Overview of the ATLAS High-Granularity Timing Detector: project status and results

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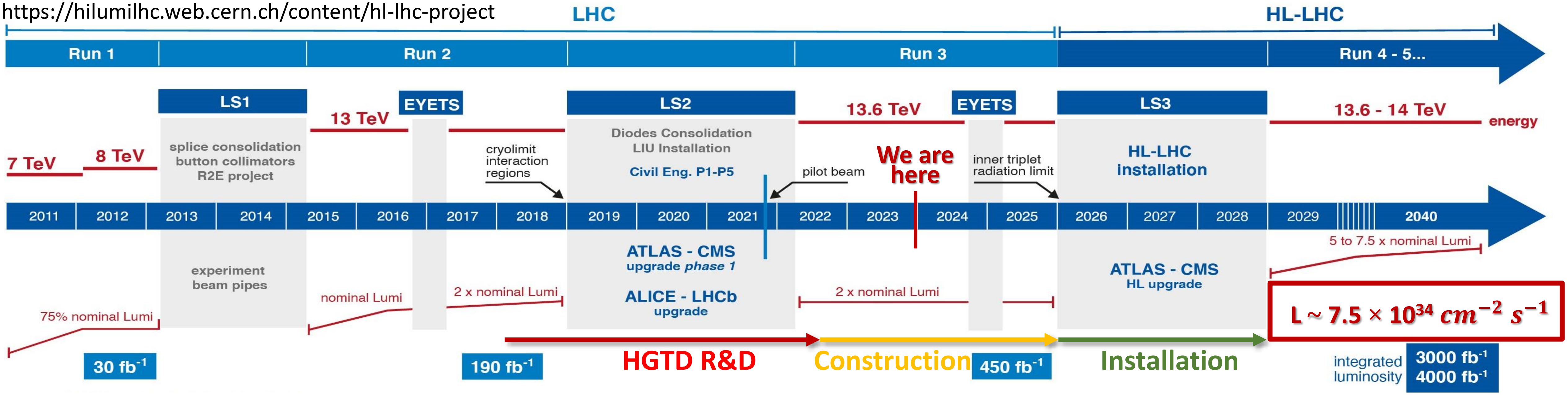
ATLAS EXPERIMENT

Outline

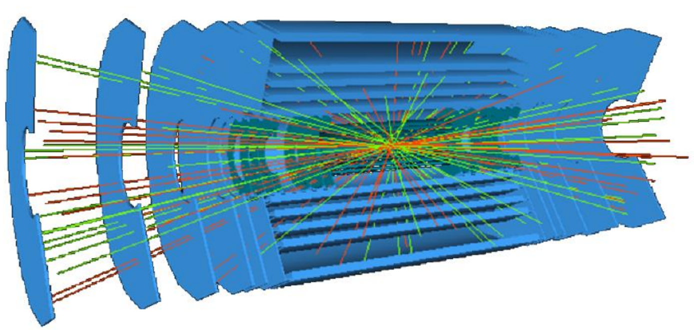
- The motivation
- The HGTD in a nutshell
- Some highlights: the LGAD sensors, the readout ASIC ALTIROC, and some beam test results; the module assembly and the peripheral electronics board (PEB)
- The status and a summary

The motivation

https://hilumilhc.web.cern.ch/content/hl-lhc-project

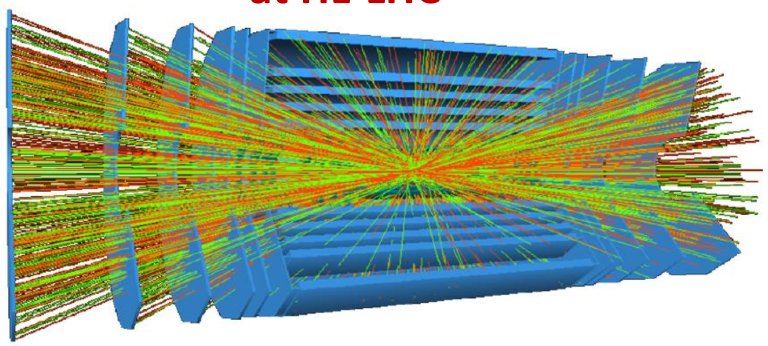


ATLAS today



19 – 55 pile-up events

at HL-LHC



140 – 200 pile-up events, or 1.5 vertices/mm

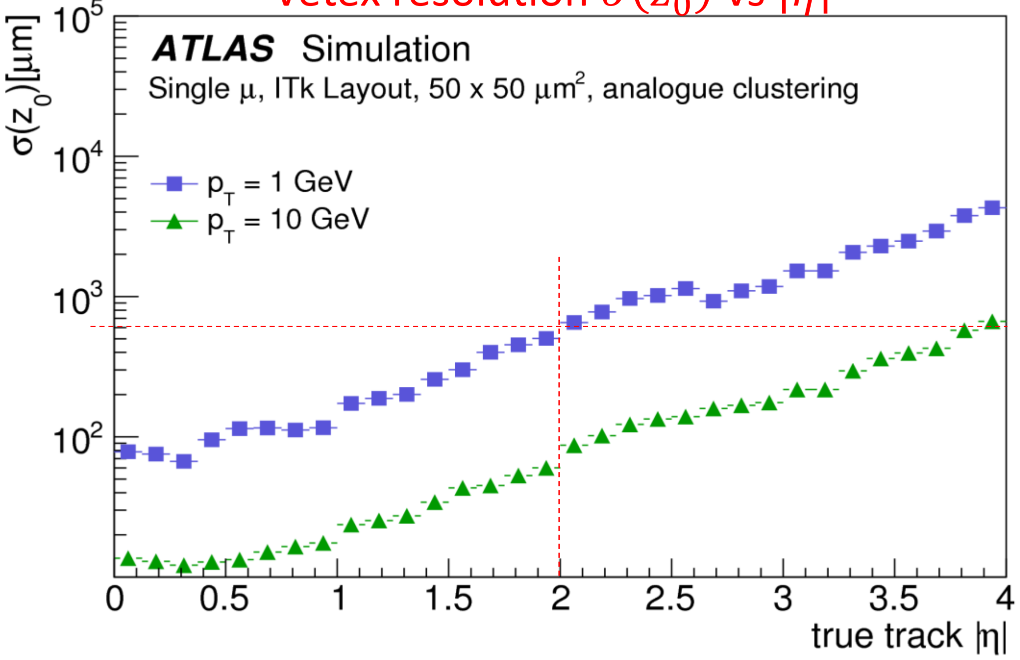
Harsh radiation environment up to 2 x 10^{15} n_{eq} cm^{-2}

The motivation

The challenges:

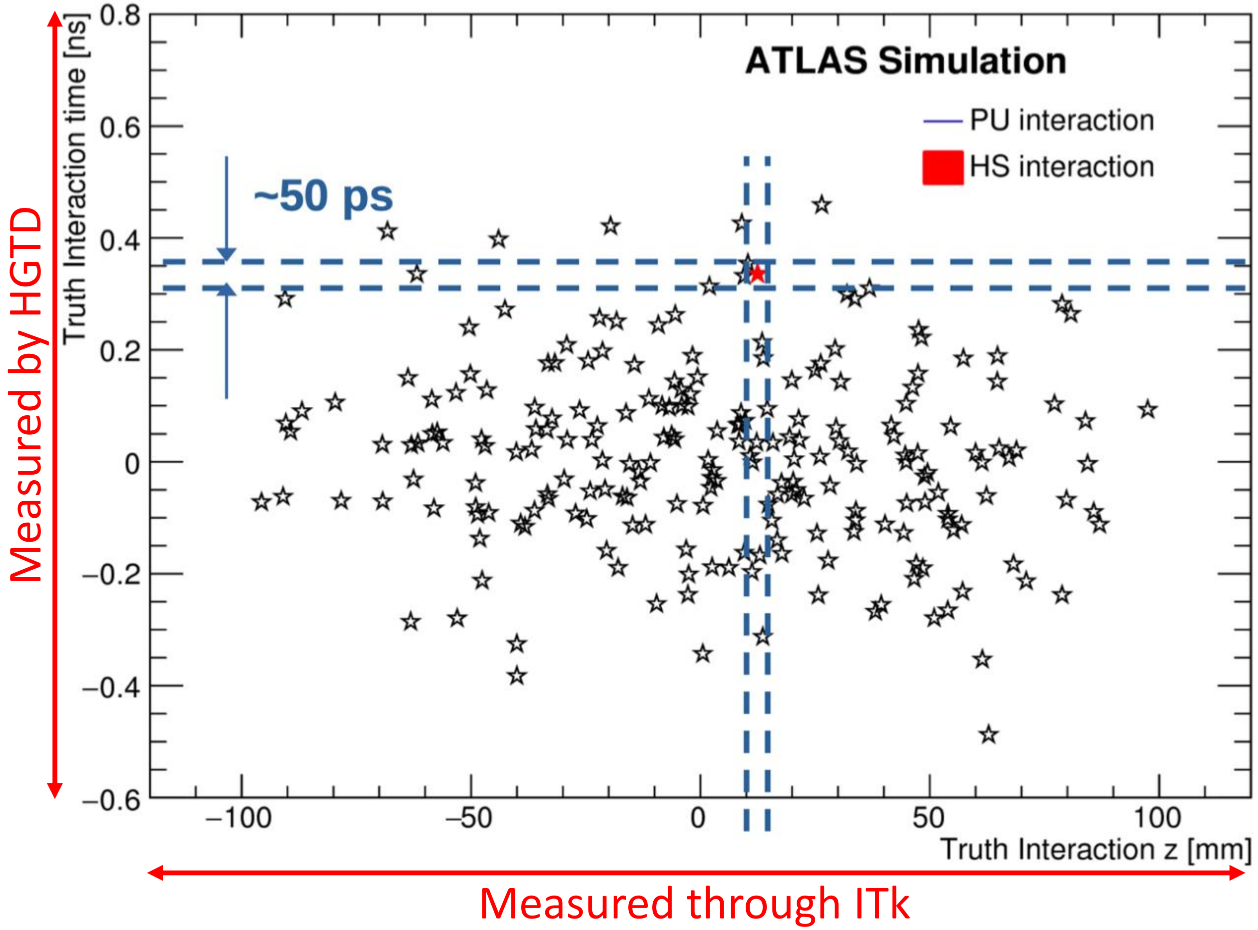
- At the interaction point, about 45 mm along the beam axis, we expect ~ 200 pile-ups, or 1.5 vertices/mm
- Although the ATLAS Inner Tracker (ITk) is designed to cope with this pile-up density, it is challenging when $|\eta| > 2$: σ_{z0} needs to be < 0.6mm to distinguish individual vertex.

Vetex resolution $\sigma(z_0)$ vs $|\eta|$



The solution:

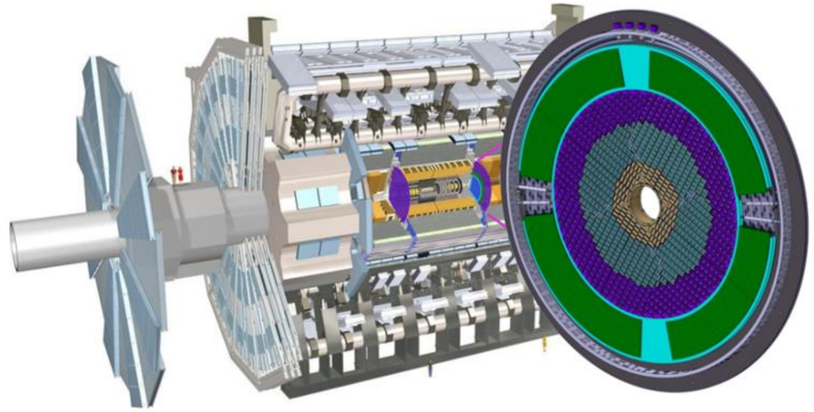
- Separate the vertices (pile-ups) also in time
- With 50 ps MIP time resolution, the pile-up suppression is expected to improve by **a factor of ~ 6**

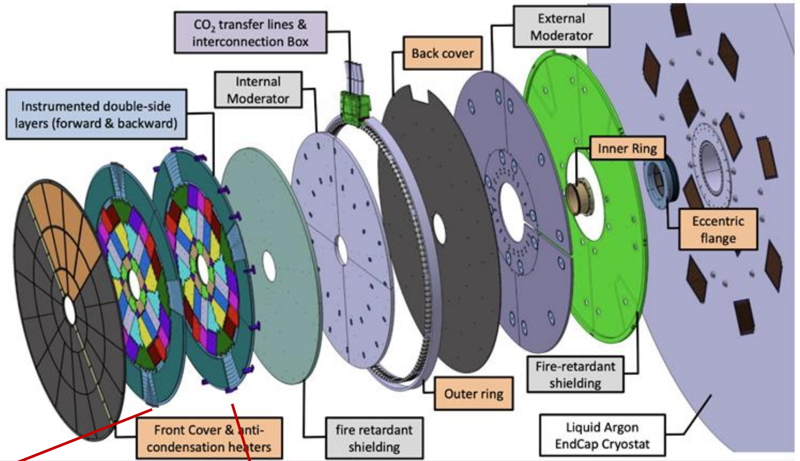


The HGTD in a nutshell

The HGTD is designed to provide timing information for ATLAS at the HL-LHC

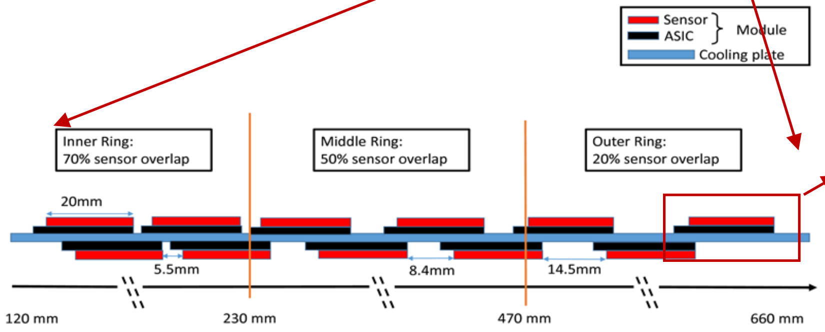
- 6.4 m^2 silicon detector and about 3.6×10^6 channels
- Based on the Low Gain Avalanche Detector (LGAD) sensor, 1.3 mm × 1.3 mm, able to work in the ATLAS detector environment
- Design time resolution: 30 – 50 ps/track (start to end-of-life),
- Provide luminosity measurement
    - Count number of hits at 40 MHz (bunch-by-bunch)
    - Goal for HL-LHC: 1% luminosity Uncertainty

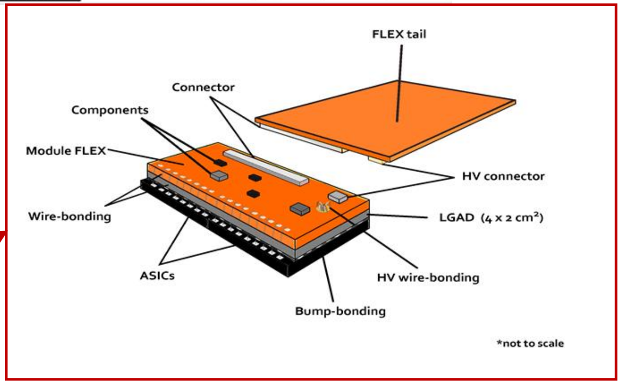




The two detectors are located between the barrel and the endcap calorimeters

- Each detector (end) has two disks with sensors mounted on both sides
- Located at ±3.5 m from the interaction point
- Active area coverage: 2.4 < |η| < 4
- Radius: 120 mm < r < 640 mm



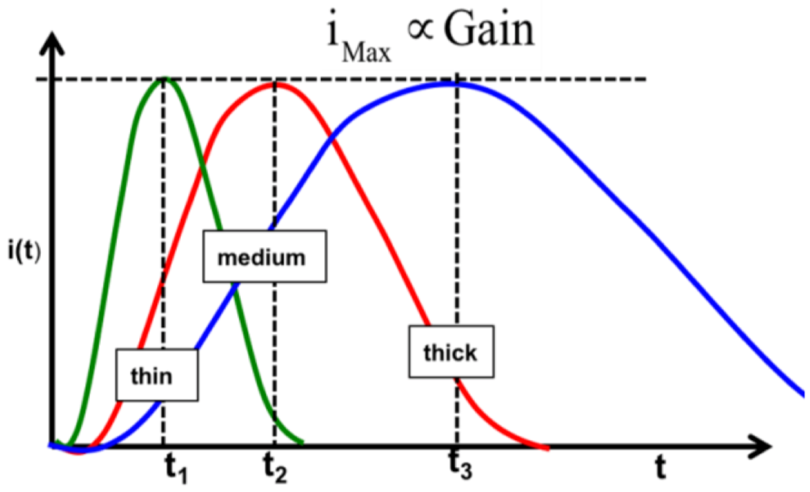


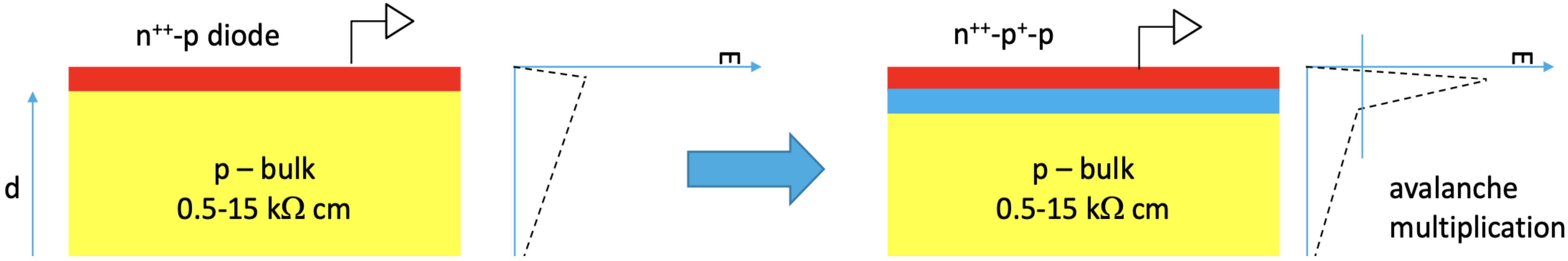
Highlight: the LGAD sensors

Compared with APD and SiPM, LGAD has

- modest gain (10-50) to increase the S/N
- High drift velocity, thin active layer to decrease the t_{rise} (fast timing), leads better time measurement:

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



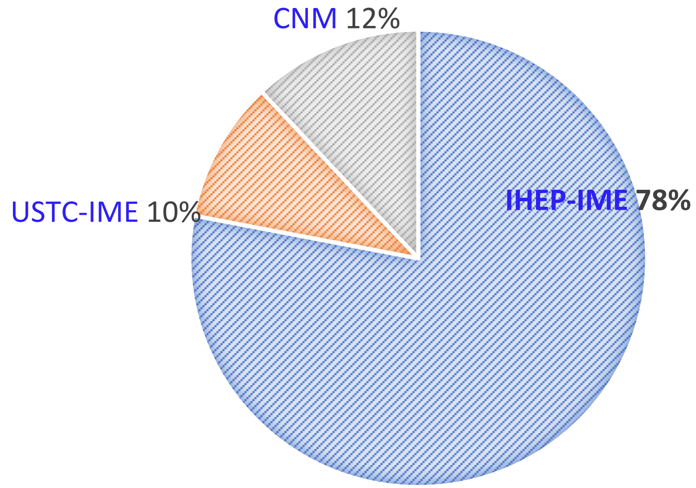


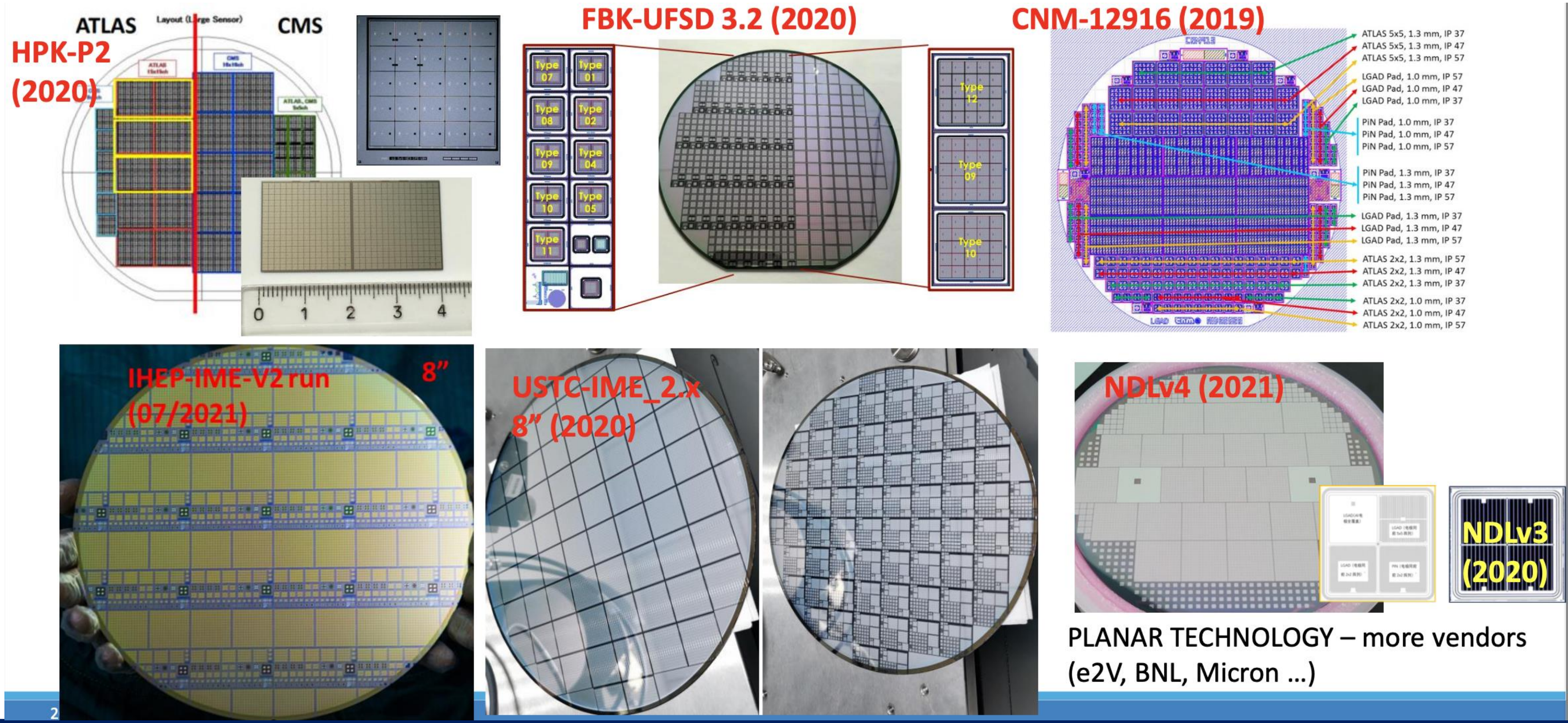
Sketch of LGAD

Highlight: the LGAD sensors

- The last few years saw increased efforts in LGAD R&D. The active entities include:
  IHEP-IME (China), USTC-IME (China), IHEP-NDL(China), FBK (Italy), CNM (Spain), HPK (Japan) …
- HGTD has finalized the CERN tendering. The preliminary production plan:
  - IHEP-IME: 78% (54% from CERN tendering+24% in-kind contribution)
  - CNM: 12% in-kind contribution
  - USTC-IME: 10% in-kind contribution

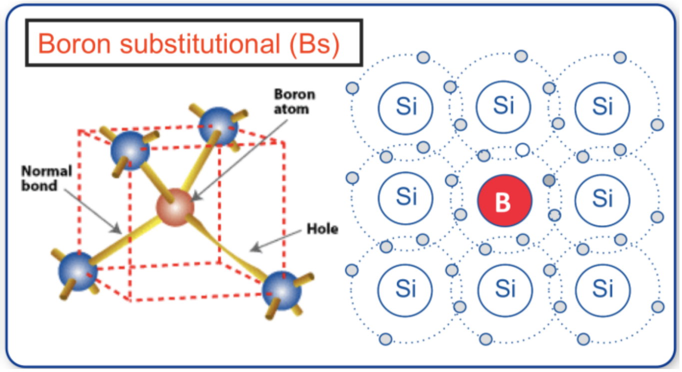
Share of production between providers



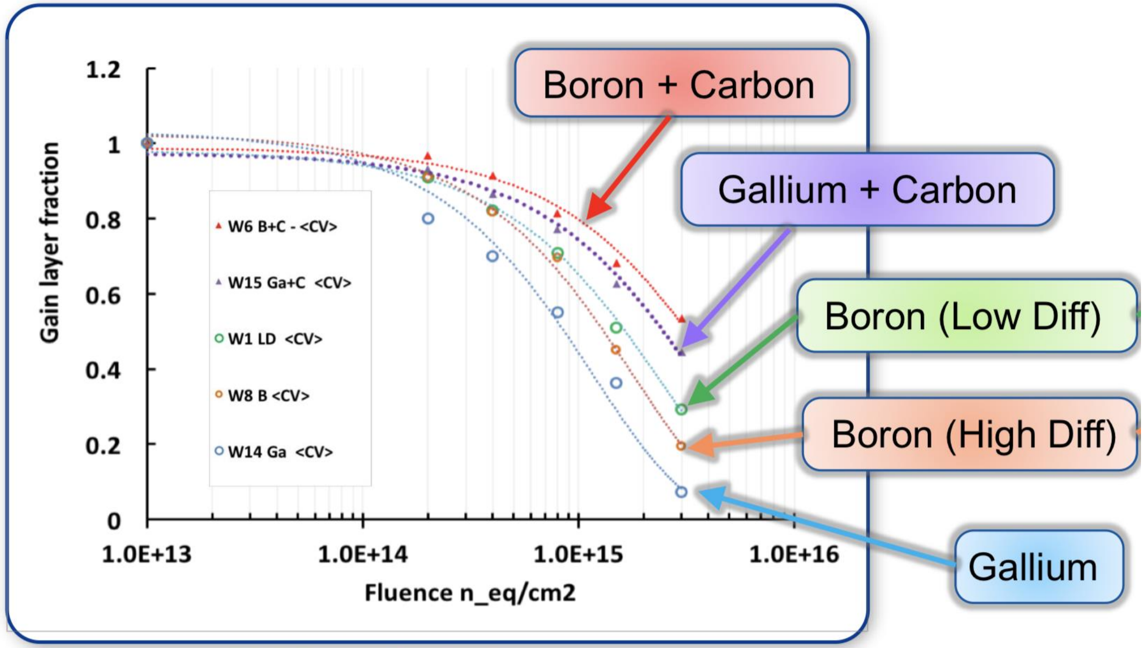


Highlight: the beam-tests on LGAD

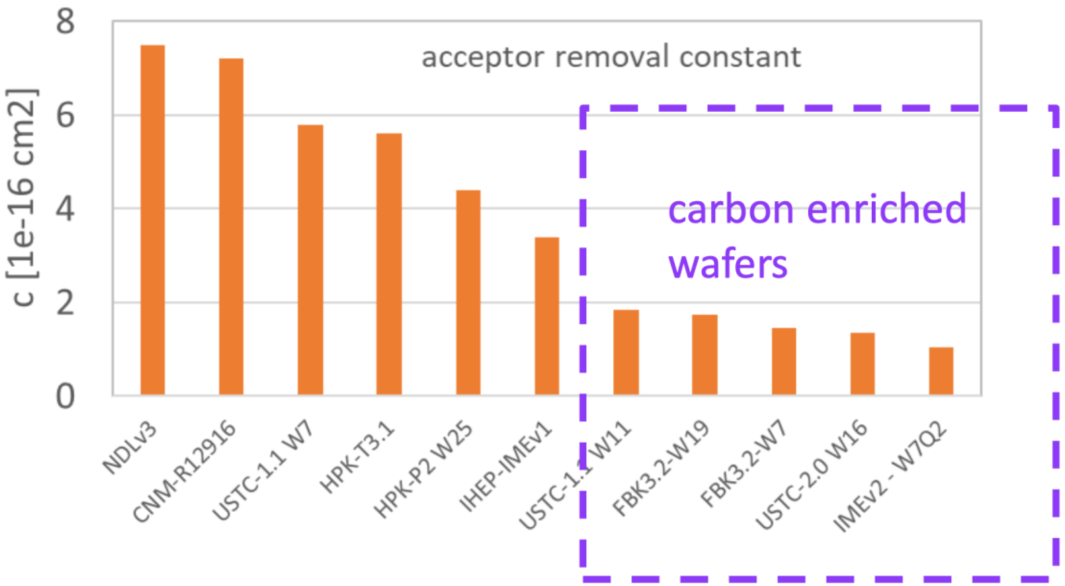
- Radiation causes boron doping in gain layer less active (acceptor removal). This can be mitigated by carbon-enriched LGAD, in which the carbon "stabilizes" the boron doping,
- The IHEP-IME/FBK/USTC-IME LGAD with carbon
  - Lower the acceptor removal ratio
  - Making the sensor more radiation tolerant



See CERN Detector seminar https://indico.cern.ch/event/1088953/



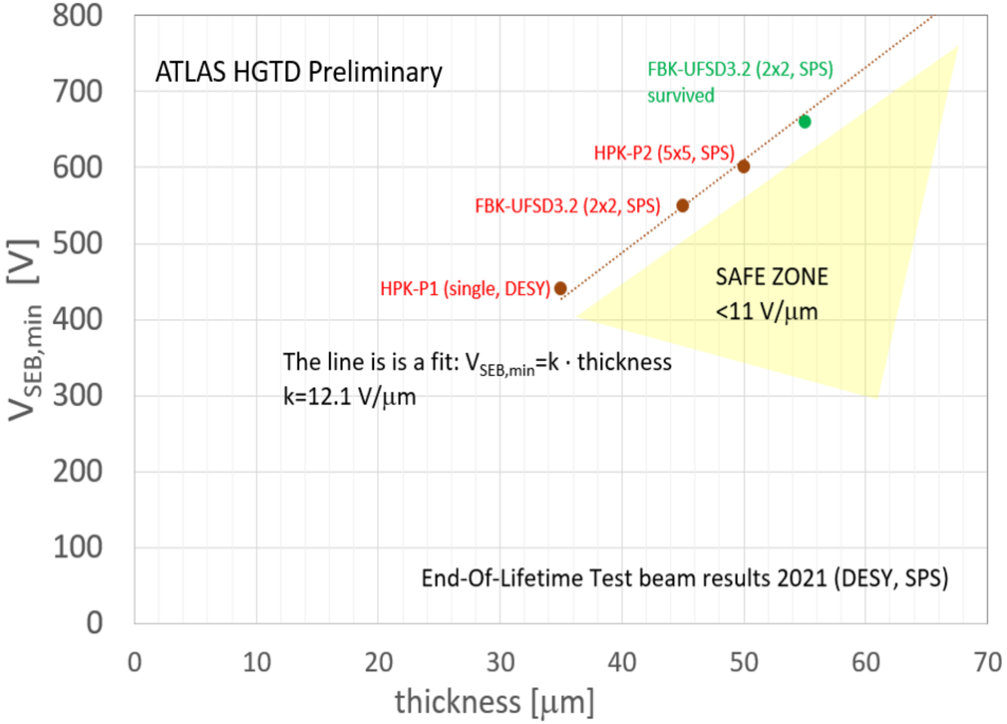
[G.Paternoster, FBK, Trento, Feb.2019]



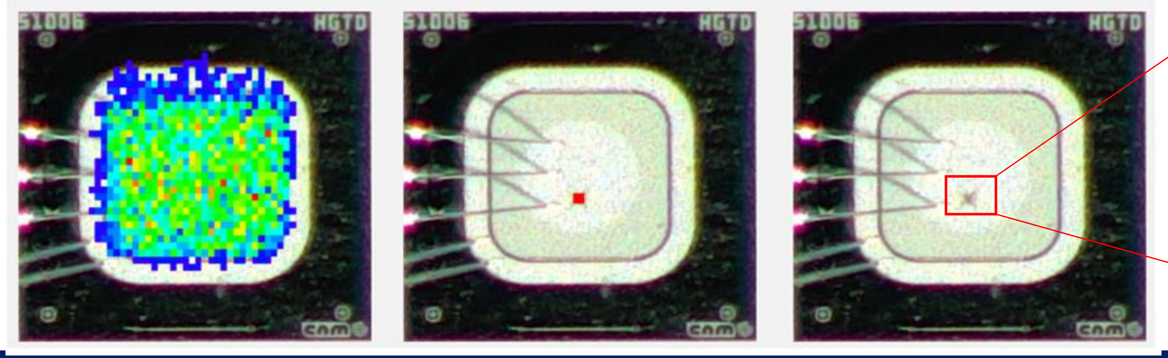
Highlight: the beam-tests on LGAD

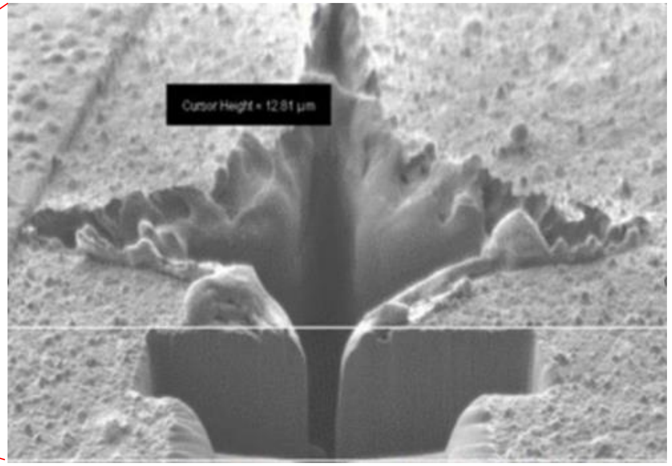
Single Event Burnout (SEB)

- Single Event Burnout (SEB) has been observed in several beam-tests
  - Radiation degrades timing performance due to the loss of gain
  - Increase the bias voltage (HV) to mitigate, but too high HV causes breakdown in the sensor
  - Also observed by CMS/ATLAS/RD50 teams
- A safe zone has been defined
  - Safe zone <11 V/μm, in our case (LGAD 50 μm) the maximum voltage is 550 V



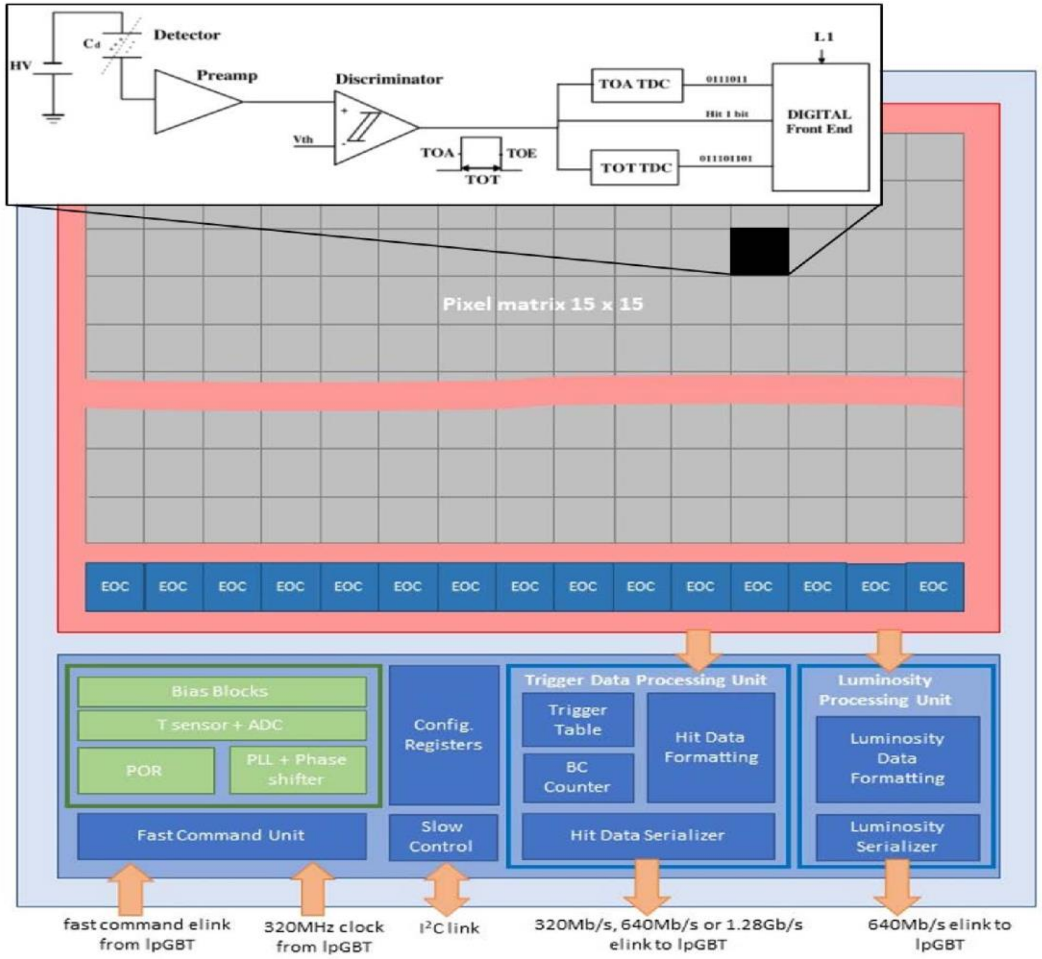
ATLAS HGTD Preliminary



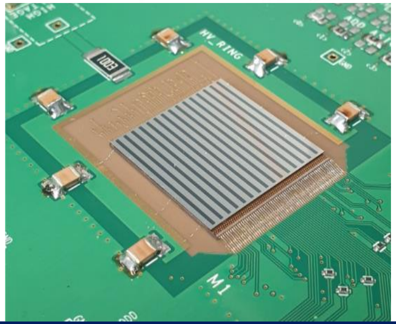


Highlight: the readout ASIC ALTIROC

- **ALTIROC (based on a CMOS 130 nm technology)**
  - Has 225(15x15) channels, matching the sensor number and pad size (1.3mm x 1.3 mm)
  - Measure the Time Of Arrival (TOA), Time Over Threshold (TOT, for time walk correction) of each sensor
  - Minimum discriminator threshold: 2 fC
  - Timing resolution: Jitter < 25 ps @ 10 fC and <65 ps @ 4 fC



- **ALTIROC prototypes**
  - **ALTIROC1:** 25 (5x5) channels, with all analog functionalities, tested
  - **ALTIROC2**: a full-scale prototype of 225 (15x15) channels, including all functionalities, tested
  - **ALTIROC3**: the radiation-tolerant version of ALTIROC2 (under test)



ALTIROC2 + HPK 15x15 LGAD

Highlight: the readout ASIC ALTIROC

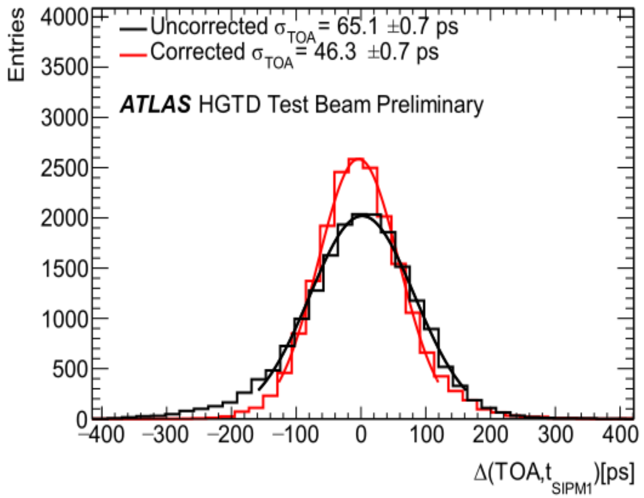
Beamtest results:

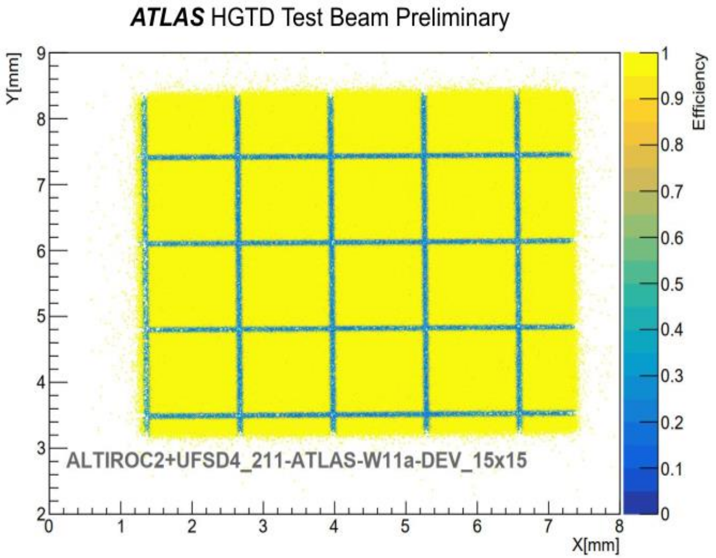
- **ALTIROC1**
  - Confirm the performance of analogue circuits
  - A fit of TOA as a function of TOT is used to calculate for the corrections of time-walk
  - After the correction, the estimated resolution is about 46 ps
  - The estimated jitter contribution is about 39 ps.

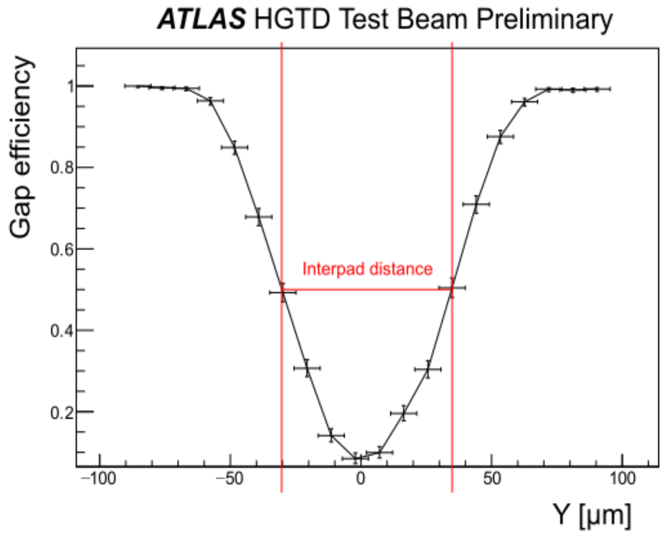
- **ALTIROC2**
- 100% efficiency for each pixel outside gaps

$$\text{Hit Efficiency} = \frac{\text{the reconstructed tracks with a hit seen by ALTIROC}}{\text{all reconstructed tracks that hit module area}}$$

- A gap in the inter sensor pad region is 65.3 +/- 0.2 µm defined at efficiency below 50%







Highlight: module assembly and the PEB

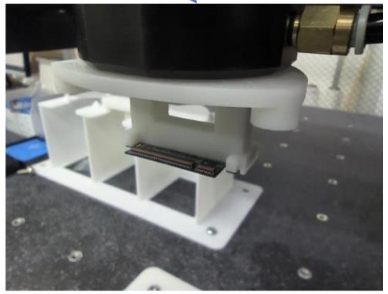
Jigs and pick-and-place machine are being developed

pick-and-place machine

Picking tool

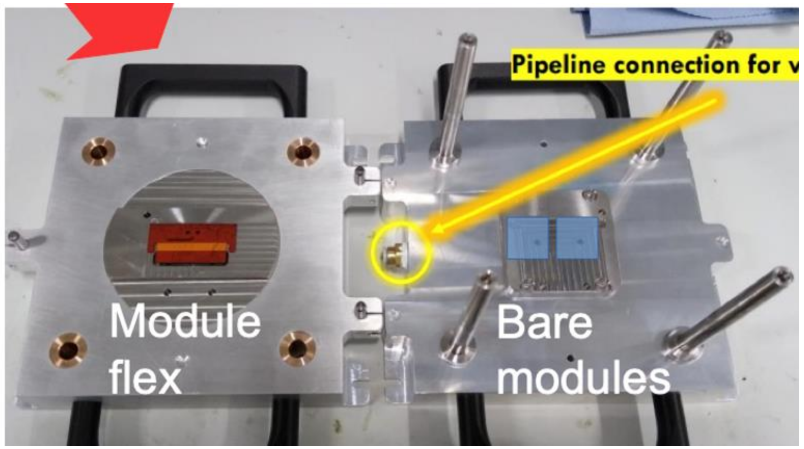
Picking dummy sensor

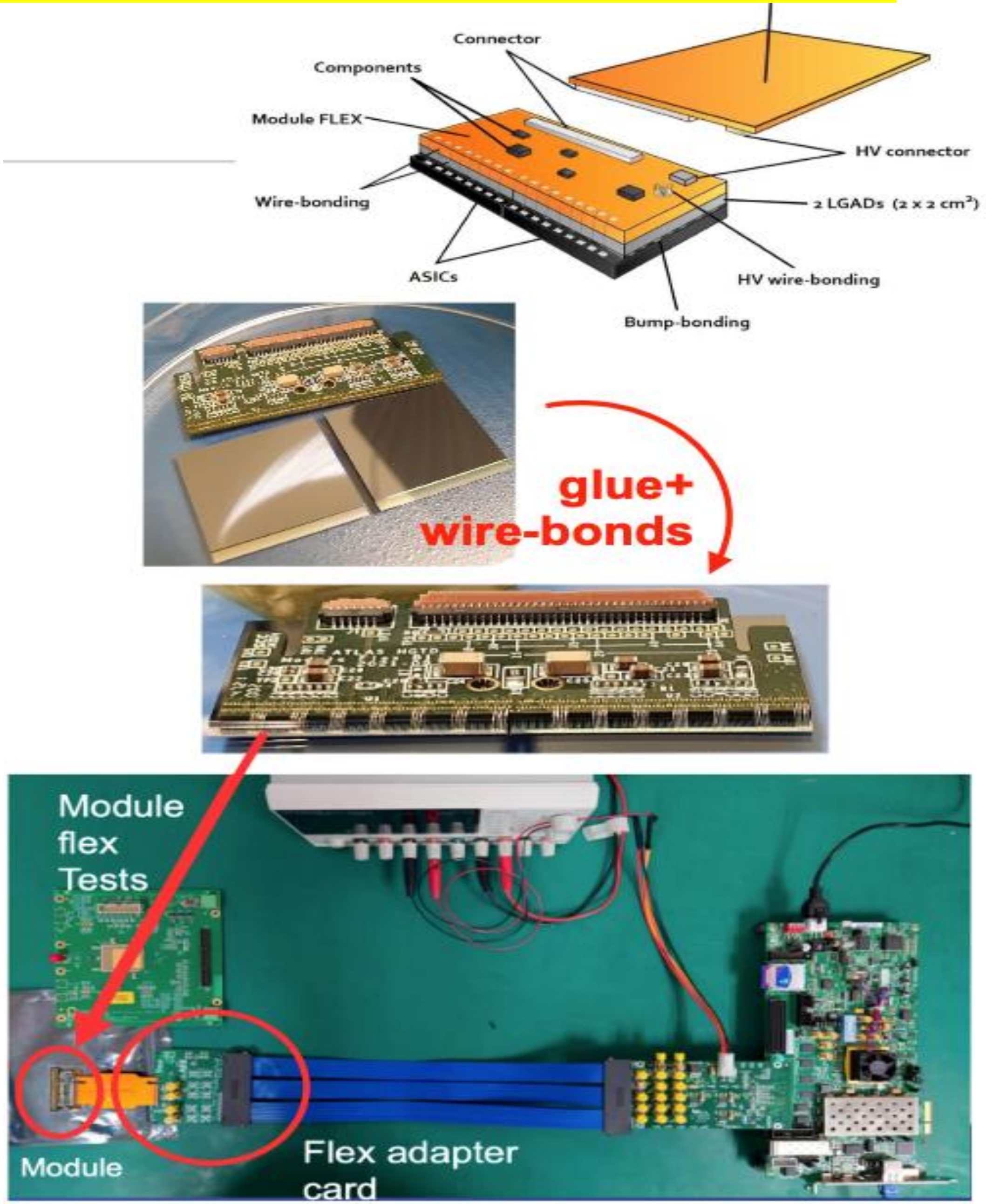
Placing dummy sensor



Picking flex

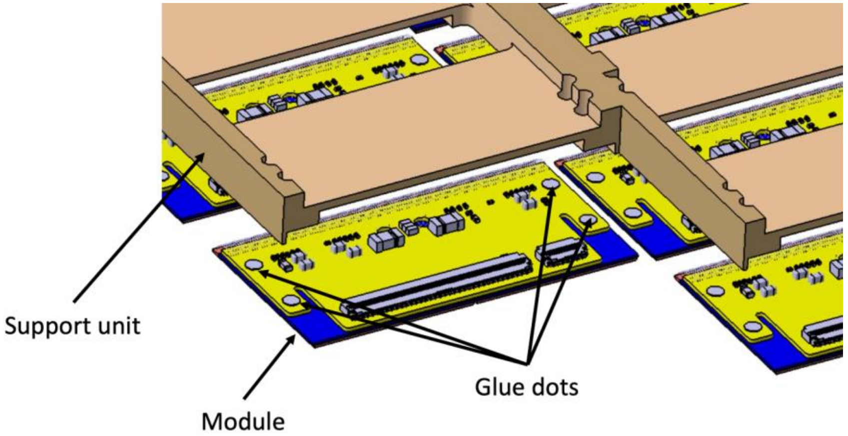
Jigs for module assembly



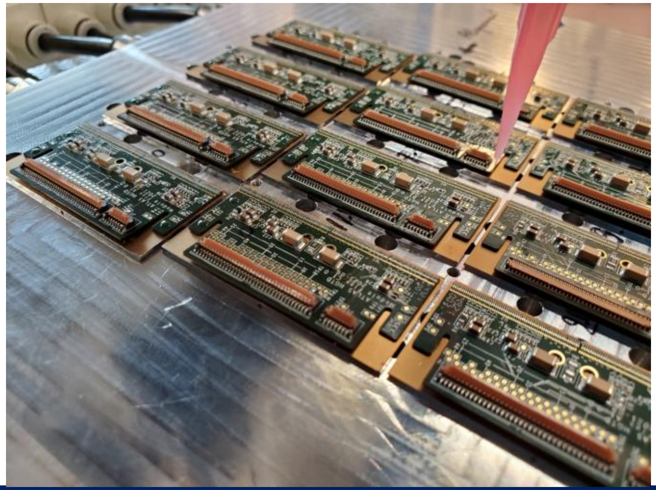


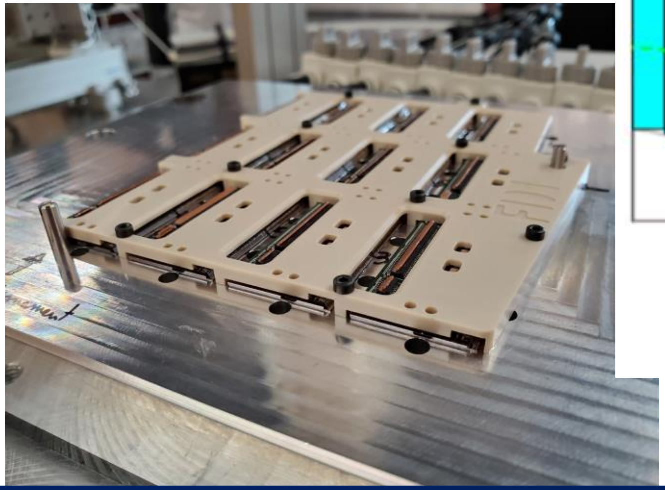
Highlight: module assembly and the PEB

Modules are installed and glued on support units (PEEK), Challenges : machining of PEEK (flatness <200µm)

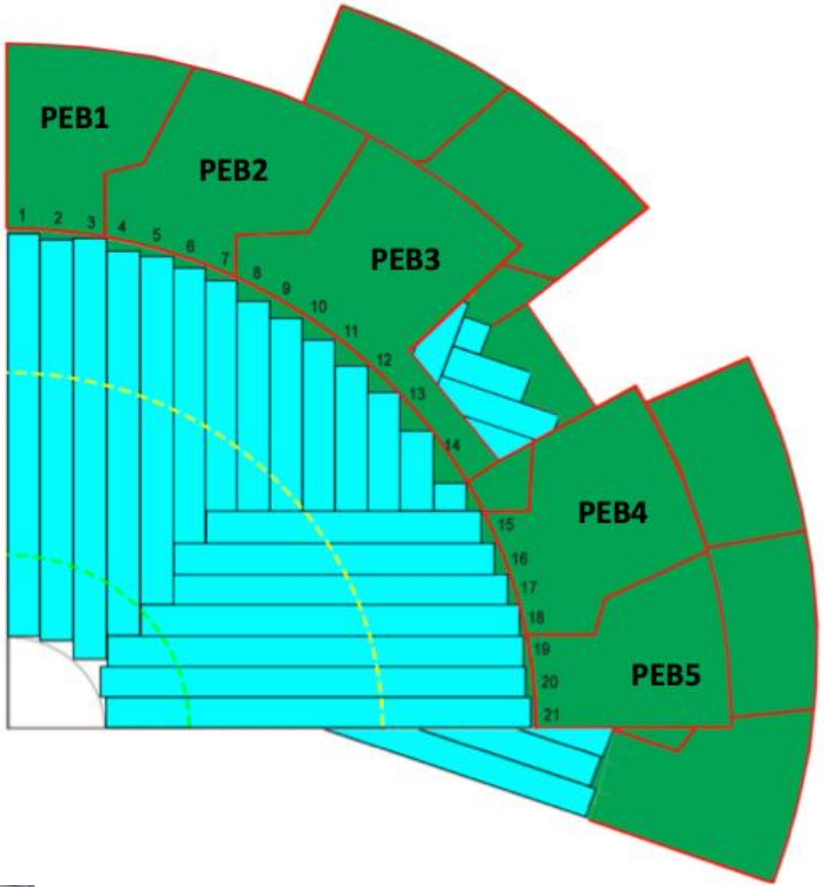


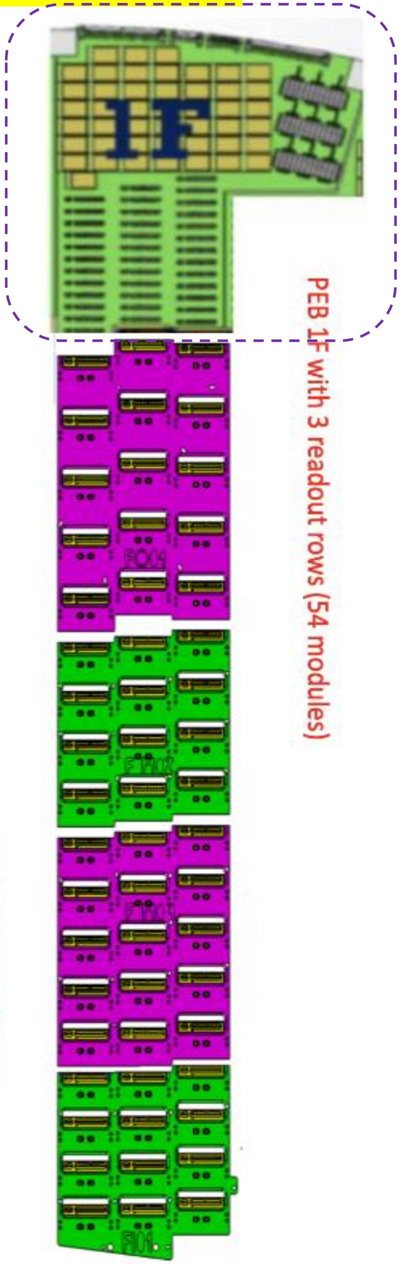
Glue and load the modules on the support units





The peripheral electronics board

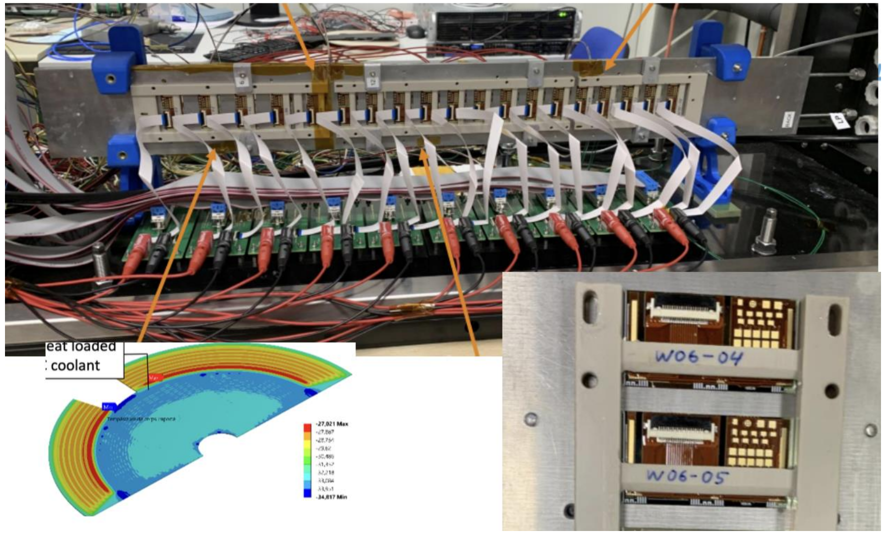




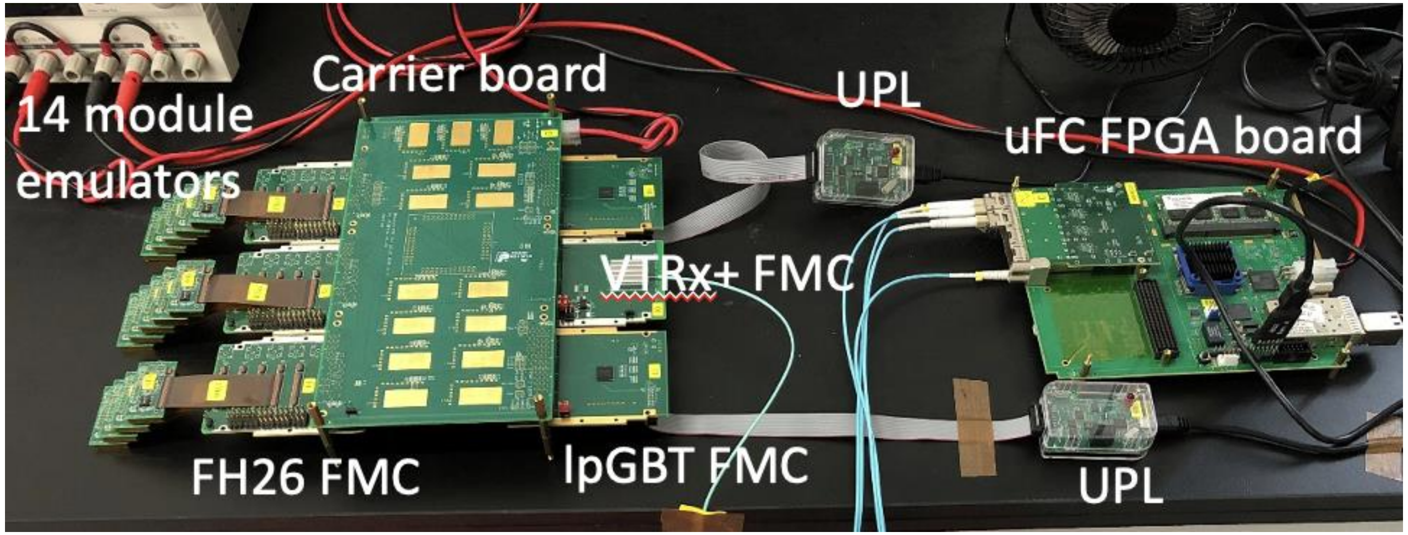
Highlight: module assembly and the PEB

- **The heater demonstrator**
  - 19 silicon heaters mounted on a single stave
  - Representing modules dissipating heat
  - on the cooling plate (CO_2 cooling)
- **The DAQ demonstrator**
  - A minimum system for the full chain readout, from the module emulator boards to the FELIX board
  - Support up to 14 modules with two lpGBTs and one VTRx+
  - Timing
    - Up to 3 modules @ 1.28 Gbps
    - Up to 7 modules @ 640 Mbps
    - Up to 14 modules @ 320 Mbps
  - Luminosity
    - 7 modules @ 640 Mbps

The heater demonstrator



The DAQ demonstrator



The status and summary

- **Good progress in LGAD, meeting the requirements of HGTD**
  - Carbon enriched LGADs meet radiation tolerance requirements
  - Sensor pre-production has started
- **Two rounds of the full-size readout ASICs ALTIROC have been prototyped, so far all circuit blocks are functional, modules with ALTIROC3 are under test**
- **Module assembly is making progress**
- **The Peripheral Electronics Boards are being developed and tested**
- **Two demonstrators are used to check heat removal and the full readout chain**
- **The next milestones:**
  - 2023: Start the PEB and LGAD sensor production, (met)
  - 2024: Start the ALTIROC ASIC, Module and the detector unit production,
  - 2026-2027: the HGTD detector Integration at CERN, and the installation.

The status and summary

Thank You!

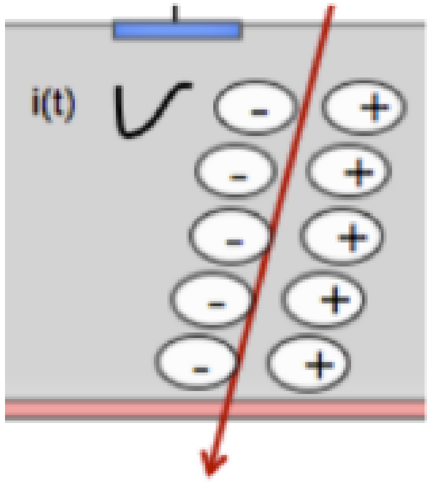
And Questions?

Backup Slides

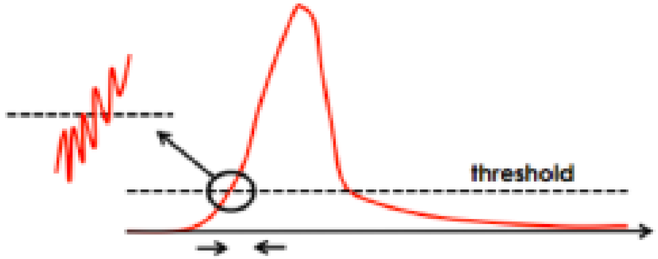
overview of contributions to the time resolution:

$$\sigma^2_{hit} = \sigma^2_{Landau} + \sigma^2_{jitter} + \sigma^2_{time-walk} + \sigma^2_{TDC} + \sigma^2_{clock}$$

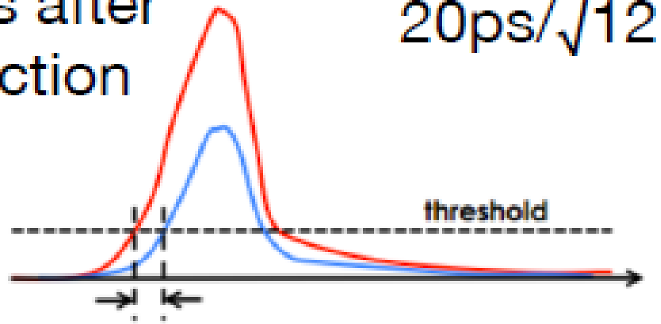
~25 ps
(thin sensor)



<25 ps at
large gain

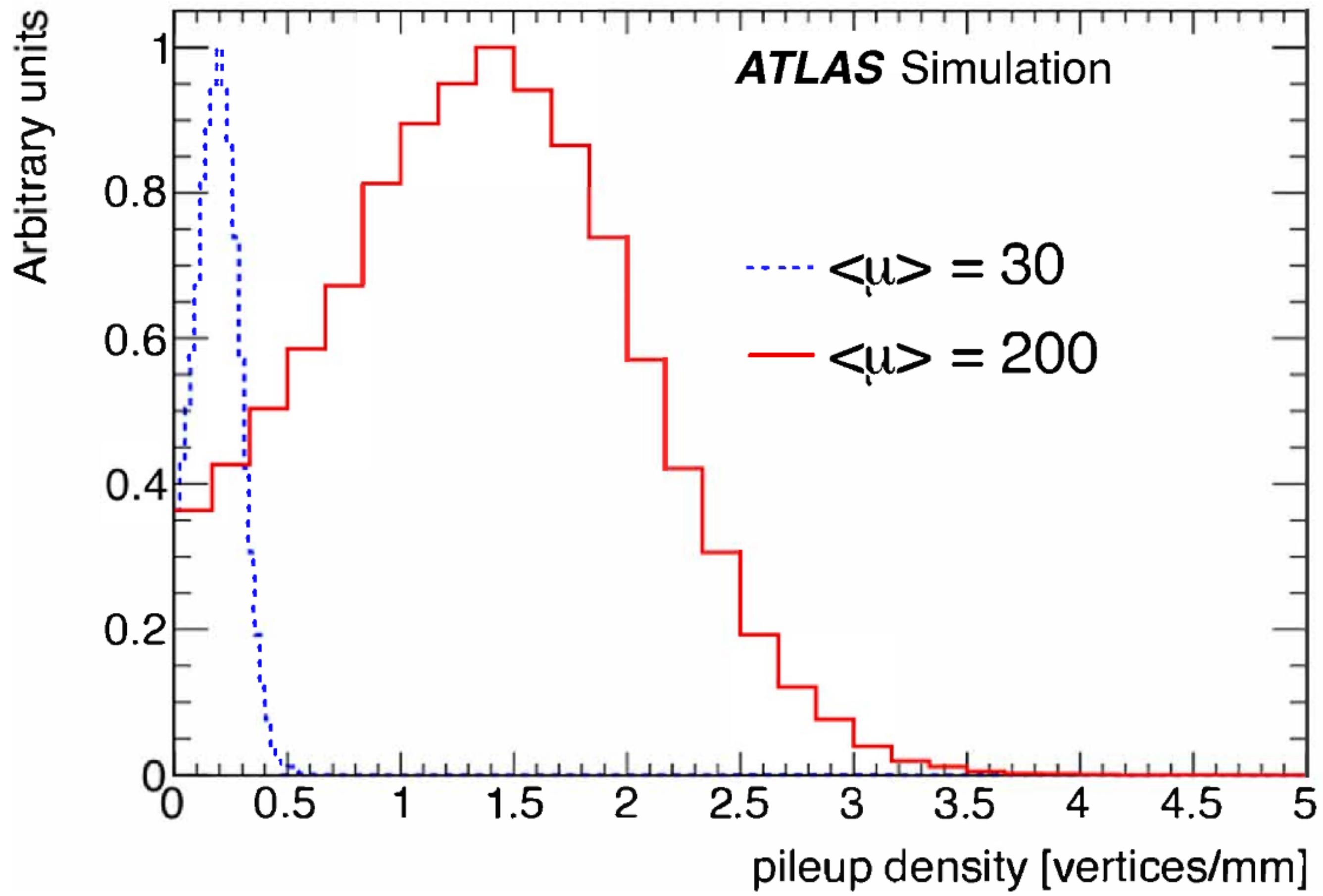


<10 ps after
correction



bin width,
20ps/√12

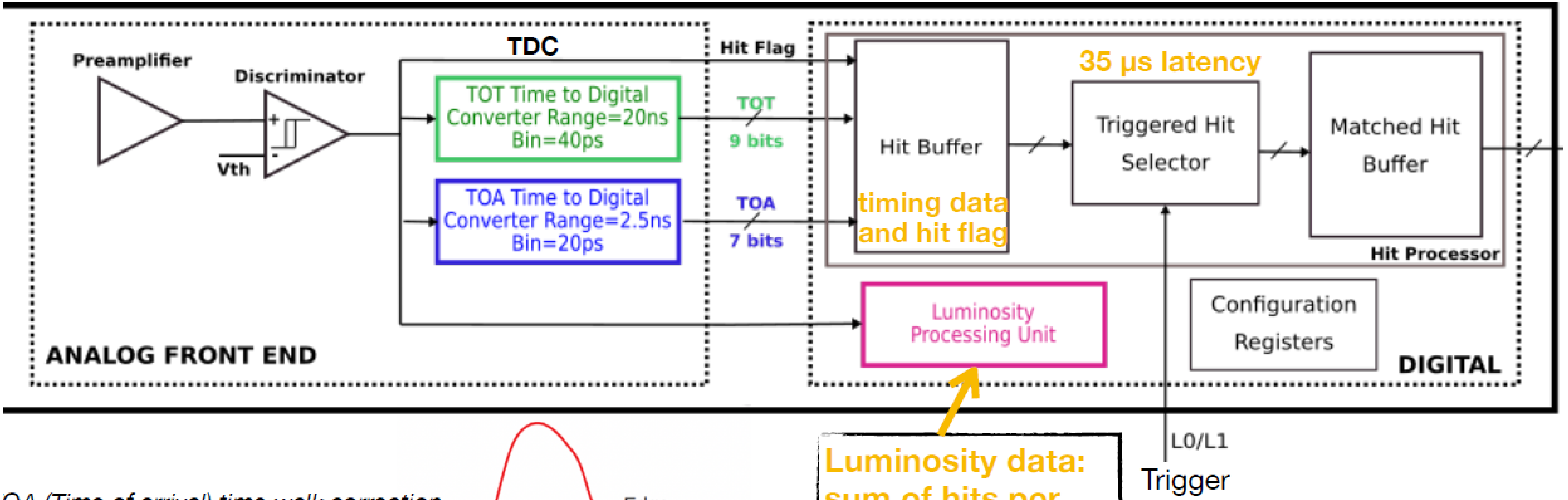
from clock
distribution, <10ps



ATLAS Simulation
<μ> = 30
<μ> = 200
Arbitrary units
pileup density [vertices/mm]
0
0.2
0.4
0.6
0.8
1
0.5
1.5
2
2.5
3
3.5
4
4.5
5

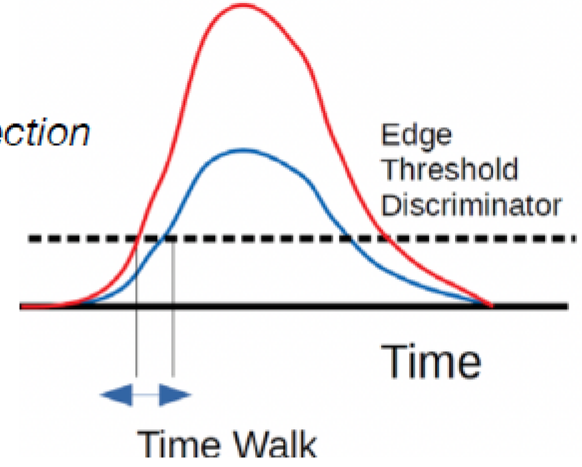
ALTIROC: ASIC architecture

Repeat for 225 channels

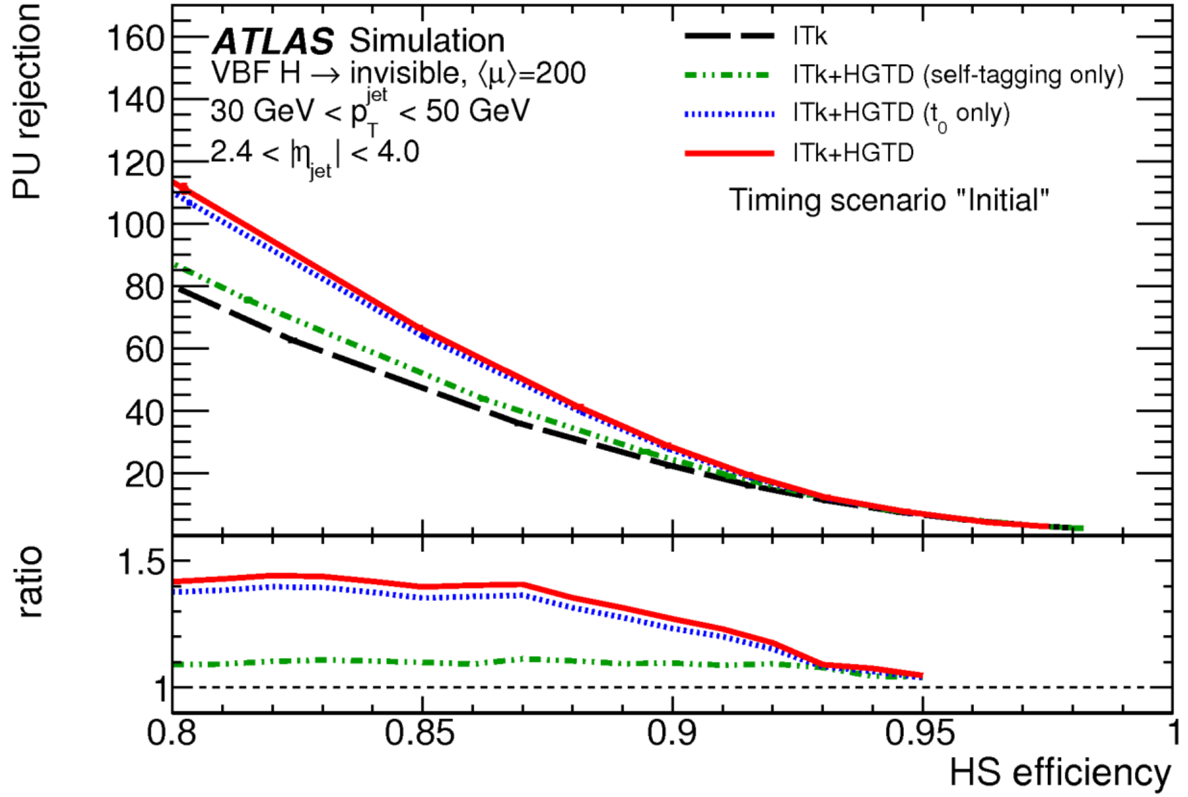


Luminosity data: sum of hits per bunch crossing

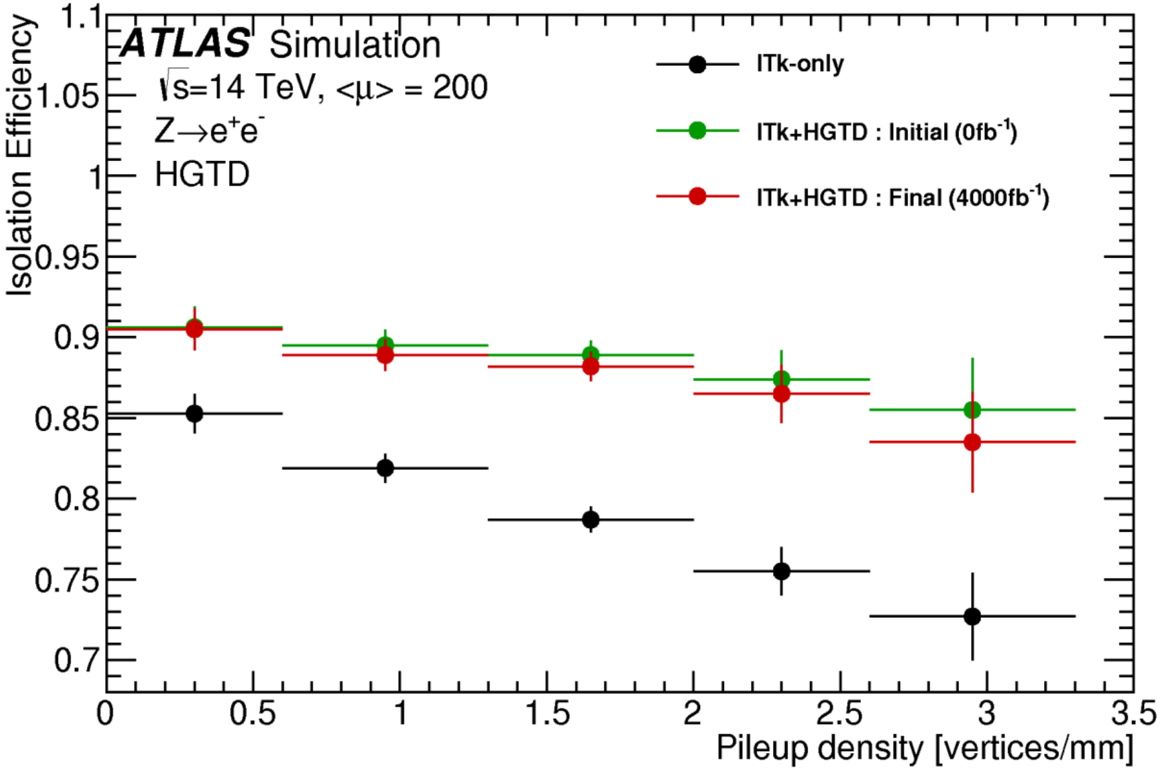
OA (Time of arrival) time walk correction sing TOT (Time Over Threshold)



Physics performance



Suppression of pile-up jets



Efficiency of track isolation requirement for forward e^-

Timing resolution per-hit and per-track