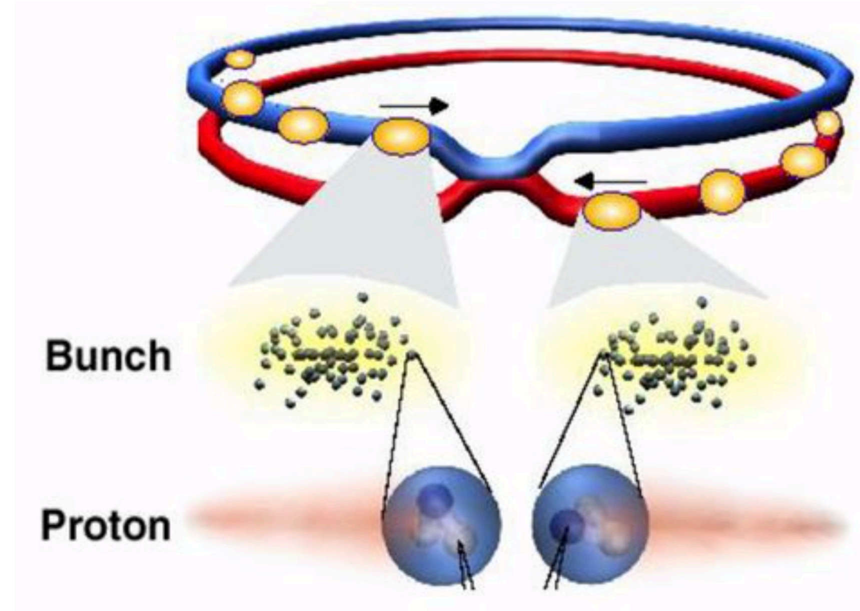


LHC and ATLAS

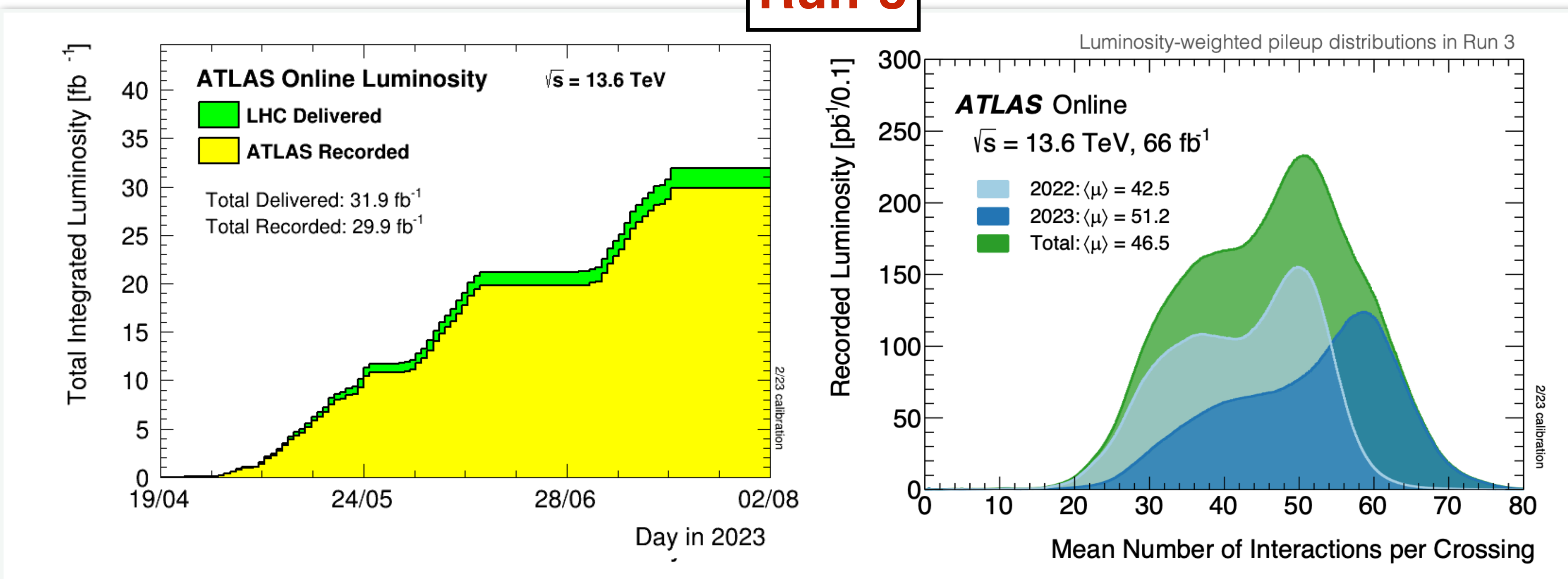
- LHC collides 'bunches' of protons:
  - **~ 10^{11} protons per bunch**

- Bunches cross every 25ns

- The centre-of-mass energy of the collisions:
  - 7 TeV, 8 TeV, 13 TeV and 13.6 TeV



Run-3



- **Increase in number of interactions per bunch crossing $<\mu>$ ~ 51 in 2023**

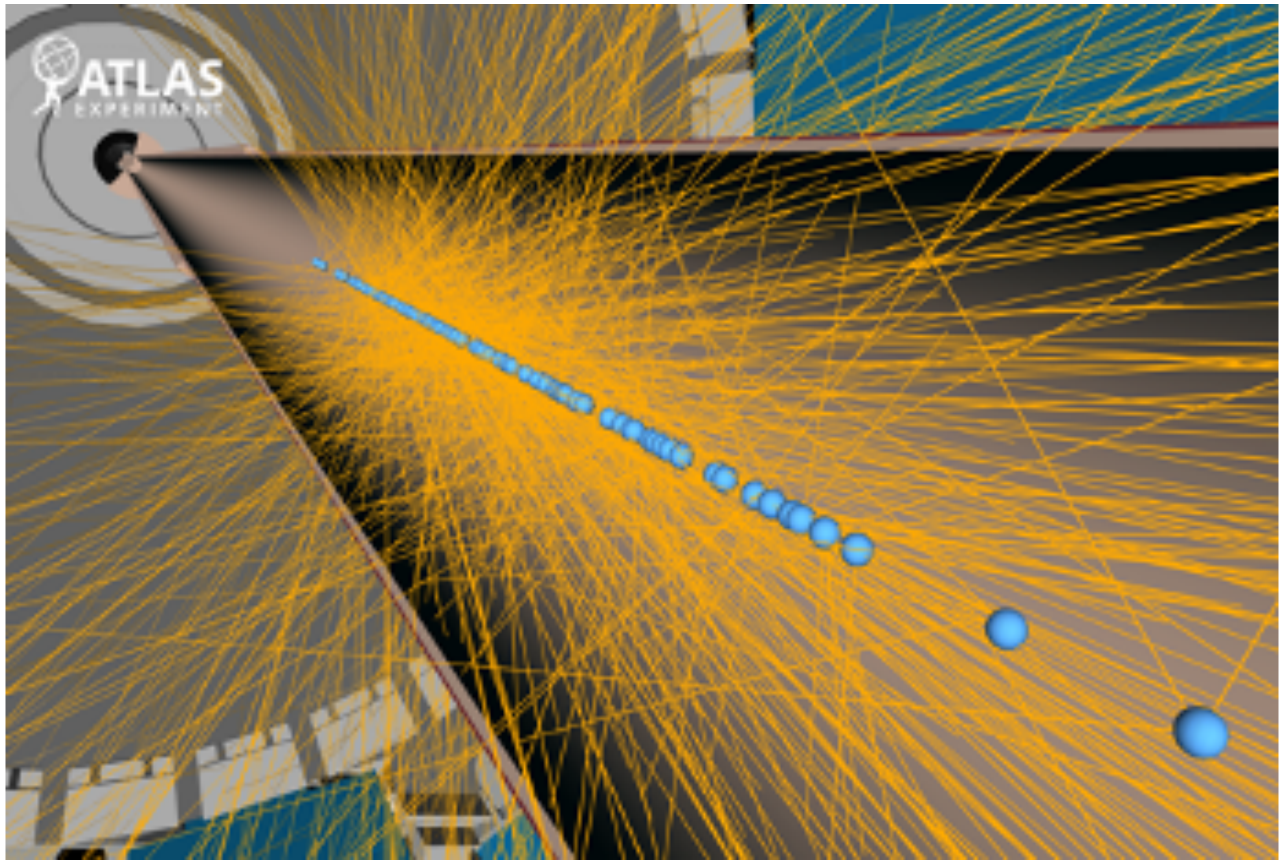
Implications of the HL-LHC on ATLAS

- **The HL-LHC is the world's flagship particle physics project during the next decades**

- **High Luminosity LHC: 2030 to 2042**
  - Deliver up to 4000 fb^{-1} integrated luminosity at 14 TeV

- **To do this, increase in instantaneous luminosities:**
  - Instantaneous luminosities up to $L \simeq 7.5\times10^{34}$ cm^{-2} s^{-1} (Run 2 ~ $2x10^{34}$)

- **Resulting impact of the conditions:**
  - **Pile-up $<\mu>$ = 200 interactions per bunch crossing (Run 2 ~ 34)**

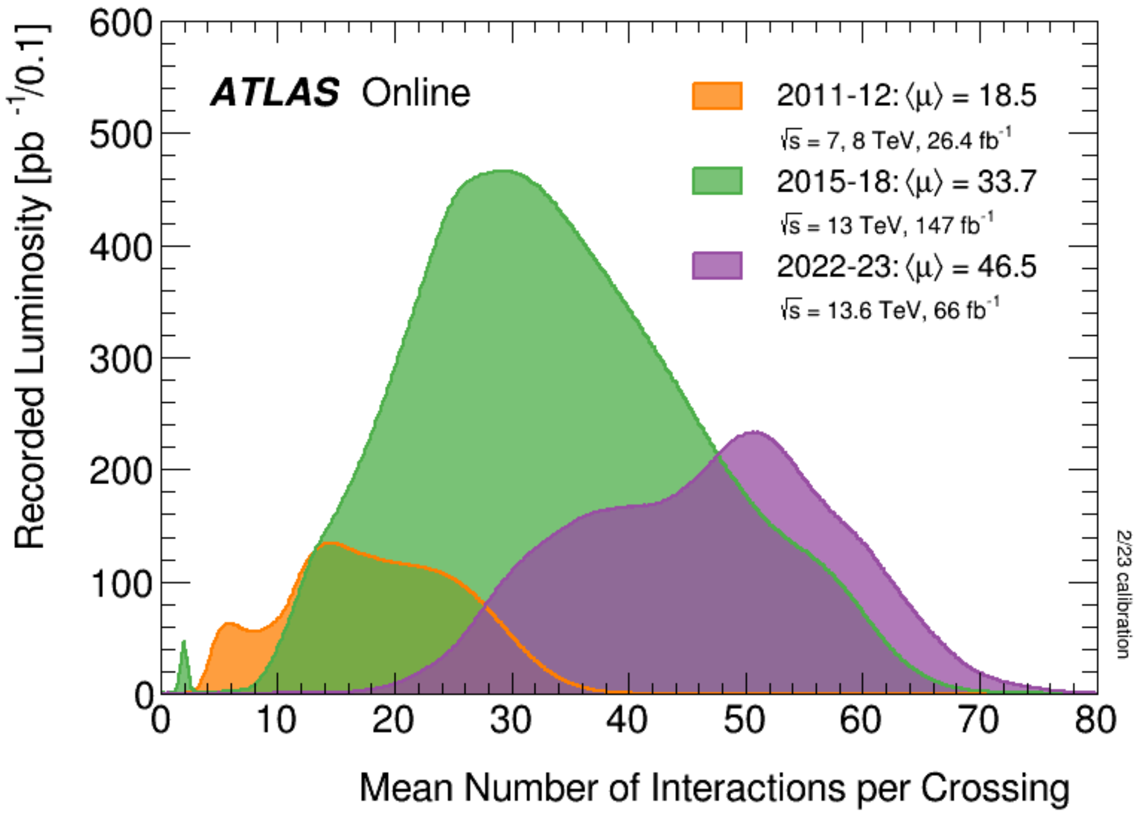


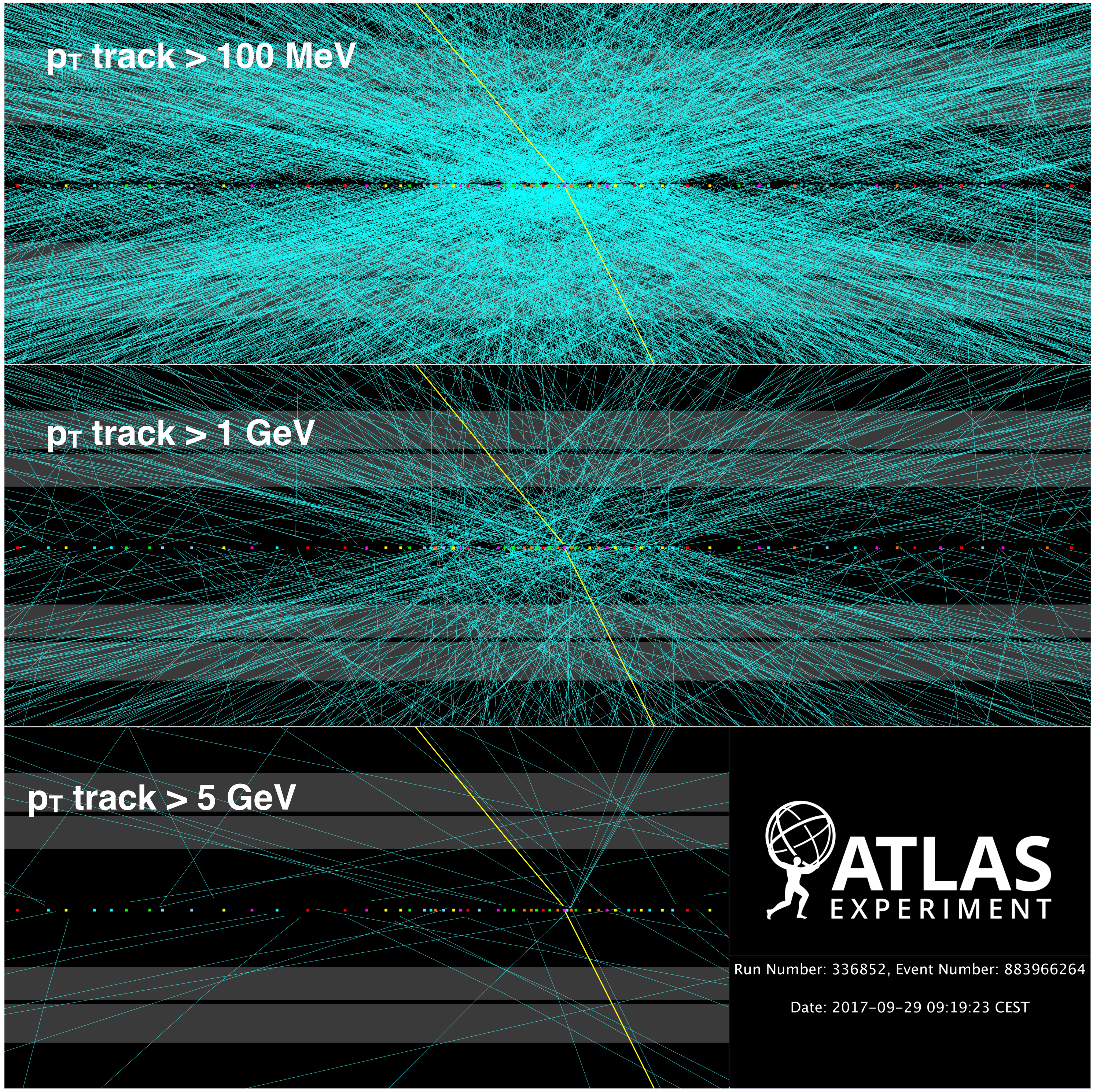
Challenges of HL-LHC Data-taking

- Z->μμ candidate event with 65 additional reconstructed vertices from other interactions (*μ ~ 90*)

- **Average number of interactions per bunch crossing for 2023: < μ > ~ 51**

- **Instantaneous Luminosity:**
  - *Challenges to online and offline detector performance*





HL-LHC Challenges

- **Why do we want <μ> ~ 200?**

- **The HL-LHC promises 20 times today's dataset**
  - *400 million Higgs bosons will be produced*

- *It would take us decades longer of running to reach the same size dataset*

- **What does <μ> ~ 200 mean in terms of a detector requirement in HL-LHC in maintaining similar performance:**

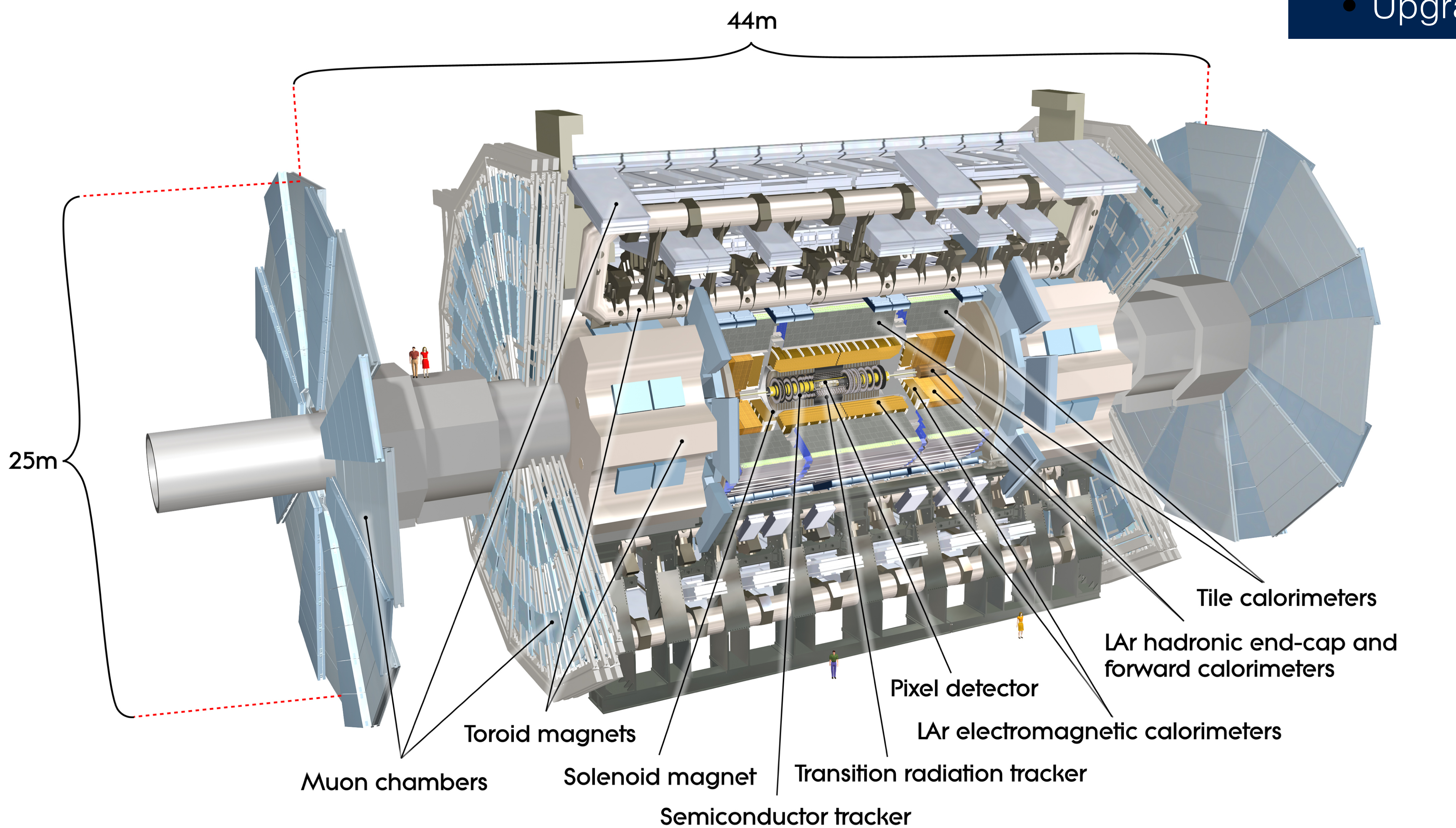
  - **Larger event sizes** —> more collisions per bunch crossing, many more tracks, …
  - **Higher detector occupancy** —> need a detector with higher granularity
  - **Higher trigger rates** —> re-design of our trigger architecture and readout system
  - **Increasing reconstruction complexity** —> Run more complex software online
  - **High radiation environment** —> need silicon with higher tolerances

- ***Requires the re-design of our current detector (or at least large parts of it) for our ATLAS HL-LHC physics programme***

Upgraded ATLAS detector

- **Major upgrades to the detector to achieve physics goals of HL-LHC**

- Trigger + DAQ
  - Upgrade for higher rates



- Electronics upgrades

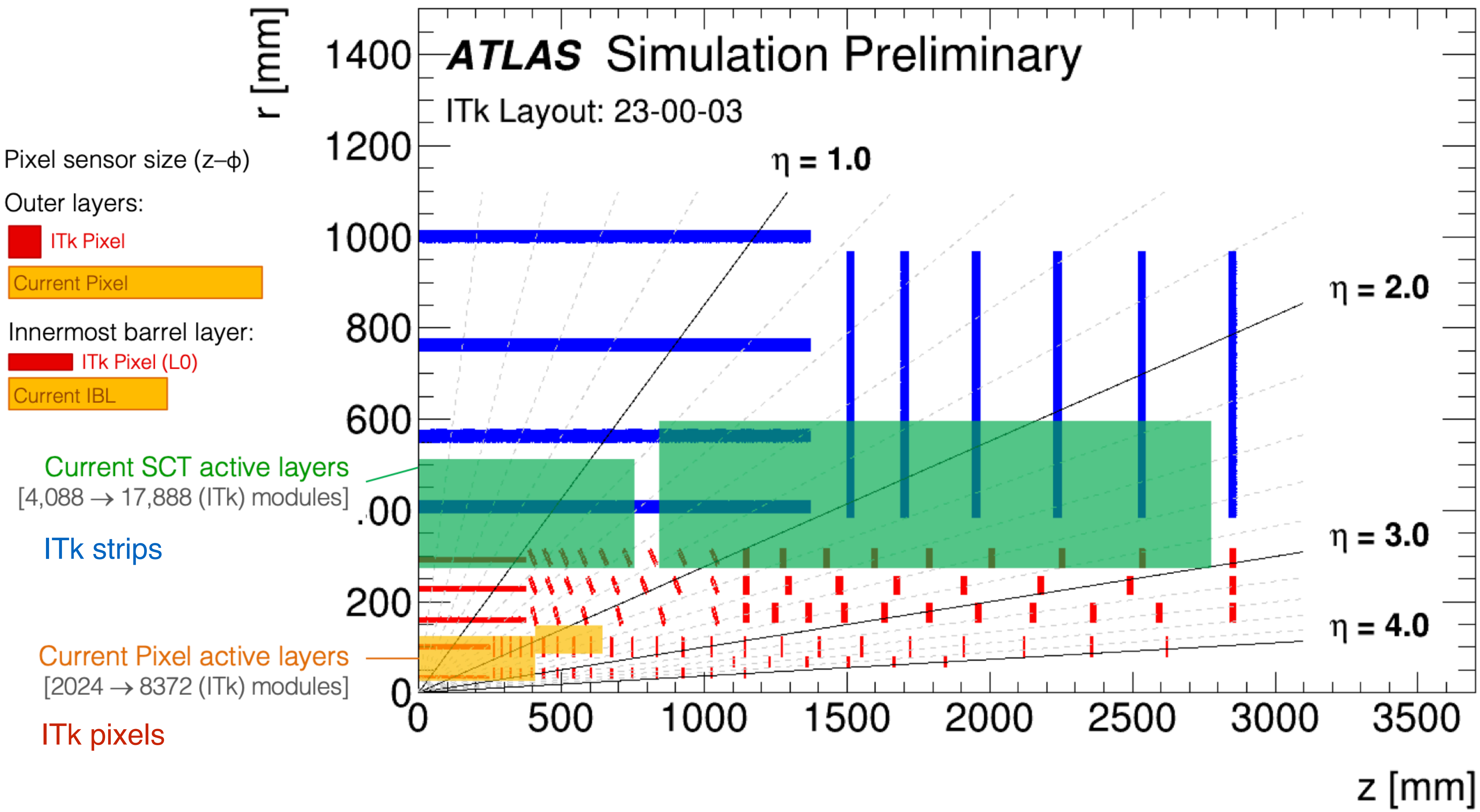
- Additional muon coverage

- Fully silicon Inner Tracker (ITk)
  - Coverage up to $|\eta| = 4.0$

- HGTD silicon timing detector
  - Coverage from $2.4 < |\eta| < 4.0$

Upgraded Inner Tracker of ATLAS (ITk)

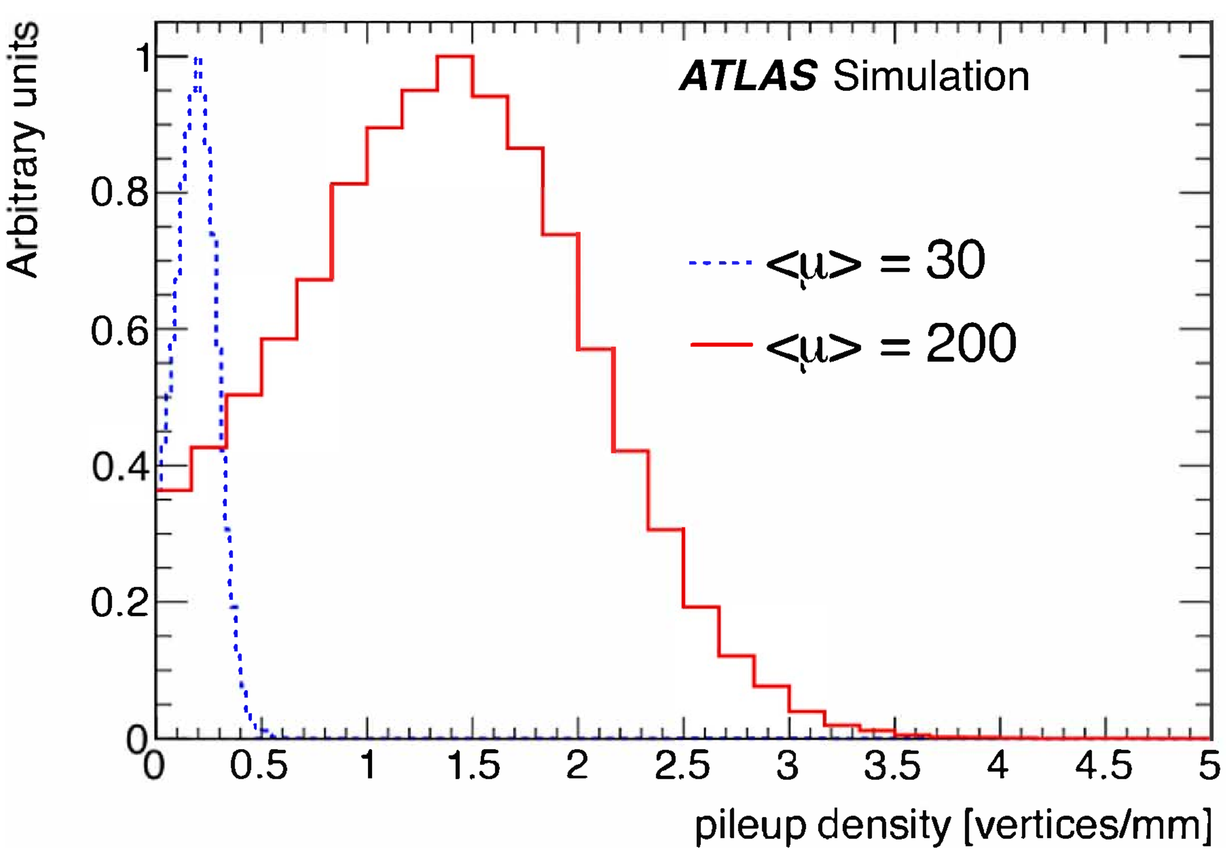
- **HL-LHC: Increased particle densities and radiation damage**

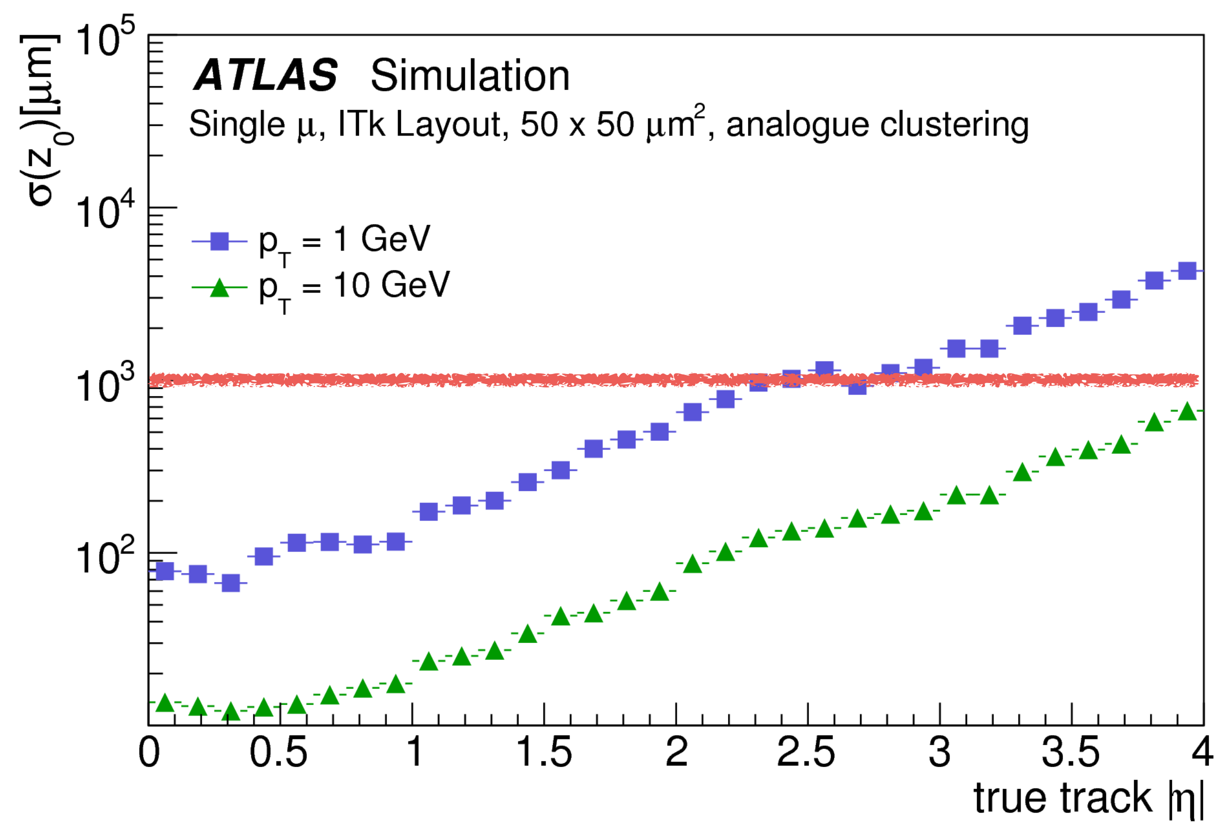


Tracking in the HL-LHC

- **Resolution in longitudinal direction (z) reduced in forward regions**
  - Pile-up density **(~1.6 vertices / mm)** > z_0 resolution in forward regions

- *Ambiguities in track-to-vertex information —> multiple tracks in the forward region can be associated to a given reconstructed vertex*

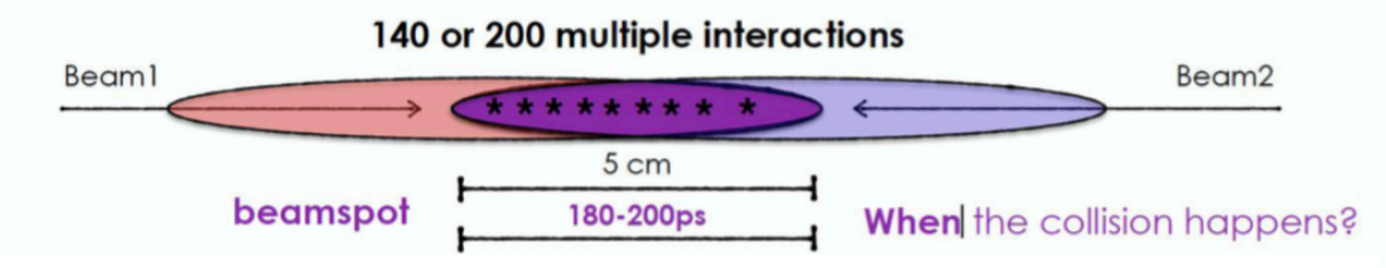




- **Physics and object performance reduced**
  - **Particularly in signatures with final state signals with |η| > 2.4**

Using the time dimension

- **Beamspot (luminous collisions) is spread in longitudinal direction and time**

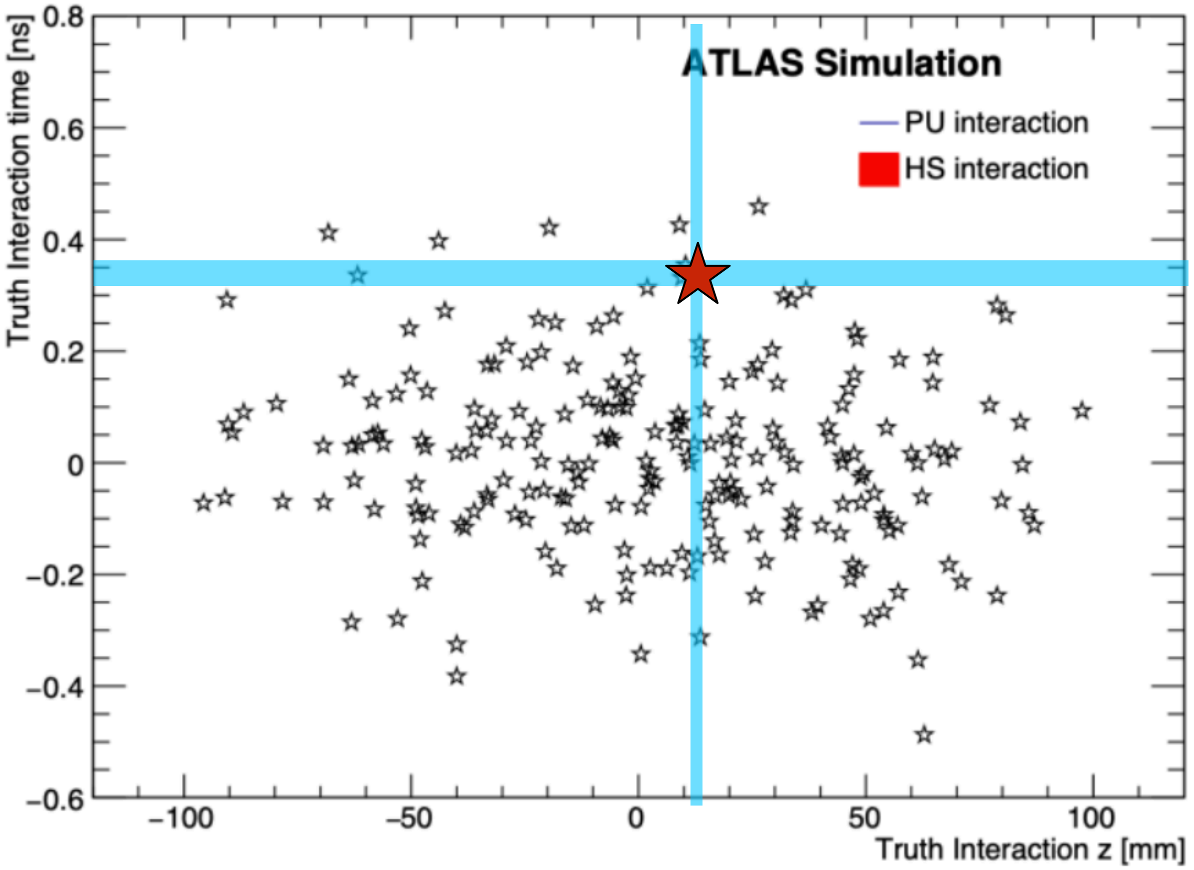


- Measure time of a track to improve track-to-vertex association for tracks |η| > 2.4

- **Vertices** have **time spread of ~ 180 ps**

- **With 30 ps resolution for reconstructed tracks**
  - **Additional ~x6 pileup rejection**

- Associate time to track using HGTD:
  - Reduce tracks in hard scatter (HS) jets from pile-up (PU) vertices
  - Reduce jets from pile-up vertices and stochastic jets

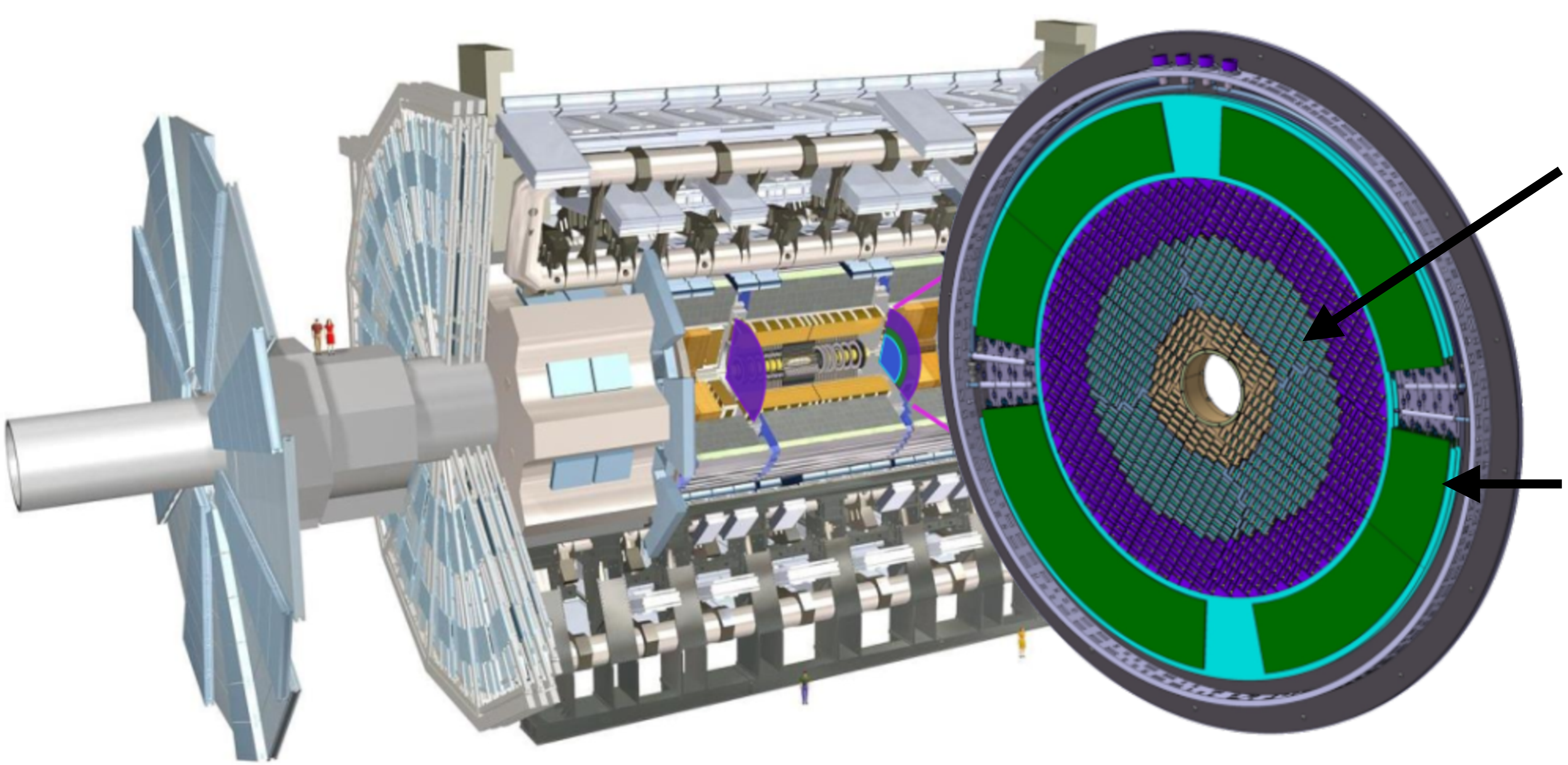


HGTD: High Granularity Timing Detector

- Active silicon area coverage: **2.4 < |η| < 4.0**
- **Both endcap regions outside of ITk**
- **Per track timing resolution of 30 ps - 50 ps up to a fluence 2.5 x 10^{15} n_{eq}/cm^2**

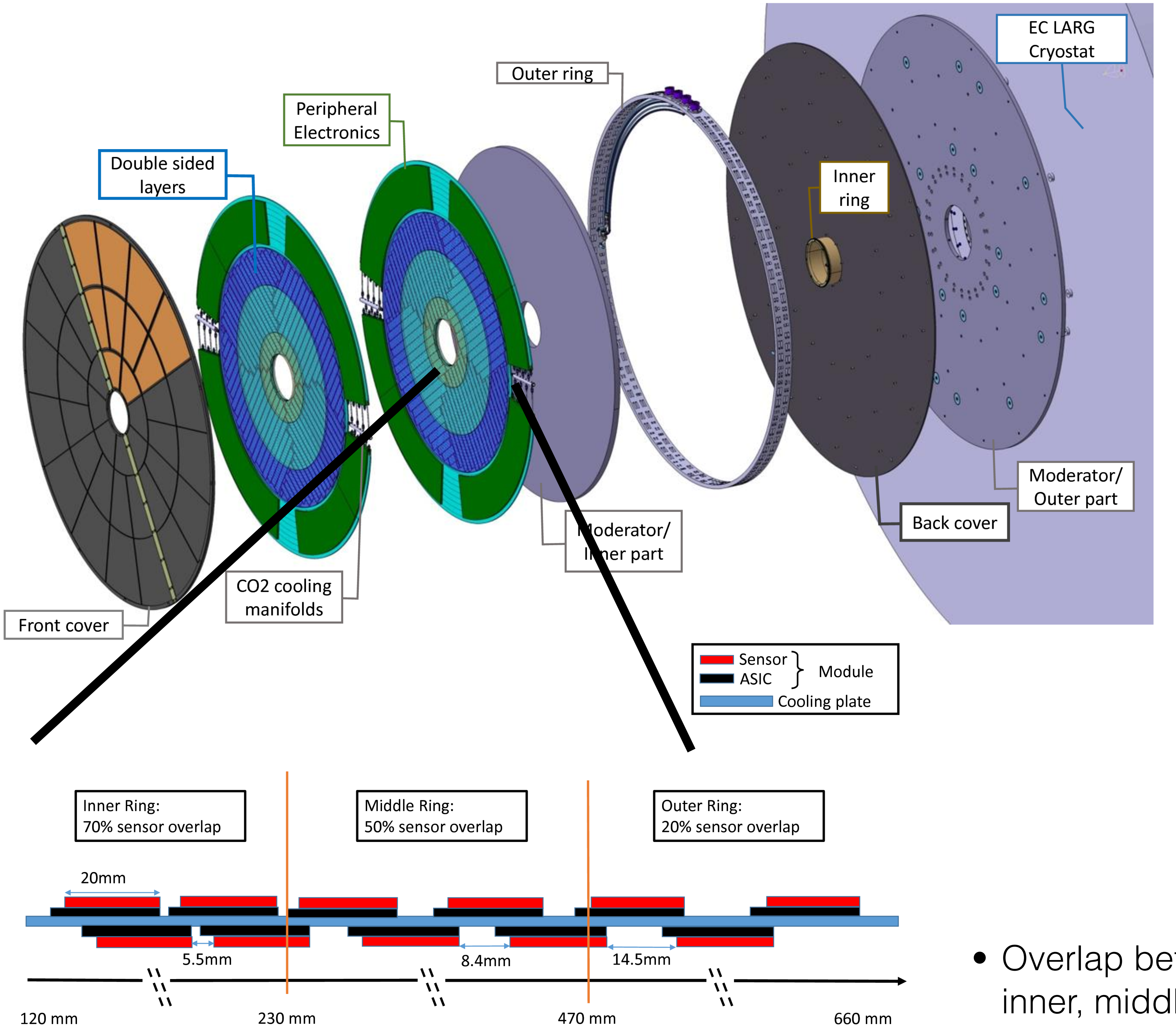
- **LGAD (Low Gain avalanche Detectors) of 50 μm thickness with pad size: 1.3 x 1.3 mm^2**

- **Sensors will be operated at -30 C**
  - CO_2 dual-phase cooling system

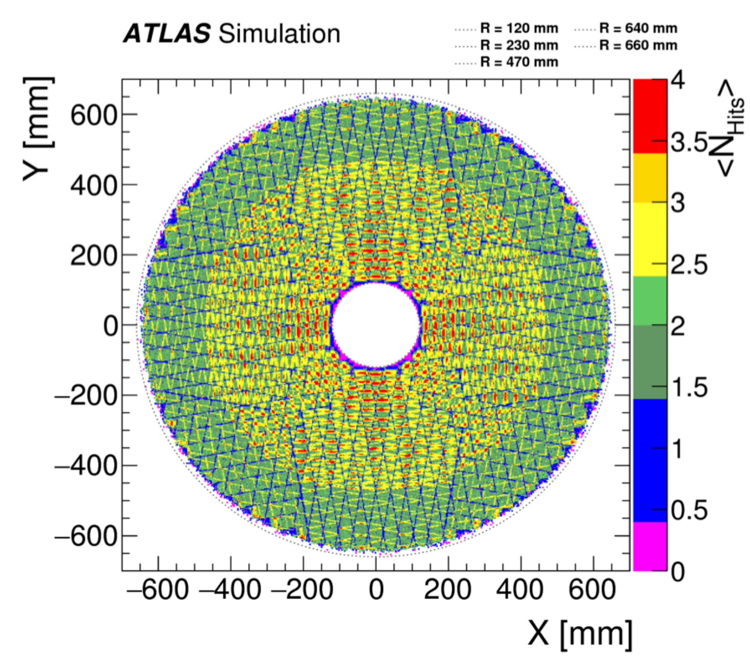


- **Active Si LGADs:**
  - **Radius from 110 mm - 640 mm**
- **Peripheral electronics boards**

Global view of HGTD



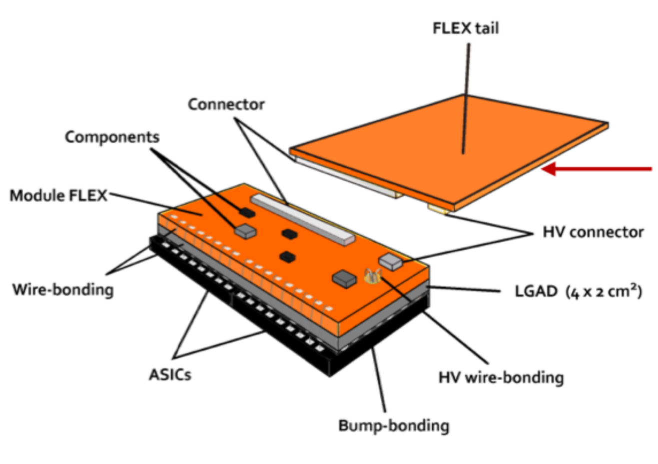
- Detector to be installed on each of two calorimeter extended barrels
- Two instrumented double. sided layers (mounted in 2 cooling disks)
    - *Rotated by 15° with respect to one another*



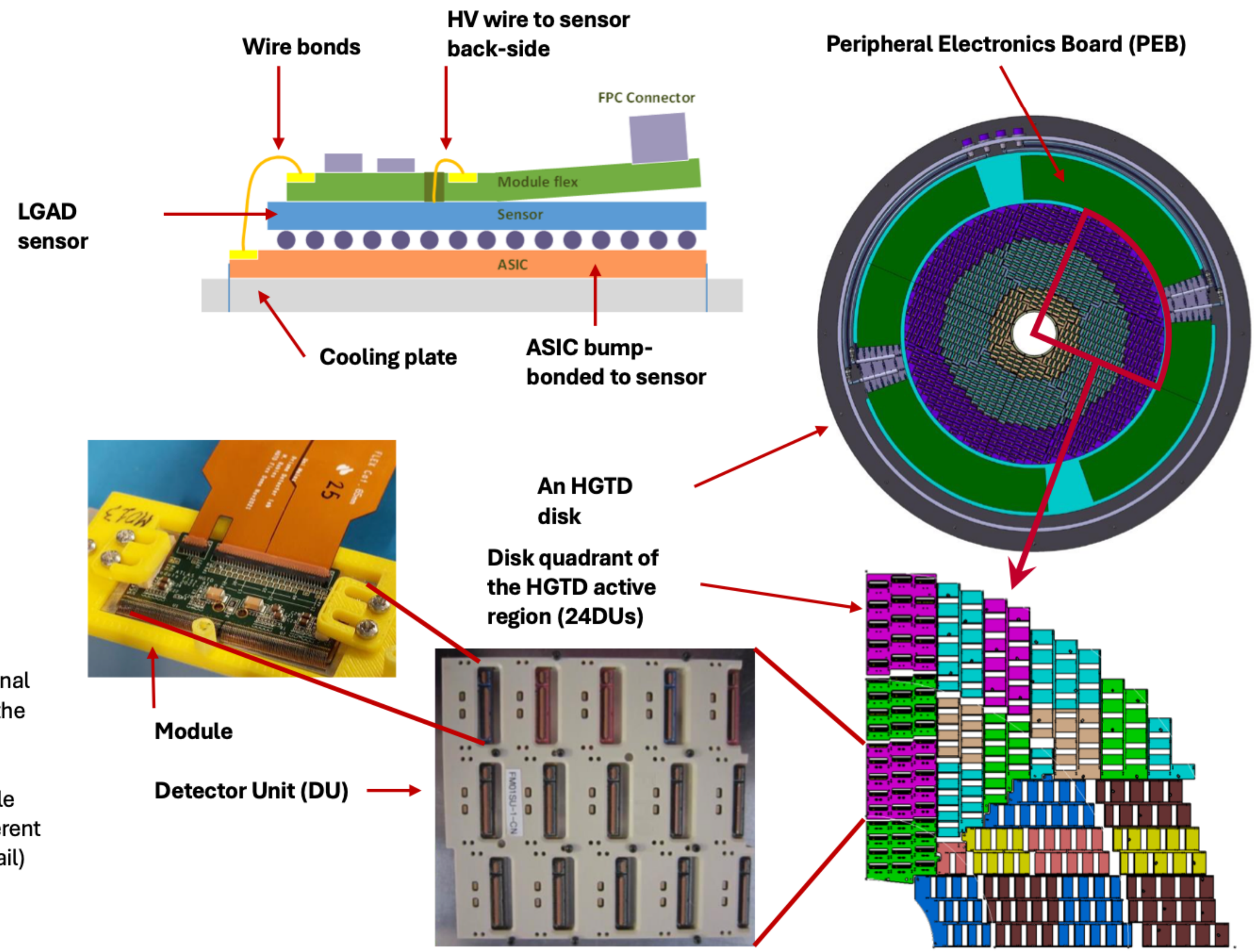
- Overlap between modules on inner, middle and outer ring

Sensor and ASIC: HGTD Module

- **HGTD *hybrid* modules:**
  - 2 LGAD Sensors: (2cm x 2cm) 15x15 pixels of 1.3x1.3 mm^2
  - 2 *ALTIROC* ASICs
  - Module flex



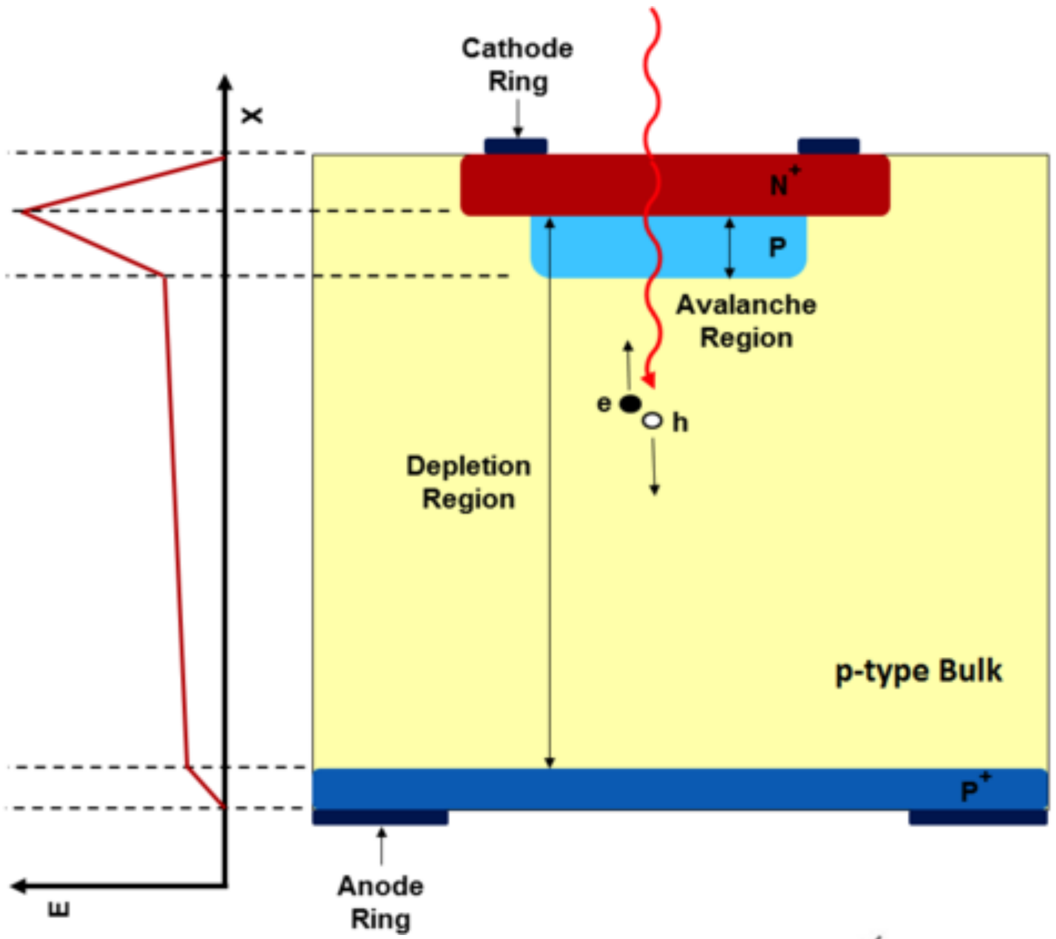
Power and signal are routed to the peripheral electronics through flexible cables of different lengths (flex tail)



LGADs

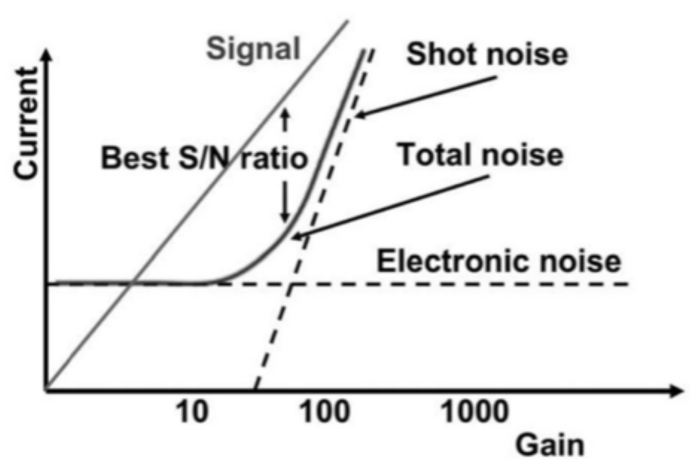
- *G. Pellegrini et al., NIM A765 (2014) 12*
- *H. Sadrozinski et al., arXiv:1704:08666*

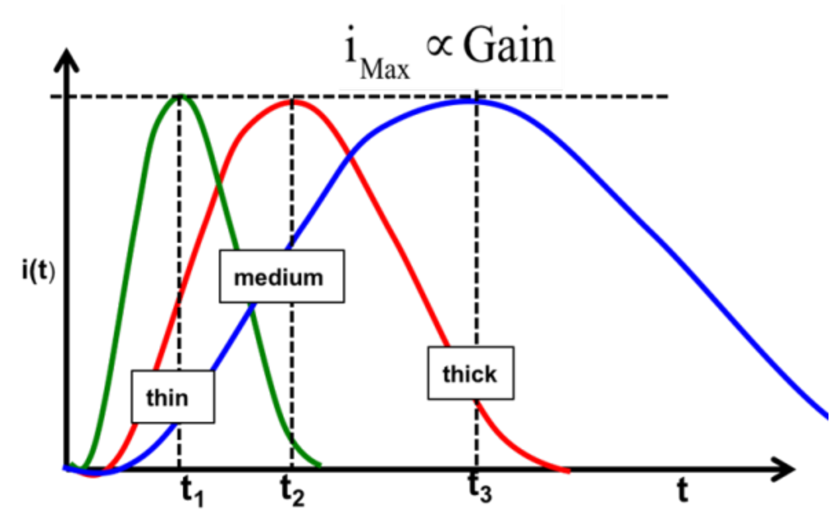
- **Low Gain Avalanche Detectors (LGAD)**
  - Developed by CNM Barcelona and CERN RD50 collaboration



- **Standard segmented N-in-P silicon detector with built-in p multiplication layer**
- Results in high E field, avalanche region
- Moderate gain ~ 10 - 20 —> **higher S/N**

- **Multiplication layer allows thinner detectors (35-50µm)**
  - Fast charge collection (~1 ns)
  - Small rise time (~400 ps)





- **Excellent time resolution < 30 ps pre-irradiation**

ALTIROC ASIC

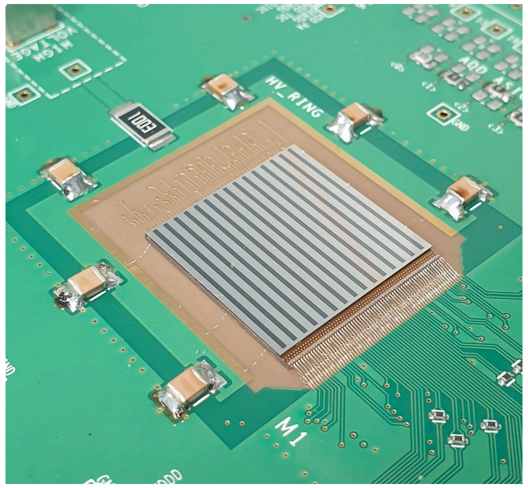
- **ALTIROC: ATLAS LGAD Timing Integrated ReadOut Chip**

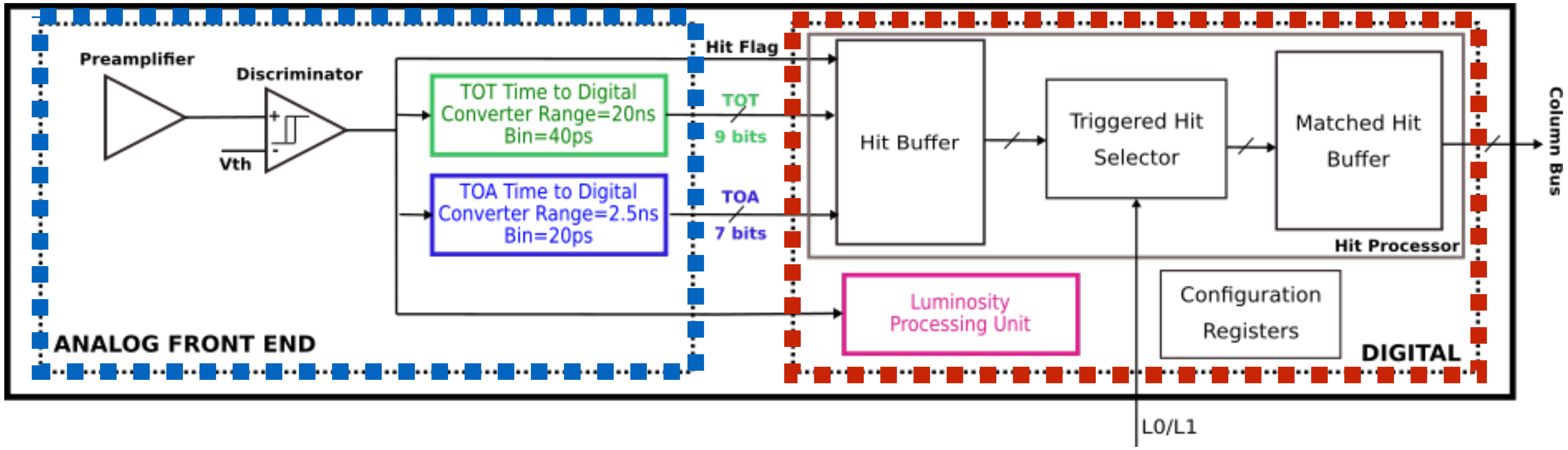
- Have to withstand high radiation levels
  - 2.0 MGy at the edge of non-replacing ring

- Each single readout channel needs to fit within the sensor pad
- **Preamplifier and a discriminator** to capture LGAD signal
- Provide **TOA and TOT** for timewalk correction (Vernier TDCs for timing)

- Timing data and hit flag stored in **local registers**
- Local data aggregated column wise and sent until ***L0 Accept*** **with a latency up to 35 μs**
- Provide **luminosity in hits** per ASIC per bunch crossing

ALTIROC2: first full-sized prototype

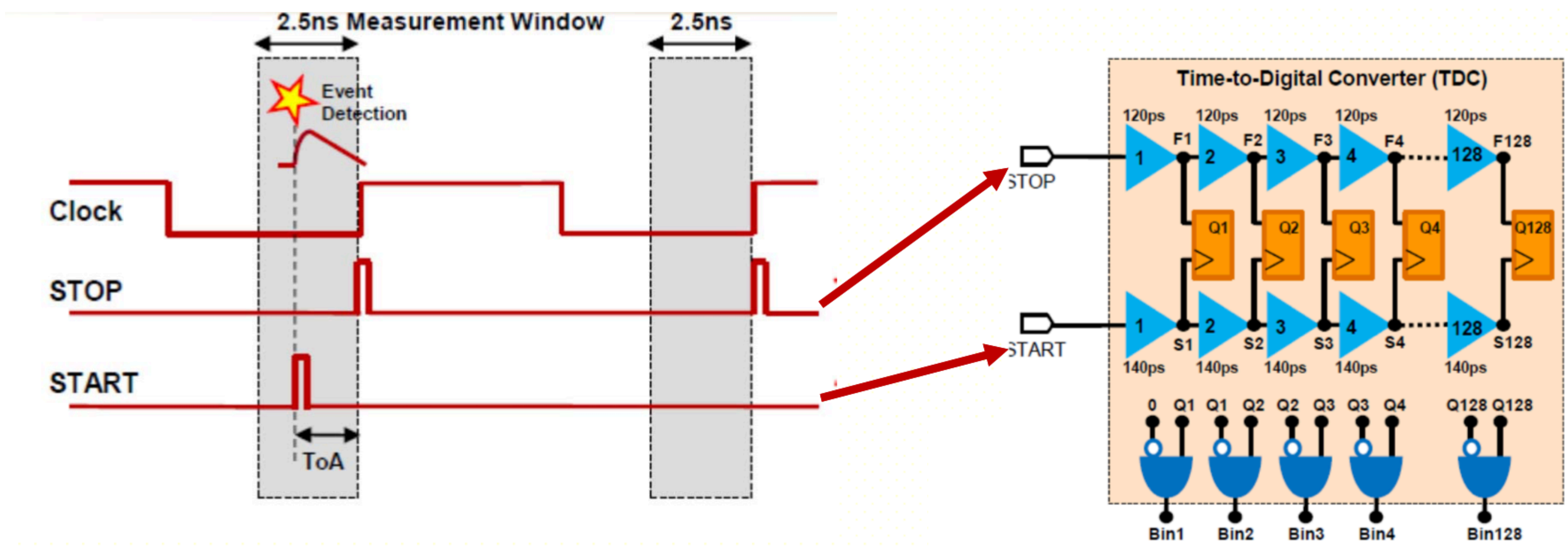




- **Provide strict jitter requirements < 25ps @ 10fC / 65ps@4fC**
- **Discriminator threshold minimum of 2fC**

Time to Digital Converter (TDC) for TOA

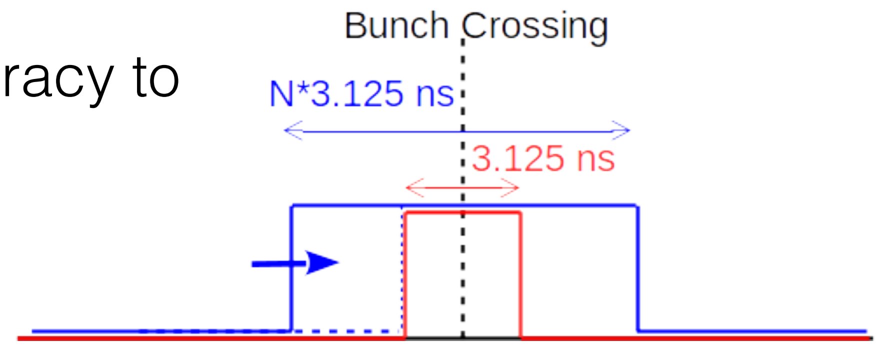
- **Vernier delay configuration with two delay lines:**
  - Time resolution of 20ps: difference between delay of cells in each slow and fast line
  - Time measurement can be made over 2.5 ns window centred on bunch crossing
  - Time of Arrival (TOA) given by bin where STOP signal passes the START

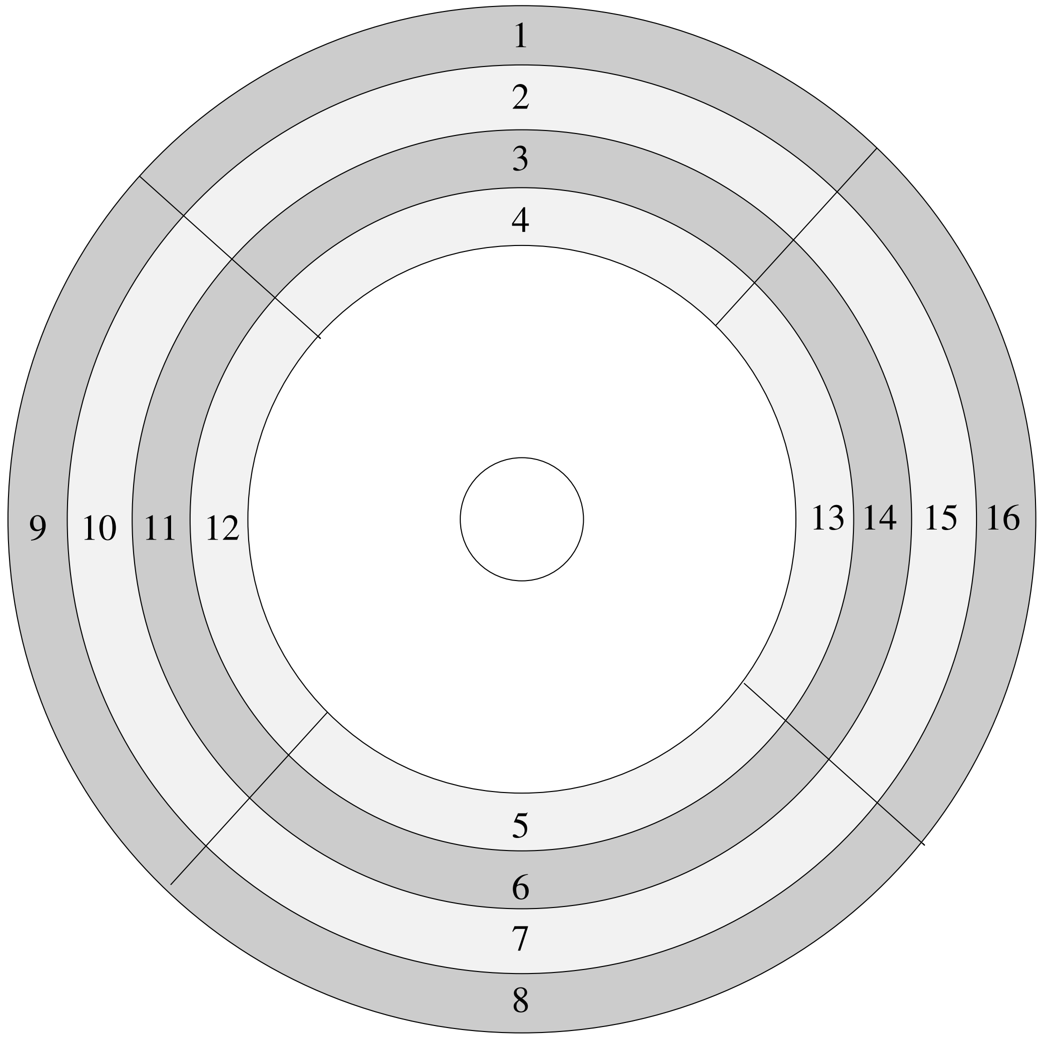


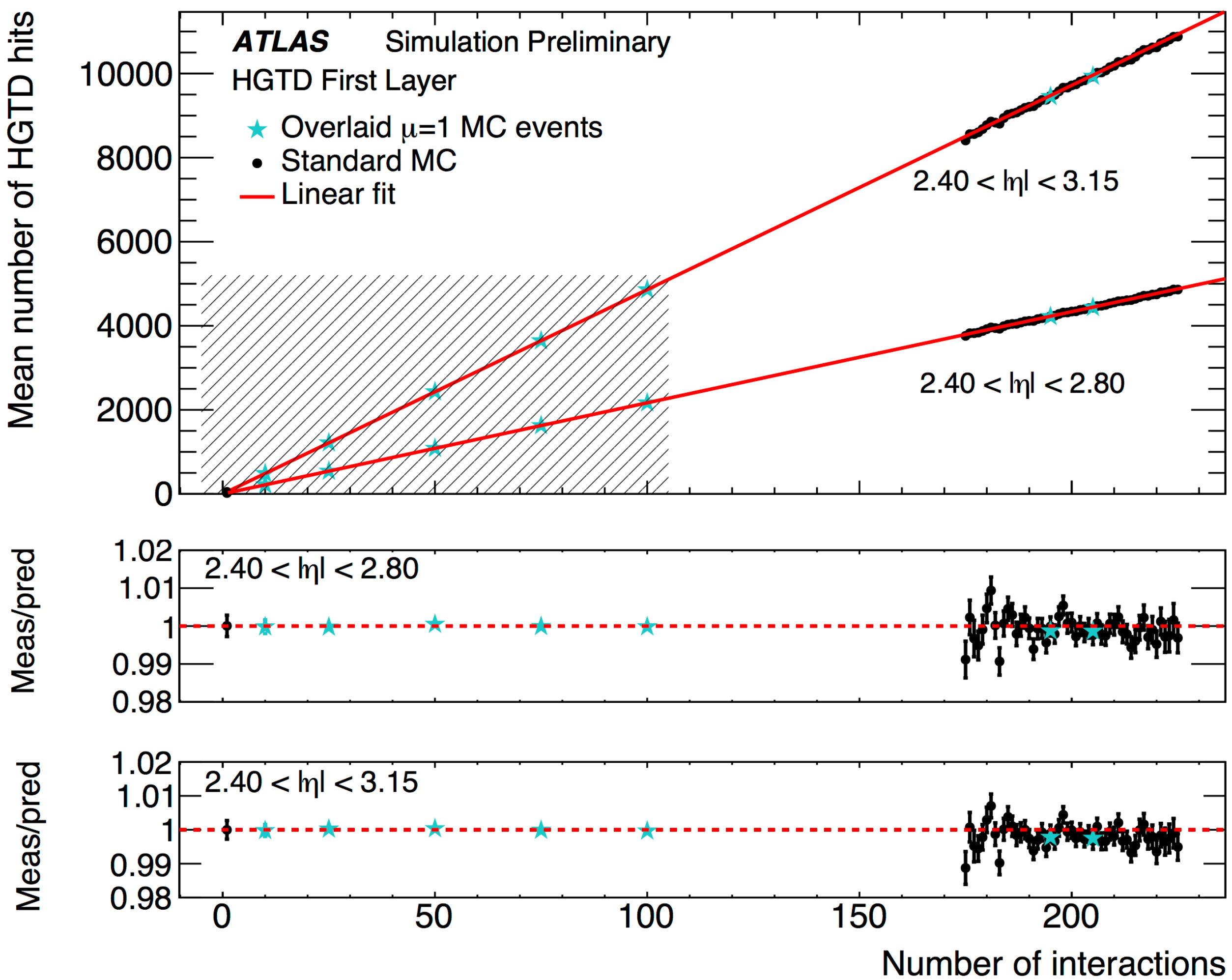
- **Timing ASICs require a high power consumption ~ 300 mW / cm²**
  - Strict requirements on CO_2 dual phase cooling ~ ASIC power 4 times the LGAD sensors
  - *No power used for TDC in case a signal is not detected*

Luminosity

- **Occupancy will be linearly correlated with the number of interactions**
- **Sum the hits** over each region to reach a sufficient statistical accuracy to provide an online measurement
- **Information sent at 40 MHz:**
  - Every bunch crossing independent of the ATLAS L0 Accept







Luminosity uncertainty one of the leading uncertainties in precision measurements

Time Resolution

$$\sigma^2_{total} = \sigma^2_{Landau} + \sigma^2_{jitter} + \sigma^2_{timewalk} + \sigma^2_{TDC} + \sigma^2_{clock}$$

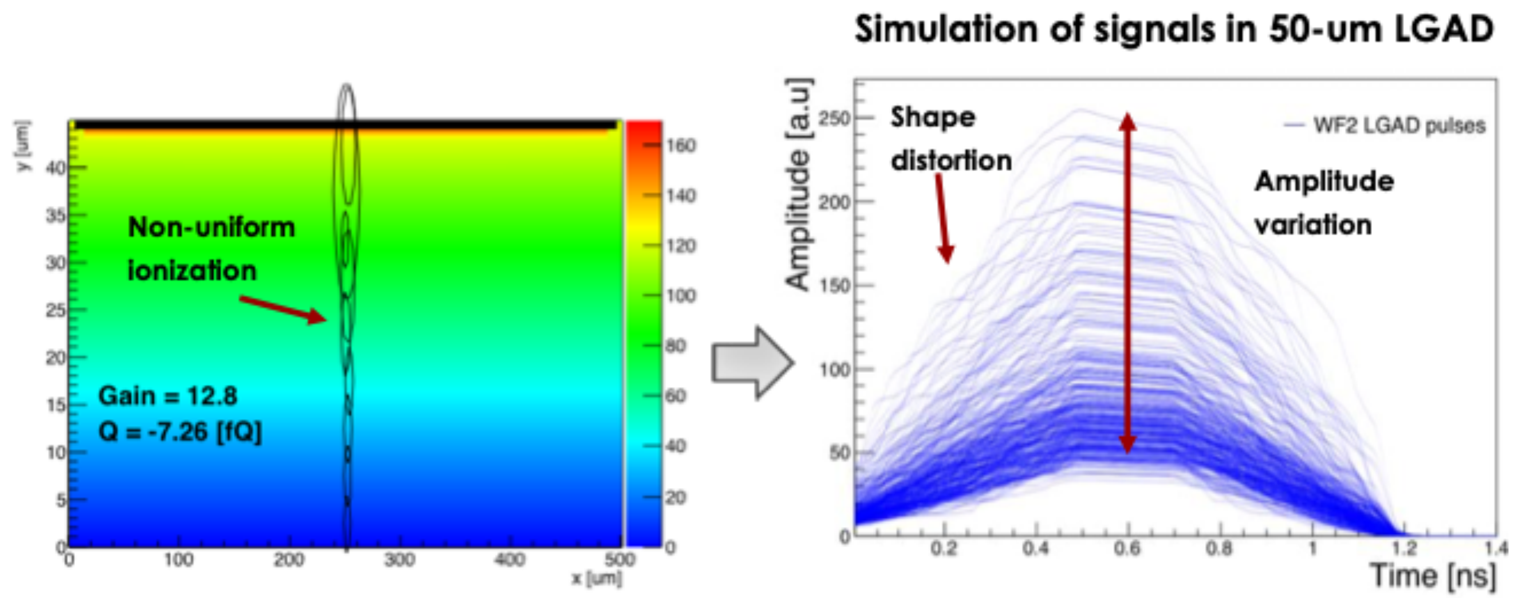
Time Resolution

Sensor

$$\sigma^2_{total} = \sigma^2_{Landau} + \sigma^2_{jitter} + \sigma^2_{timewalk} + \sigma^2_{TDC} + \sigma^2_{clock}$$

σ^2_{Landau}

- **Landau fluctuations** from deposited charge as charged particle traverses the sensor: **< 25 ps pre-irradiation: thin sensors**



N. Cartiglia PSD 12

Time Resolution

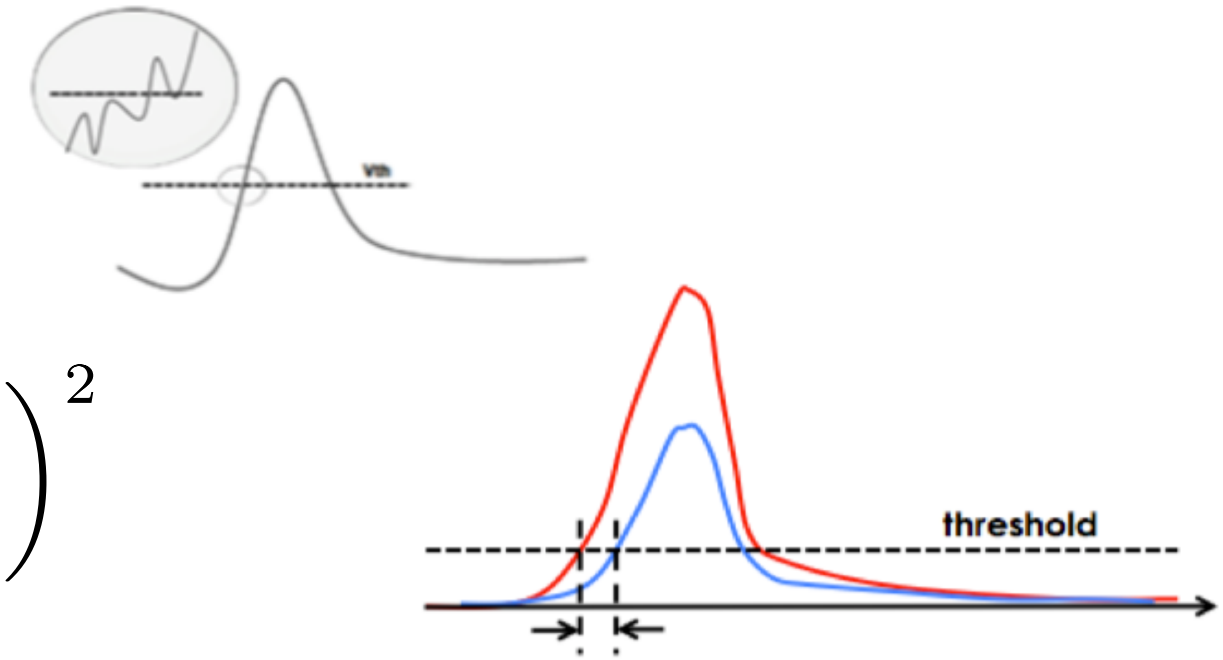
Sensor + ASIC

$$\sigma^2_{total} = \sigma^2_{Landau} + \sigma^2_{jitter} + \sigma^2_{timewalk} + \sigma^2_{TDC} + \sigma^2_{clock}$$

$$\sigma^2_{Landau}$$

$$\sigma^2_{jitter} = \left(\frac{t_{rise}}{S/N}\right)^2$$

$$\sigma^2_{timewalk} = \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{\mathrm{RMS}}\right)^2$$



Figures taken from 1704.08666

- **Largest components from jitter (total target < 25 ps)**

Time Resolution

ASIC + Readout

$$\sigma^2_{total} = \sigma^2_{Landau} + \sigma^2_{jitter} + \sigma^2_{timewalk} + \sigma^2_{TDC} + \sigma^2_{clock}$$

$$\sigma^2_{Landau}$$

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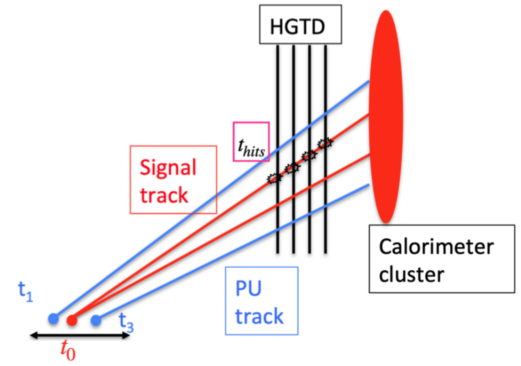
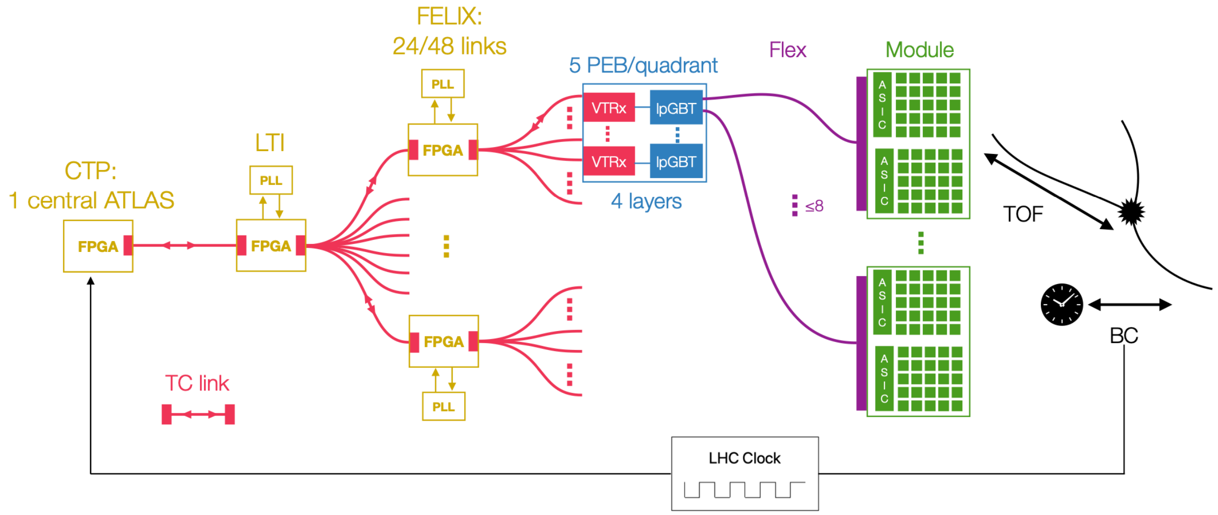


σ^2_{clock}

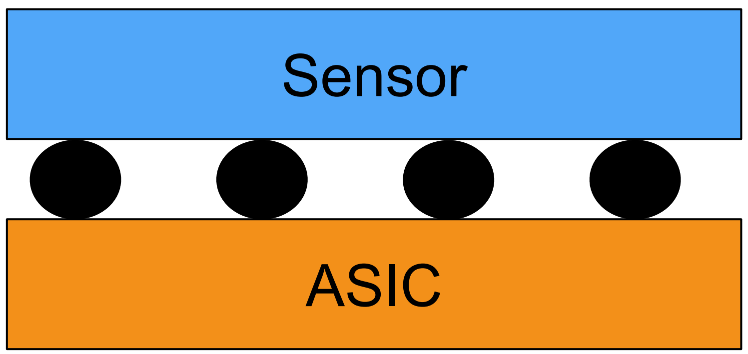
- **TDC granularity**
- **Clock distribution: < 10 ps**



DRD7 meeting

LGAD R&D for hybrid detector

- **HGTD modules are hybrid silicon detectors**
  - LGAD bump-bonded to an ASIC



Jitter of a preamplifier:

$$\sigma_{\text{jitter}} = \frac{e_n C_d \sqrt{t_d}}{Q_{\text{inj}}}$$

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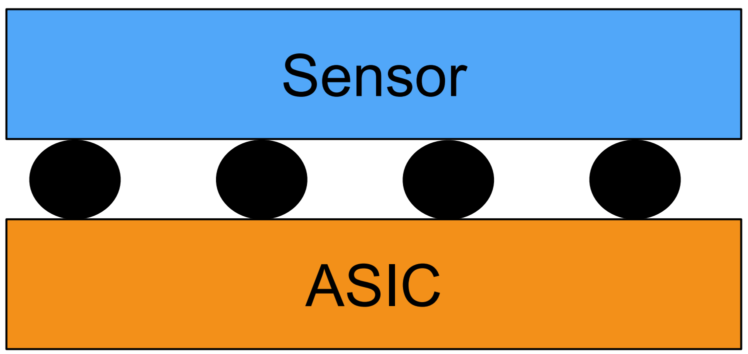

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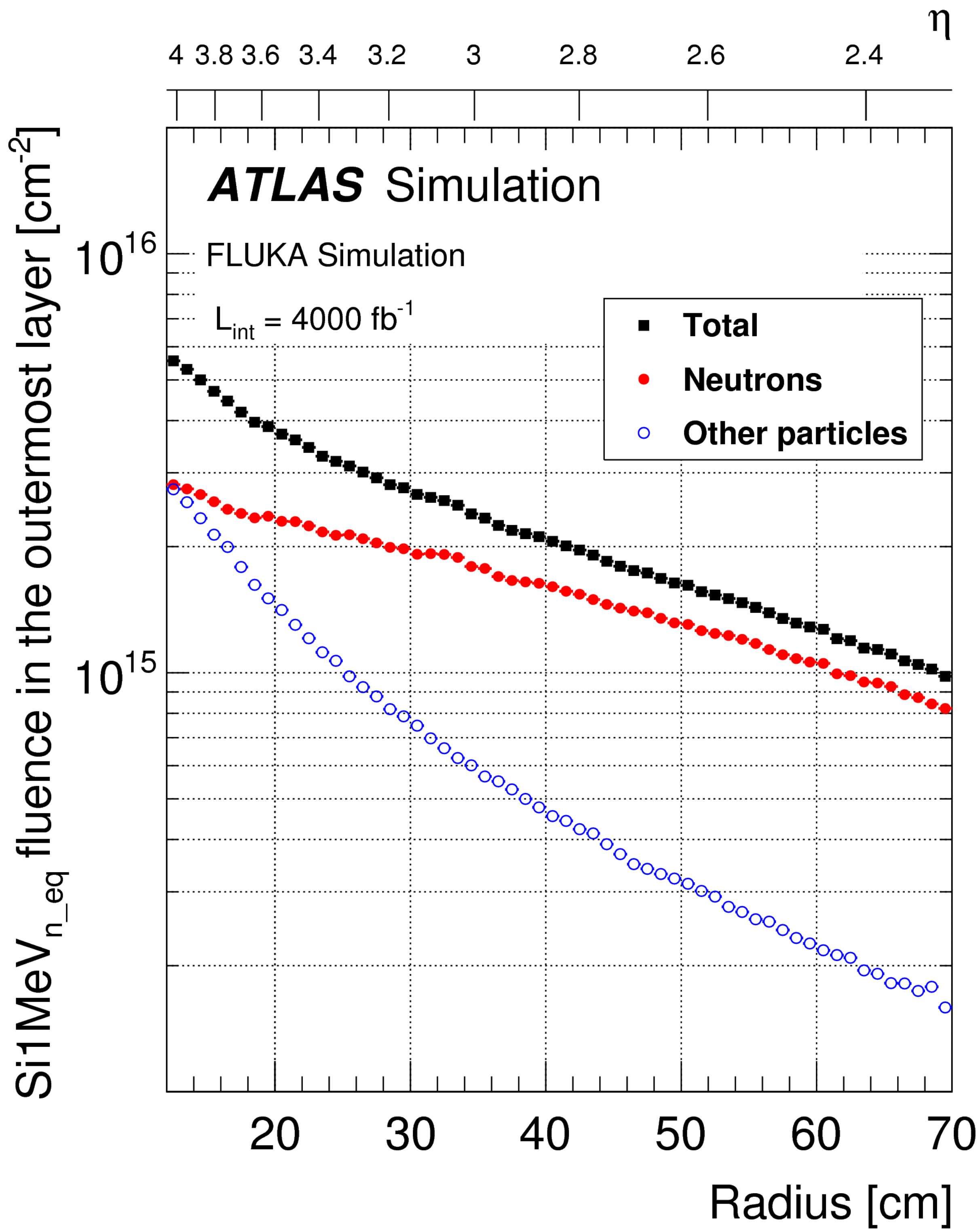
- **Thickness of LGADs**
  - Tested LGADs down to ~ 35 μm active Si:
  - Smaller rise time, faster signal, less impact due to Landau fluctuations
  - Smaller bias voltages —> less power required (better for cooling)
  - *Large capacitance with thinner sensors (C_d) —> ~ 50 um = 4 pF*

- **Depth and design of multiplication layer**
  - Gain limitations due to noise (< 100)
  - Gain layer depth (up to 2.5 μm)
  - Implant width (up to 1-2 μm)
  - Different materials —> Boron or Gallium
  - Additional impurities —> Carbon

Time resolution < 70 ps
Collected Charge > 2.5 fC

Radiation damage

- **Occupancy < 10 % even in the innermost part of the detector + position resolution**
  - Size of the sensing element 1.3x1.3 mm^2
- **Sensors will be operated at -30°C to mitigate impact**
  - CO_2 cooling
- **Radiation damage is a main concern**
  - 6×10^{15} n_{eq}/cm^2 and > 3 MGy



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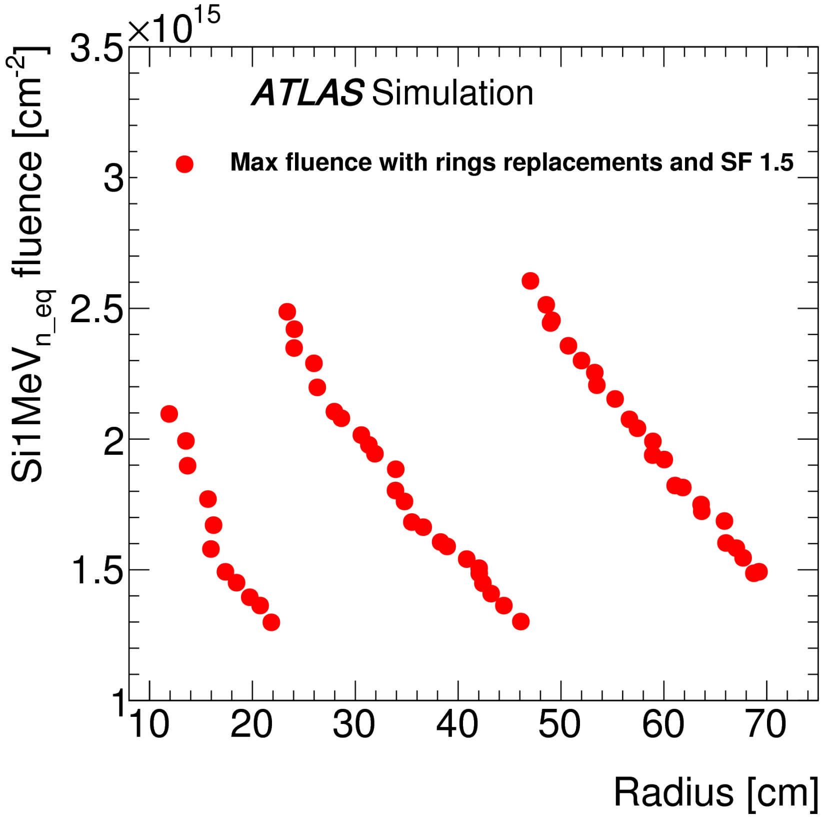
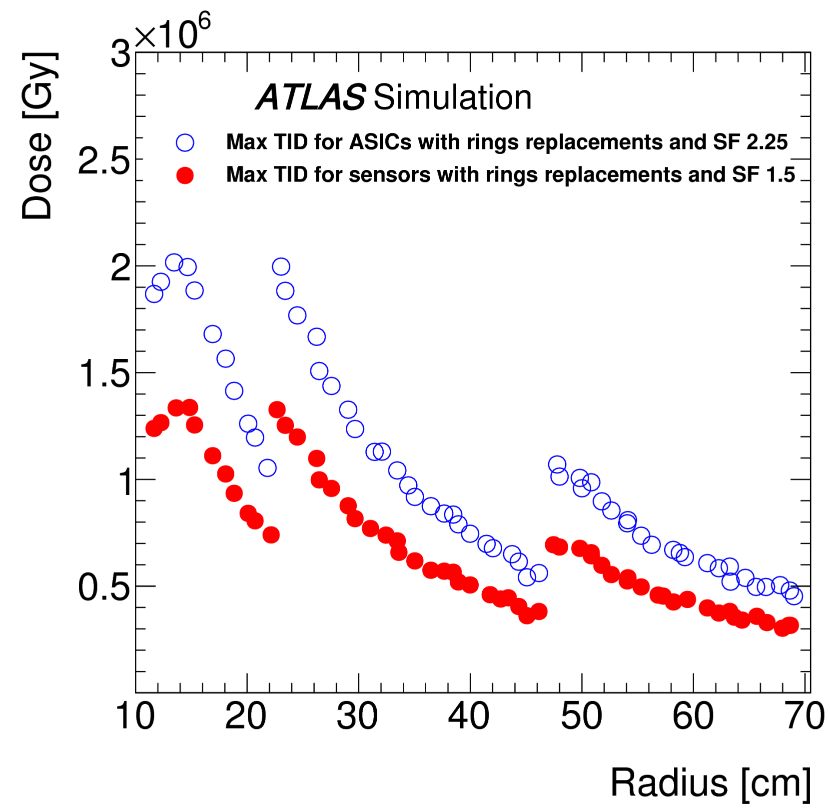
  - CO_2 cooling
- **Radiation damage is a main concern**
  - 6×10^{15} n_{eq}/cm^2 and > 3 MGy
- **Replacement of inner most part of sensors to keep good performance (every 1000 fb^{-1})**
  - **Maximum fluence of 2.5×10^{15} n_{eq}/cm^2 and 2 MGy**

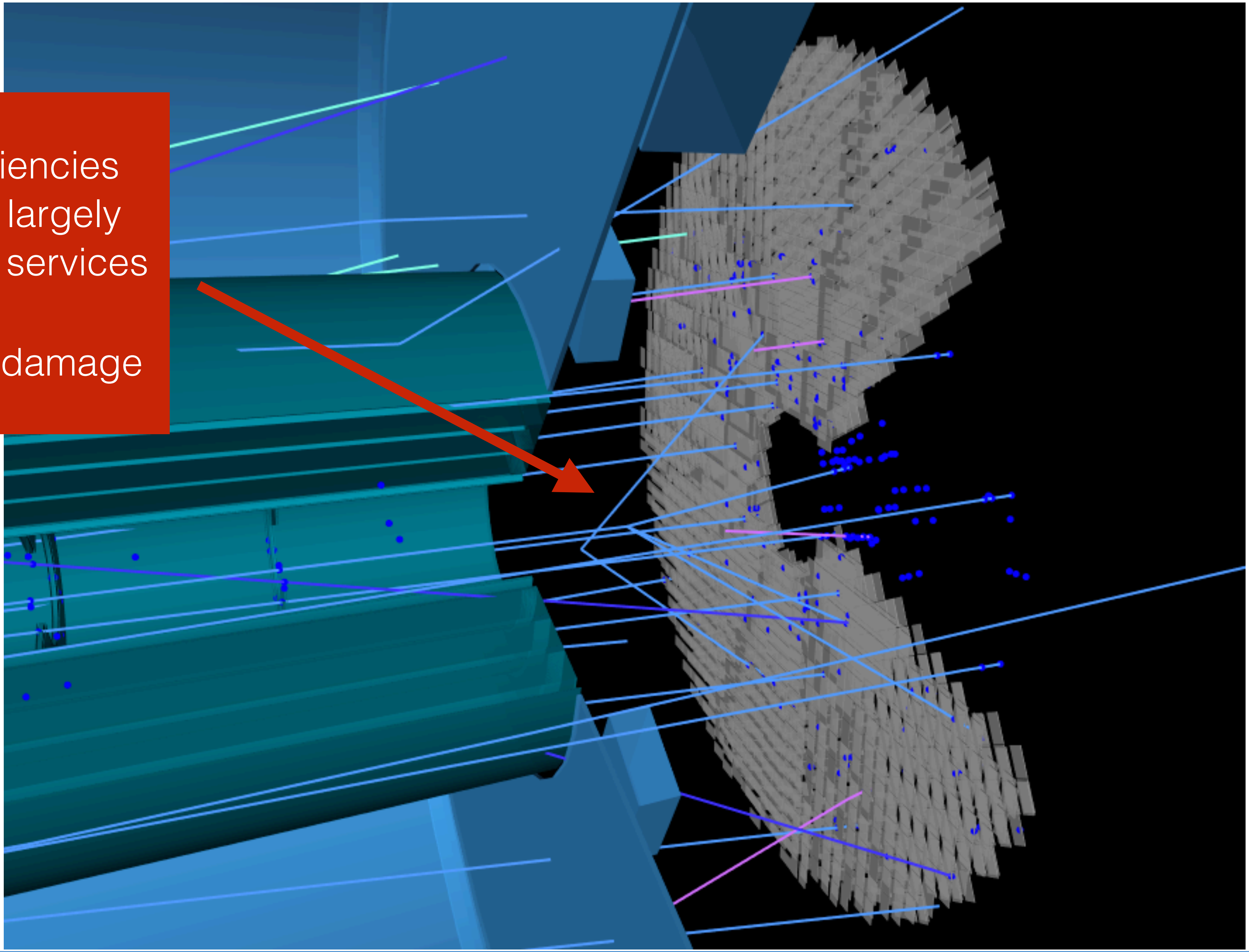




Simulation of HGTD

- **QCD dijet event showing HGTD hits and trajectories of charged particles**

- Occupancy, hit efficiencies (clustering) depend largely on material from ITk services
- Additional radiation damage

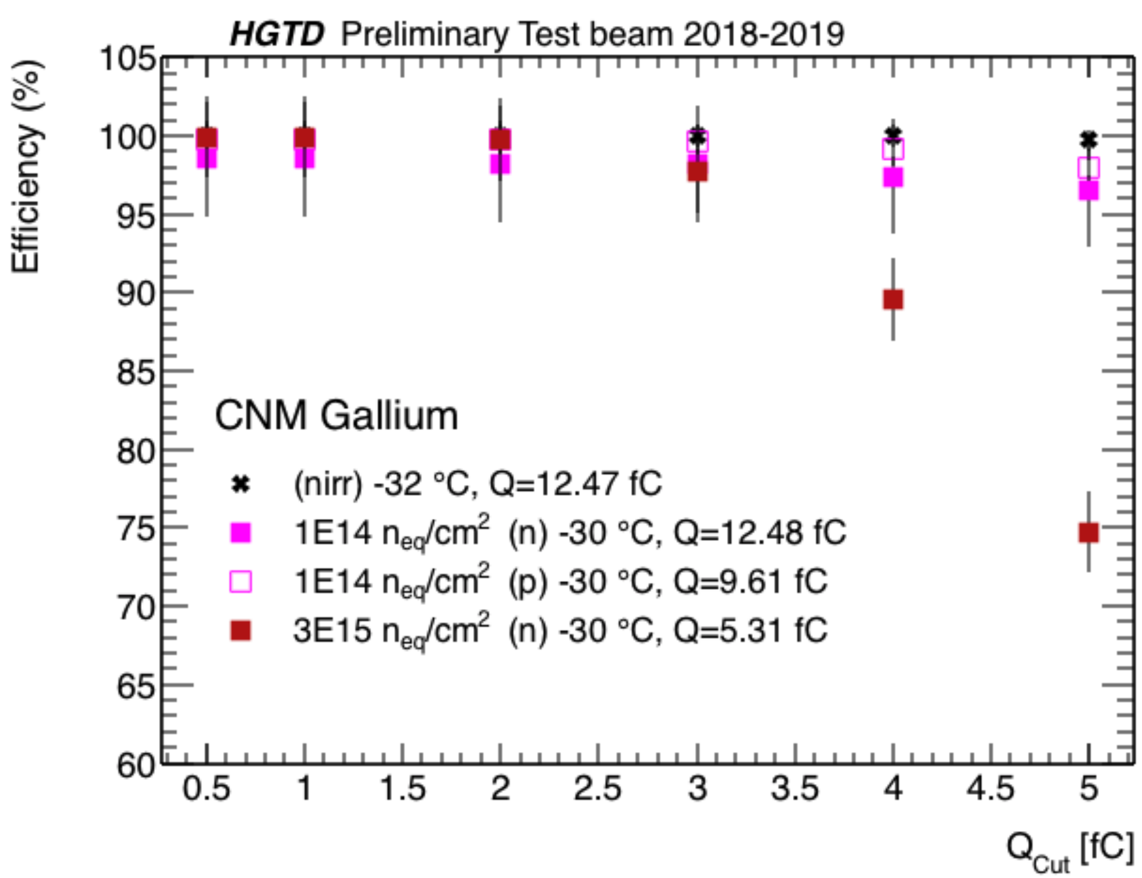


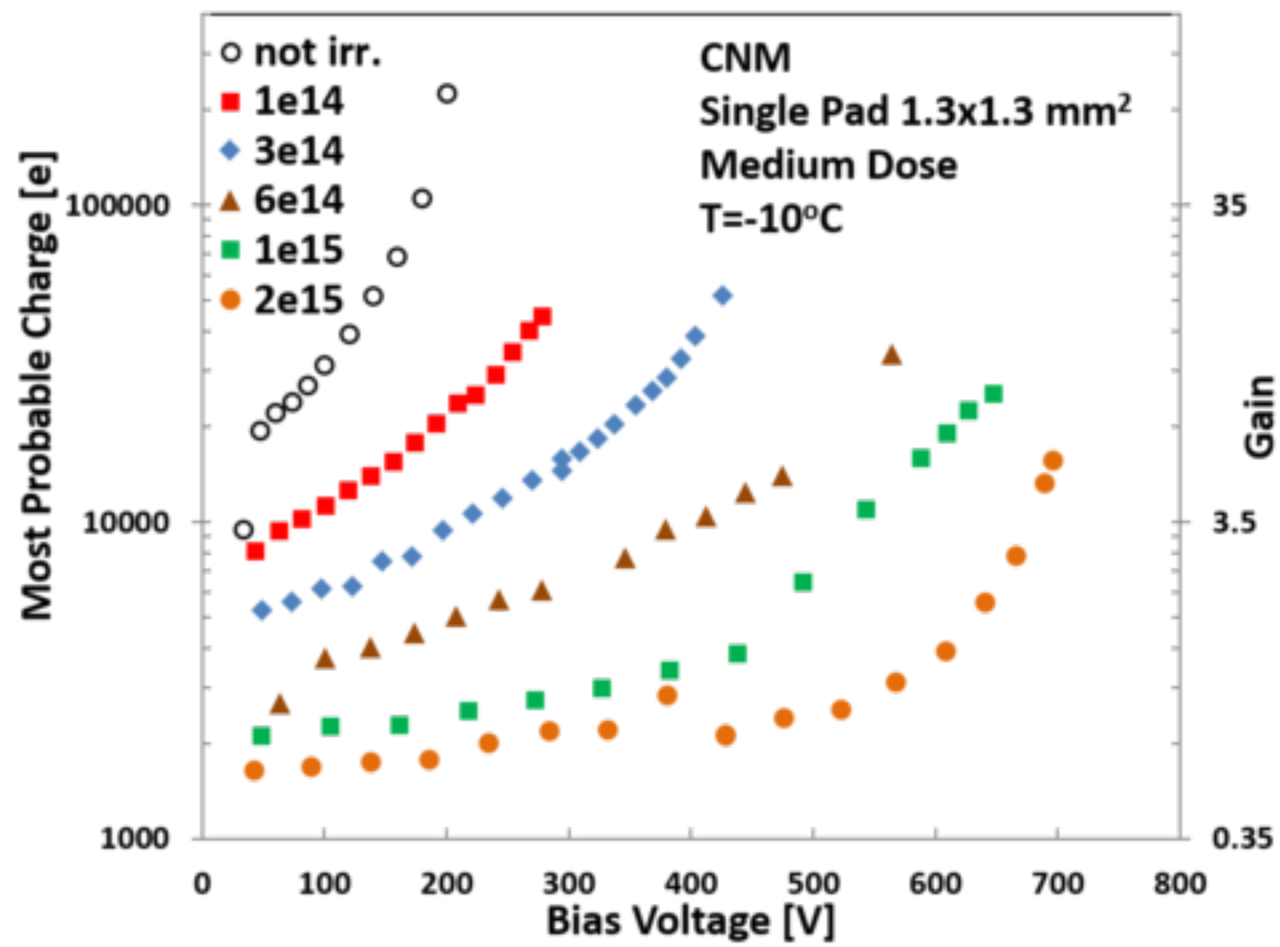
LGAD radiation studies

- **Sensor irradiated campaigns:**
  - Neutrons at IJS (Ljubljana)
  - Protons at PS-IRRAD (CERN)

- **Up to fluences of 6 × 10^{15} n_{eq}/cm^2**

- Bias voltage increase recovers Gain loss due to higher fluences





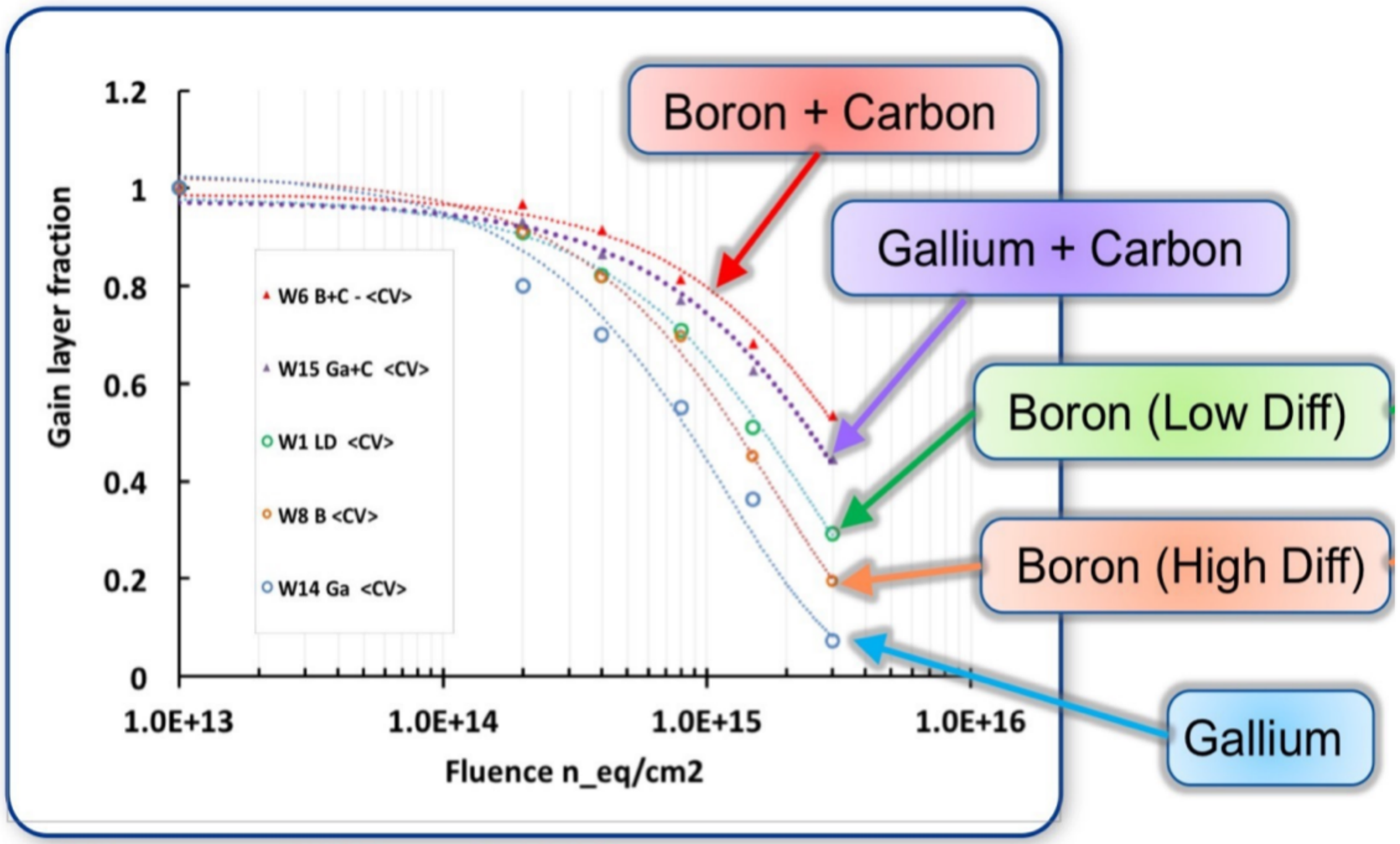
1711.06003

- **Higher fluences result in losses of efficiency for a certain charge**

Radiation hardness of LGADs

- **With irradiation (fluence > 1.5e15 n_{eq}/cm^2):** the effective doping in the gain layer is significantly reduced
  - Due to the 'acceptor removal' process —> loss of free carrier concentration in p-type silicon

- **LGAD gain layer reduction with radiation damage**



- **Studies of different gain layer designs, doping materials and C-enriched substrates**

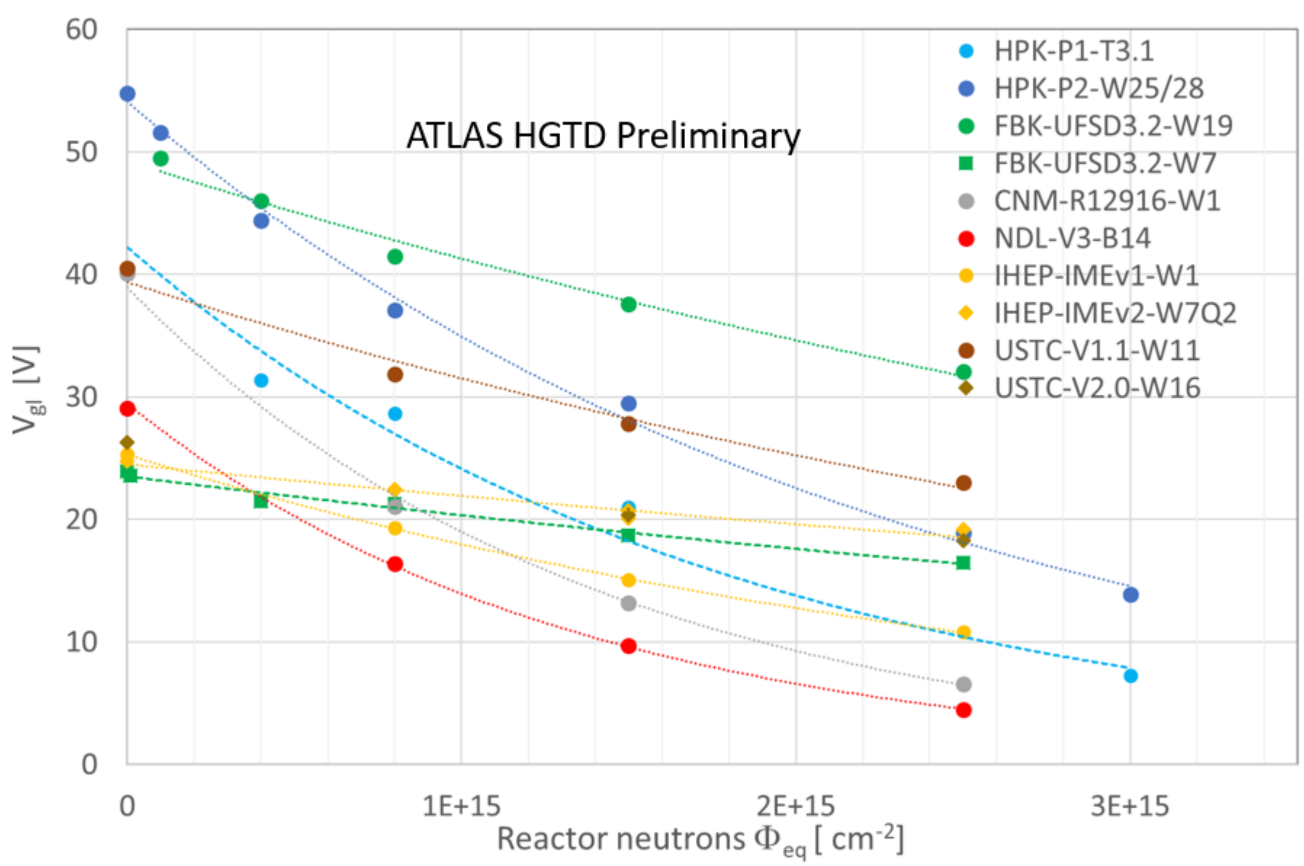
- **Least loss in gain from Boron + Carbon**

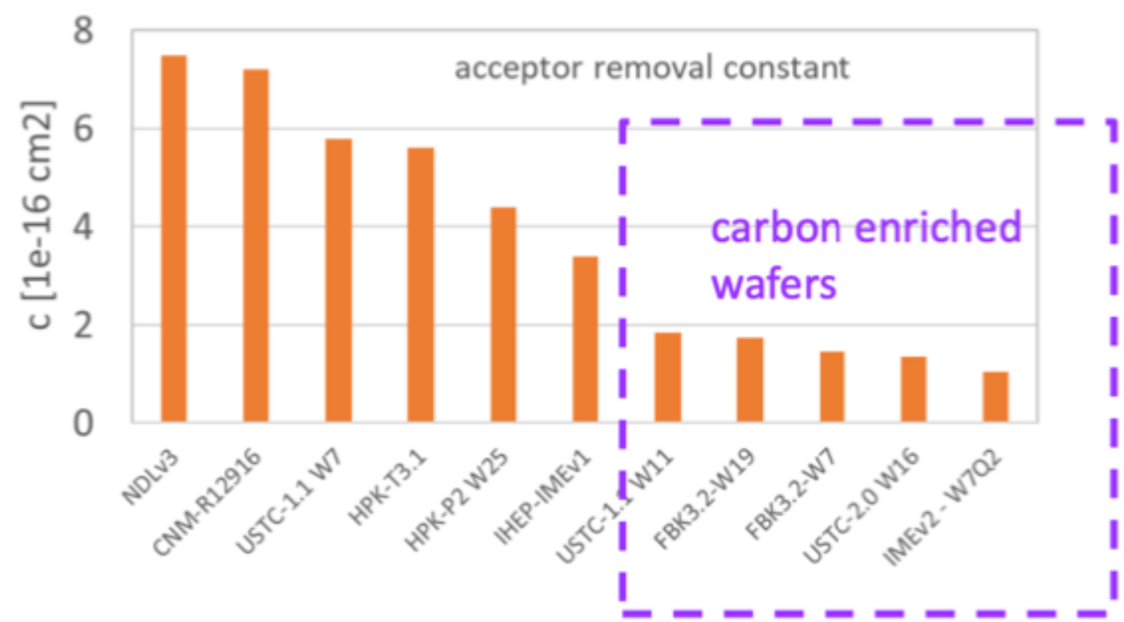
G. Paternoster, TREDI 2019

Acceptor removal

- Quantify the **acceptor removal coefficient** (c-factor) from Capacitance-Voltage (CV) measurements
    - Identify the **gain layer depletion voltages** (V_{gl}) before and after irradiation

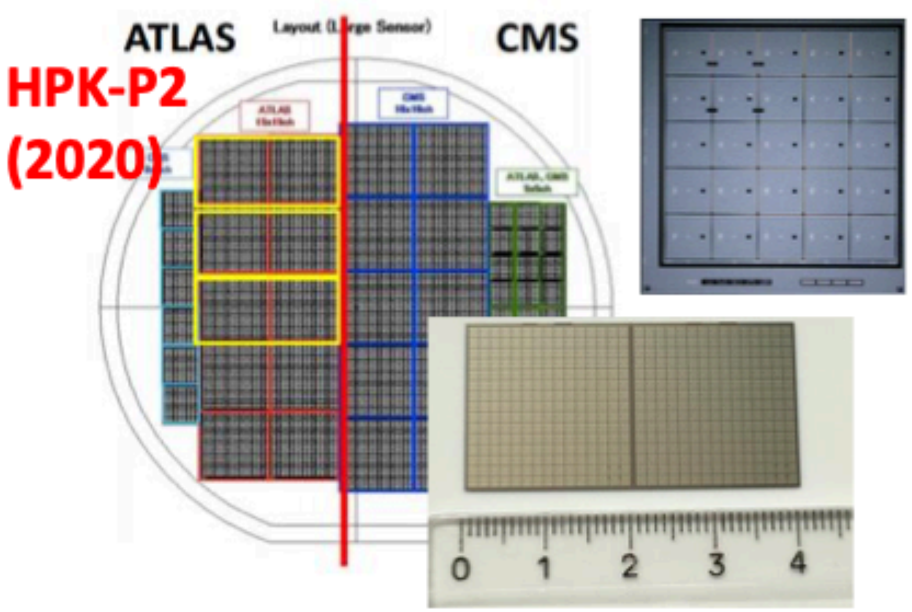
$$V_{GL,\Phi_{eq}} = V_{GL,0}\exp(-c \cdot \Phi_{eq})$$



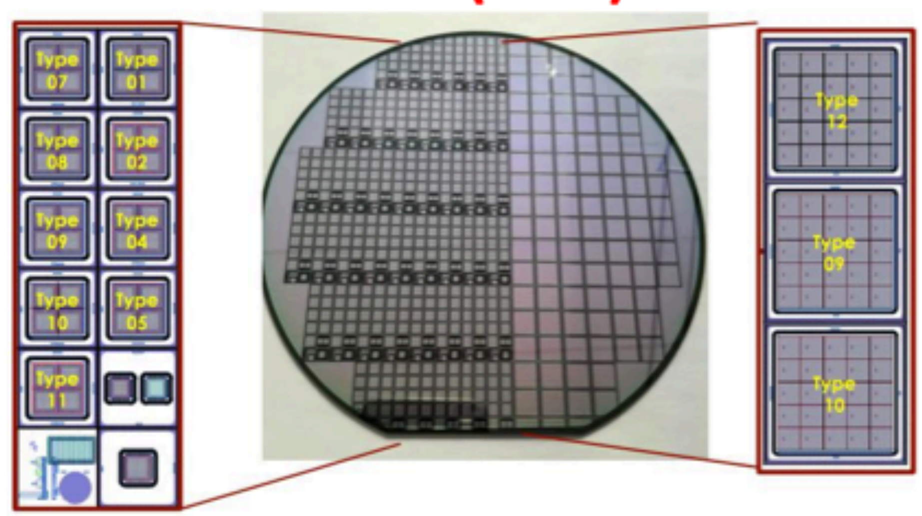


- **Optimization** of dopants, depth, concentration of gain layers from various vendors and runs
    - Carbon enriched wafers achieve lowest acceptor removal coefficient

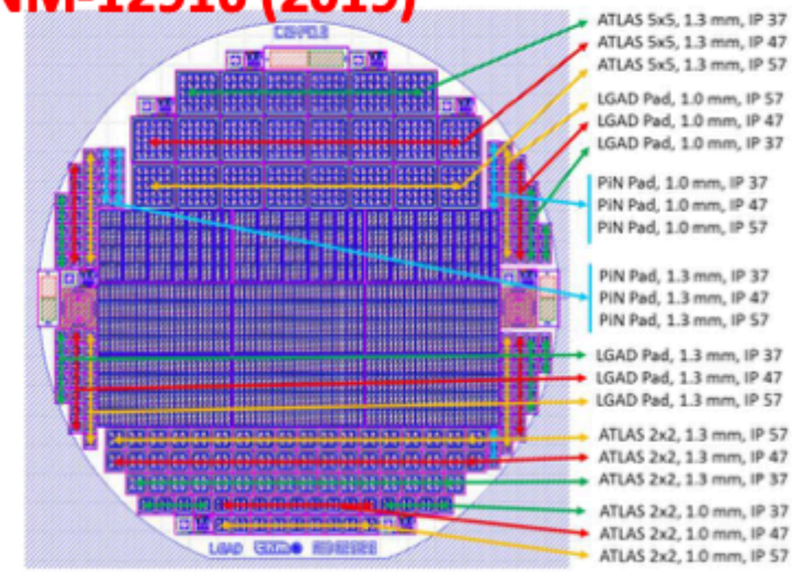
Extensive R&D for ATLAS + CMS

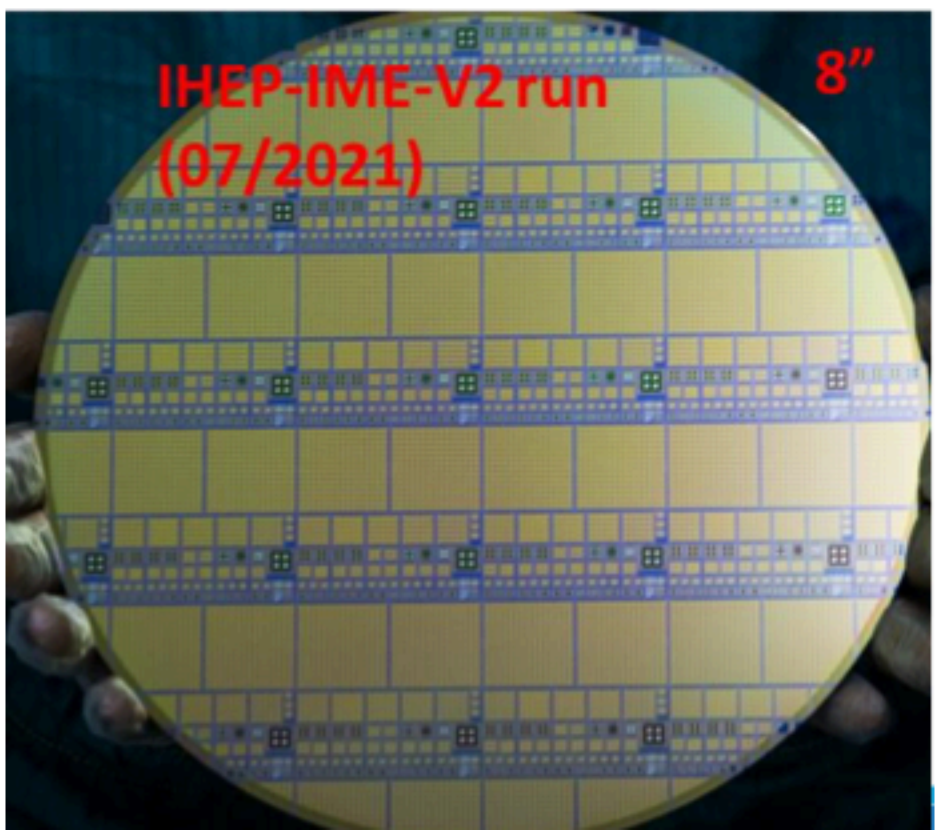


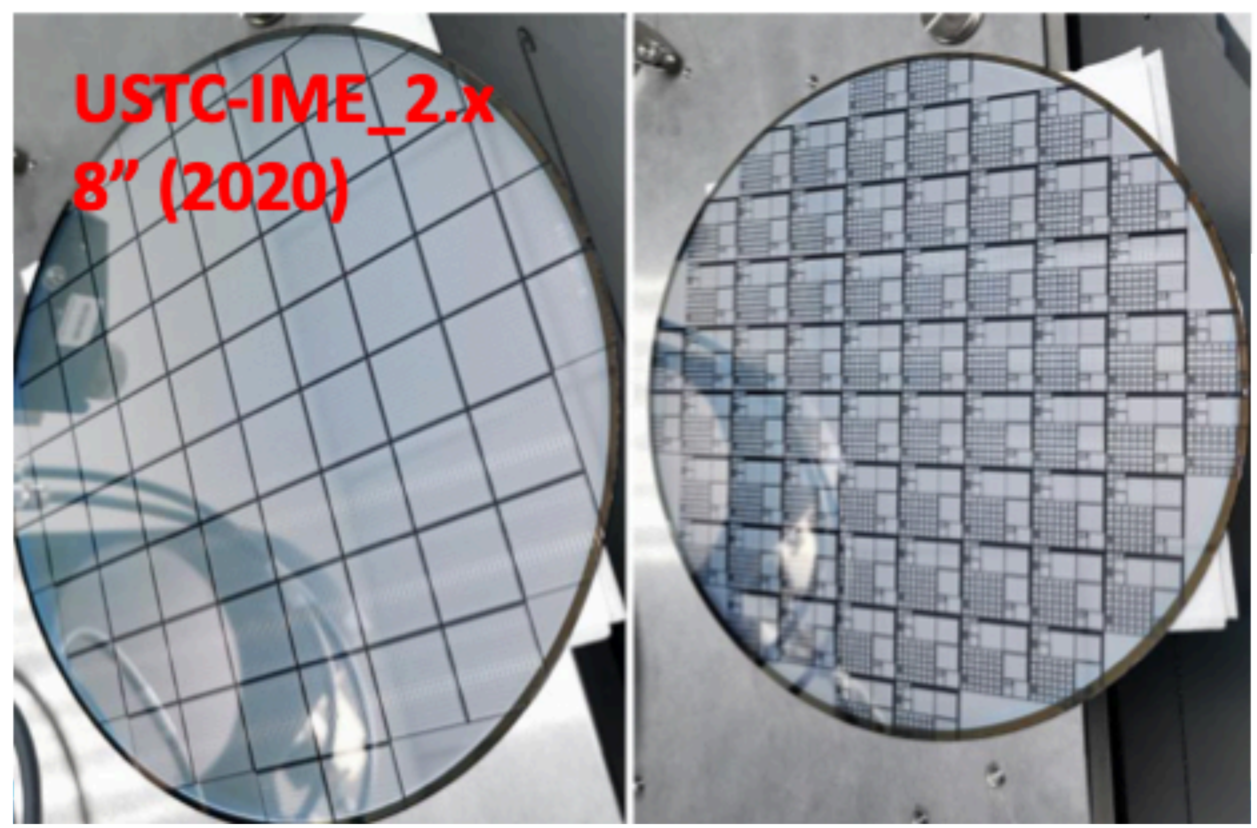
FBK-UFSD 3.2 (2020)



CNM-12916 (2019)

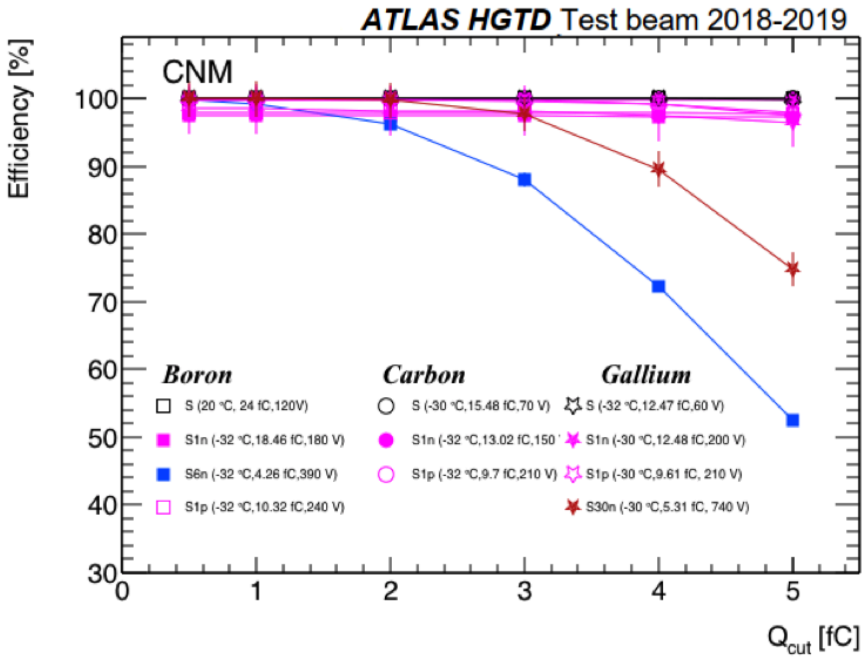






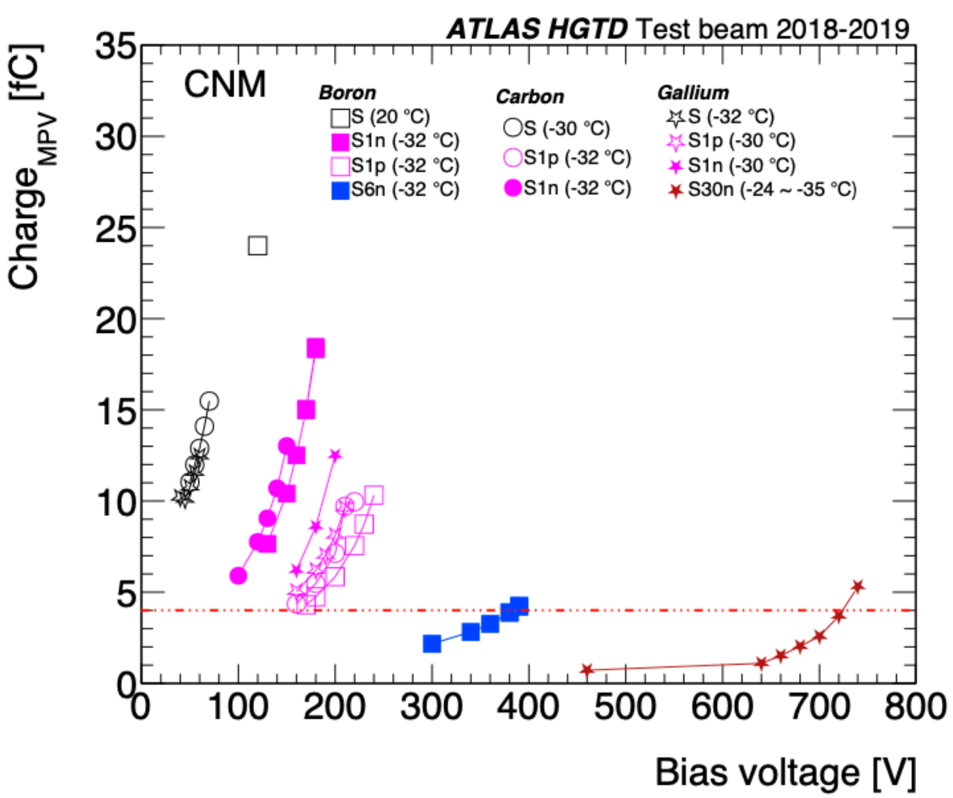
LGAD studies

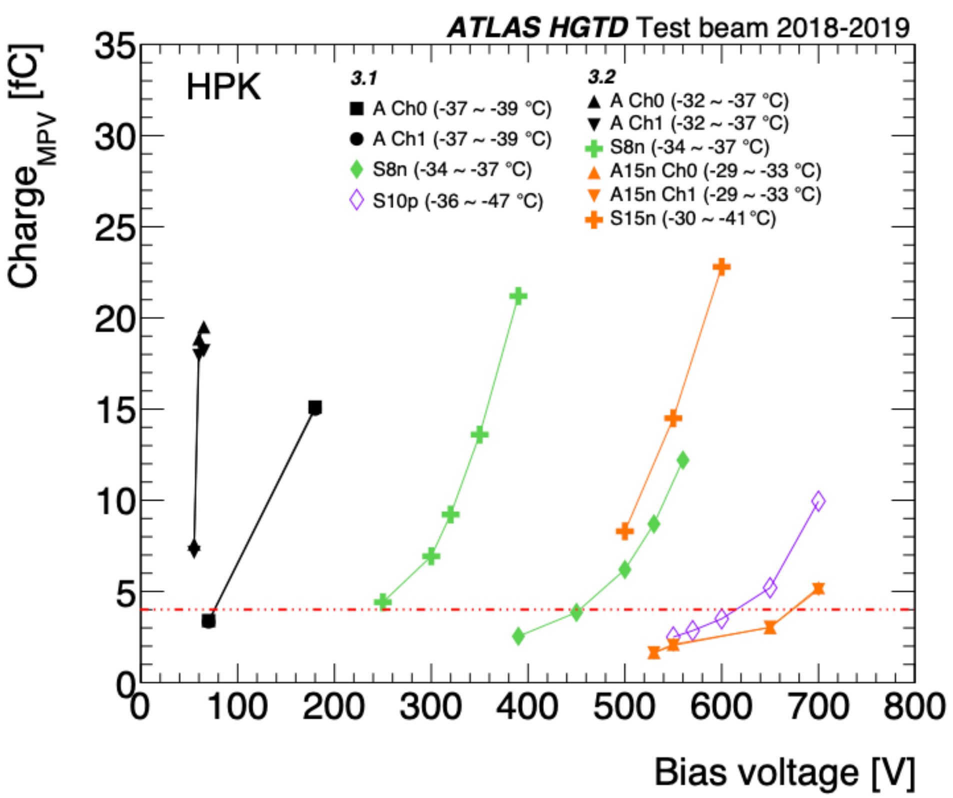
- **R&D phase over several years of LGAD testing in lab and testbeam**
- Tests of radiation-hardness up to maximum fluence:
  - Use of different designs and doping materials
  - Carbon implanted gain layers



- **Carbon implanted gain layers reduce impact of irradiation**
  - Larger charge collection at similar bias voltages

- Optimization of carbon enrichment dose and diffusion techniques to target acceptor removal coefficient



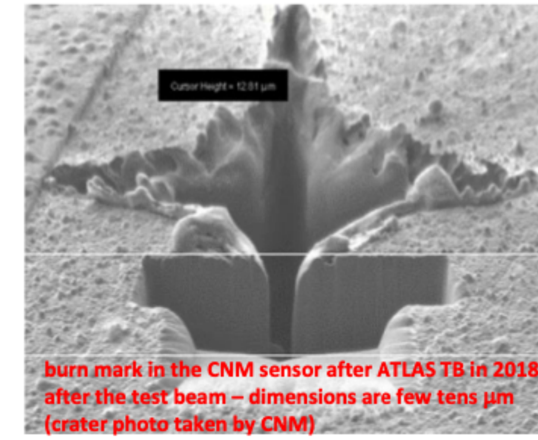


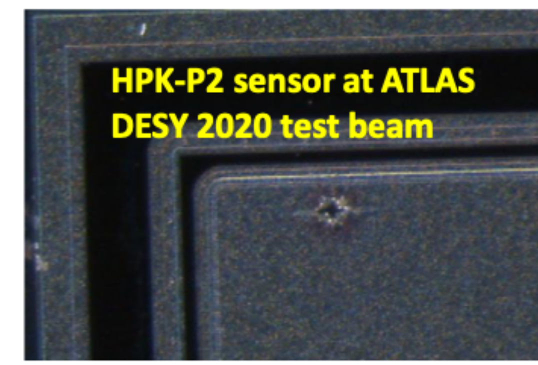
- Published in: JINST 17 P09026

Single Event Burnout (SEB)

- **During testbeam campaigns in 2017, 2018, and 2019 several sensors lost**
  - All with fluences above 1.5×10^{15} n_{eq}/cm^2

- No incidents in lab testing (laser or Sr90)
- Many testbeams trying to capture event





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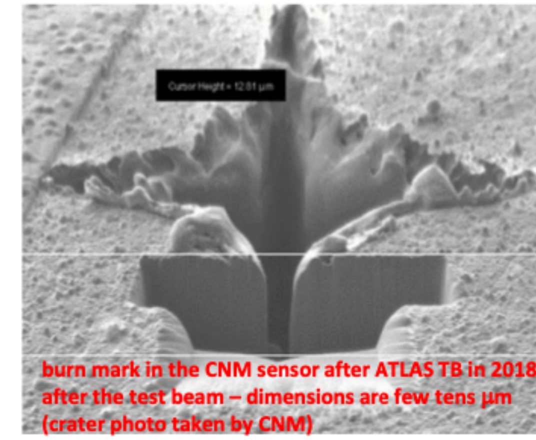

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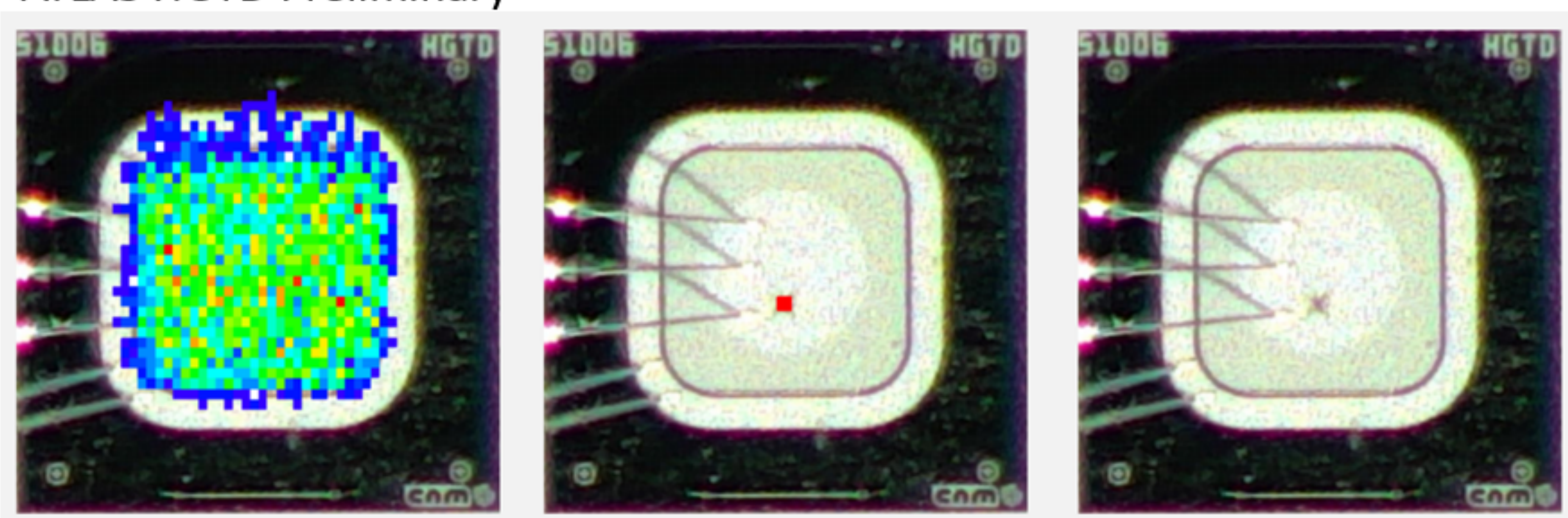
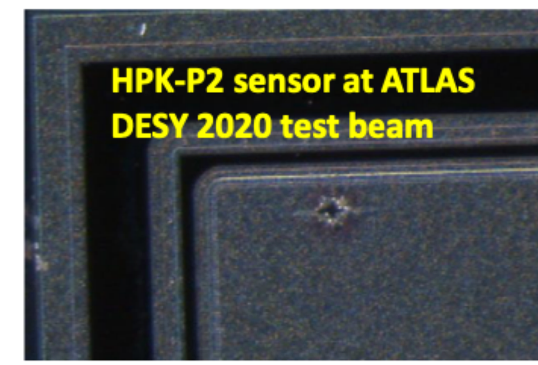
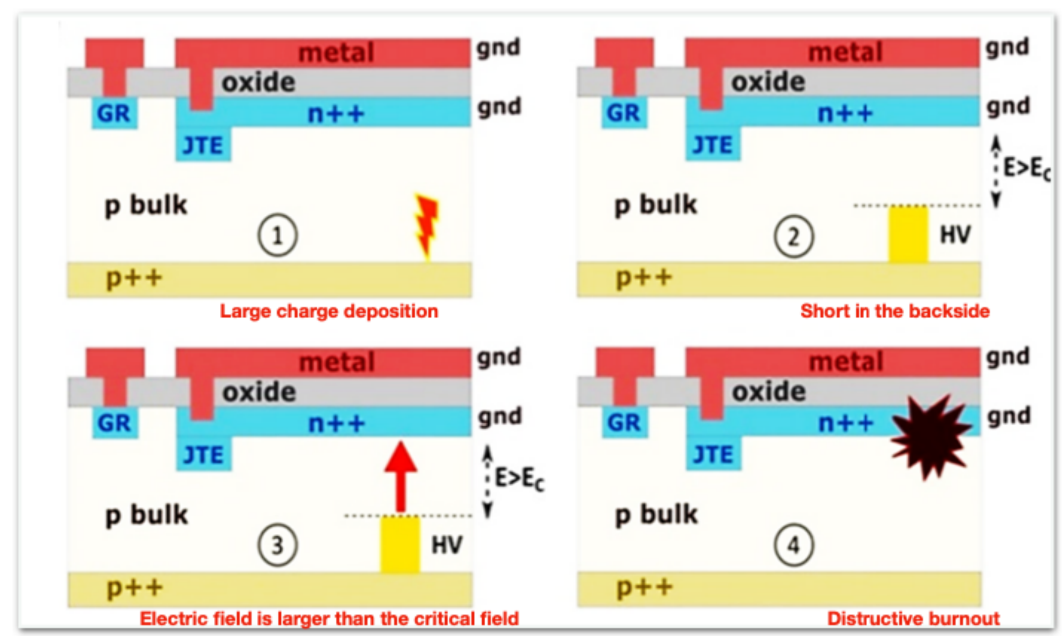
ATLAS HGTD Preliminary





- A single beam particle was found to be responsible for the fatality
- **Field collapse in the presence of high concentration of free carriers is the probable cause**
  - ***Irreversible breakdown at high voltages***



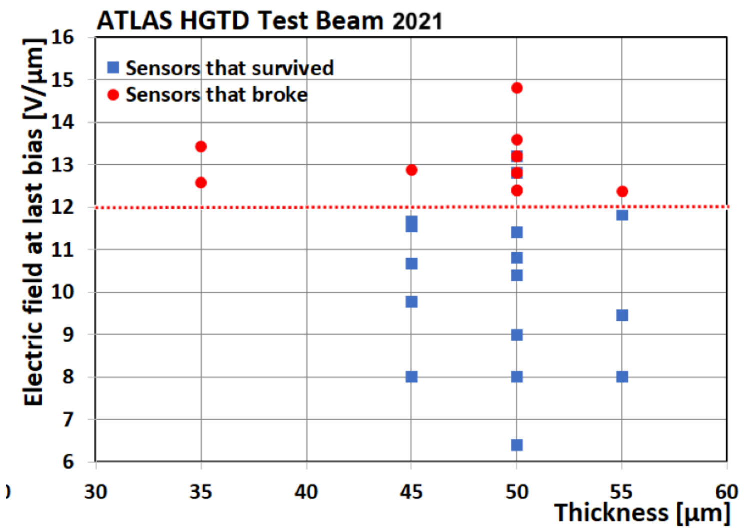
https://iopscience.iop.org/article/10.1088/1748-0221/18/07/P07030/pdf

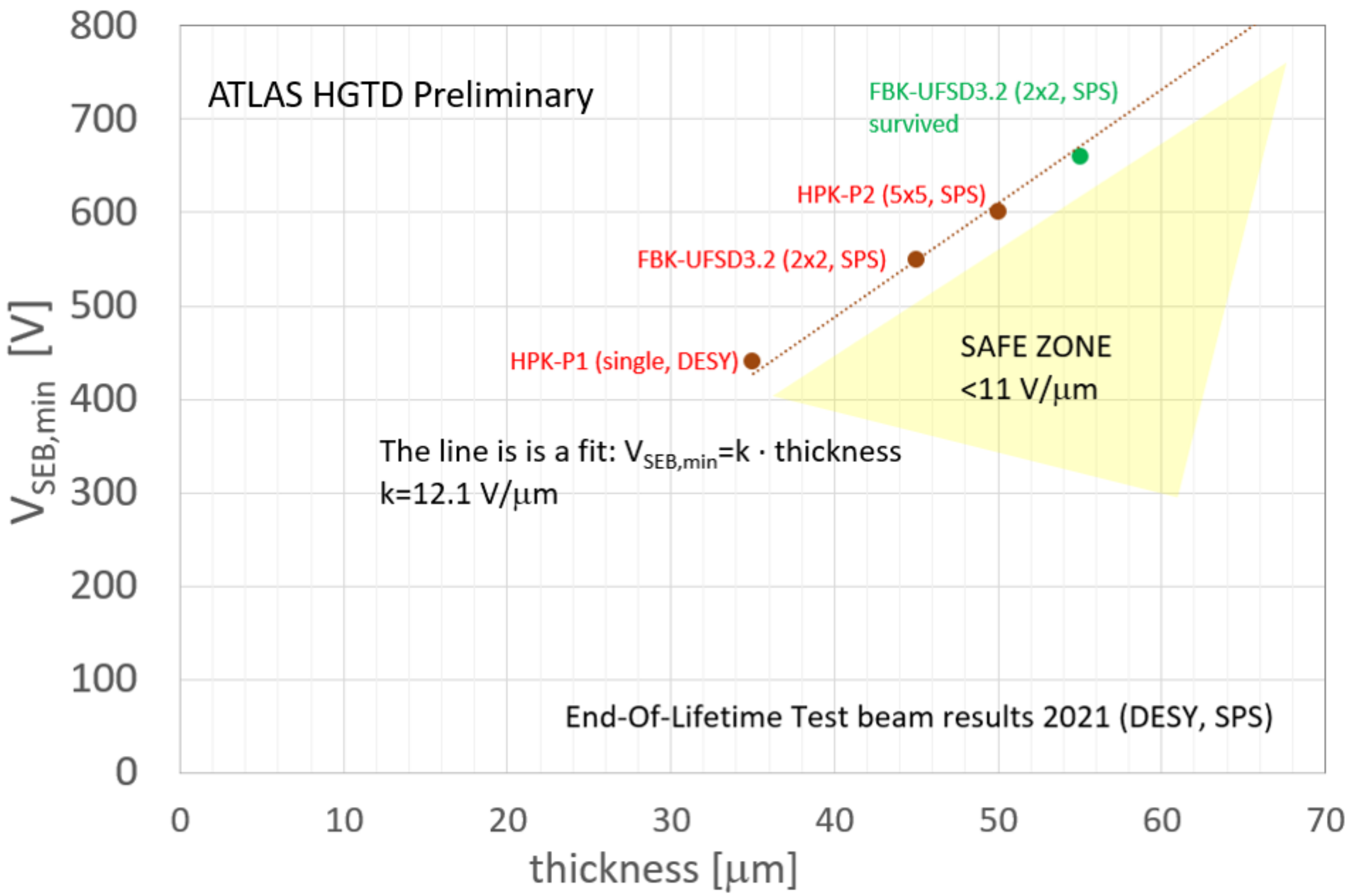
Defining safe operation

- **2020 and 2021 campaigns at DESY to quantify this issue**
    - Detailed collaboration with vendors, RD50 and CMS ETL

- Able to determine a safe operating operating zone dependent on thickness

$V_{op} < 11$ V/μm





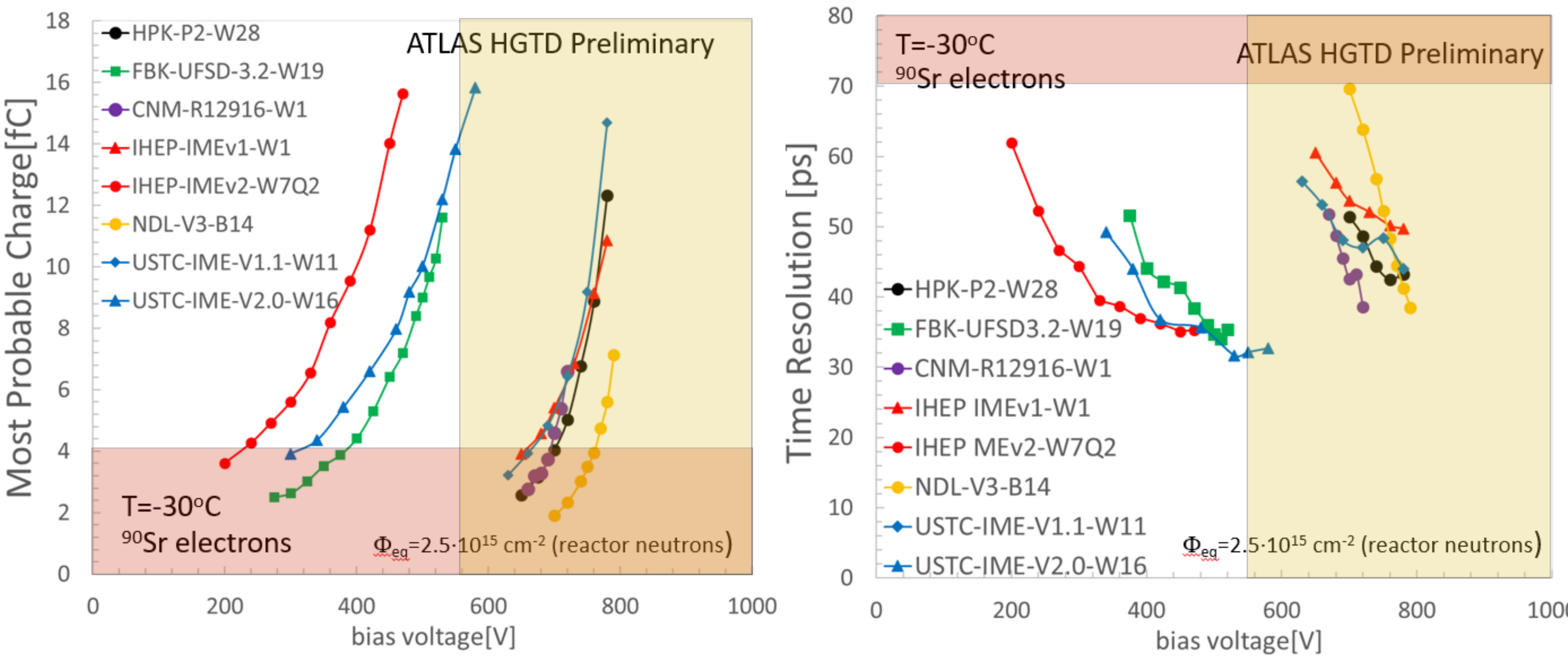
- **Apply voltage < 550 V for a 50 μm sensor**

- **Additional constraint for HGTD**

LGAD performance in lab

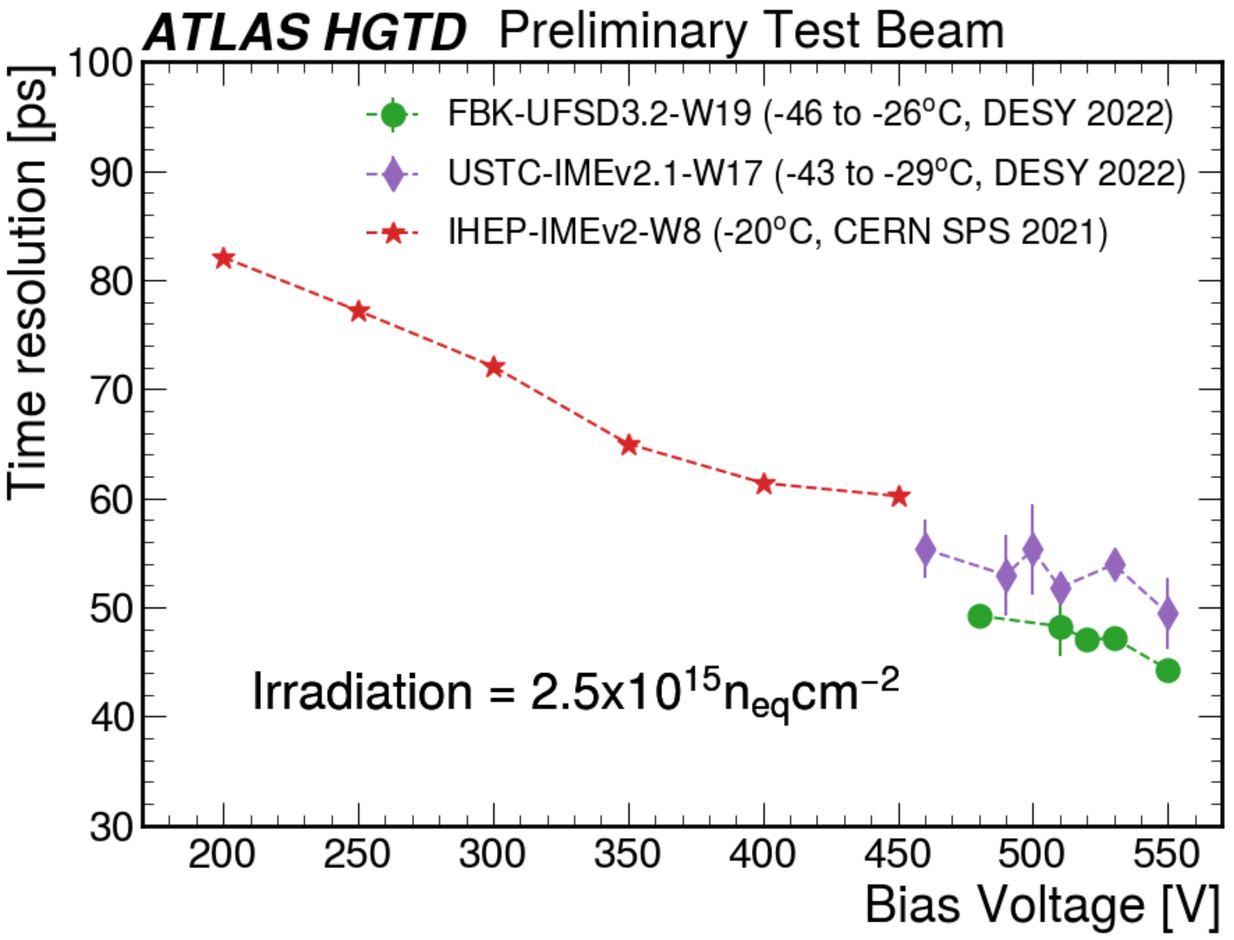
- **Lab measurements using Sr90 source**
  - Collected charge (> 4 fC) and time resolution (< 70 ps) **criteria met**
  - Many sensors need to be pushed **beyond safe limits** to achieve performance necessary for HGTD

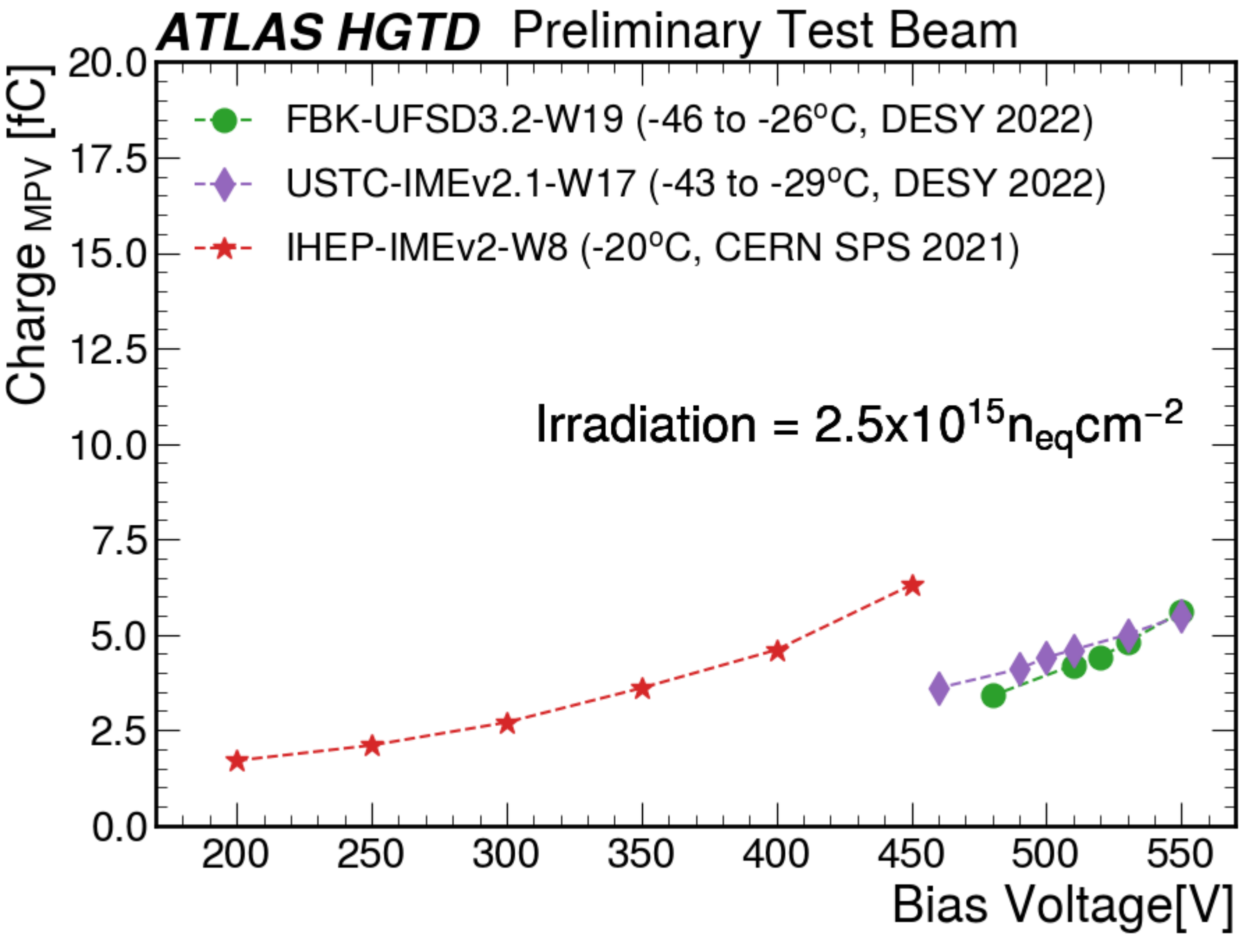
- Focus on verifying **carbon implanted sensors** can meet HGTD criteria
  - Reduce the required bias voltage to achieve similar performance (lower V_{bias} with same thickness)



Test beam performance

- **Boron + Carbon** gain layers meet all requirements of the LGAD sensors at highest fluence



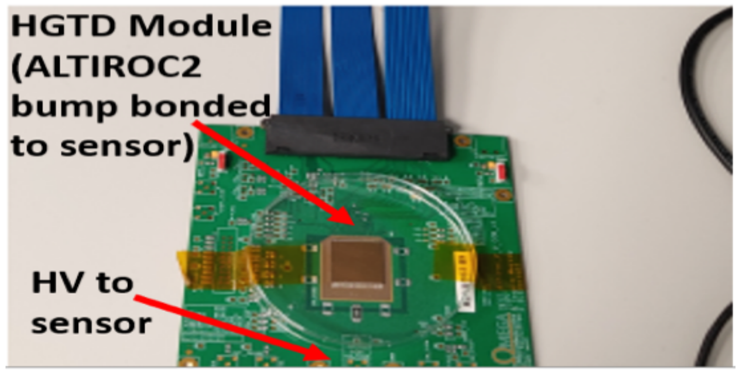


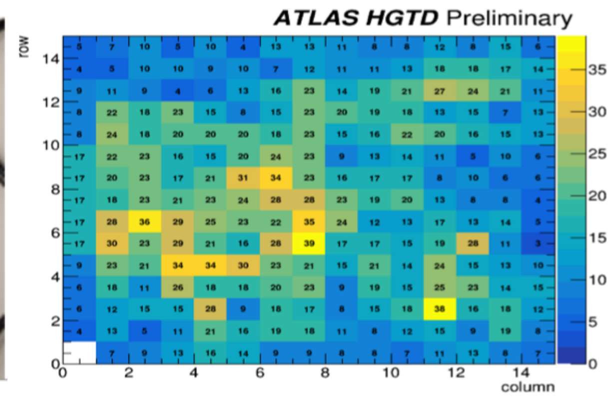
- **HGTD will use only carbon implanted LGAD sensors from IME**

HGTD large scale testing

- **Testing of full sized objects on-going towards production**

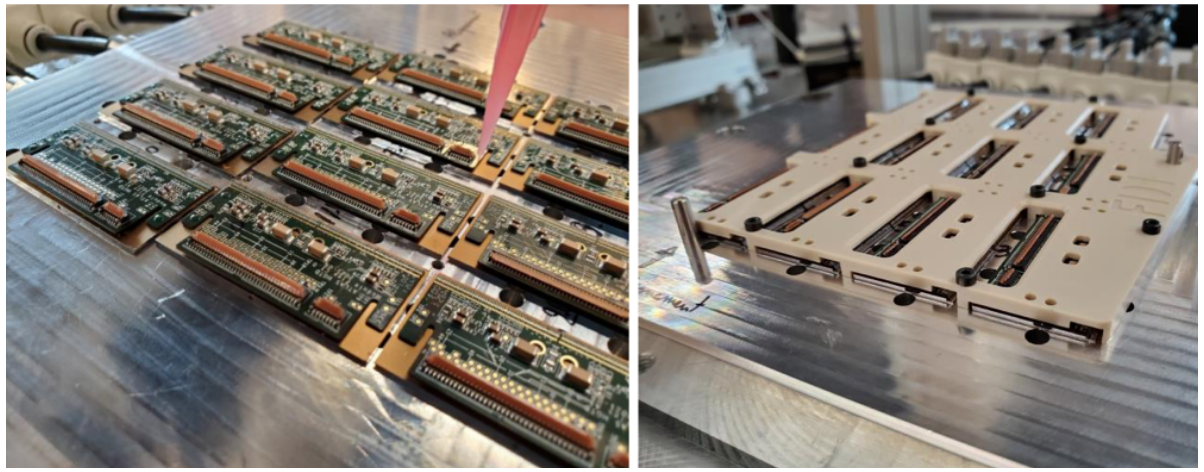
- **Hybridization and module assembly testing**
  - Source scan after thermal cycling

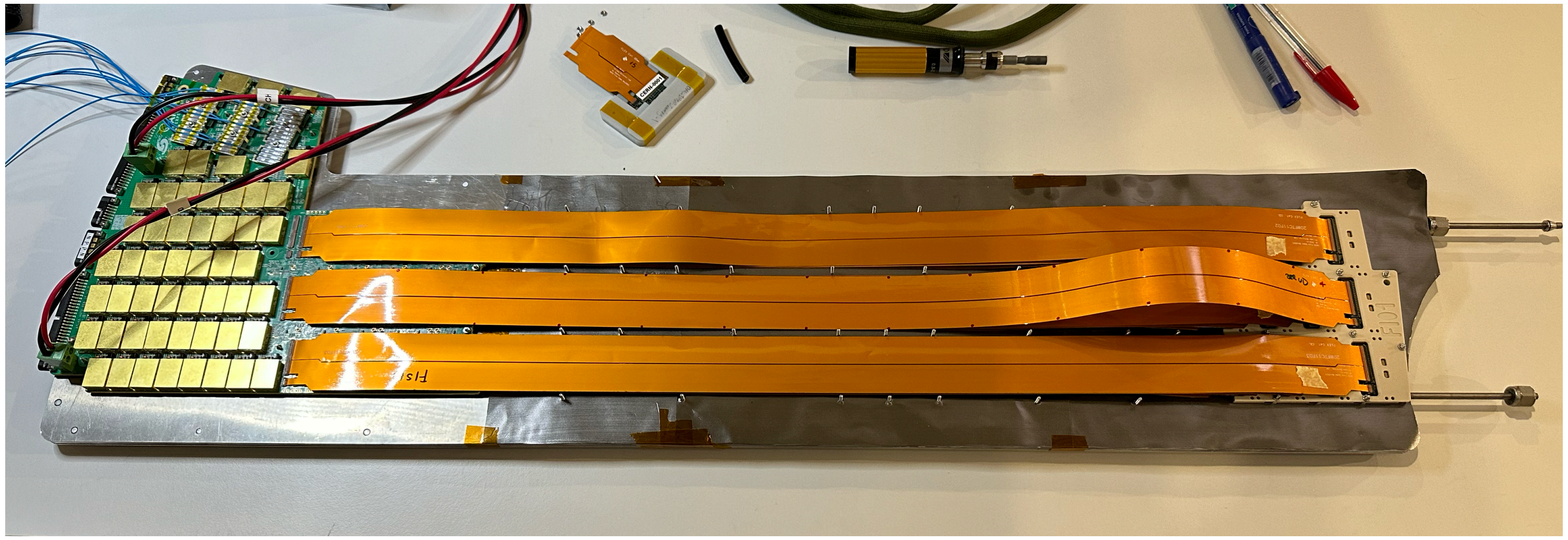




ATL-COM-HGTD-2024-005

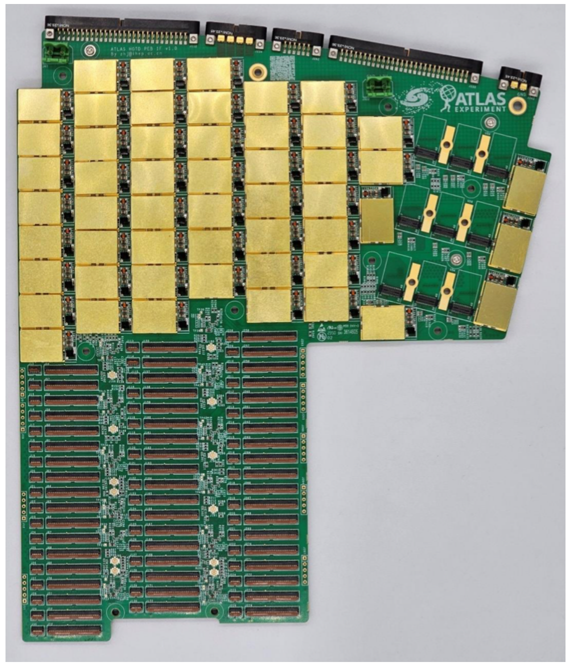
- **Module gluing and loading onto detector units**





- **Full scale read-out tests using the demonstrator at CERN**

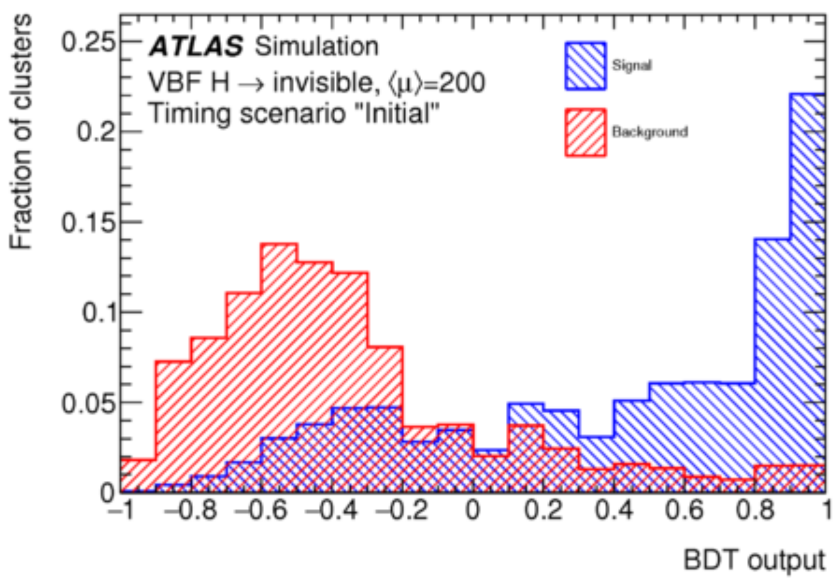
- **Peripheral electronics board testing**

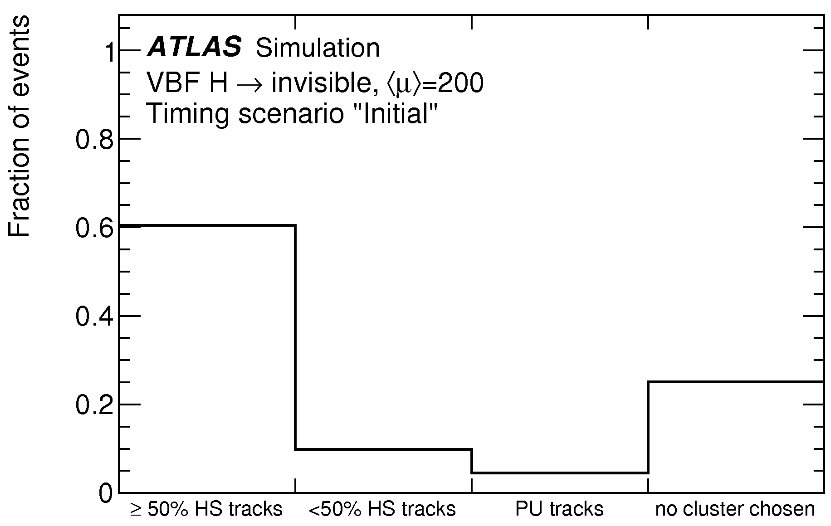


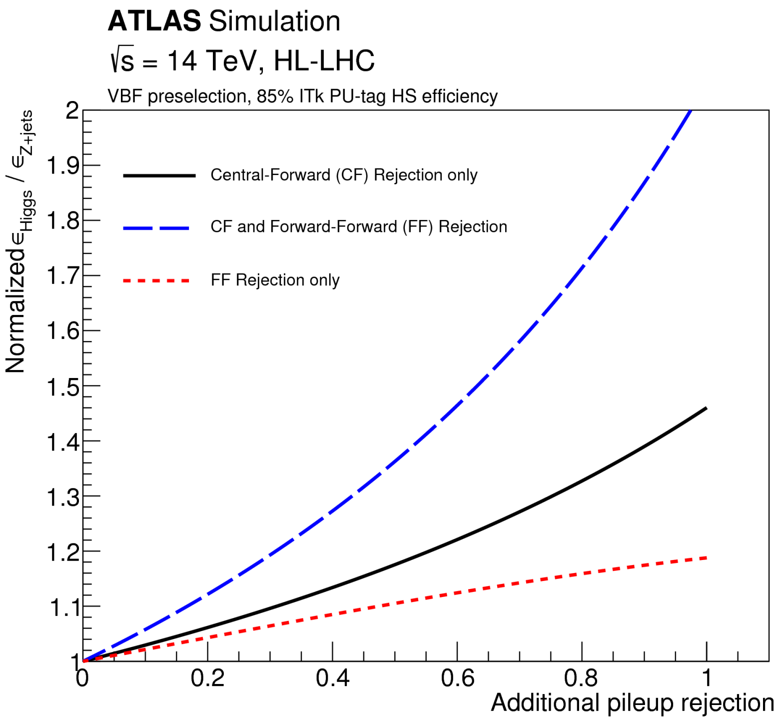
Challenges and Potential: Vertex t_0 determination

- **Challenges of HGTD: No coverage in central region of detector**
  - Very difficult to associate time to hard scatter vertex

- **R&D: Use Machine Learning technique to determine HS vertex time (t_0)**
  - Kalman filter for track extrapolation
  - Collect all tracks spatially compatible (in Δz) with selected PV
  - Cluster them using their measured times







- **Track time comparison in reconstruction**
  - Useful to reject jets from stochastic or pile-up

Roadmap

- **The HGTD will mitigate pile-up effects and improve object/physics performance and provide a luminosity measurement for ATLAS**

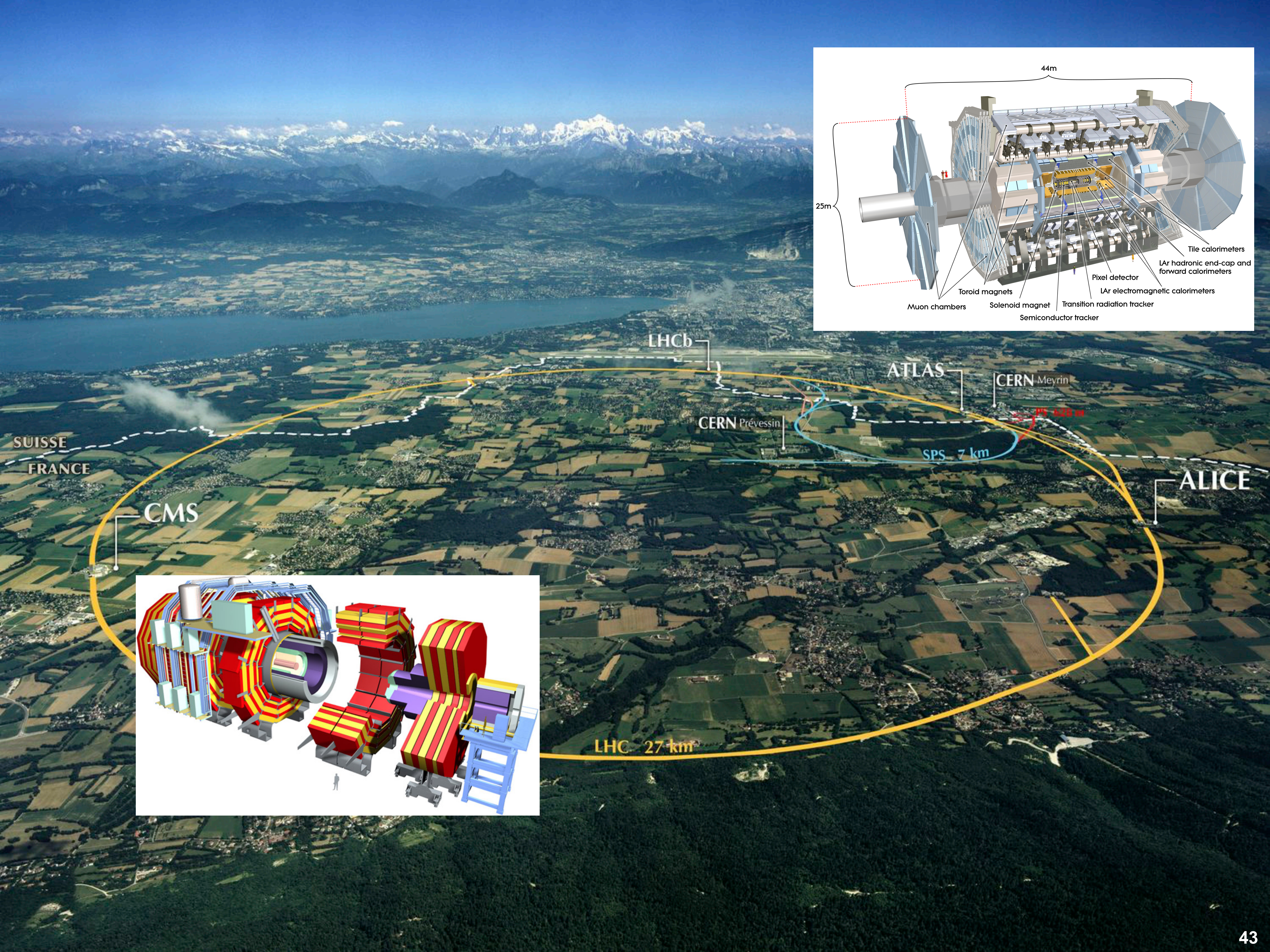
- **Intense R&D program on LGAD sensors over the last 5+ years**
  - Single-pad / 5x5 and 15x15 arrays tested in lab and testbeam
  - *During the last years we have profited from a very open and fruitful collaboration with RD50 and CMS colleagues*

- **< 50 ps per hit achievable up to 2.5 x 10^{15} neq/cm^2 with 50 μm thin LGAD sensors**

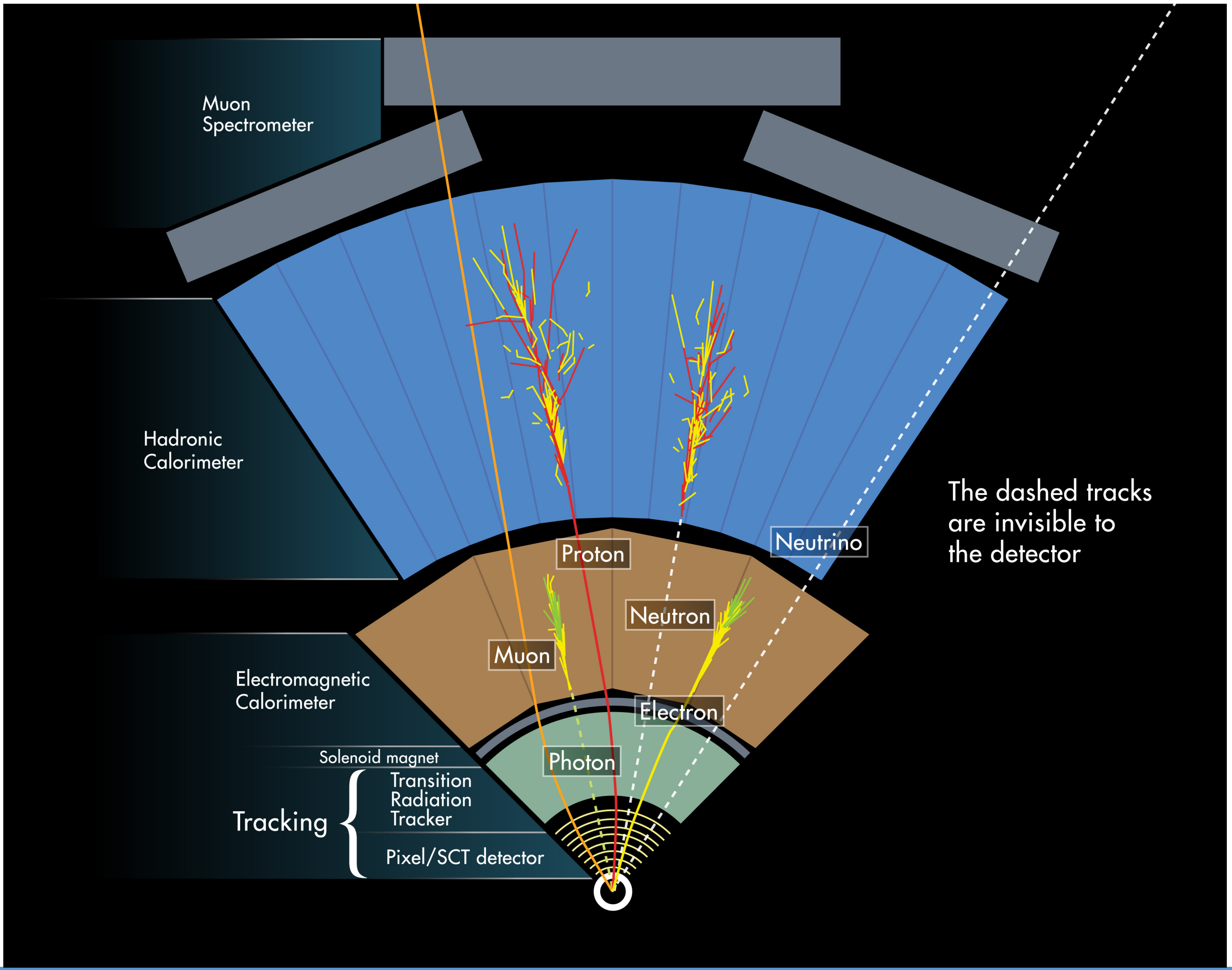
- **HGTD is moving into the full scale system tests and production phase**
  - ***Exciting and challenging project for ATLAS***

- **Silicon timing is a very active area of detector R&D for HL-LHC and beyond**
  - ***Many areas of research continues***

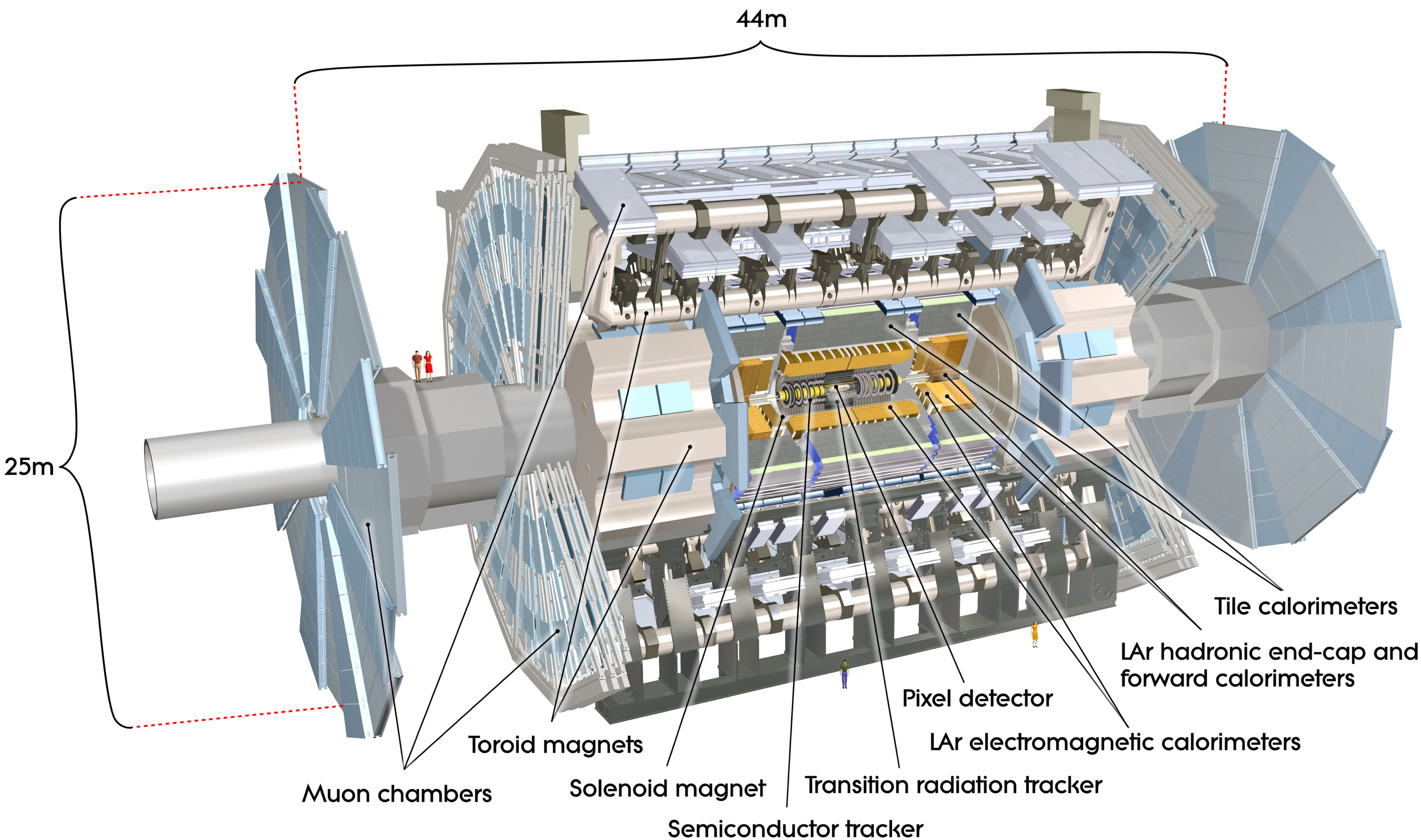
Additional Slides


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

Data Recorded at ATLAS



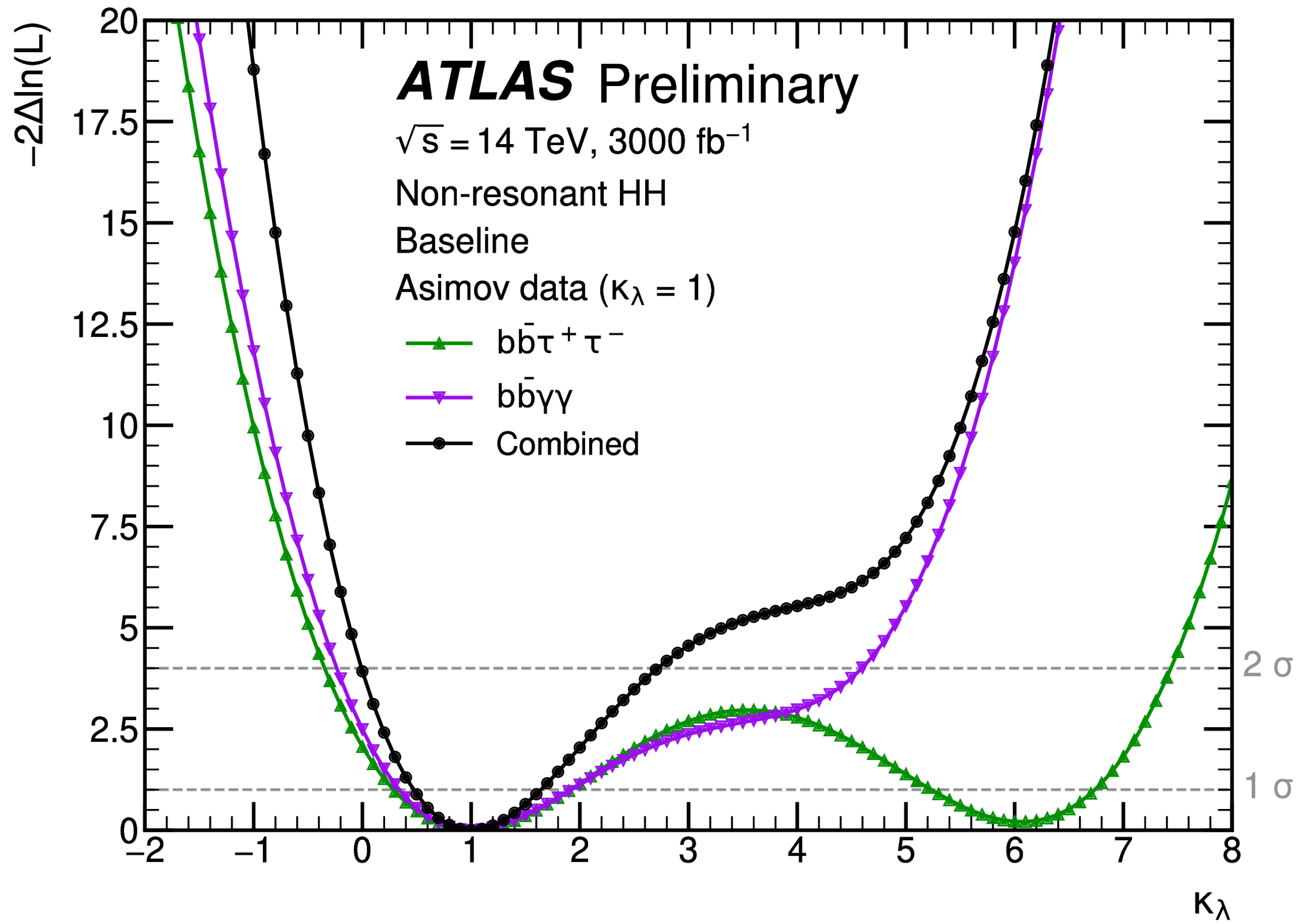
ATLAS detector

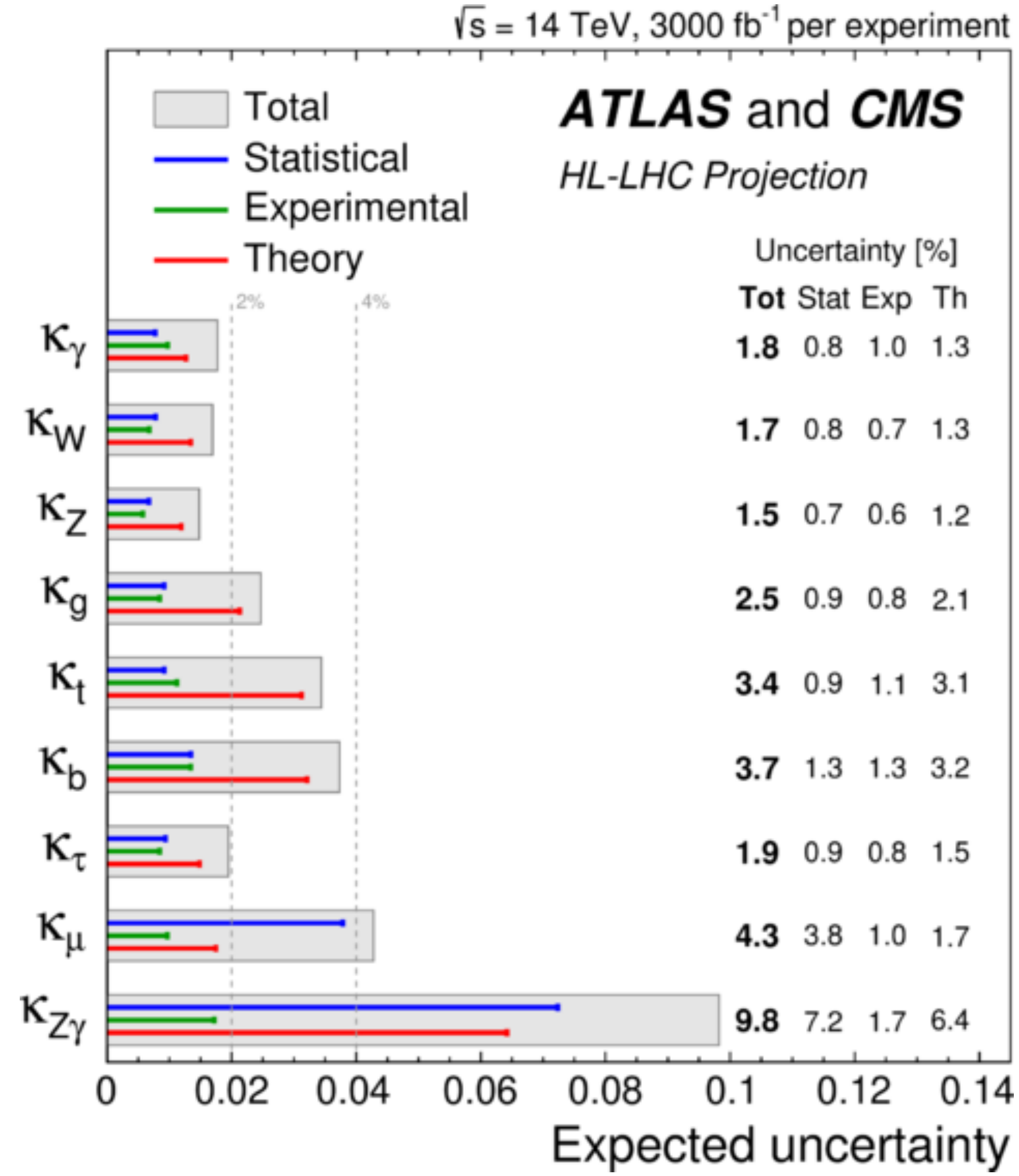


Motivation for HL-LHC

- **Fully exploit the physics potential of the HL-LHC:**
- ***Extensive tests of SM at the TeV scale***
  - Precise measurements of Higgs couplings, including self-coupling
  - Precision SM measurements
- Searches for new physics
- Higgs as a portal to the dark sector

Snowmass White Paper

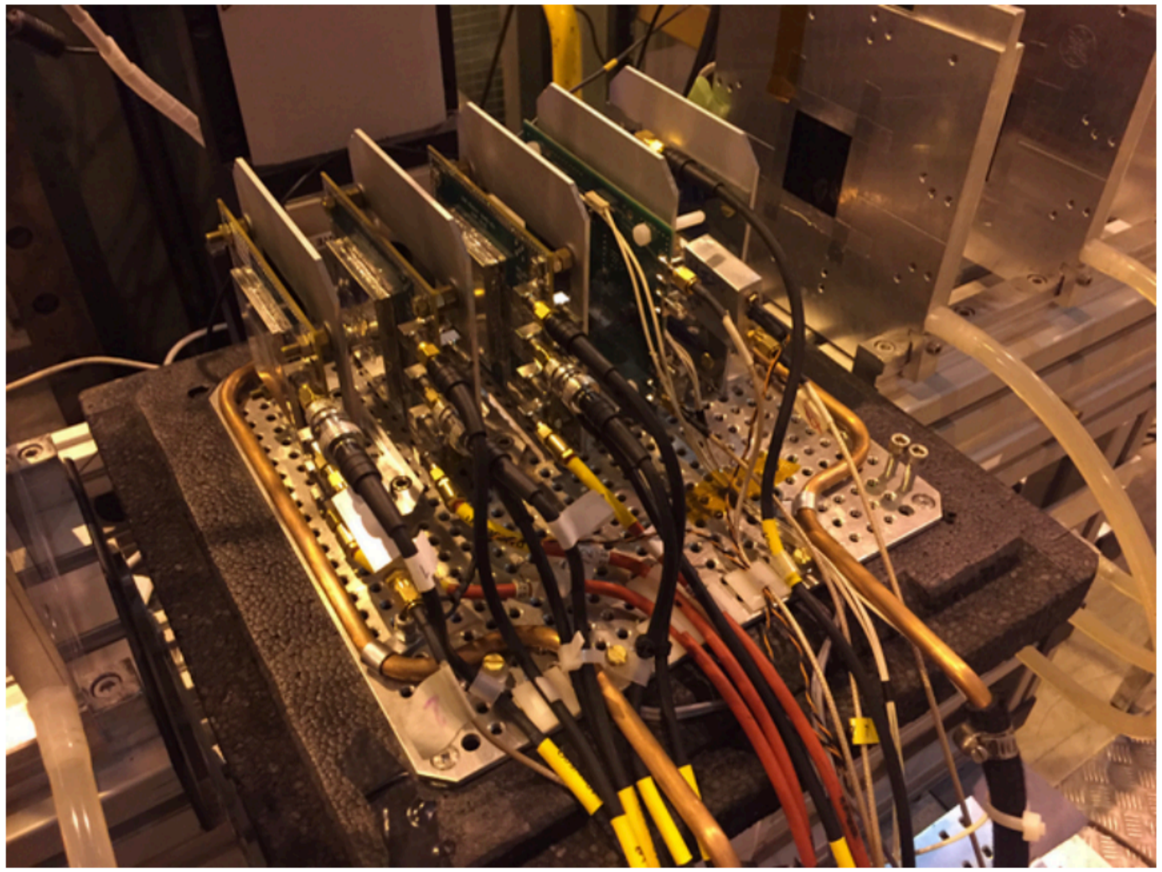




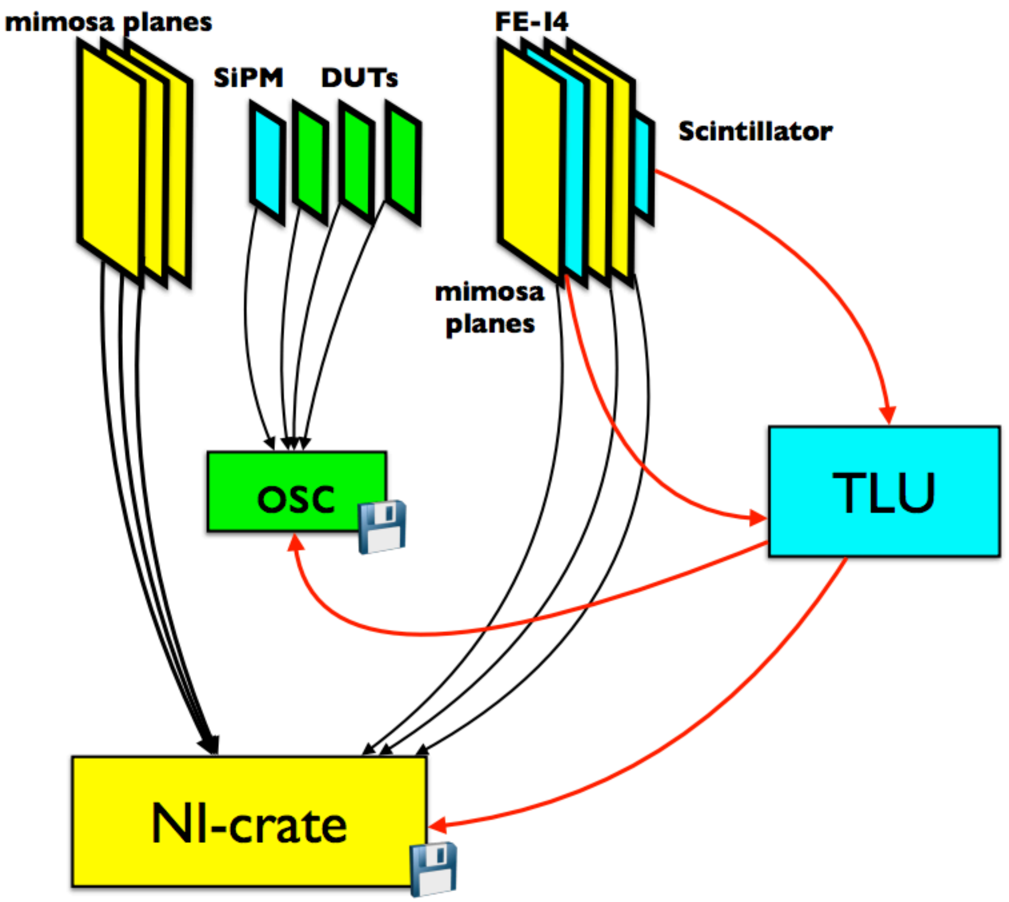
- **For the additional luminosity: requires the upgrades of both the accelerator and the detectors**

Testbeam Setup

- DUTs: LGADs sitting inside a cooling box
- SiPMs: for timing reference which sit in a separate cooling box (closed to light)



(a) Sensors under test



(b) Data acquisition setup

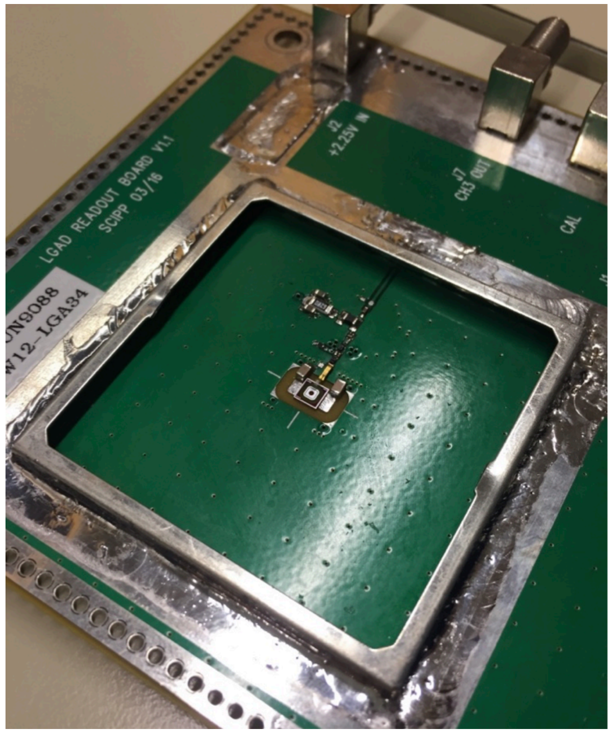
- Mimosa planes: Telescope used for tracking position / efficiency
- FeI4 + Scintillator: used for triggering

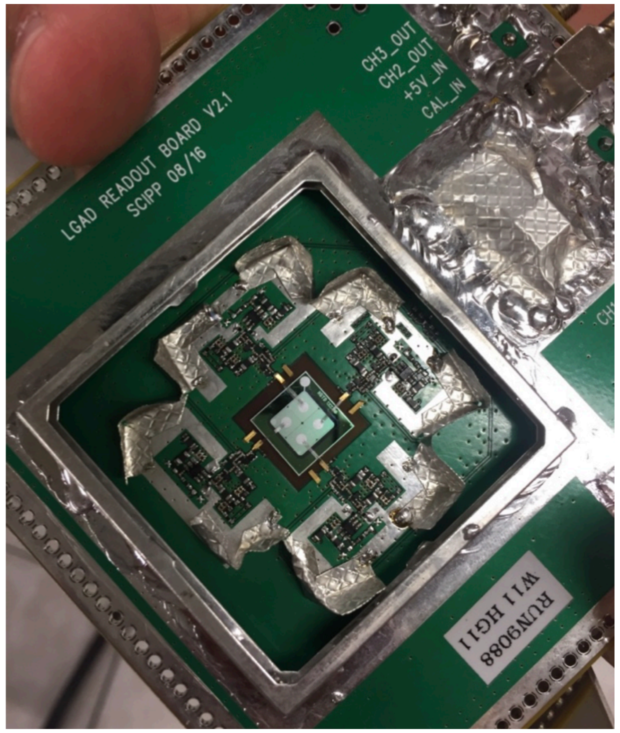
- Trigger Logic unit receives signal from FE-I4 and scintillator and sends signal to oscilloscope and NI-crate to save data

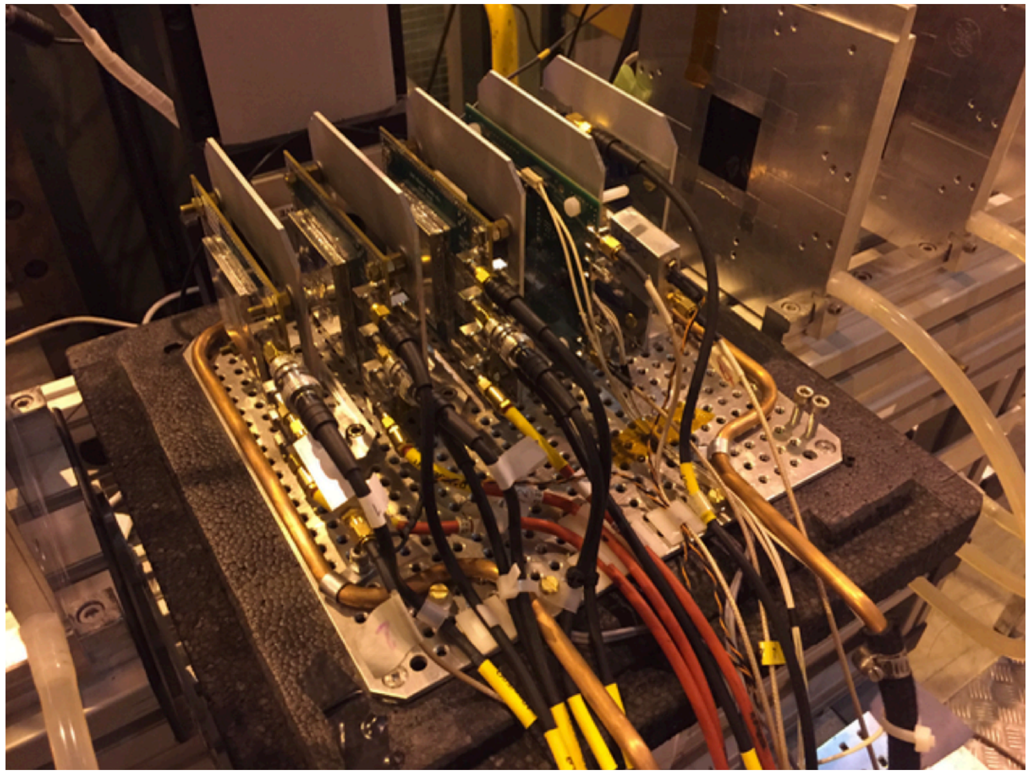
LGAD Sensor Studies

- **Several on-going LGAD R&D studies at various HGTD Institutes:**
  - Laboratory testing (IV,CV)
  - Laboratory dynamic testing (β,α,laser)
  - Testbeams with pions or electrons

- **Time resolution analysis**
  - Measure spread of ToA with well known devices (LGAD / SiPMs)
  - Time walk corrected via amplitude/ToT correction or Constant Fraction Discrimination

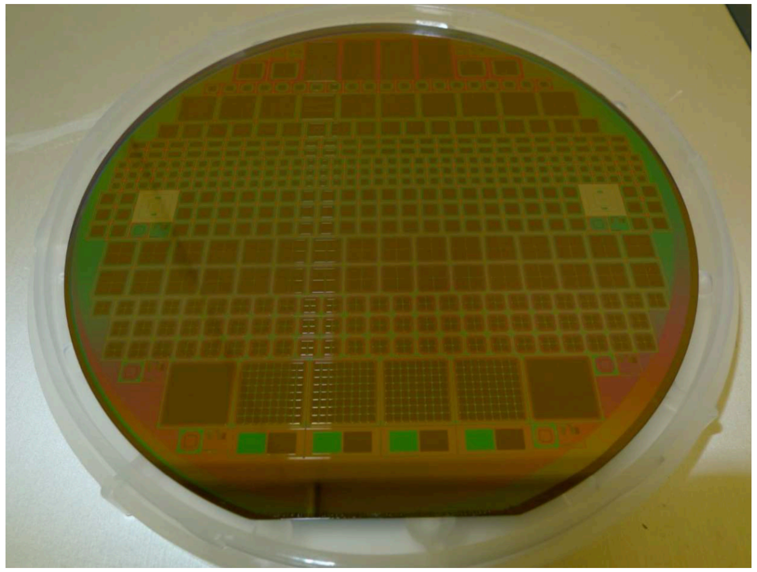




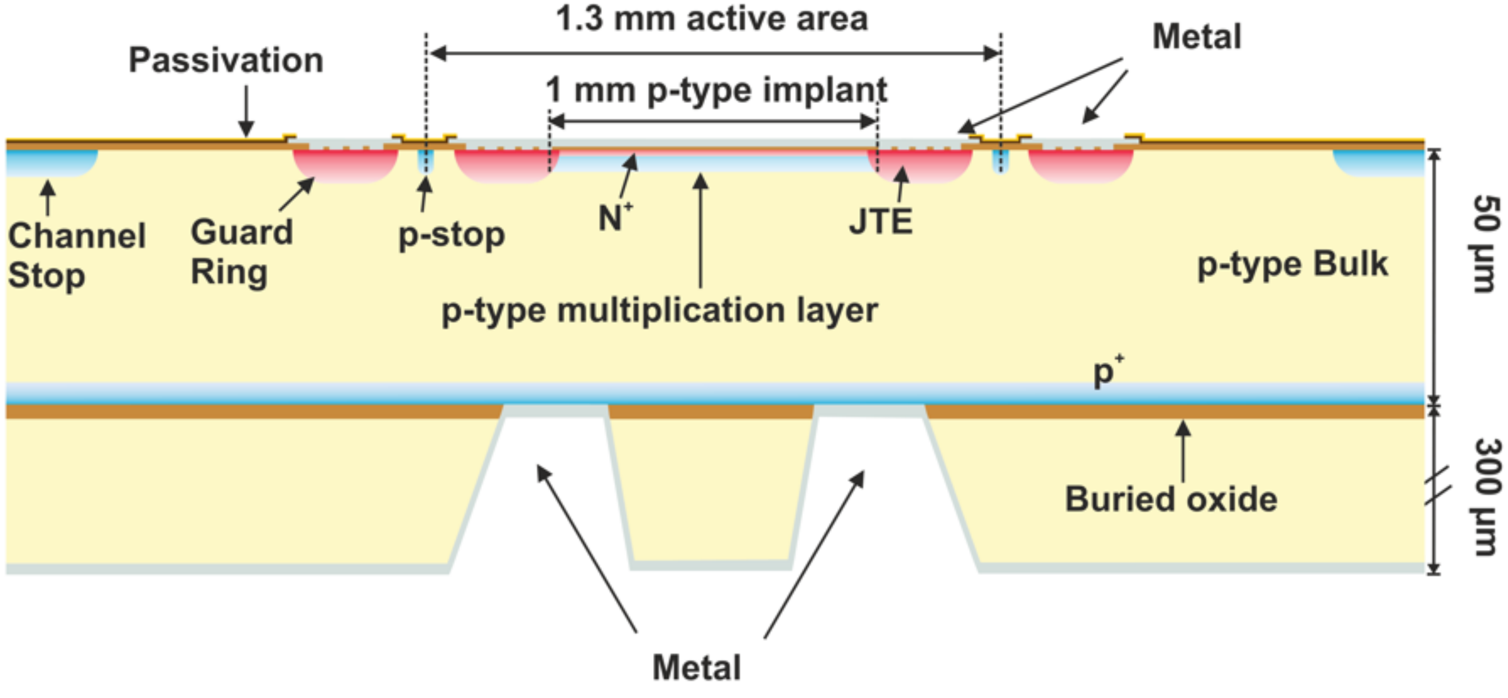


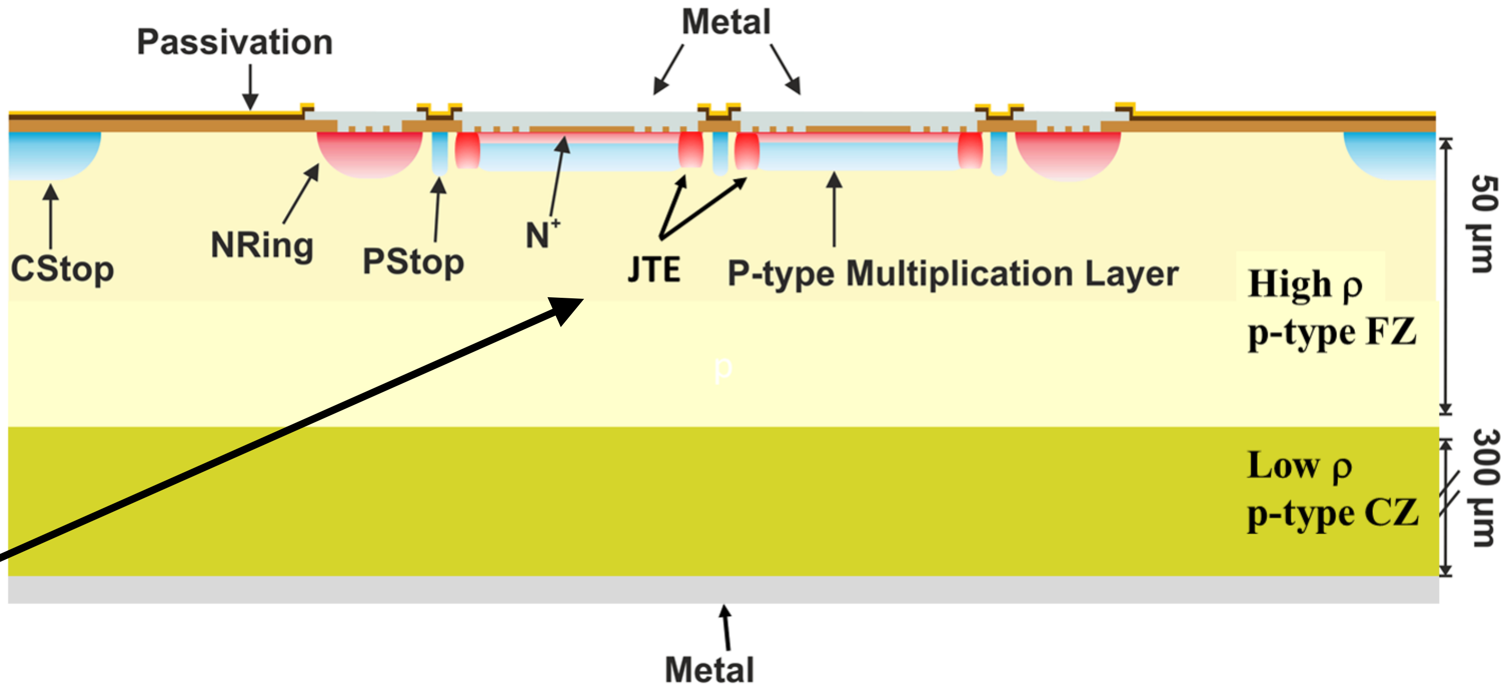
LGAD Technology

- **Up to 8" wafers in production**



- 35 and 50 µm active thickness on substrate (*50 µm default for HGTD)*
- Tested B and Ga for highly doped multiplication layer
  - *Carbon for improved radiation hardness*
- **Junction Termination Extension (JTE) on all sensors**
  - Controls E-field against early breakdown
  - No multiplication layer between pads



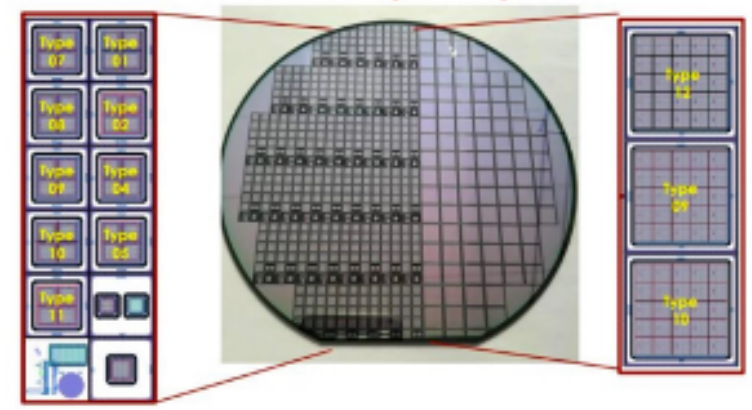


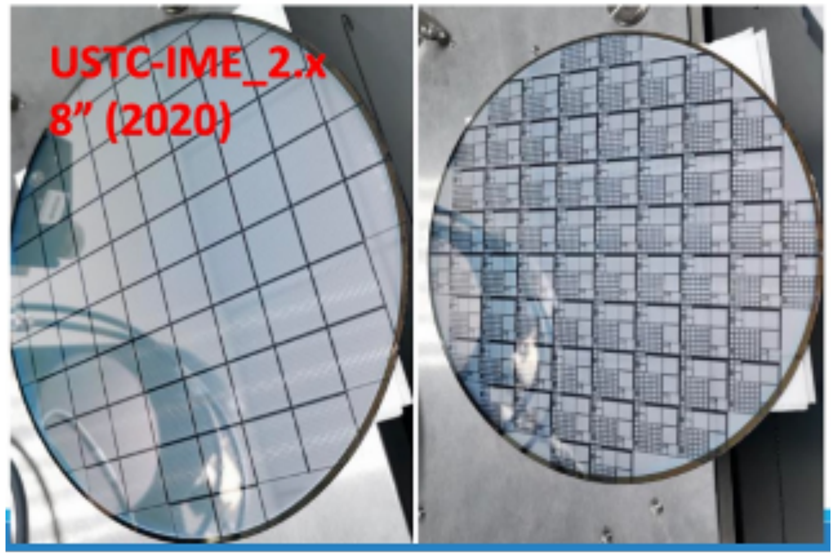
G. Pellegrini et al., Status of LGAD production at CNM, 30th RD50 Workshop, Krakow, Poland, 2017

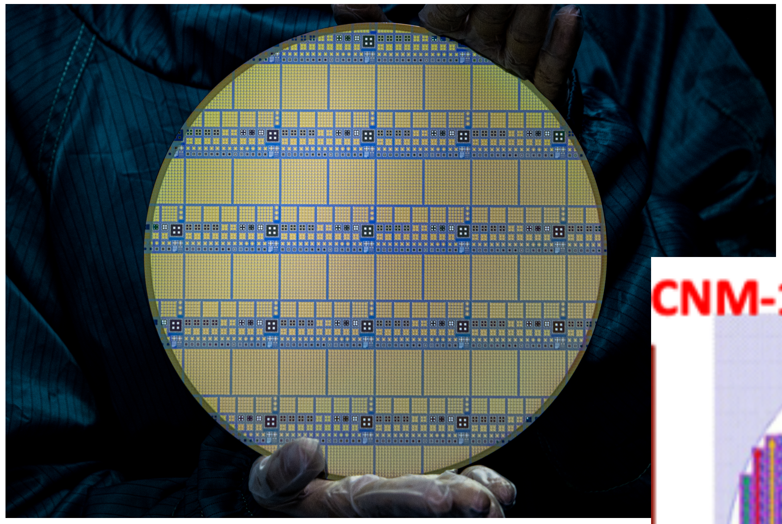
LGAD Requirements for HGTD

- **Testing various LGAD vendors: IHEP-IME, USTC-IME, CNM, FBK, HPK**
  - Different doping materials, substrates, thickness
- **Requirements on LGAD sensors:**
  - Detector can withstand the lifetime of the HL-LHC running:
    - Maximum fluence: **2.5×10^{15} neq/cm^2** and TID: **2 MGy** at the end of HL-LHC **(4000 fb^{-1})**
  - Average time resolution: **35 ps (start), 70 ps (end) per hit / 30 ps (start), 50 ps (end) per track**
  - Collected charge per hit **> 4 fC**
  - Hit efficiencies of **97% (95%)** at the start (end) of their lifetime

FBK-UFSD 3.2 (2020)

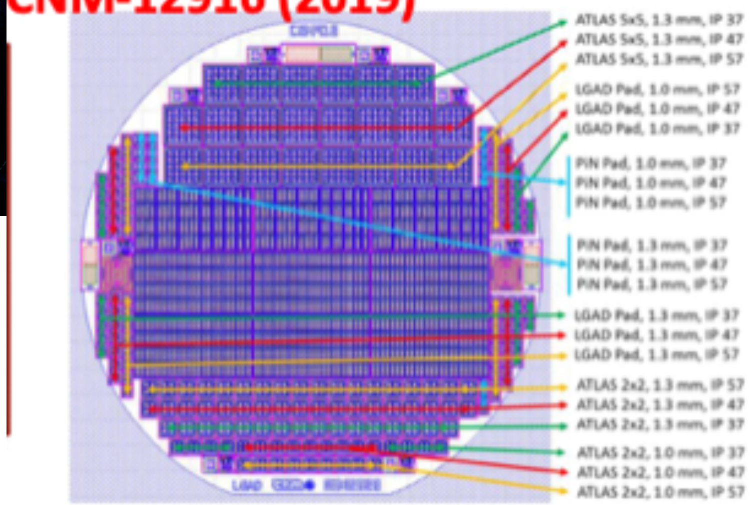






IHEP-IME

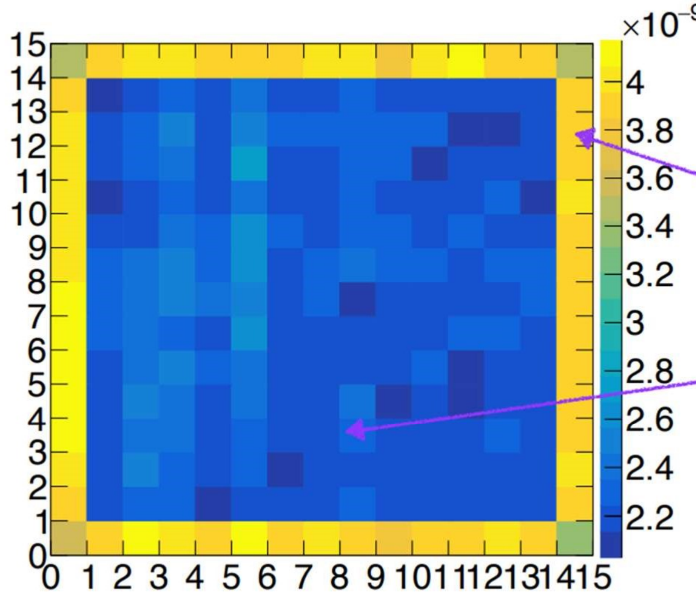
CNM-12916 (2019)

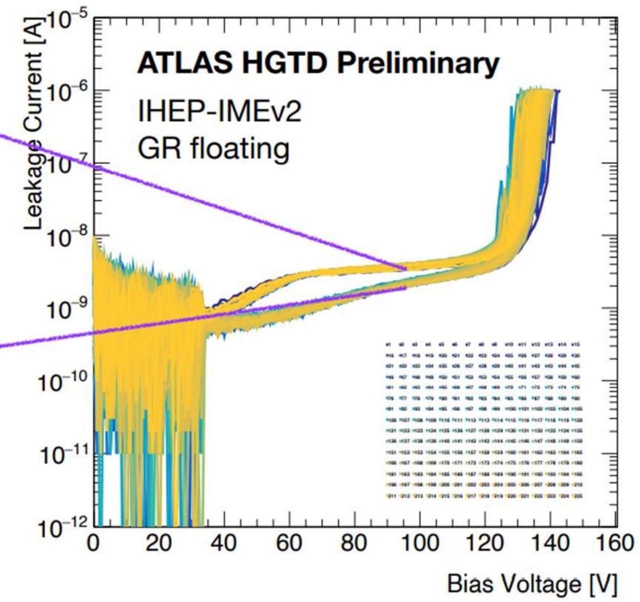


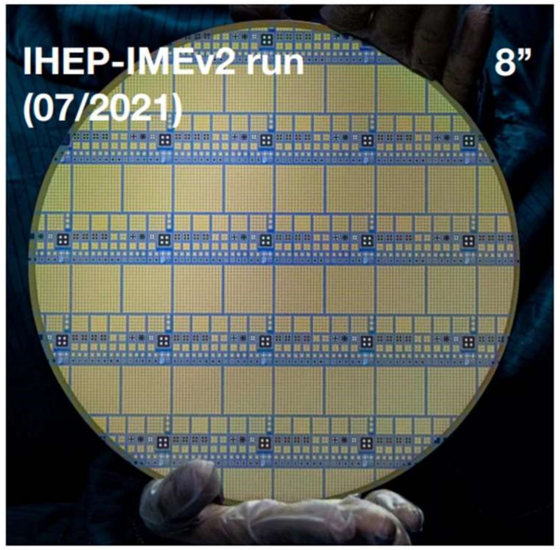
- Full-sized sensor composed of 15x15 pads
- Extensive R&D in lab and test beams
- **Focus on more radiation hard performance**

Full-sized Sensor Tests

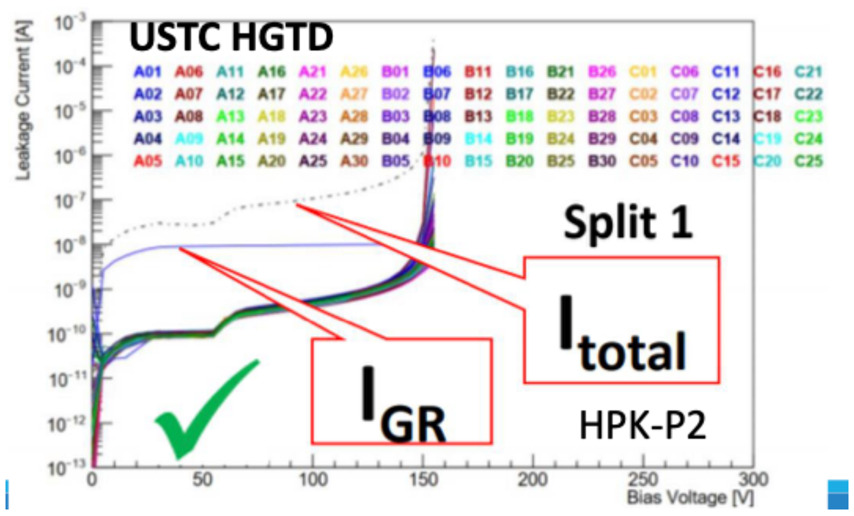
- **Study of performance full-sized LGADs (15x15) from various vendors**



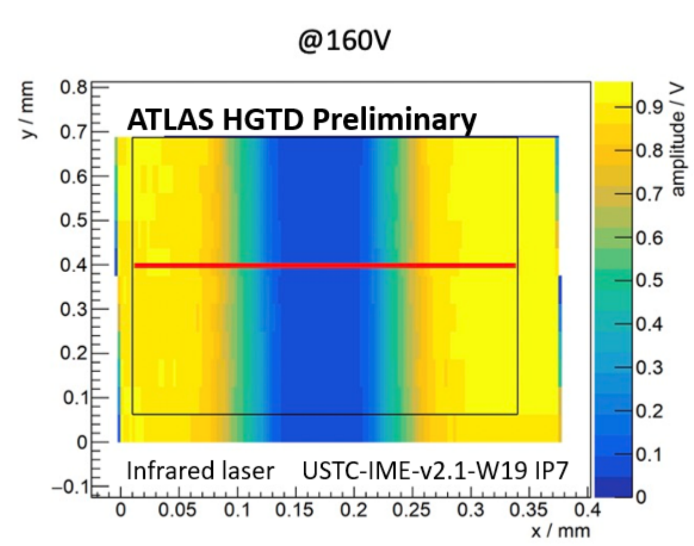


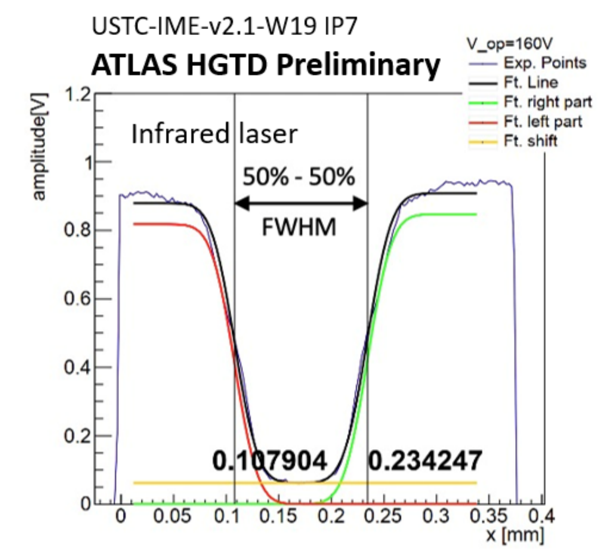


- **The production of uniform gain layer on large devices has been shown for several vendors**
- V_{gl} and V_{foot} studies



- IP gap studies

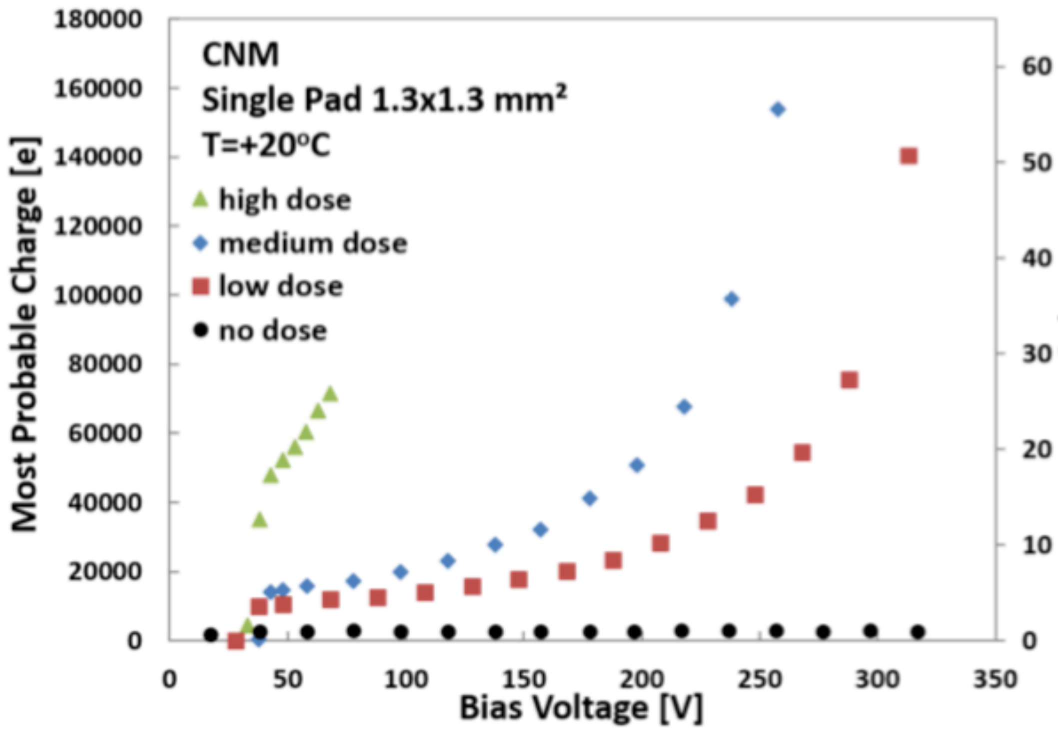




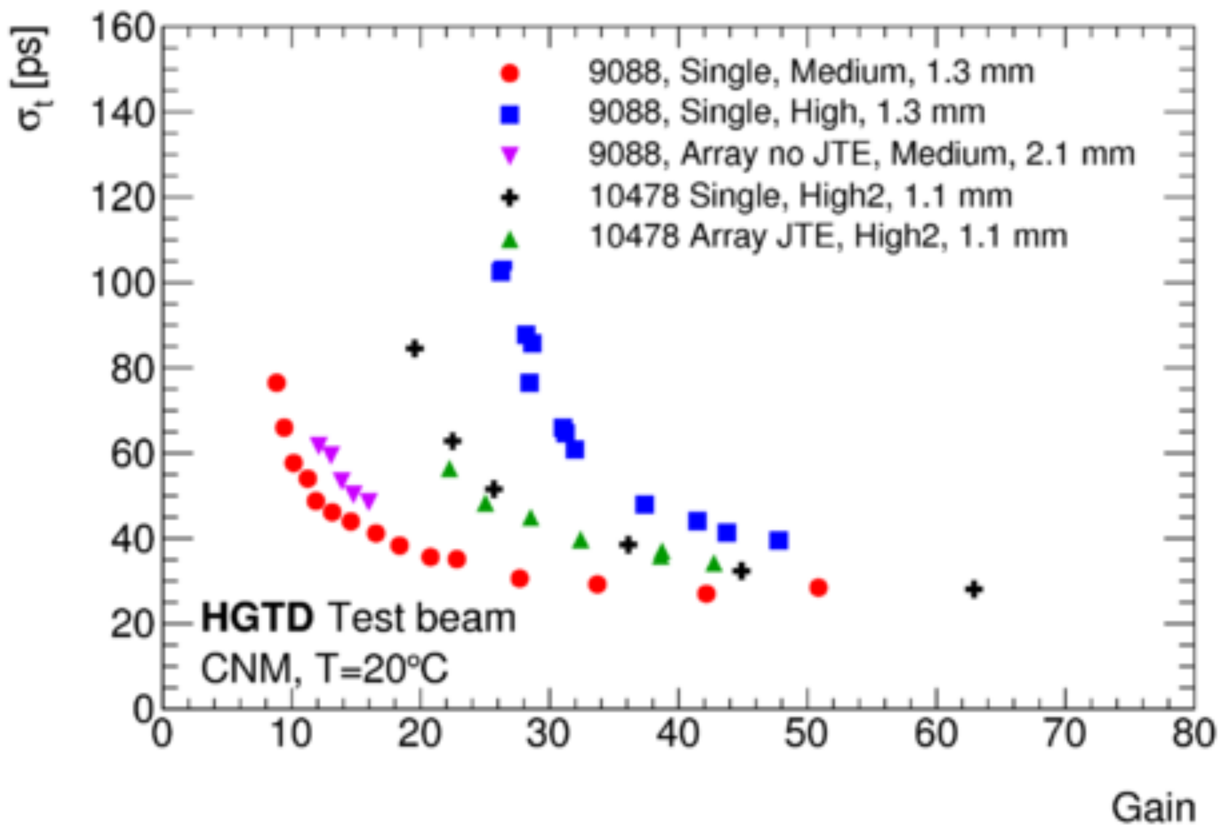
Sensor studies: doping

1711.06003

- **Gain and charge** as a function of bias voltage for a CNM LGAD with **different doping doses** of the multiplication layer.



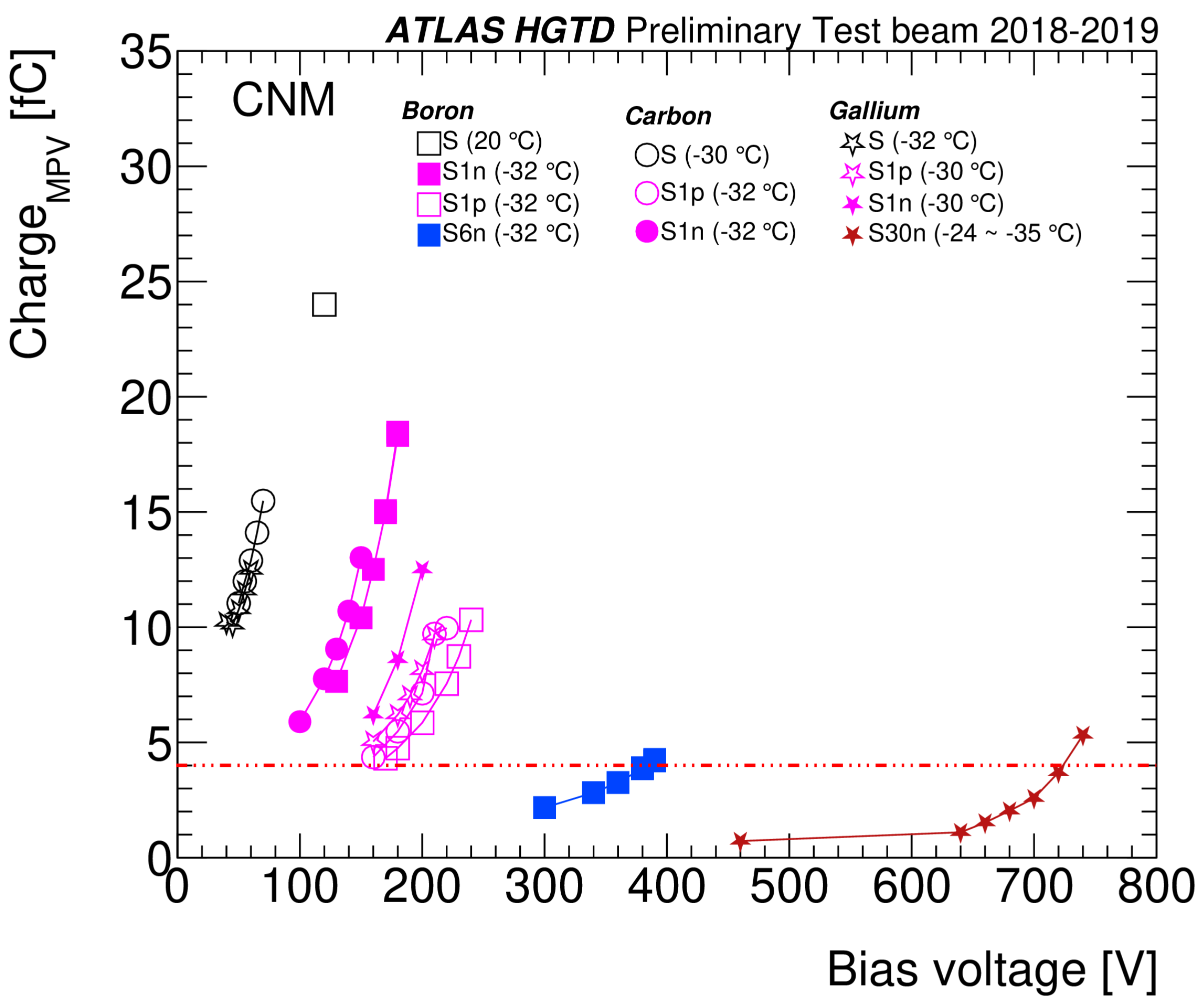
- CNM single-pad sensors and arrays
  - **With and without JTE**
  - **Medium and high doping**

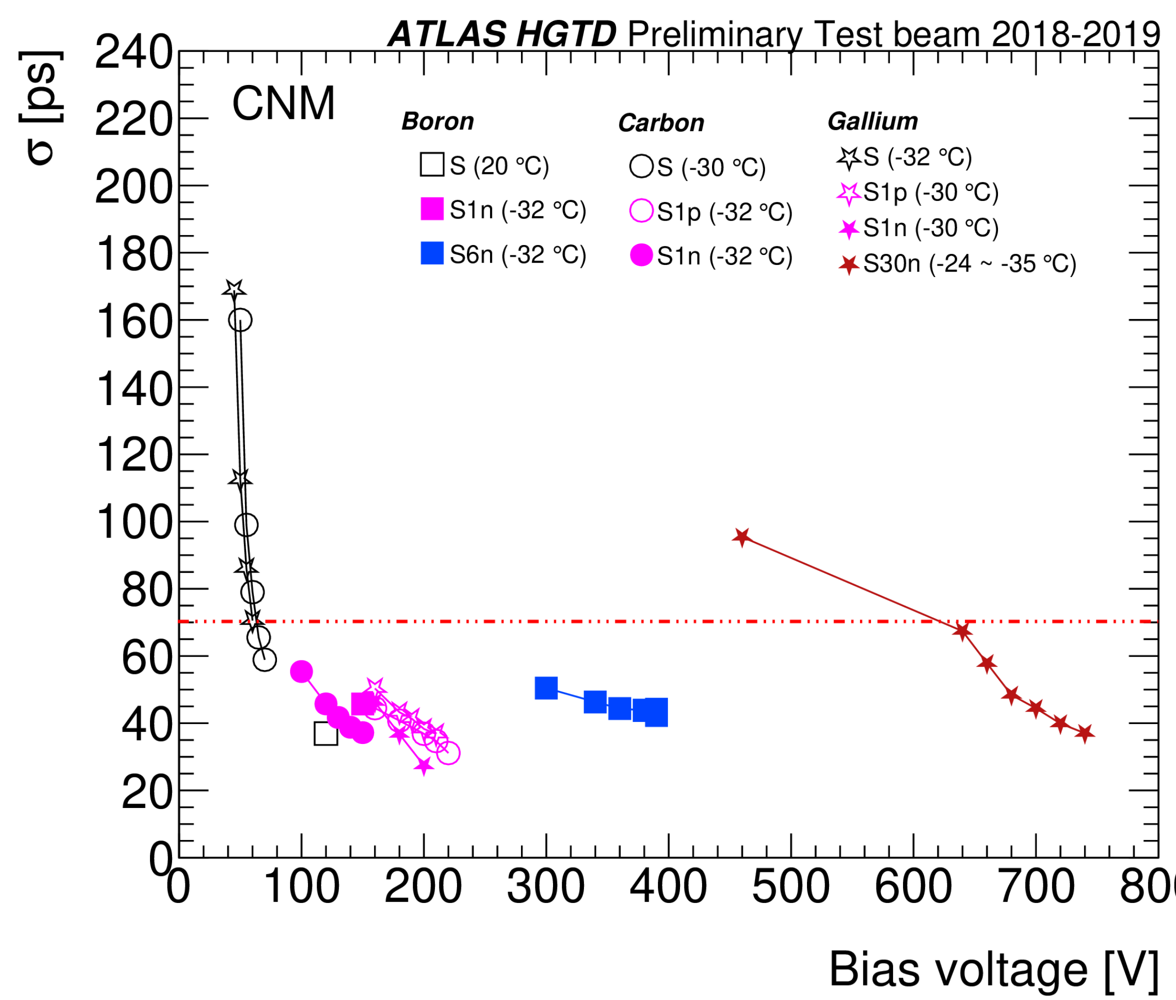


- **Time resolution of sensor of 30 ps achievable**

Sensor studies: doping

- **Different doping profiles: Boron, Carbon, and Gallium**
  - Fluences up to 3 x 10^{15} neq/cm^2
- **Boron and Boron+Carbon showing the best performance**
  - Gallium also contains a very high leakage current —> higher power

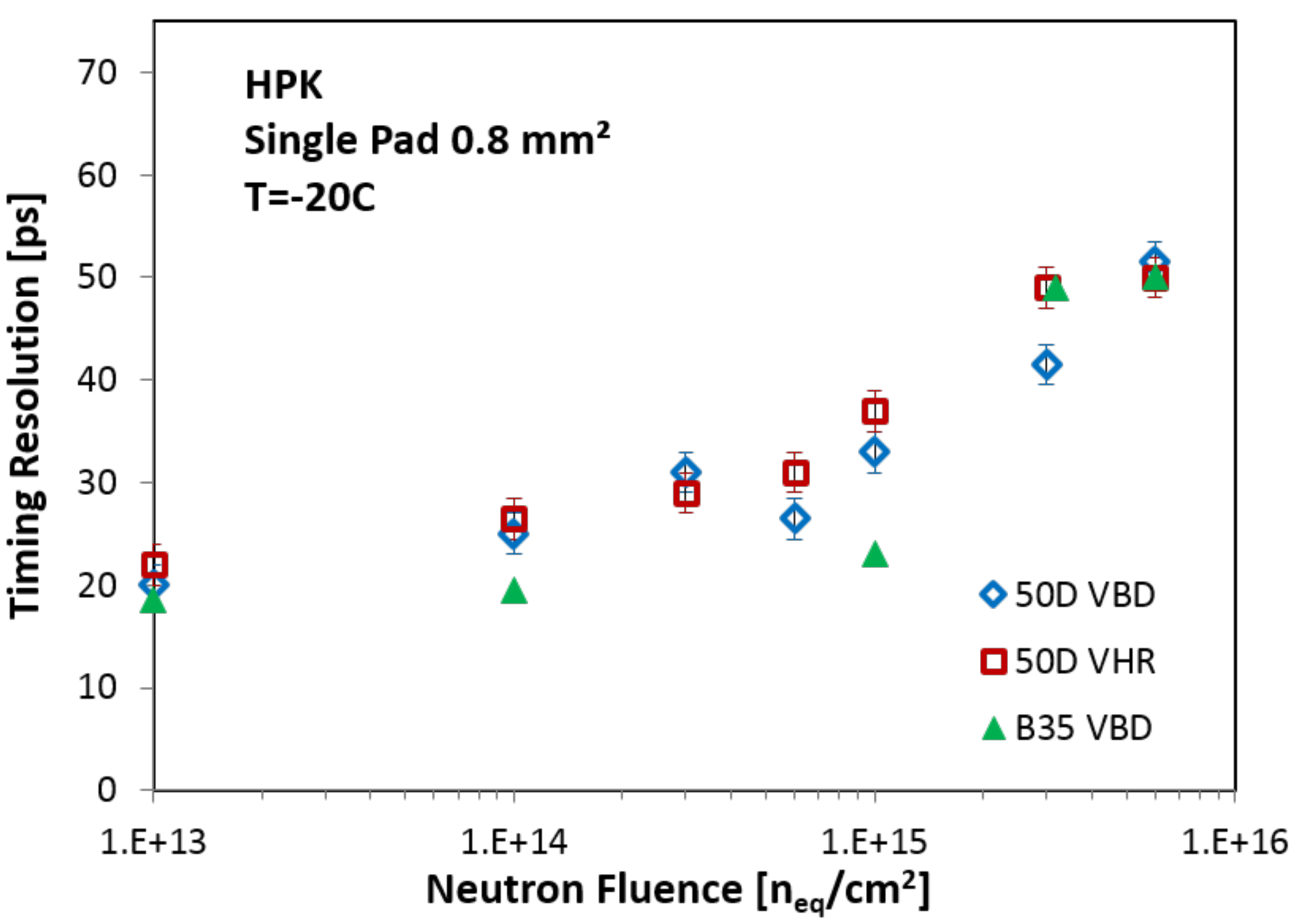


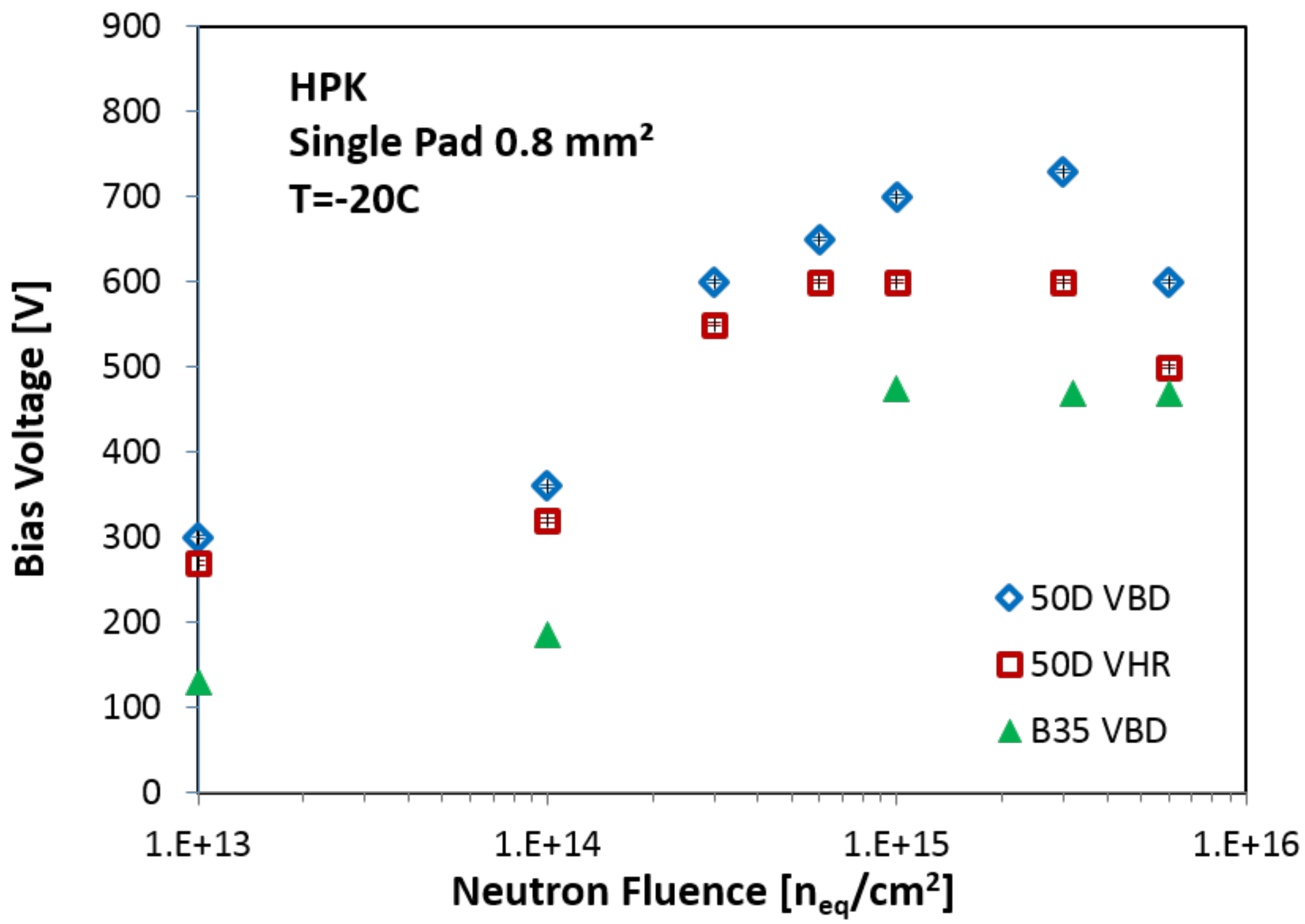


Sensor studies: time resolution

- **Time resolution as a function of neutron fluence**
  - **HPK 50D** at breakdown (VBD) and with headroom (VHR) at -20 ˚C
  - *Headroom defined to be ~ 10 % or more below breakdown*
  - **HPK B35** at VBD
- **Time resolution** found to be 20 ps before irradiation and 50 ps at 6 x 10^{15} n_{eq}/cm^2

- **VBD and VHR dependence on neutron fluence**





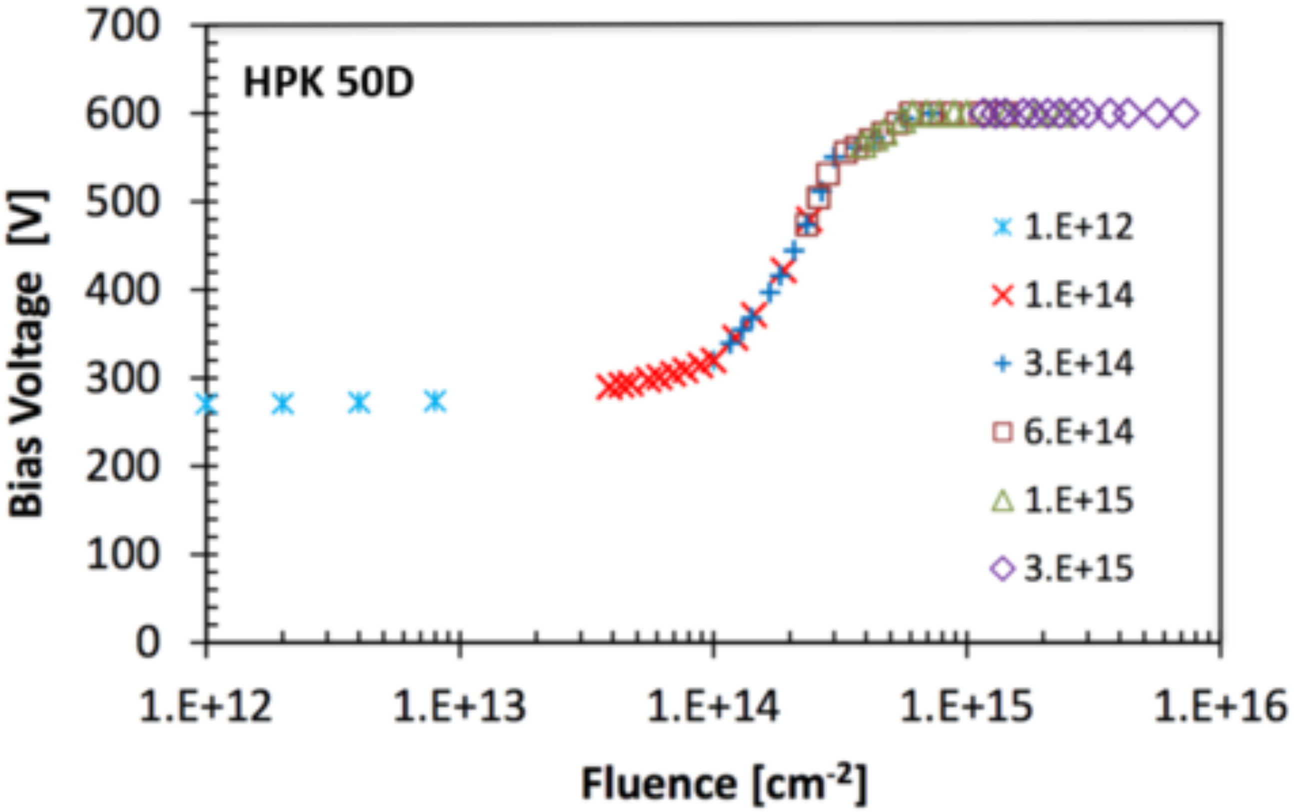
1707.04961 and 1803.02690

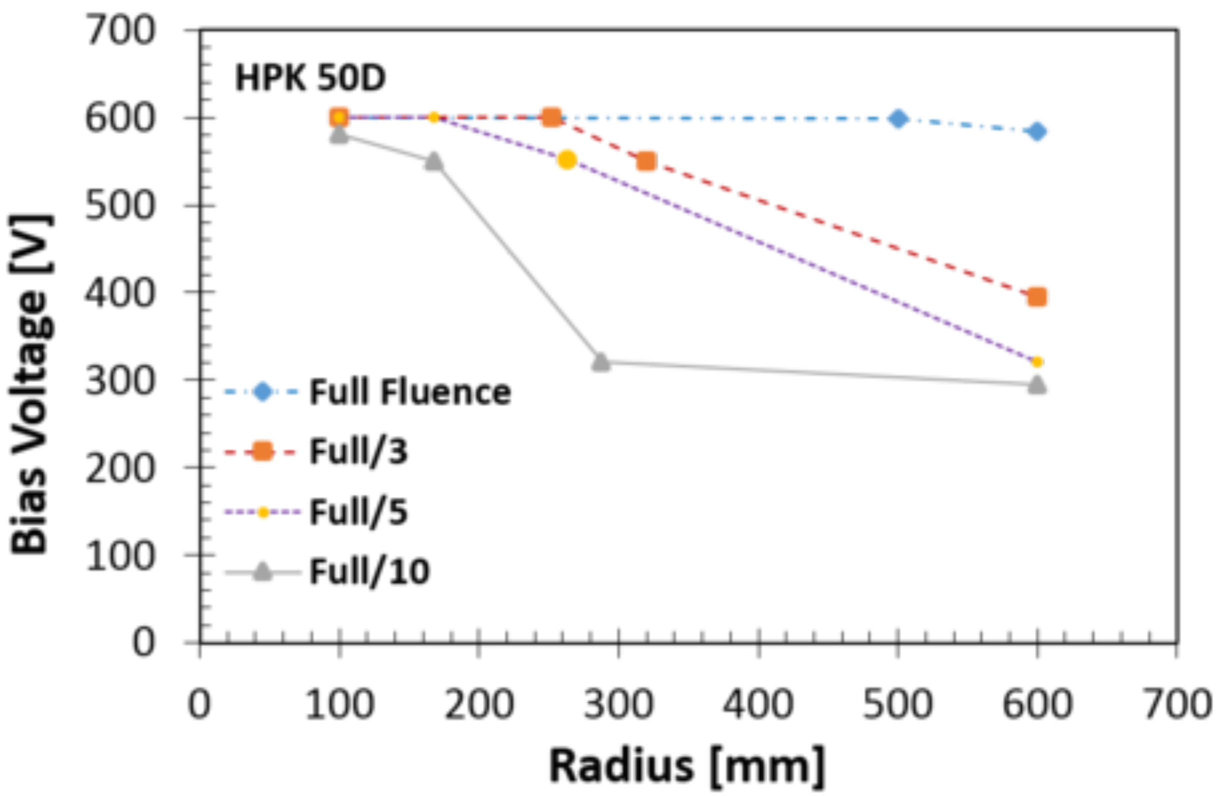
Sensor studies: bias voltage vs radius

- **Given the fluence vs. R dependency:**
  - Bias voltage of sensors will need to be adjusted during detector lifetime

- **Required bias voltage vs. fluence**
  for different fluence levels at R = 300 mm

- A rapid increase is seen between:
  - 1 x 10^{14} and 3 × 10^{14} n_{eq}/cm^2





- **Increase bias voltage over lifetime of detector and as a function of R**

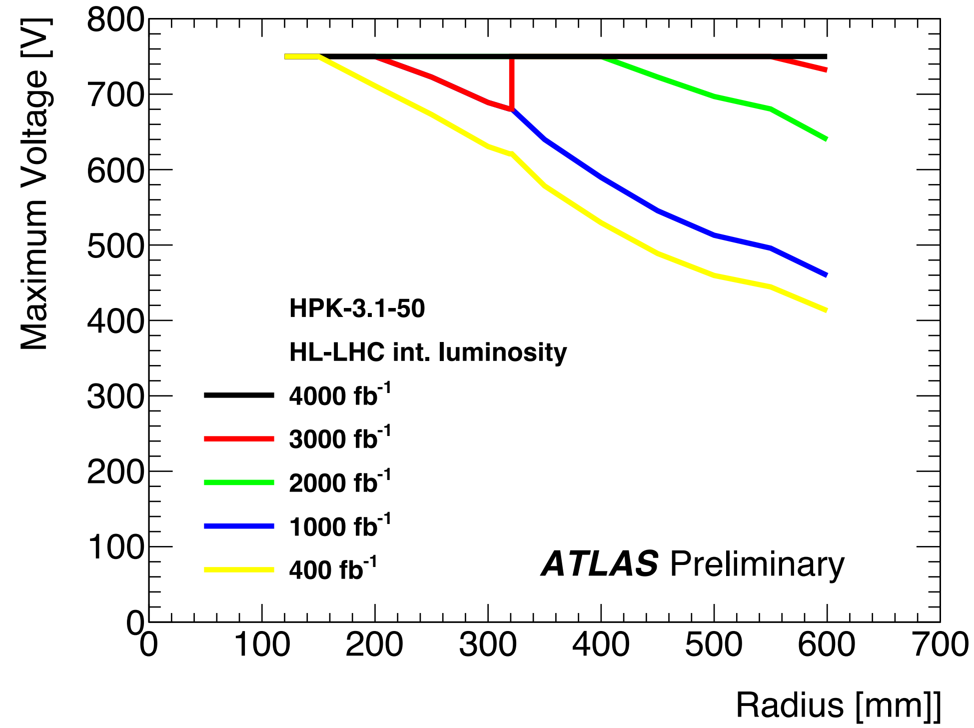
- Also include replacement of inner section

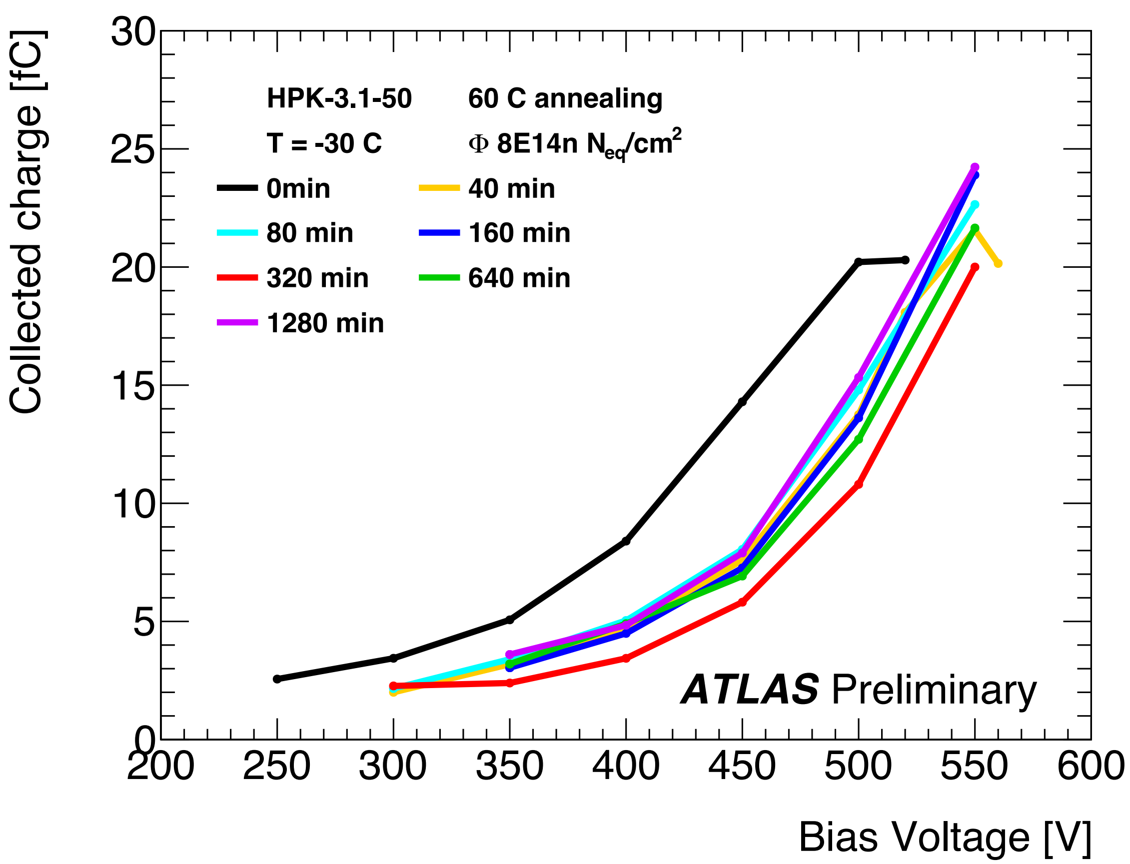
Sensor studies: bias voltage vs radius

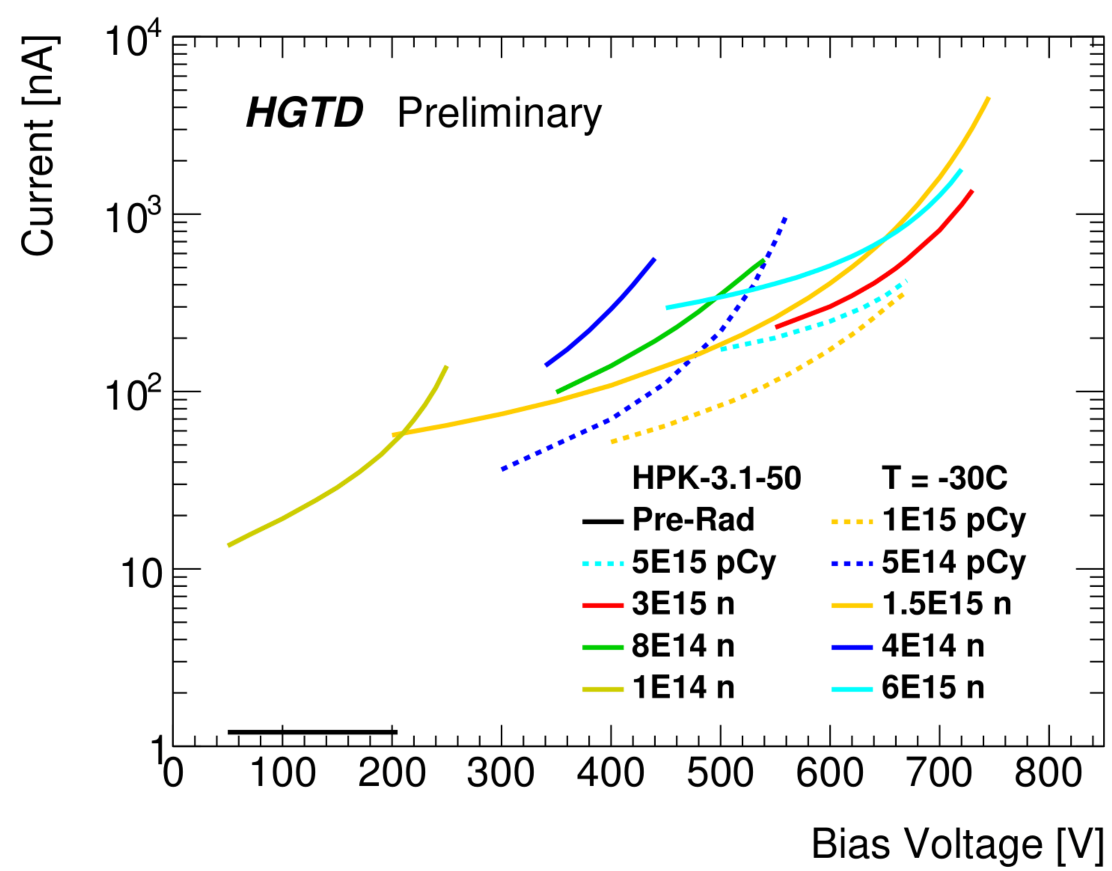
- **Given the fluence vs. R dependency:**
  - Bias voltage of sensors will need to be adjusted during detector lifetime
  - *Power density increased with higher fluence*

- **Annealing studies: initial studies**
  - No significant differences in annealing performance

- Studies continue on inter-pad gap, B+C dopants, deeper multiplication layer

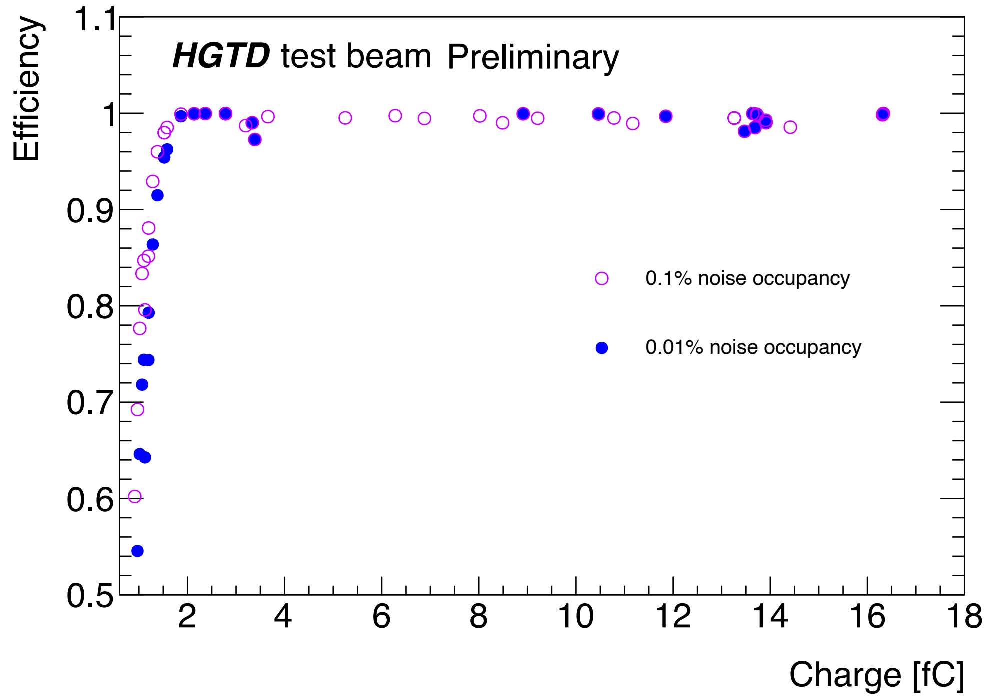


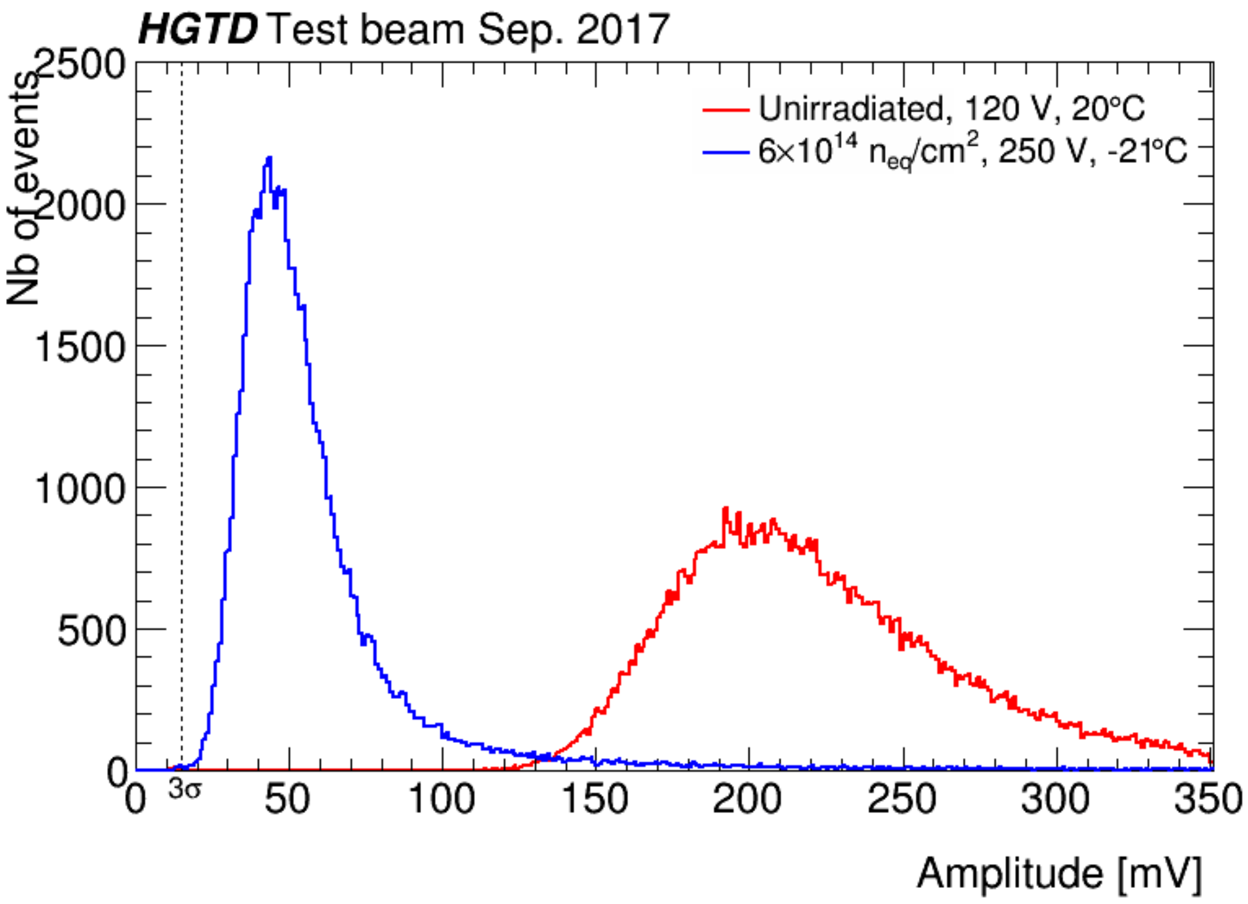


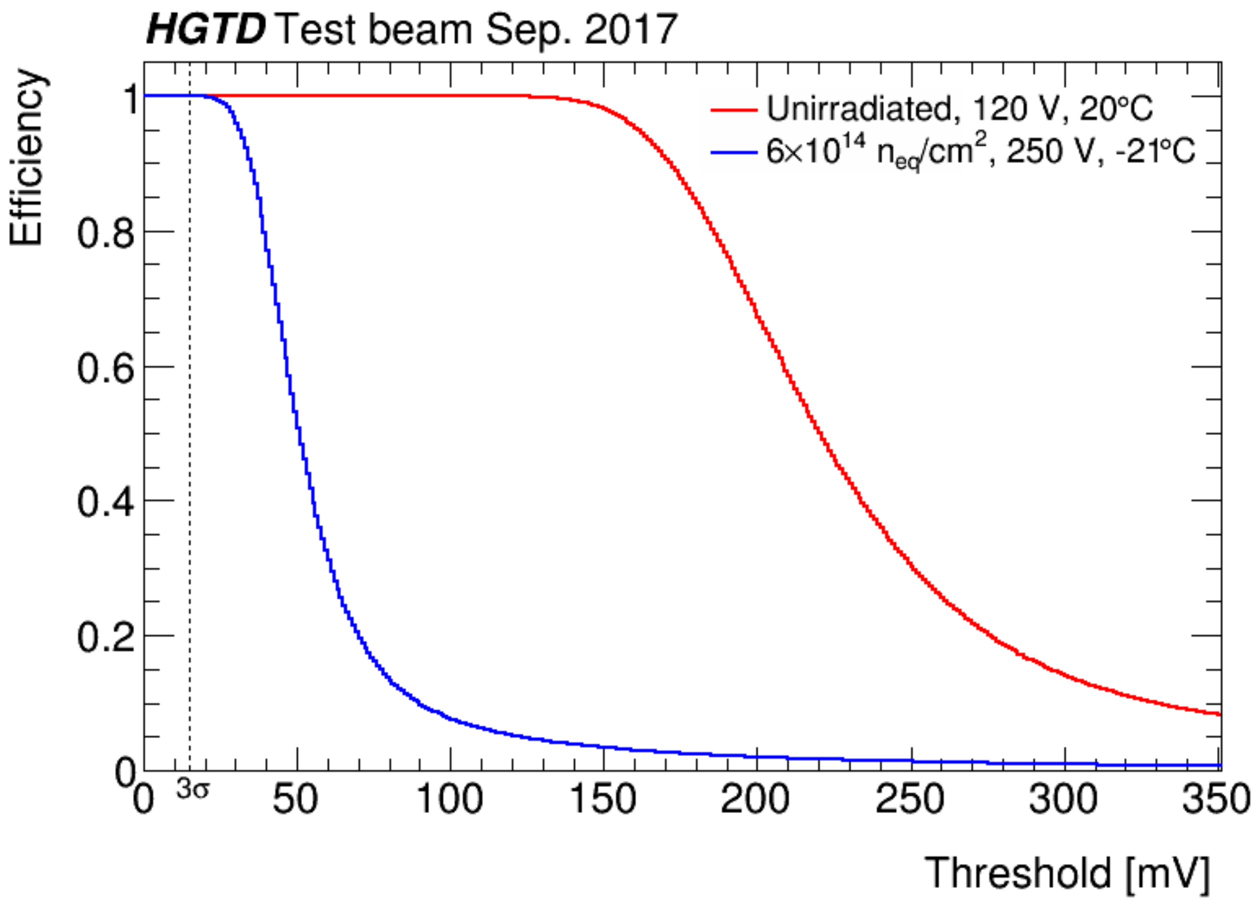


Arrays: efficiencies vs threshold

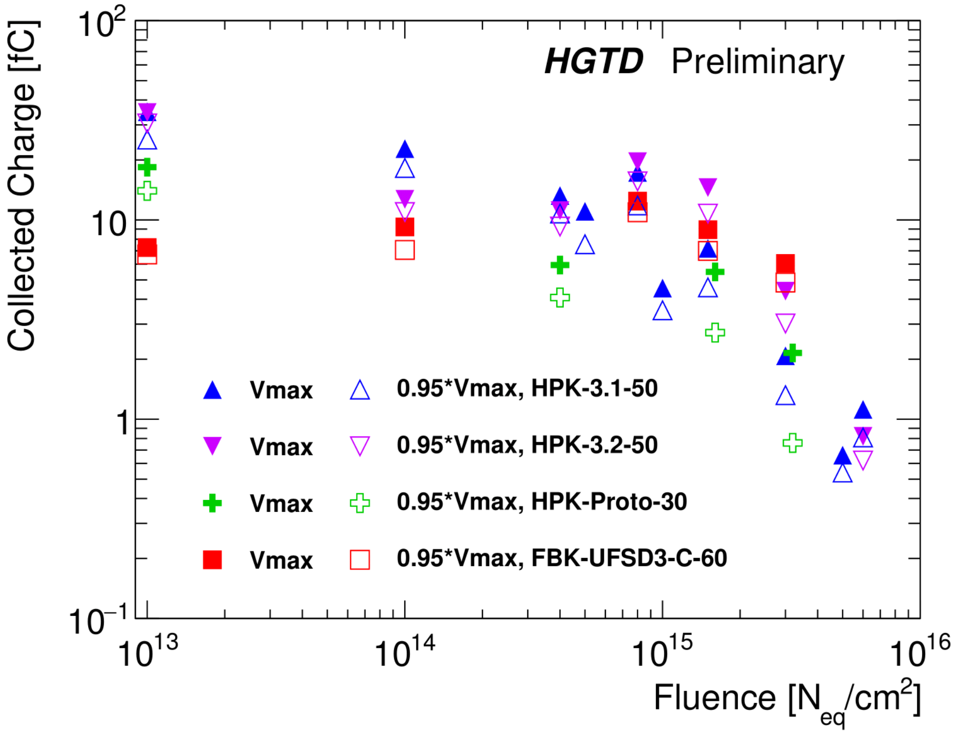
- **Signal amplitude for un-irradiated and irradiated 6 × 10^{14} n_{eq}/cm^2**
  - Signal amplitude is reduced after irradiation
- **Signal efficiency vs the amplitude threshold**
  - Efficiency drops much quicker for irradiated LGAD with higher threshold
- **Hit efficiency as a function of collected charge** at a noise occupancy of 0.1 % and 0.01%



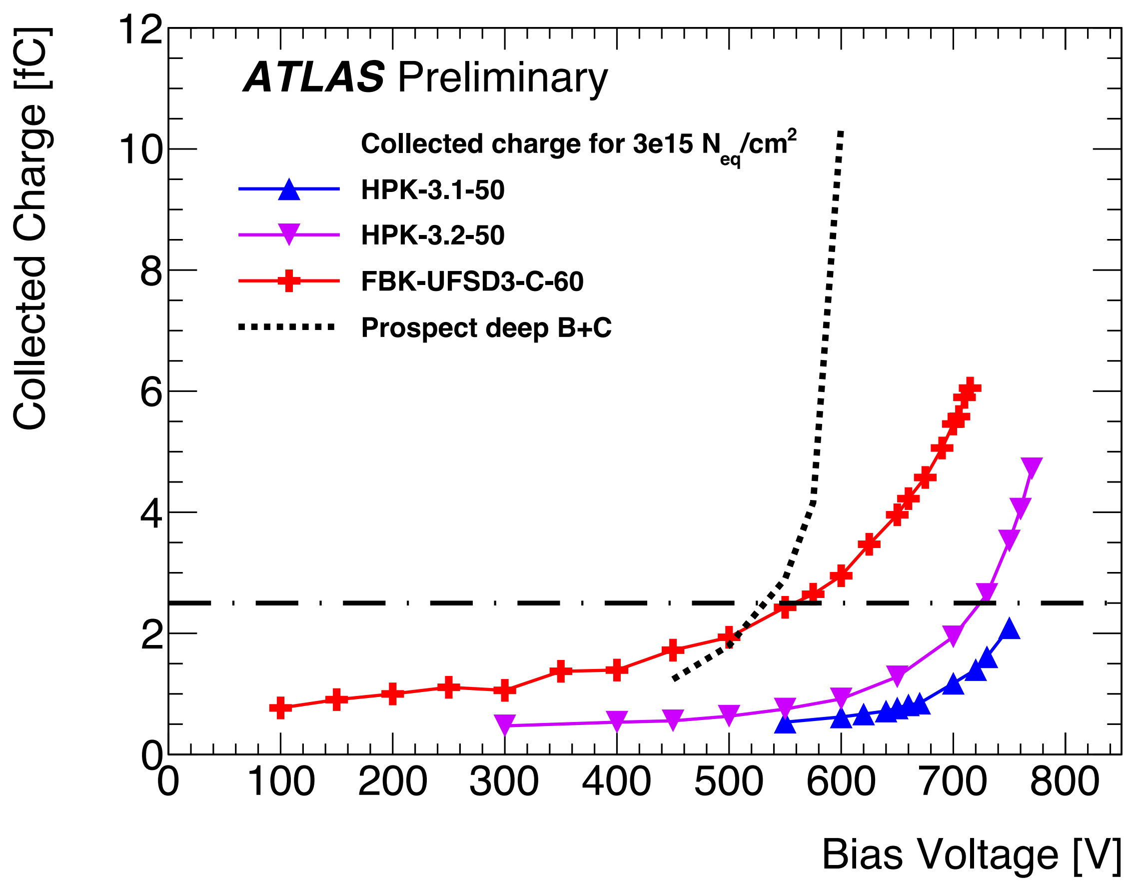


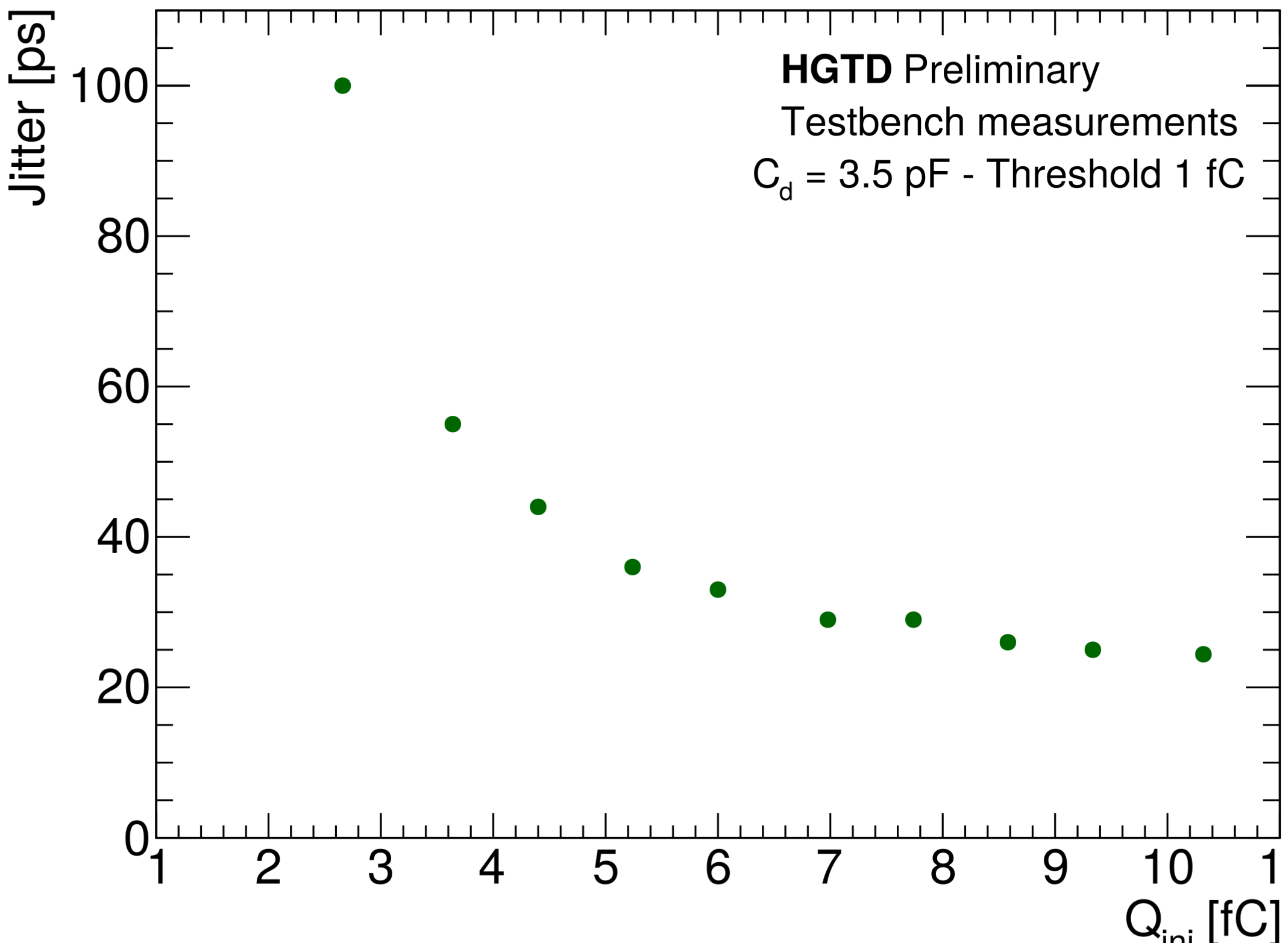


Sensor + ASIC: Jitter



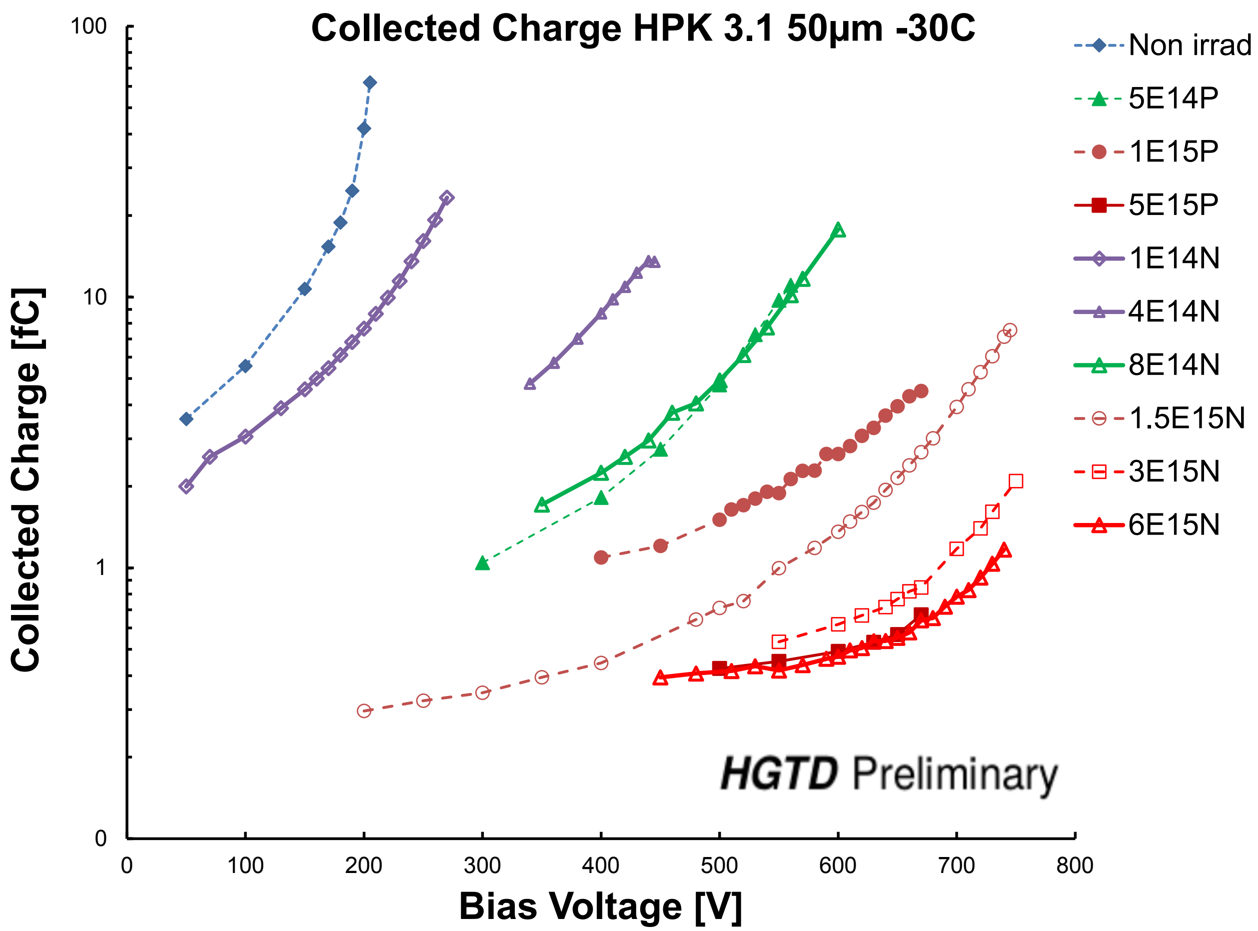
- **Measurements of collected charge up to $6x10^{15}$ neq/cm^2**
  - Large reduction once above 10^{15} neq/cm^2
- Can reach in HPK 3.2 —> 4 fC at 3 x 10^{15} neq/cm^2
  - Testbench measurements of ALTIROC vs injected charge
  - *Optimization of entire module*

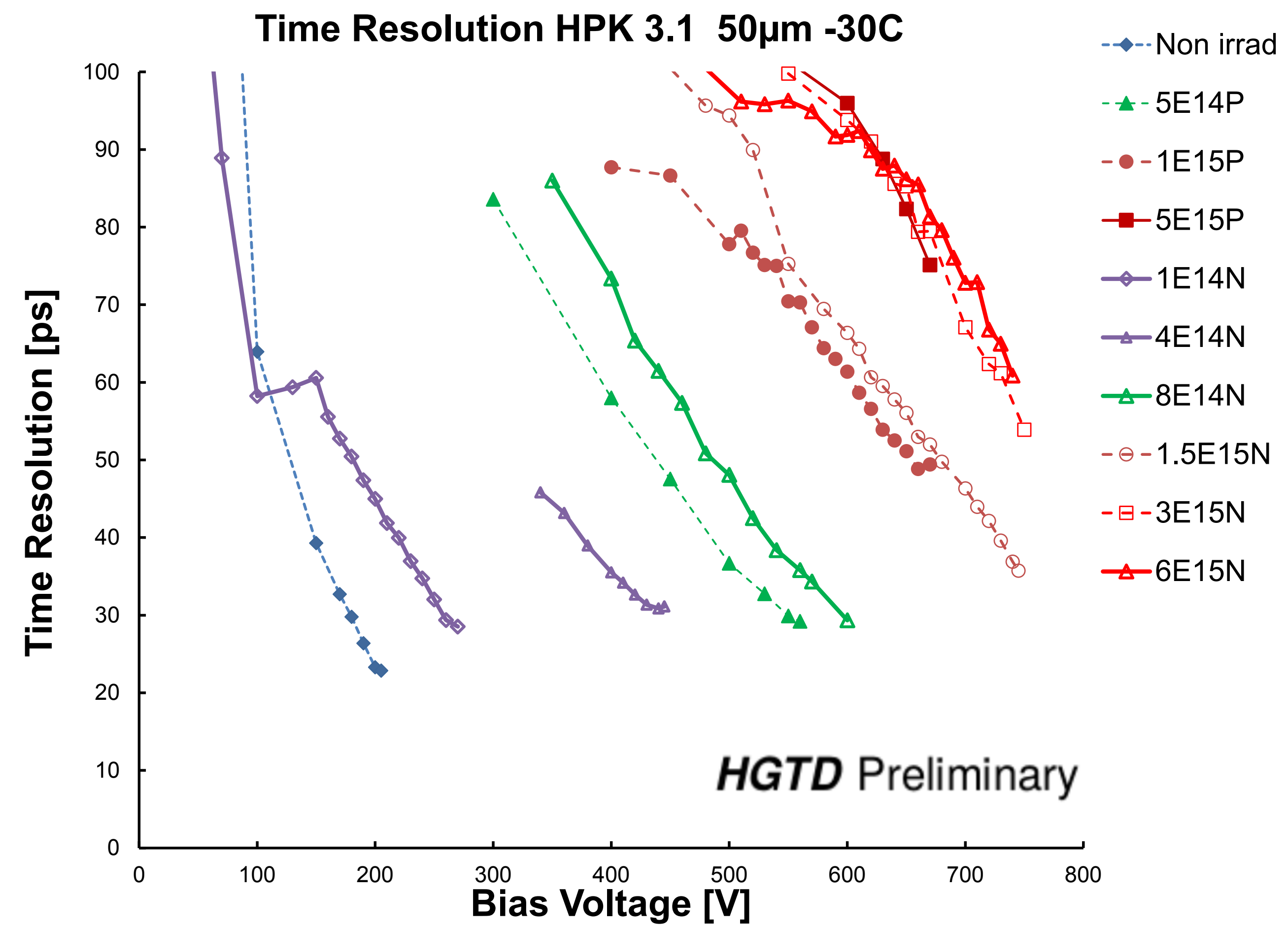




- **Important to ensure sufficient CC for entire lifetime (> 4 fC)**

Sensor studies: charge and time

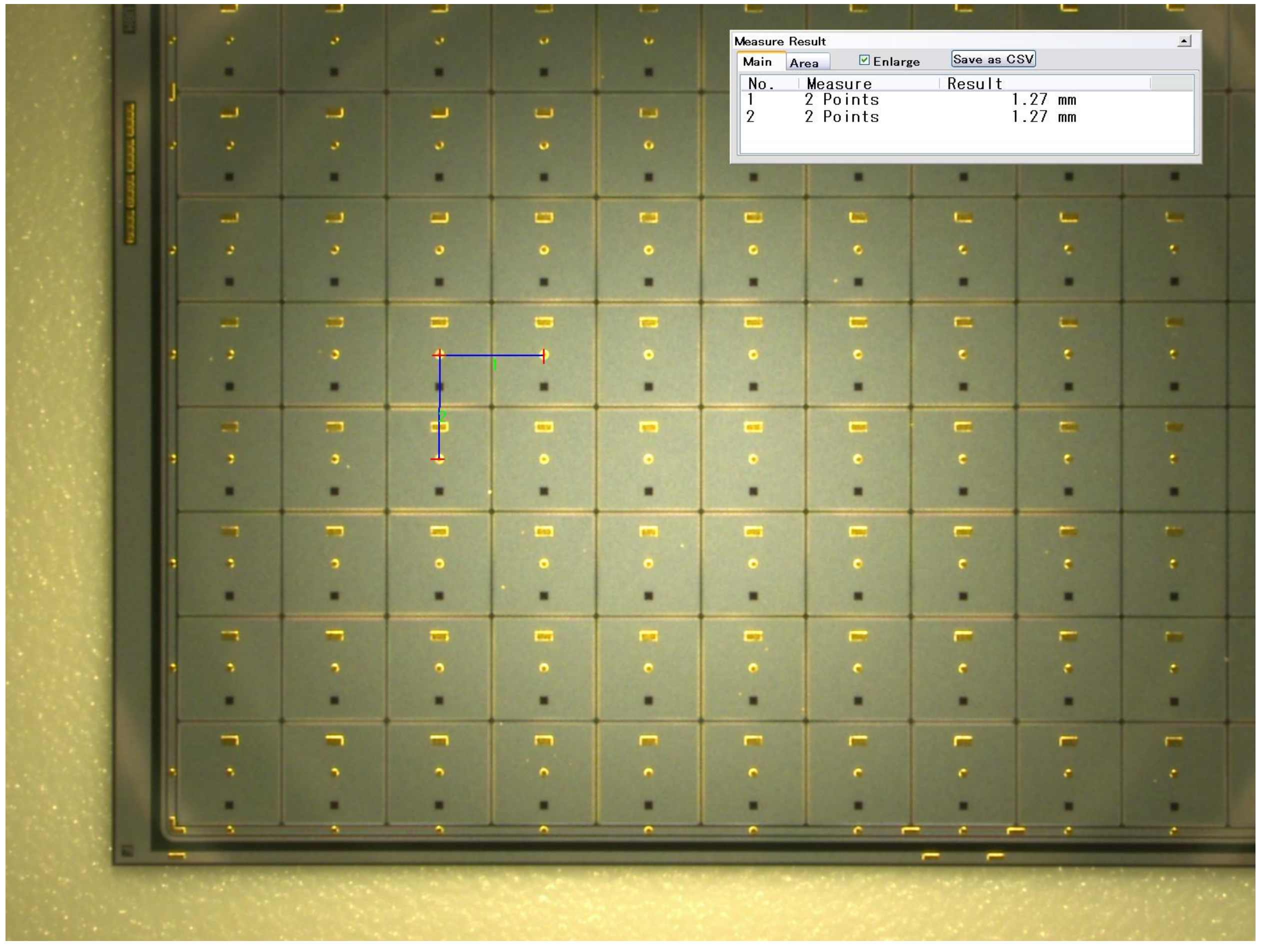


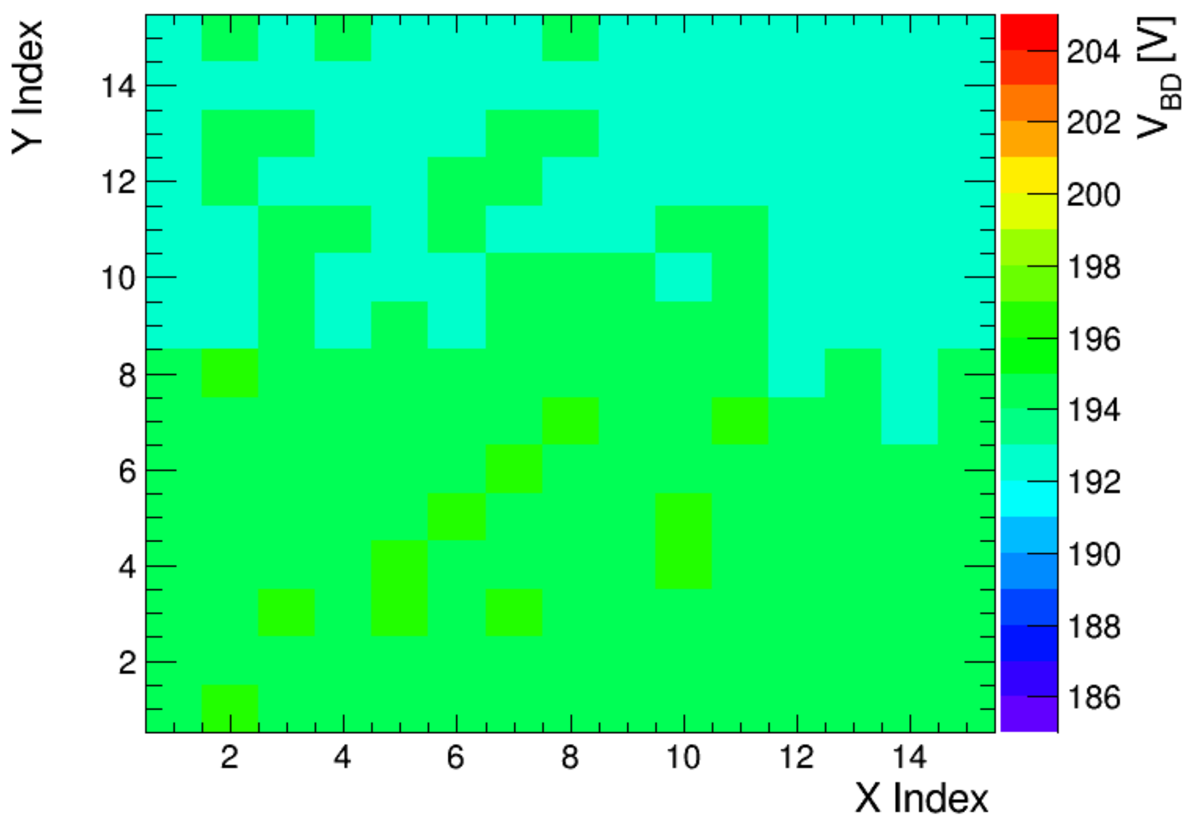


- **Collected charge and time resolution for HPK 50 μm at -30 C**
  - CC of 1 fC for all fluences, 2.5 fC up to 3 x 10^{15} n_{eq}/cm^2
- **50 ps achievable up to 3 x 10^{15} n_{eq}/cm^2 with 2.5 fC collected charge**

Arrays: 15 x 15 pads

- **Studies of 15 x 15 LGAD arrays on-going (half-size of final sensor)**
- Microscope photo of an HPK-ATLAS Type 3.1 15×15 array.

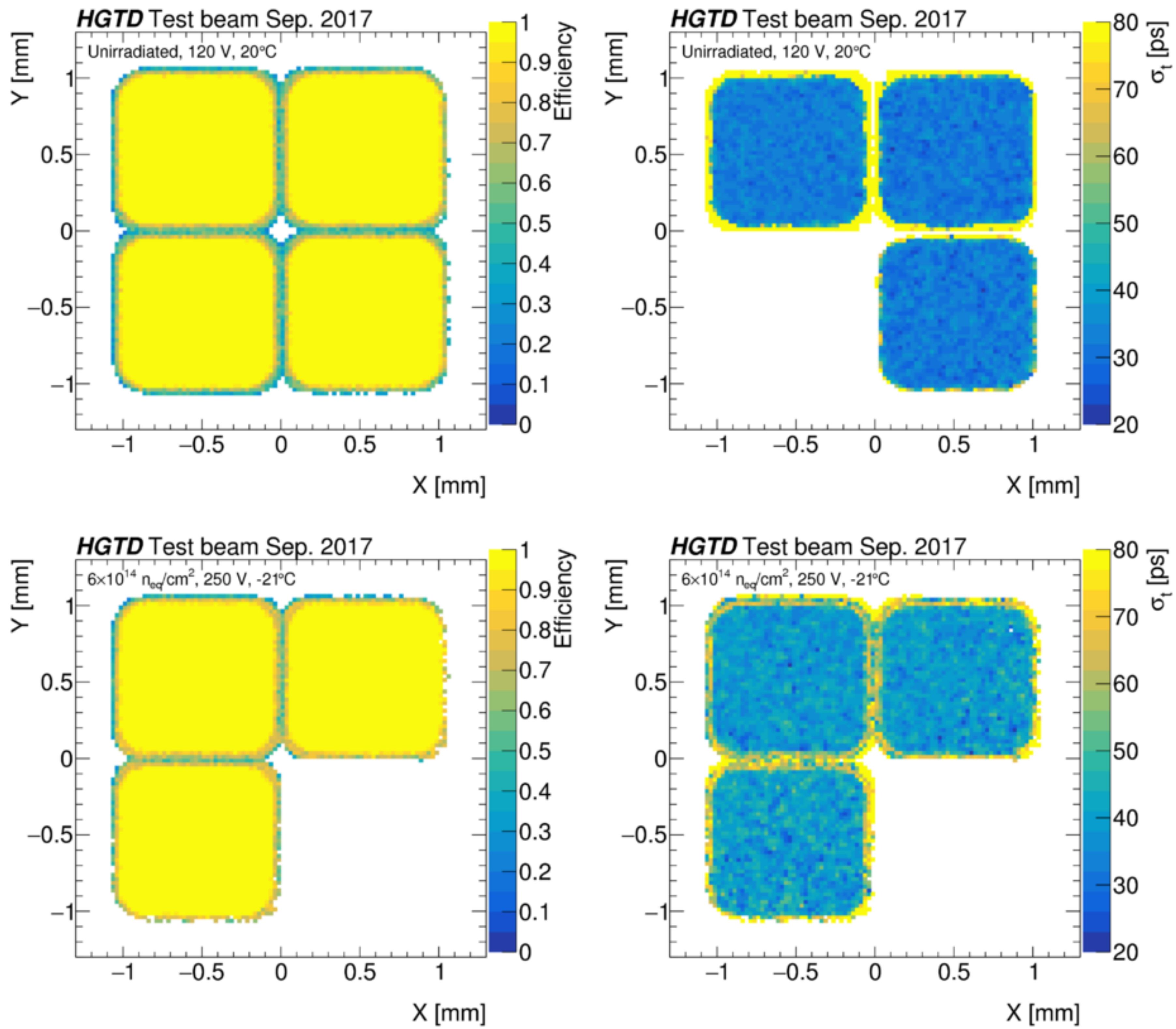




- **V_{BD} map of a 15 × 15 HPK type 3.1 array**
  - Measurement at room temperature
  - Neighbours and GR floating
- **Excellent uniformity observed**
- **Feasibility of large-size LGAD arrays demonstrated**

Arrays: efficiencies and time resolution

- **Hit efficiency (left)**
- **Time resolution (right)**
  - Top: Un-irradiated
  - Bottom: $6 \times 10^{14}\ n_{eq}/cm^2$



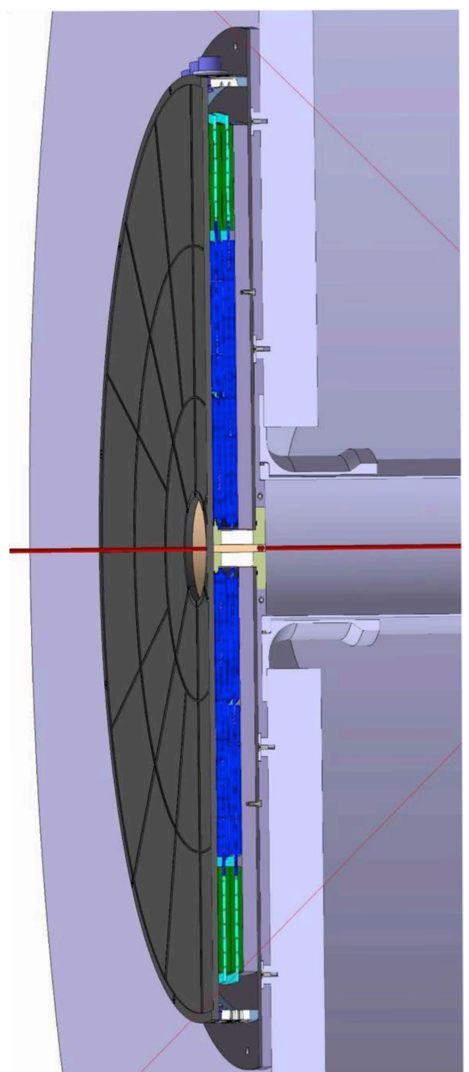
- **Efficiency ~ 100 %**
  - Inter-pad gap slightly more efficient after irradiation
  - Voltage threshold is 3 times larger than the noise (~5mV)

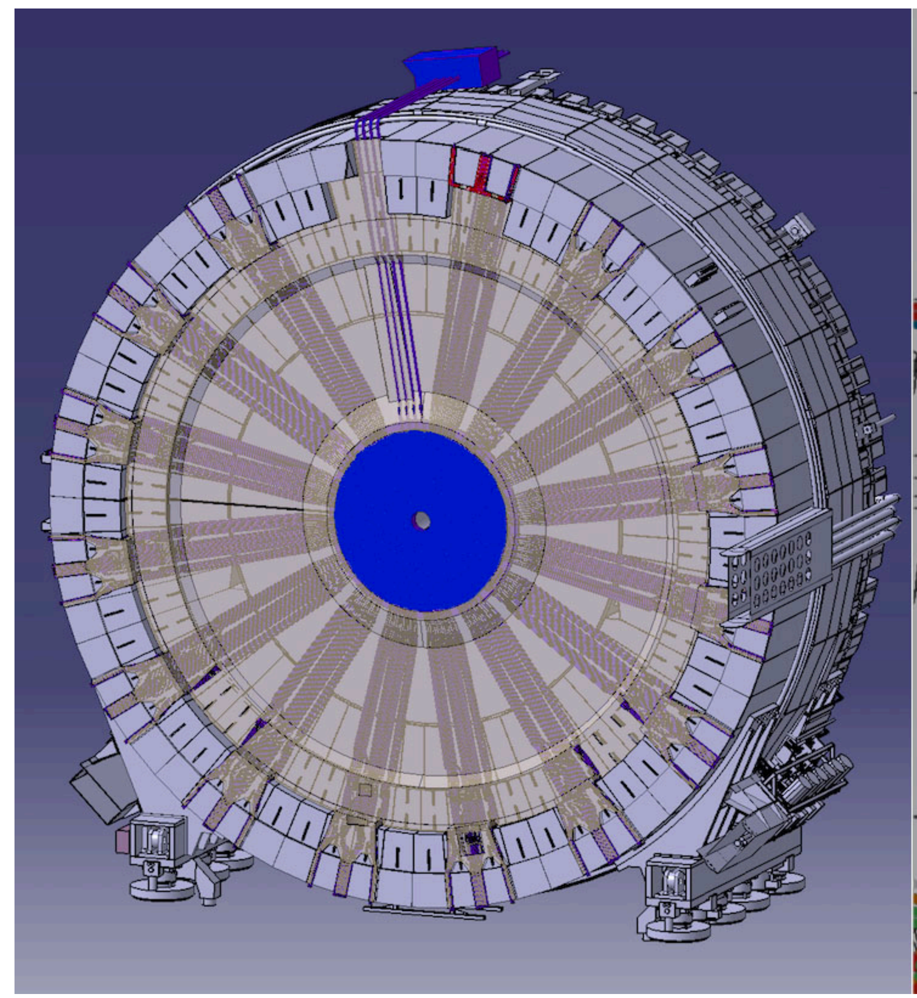
Mechanics and Assembly

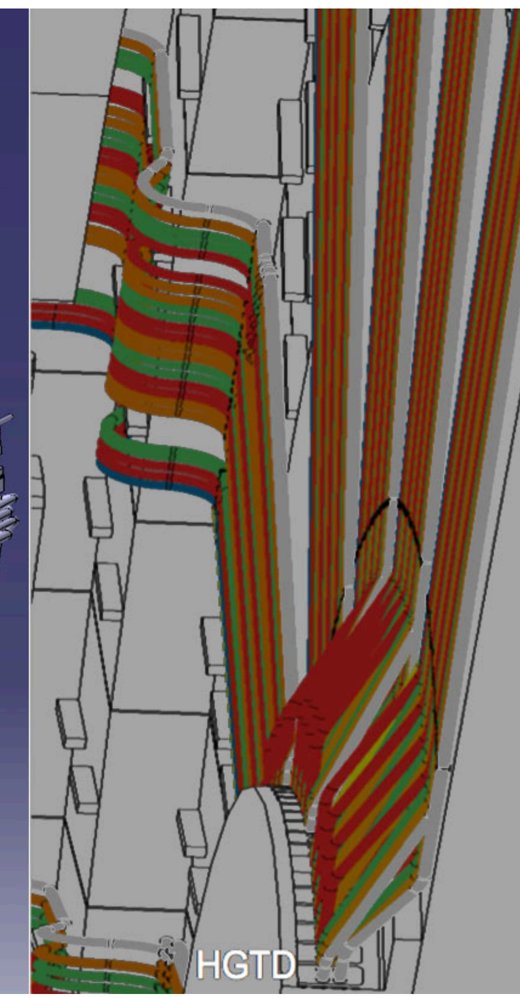
- **Detector mechanics and infrastructure were designed taking into account the severe constrains of space to accommodate the detector**
  - Services need to be routed in the gap between the barrel and end-cap calorimeters, sharing the space with ITk

- **HGTD hermetic vessel made of carbon fibre composite sandwich structure**

- **Temperature inside vessel: -35C.**
- To avoid condensation, heaters will be placed on HGTD cover and LAr cryostat wall



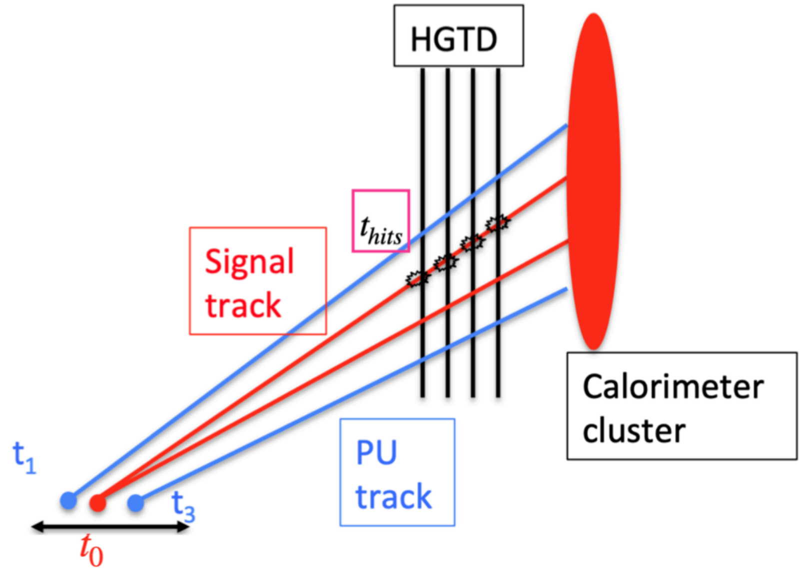


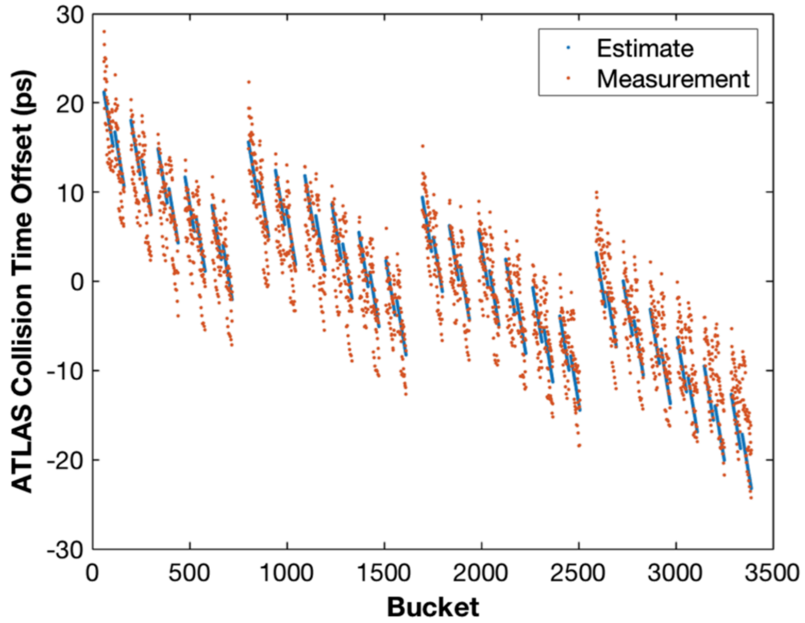


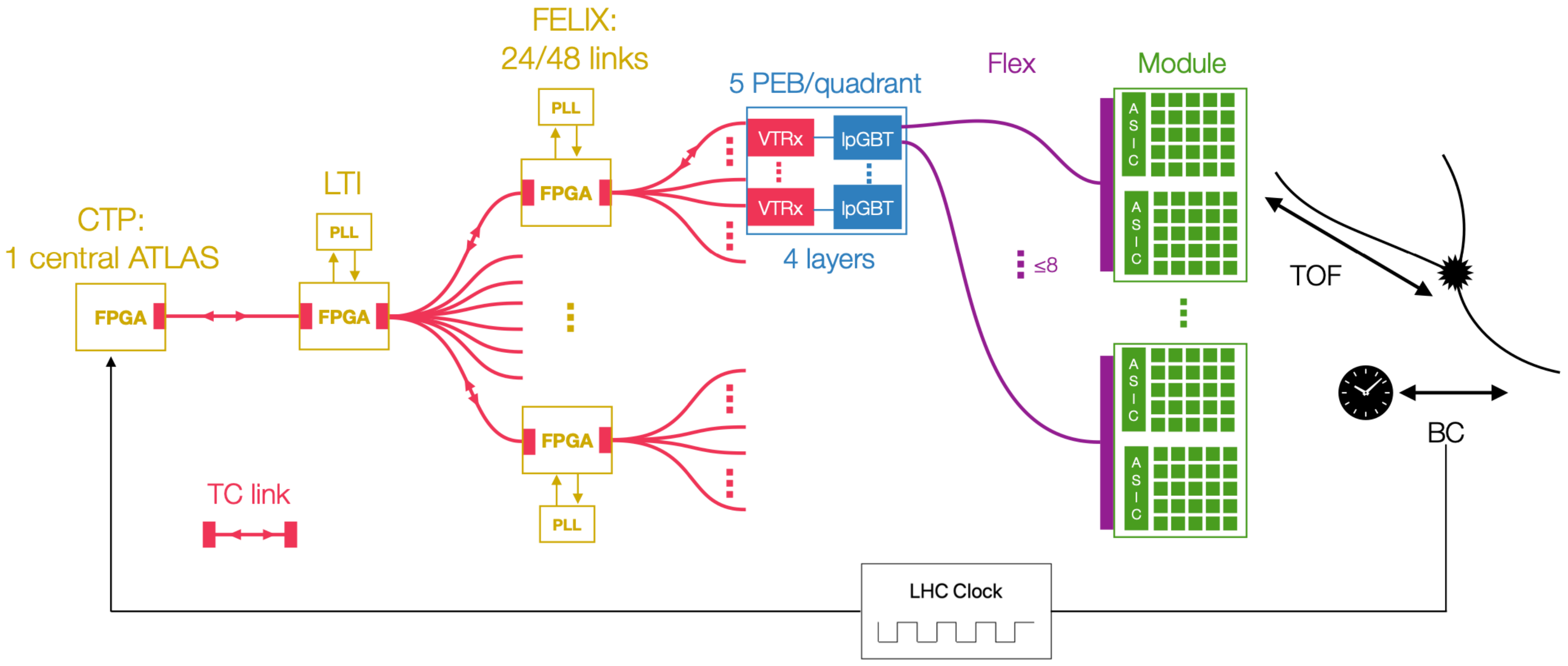
- Services routed along the end-cap calorimeter face

Challenges and Potential: High precision timing

- Associating the correct time to all hits/tracks in a given event
- Contributions from time of flight of particles and from collision time offset from the LHC
- Calibrations needed to correct for short and long variations







- Global sketch of the the full HGTD system with LHC clock distribution to each pixel block
- Contributions will need to be very well understood and calibrated

Object Performance

- Track candidates from ITk are extended to HGTD using a progressive **Kalman filter**
  - *Extrapolation resolution when using last silicon hit < 1 mm*
- **Improved performance of objects beyond ITk-only scenario**
  - Pileup jet rejection
  - b-tagging and light-jet rejection
  - Lepton isolation
- ***Performance of central region mostly recovered***