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

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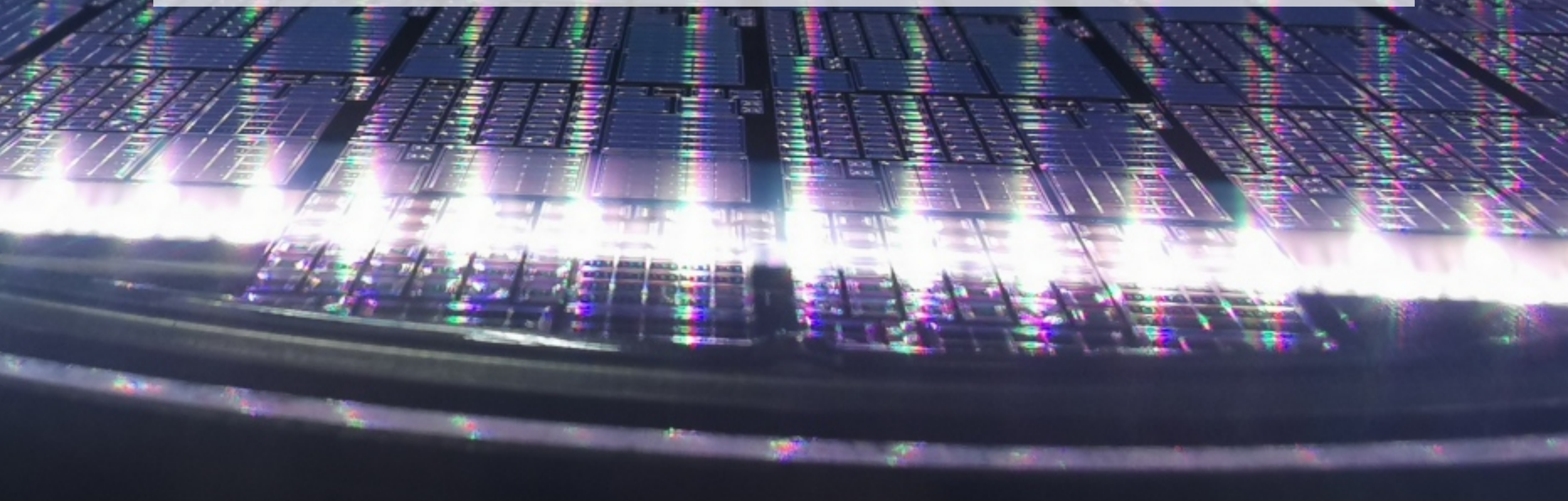
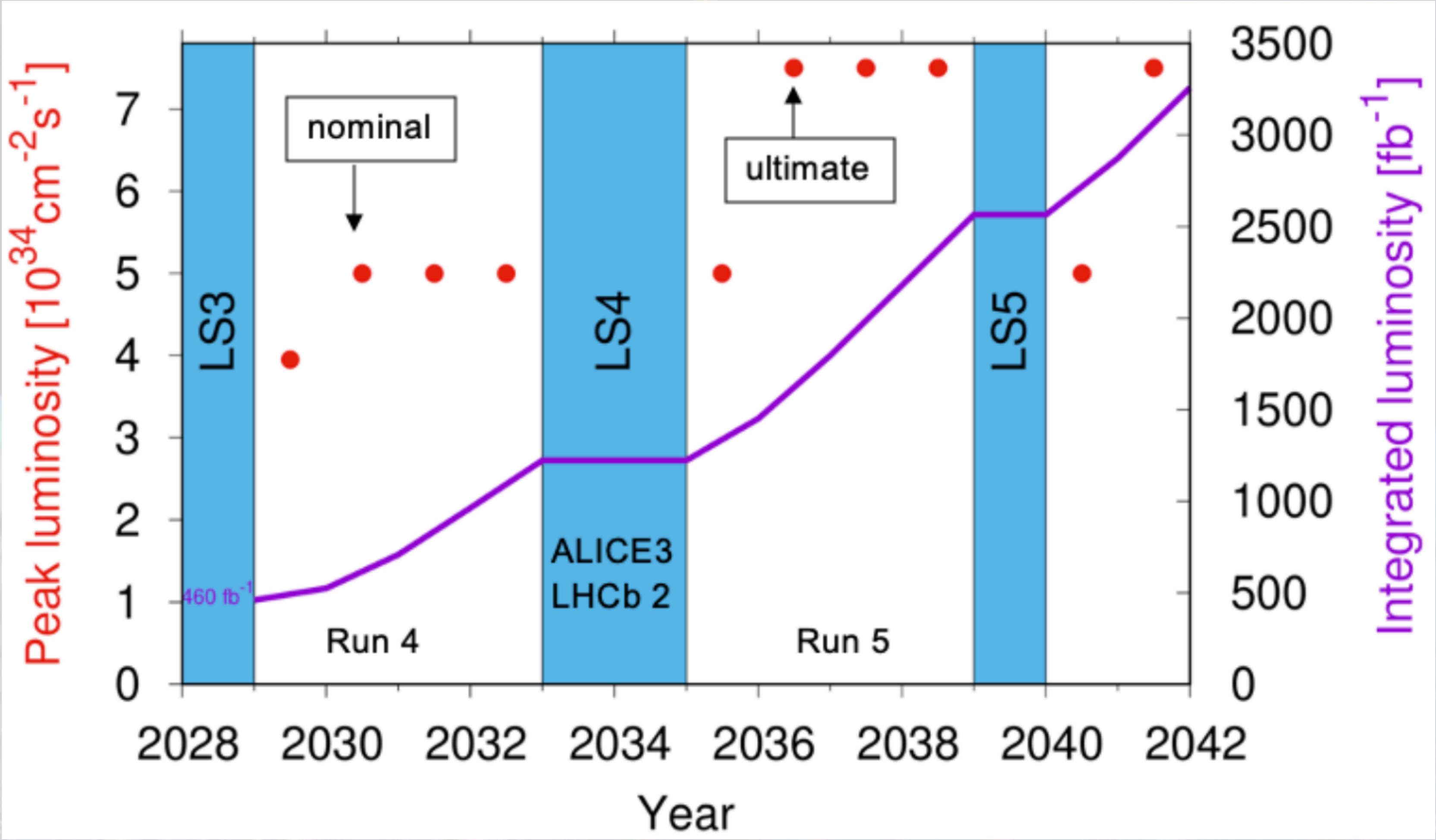
for the ATLAS HGTD Collaboration



The High-Luminosity LHC Phase

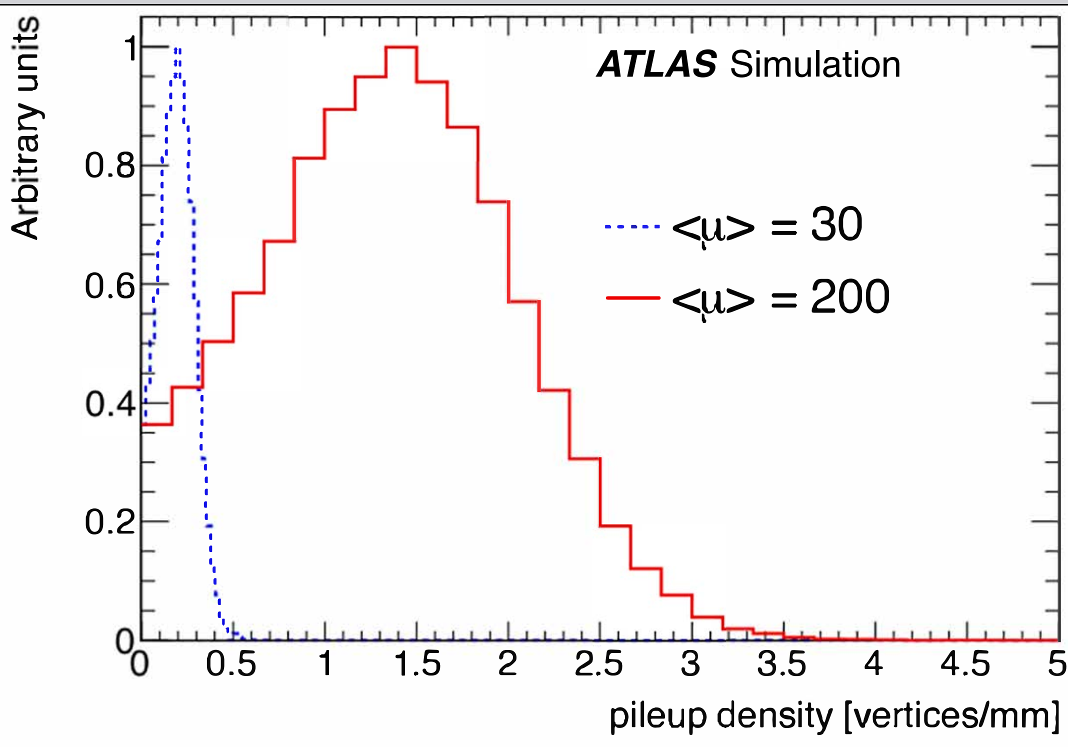


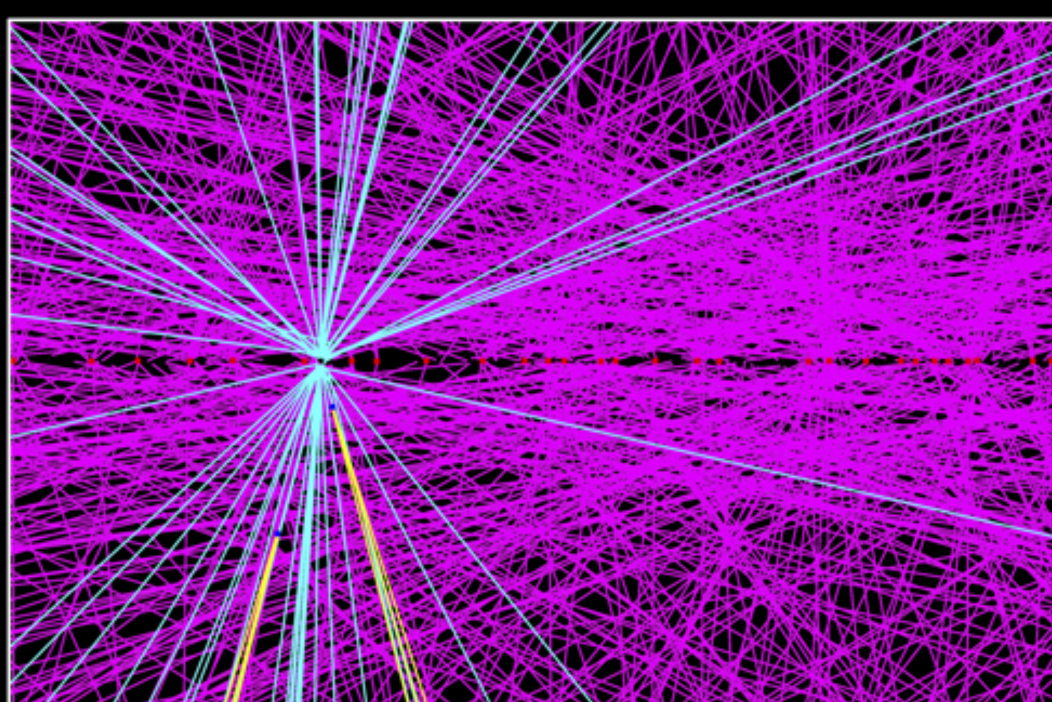
LHC luminosity roadmap

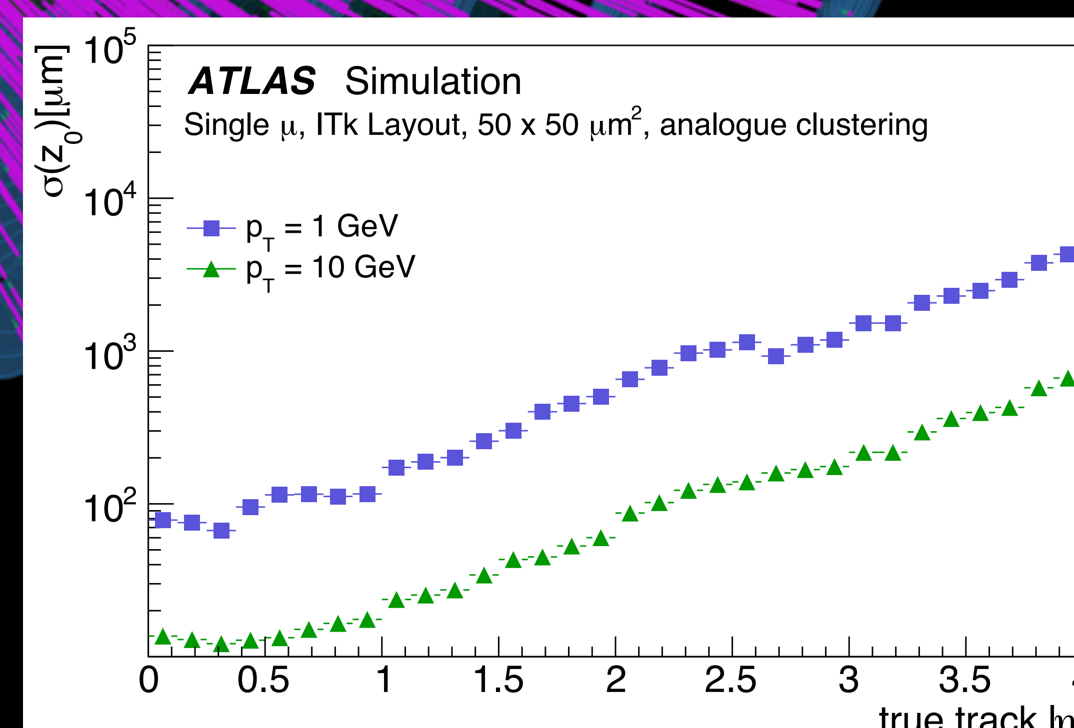
Ultimate luminosity to be delivered by the LHC in Run 5: $7.5 \cdot 10^{34}$ cm^{-2} s^{-1} (total integrated luminosity of up to 4 ab^{-1})

- up to 200 inelastic $p - p$ interactions ("pile-up") on average per bunch crossing ➠ driving motivation for HGTD

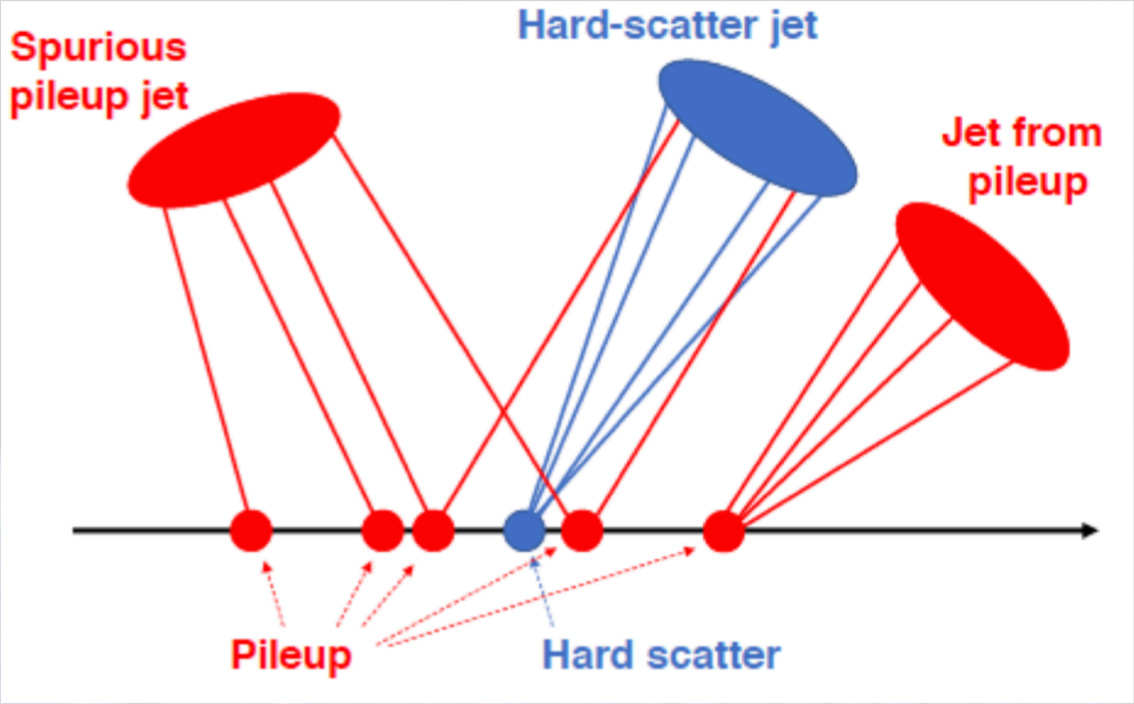
Reconstruction challenges at $\langle \mu \rangle = 200$

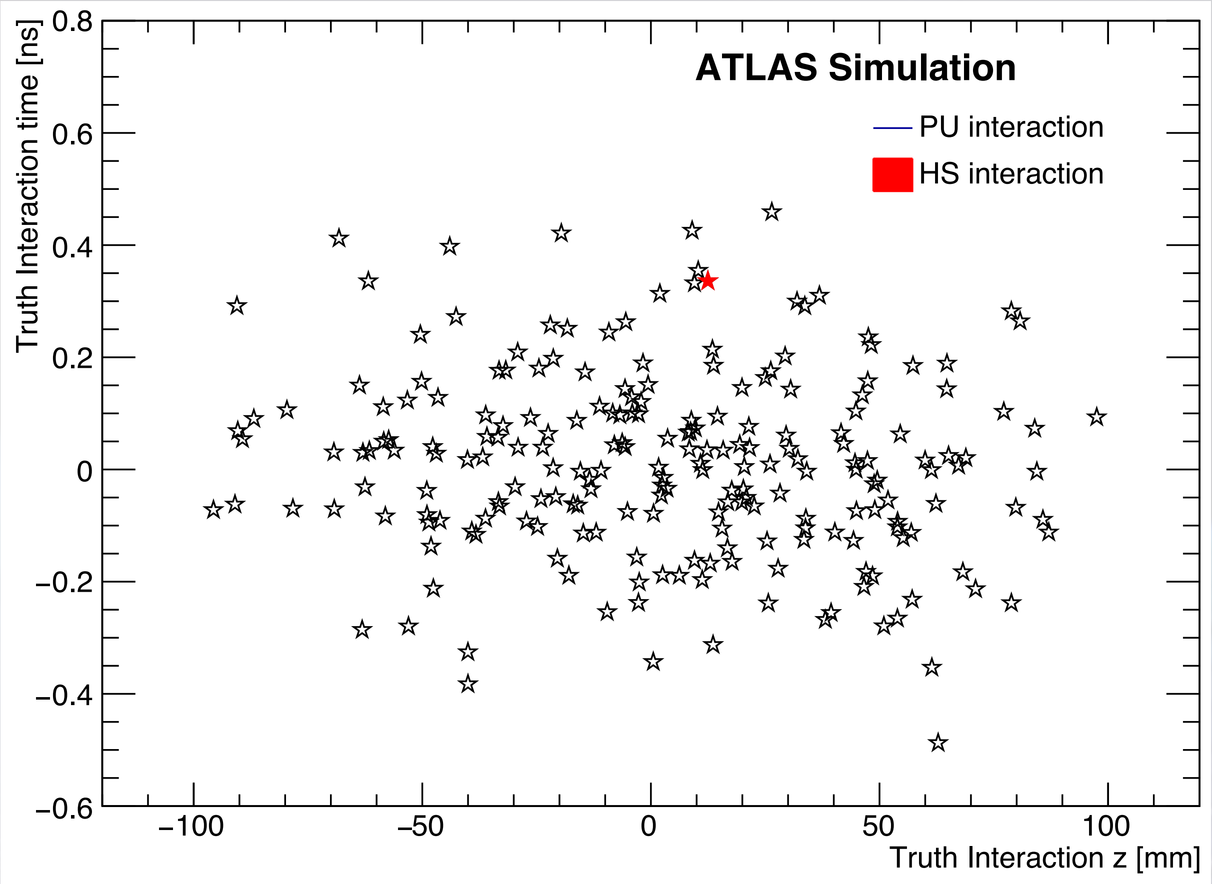






Anatomy of a bunch crossing





Interactions are spread not only in z but also in t (RMS ≈ 175 ps)

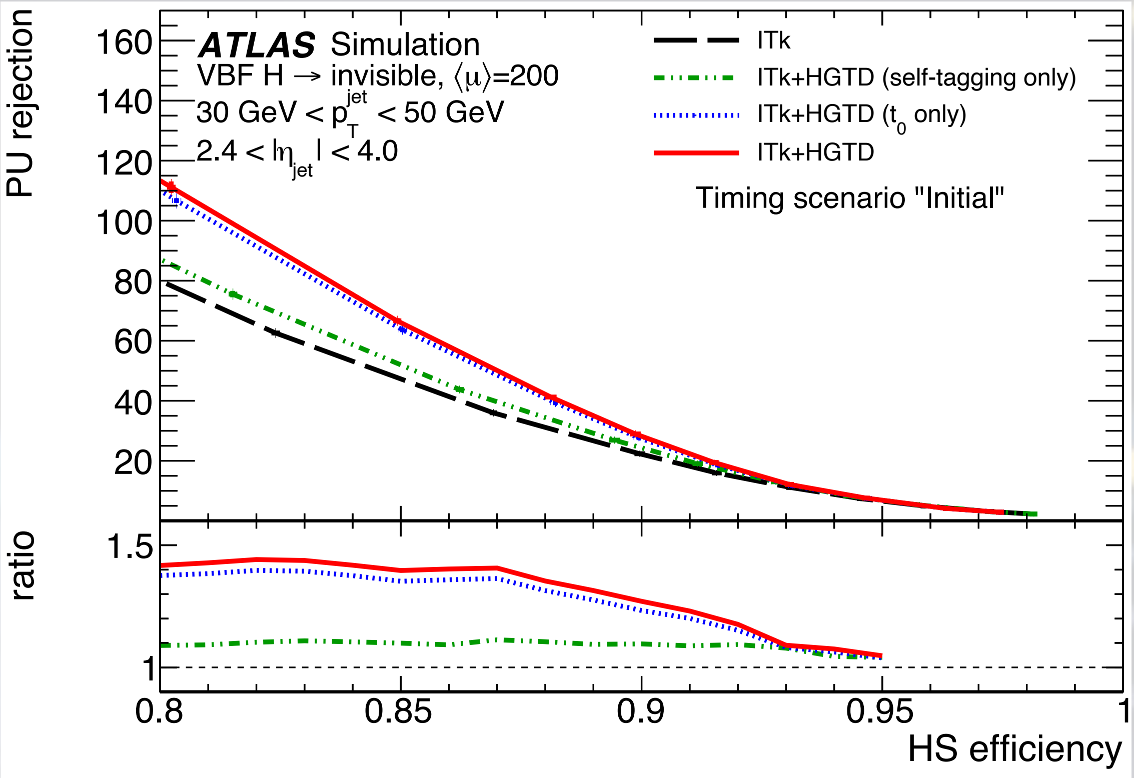
Exploit this by measuring also *time* of charged particles, at least for tracks with high $|\eta|$

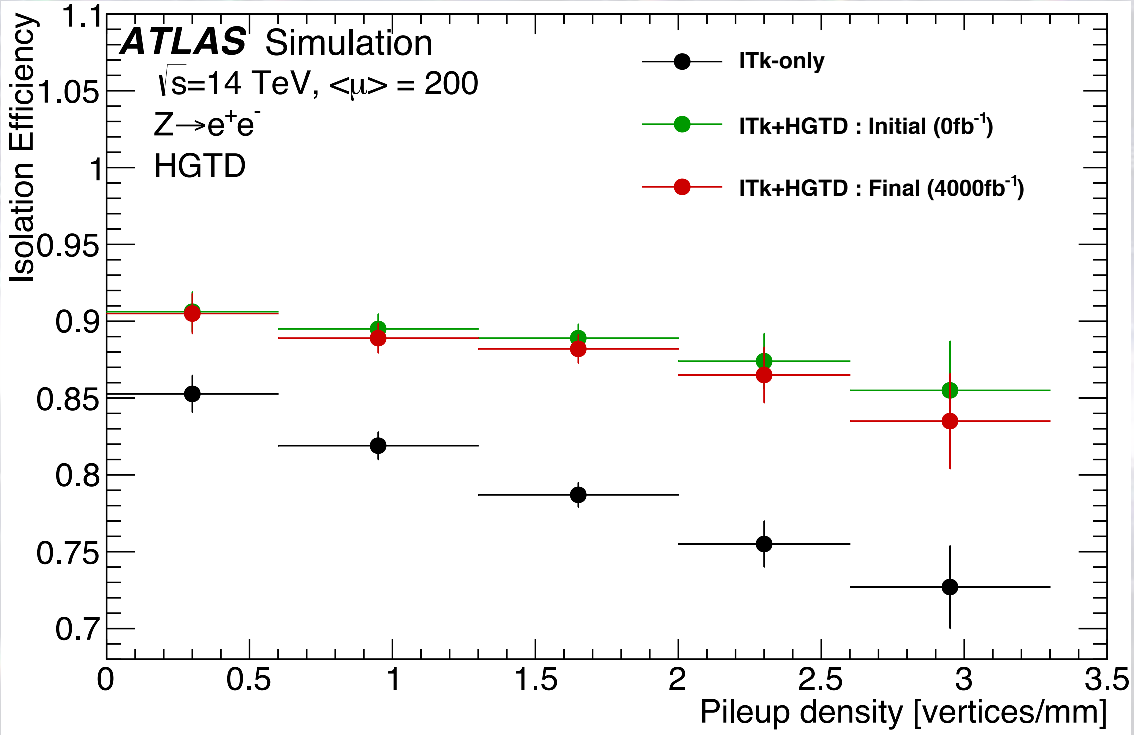
- needs $\sigma_t \ll 175$ ps

Design goal: 30 — 50 ps per track

- this should allow for a factor of ~ 6 in pile-up suppression

Physics performance gain





Suppression of pile-up jets in VBF event topologies

- "self-tagging": consistent time measurement of a jet's tracks
- t_0: use only tracks with times compatible with hard-scatter t_0
  - requires t_0 to be determined ➠ lower efficiency

Efficiency of track isolation requirement for forward e^-

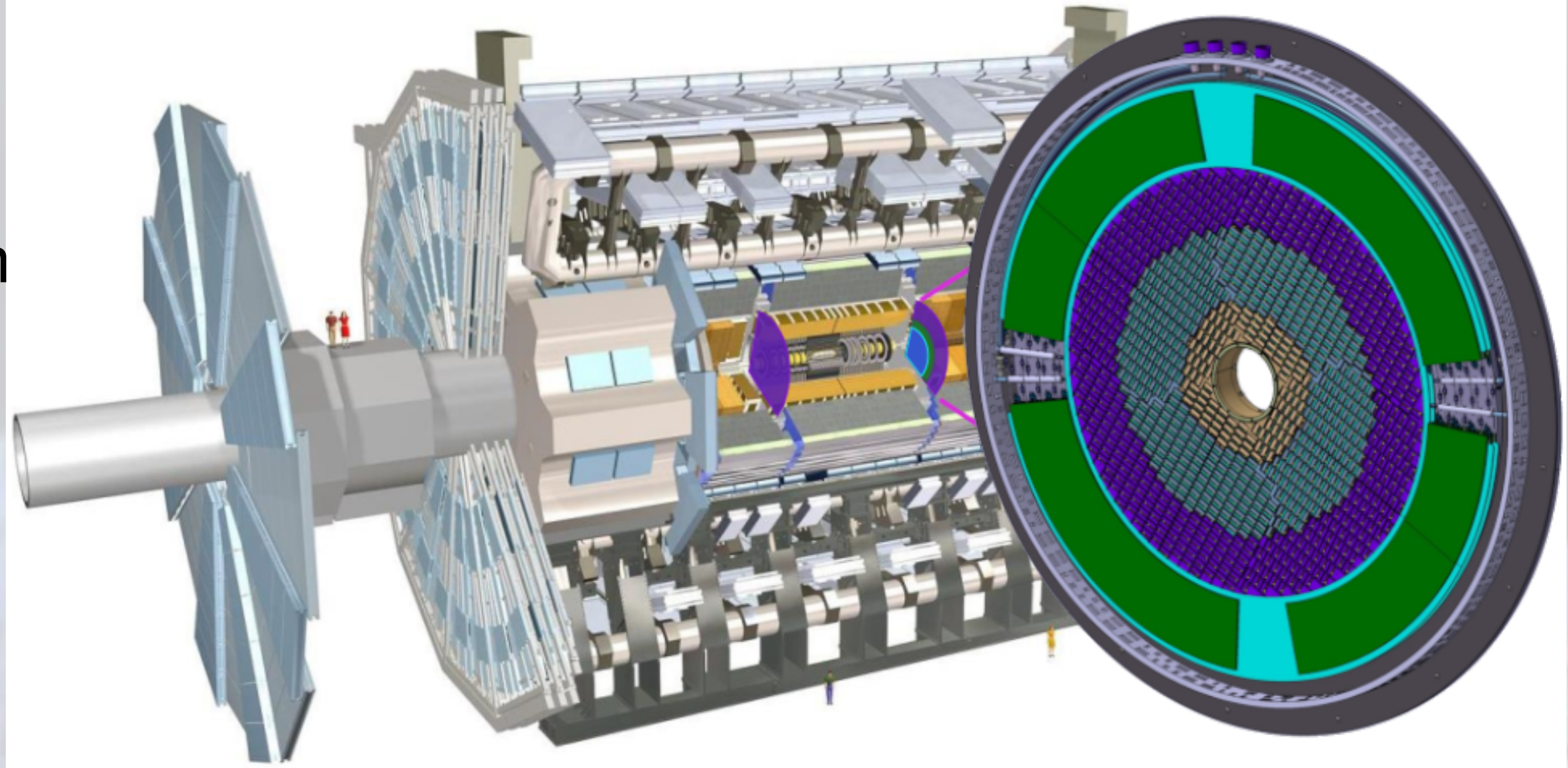
- $\sum_{i \in \Delta R < 0.2} p_{T,i}/p_{T,e} < 0.1$

More detailed performance studies ongoing

The High-Granularity Timing Detector

Coverage: $2.4 < |\eta| < 4$

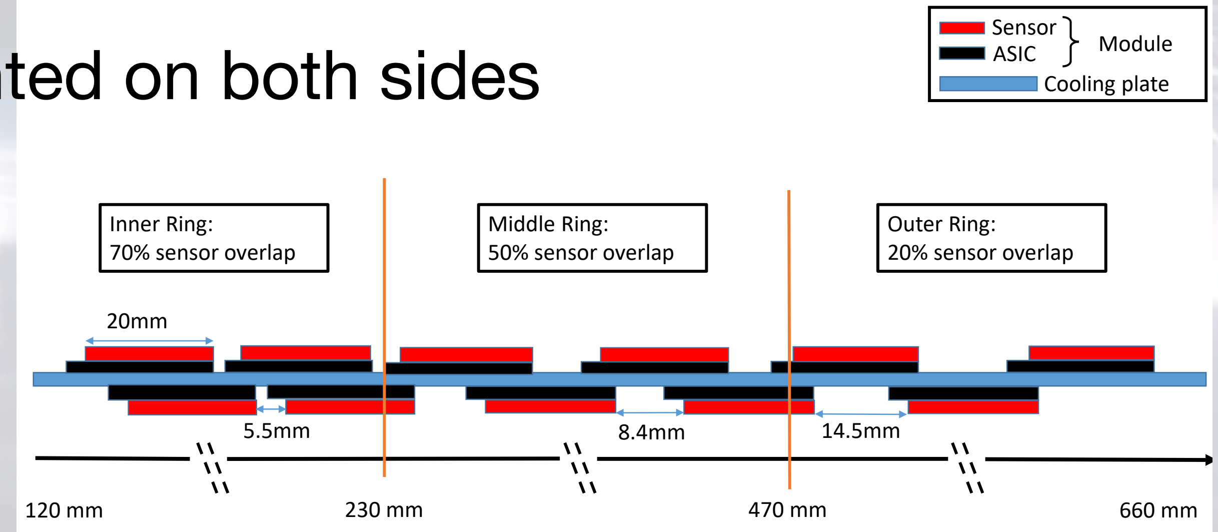
- $|z| = 3.5$ m, $\Delta z = 75$ mm
  - plus moderator (50 mm)
- 120 mm $< r <$ 640 mm



Achieve desired σ_t by up to 4 independent time measurements, each with 35—70 ps resolution

Technology: LGADs (15 × 15 pads of size 1.3 × 1.3 mm^2, 50 μm thick)

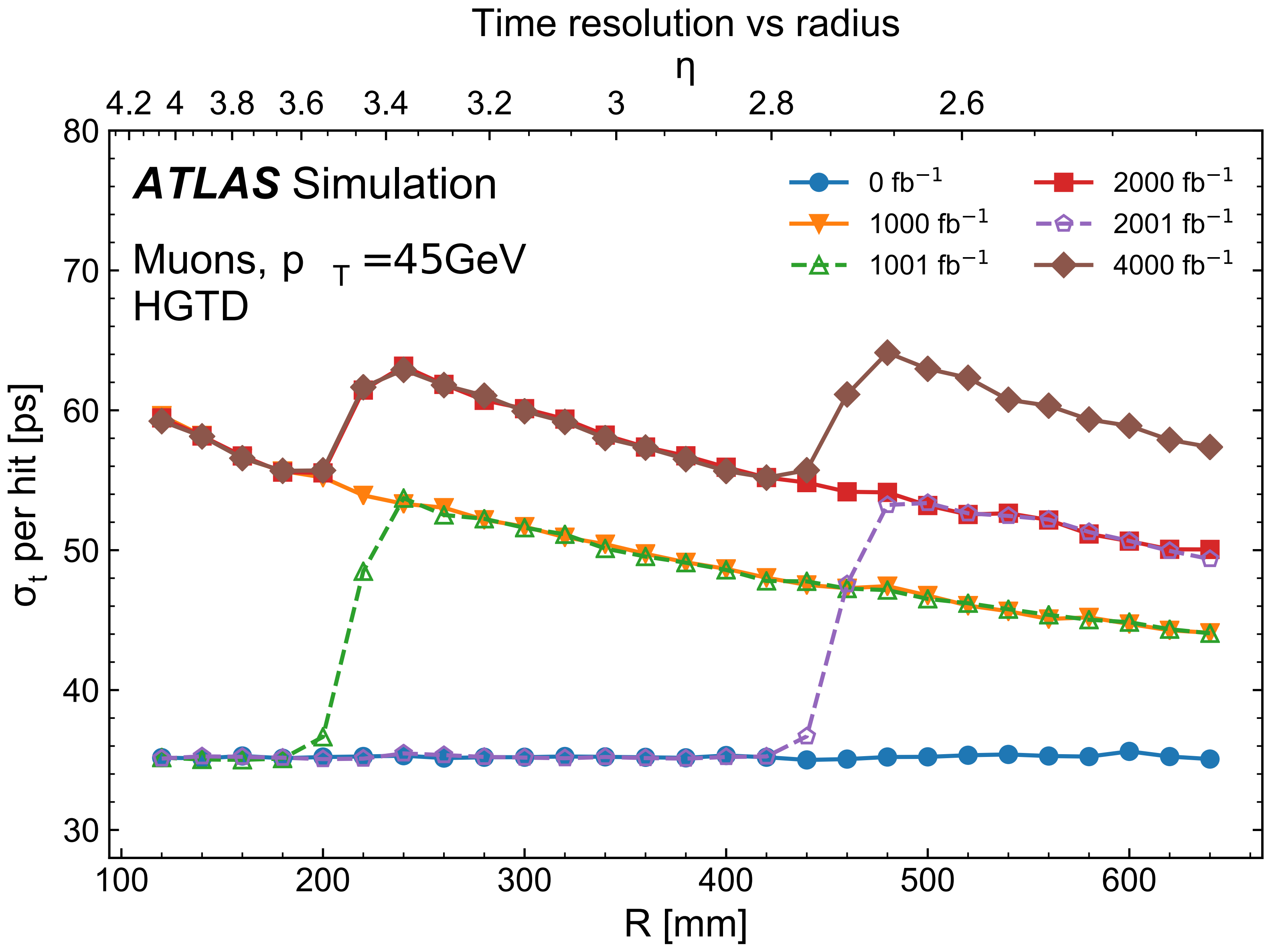
- arranged on 2 disks each instrumented on both sides
- 3.6 M channels; occupancy < 10%
- radiation tolerance: $2.5 \cdot 10^{15}\, n_{\text{eq}}$ cm^{-2}, 2 MGy
  - operation @ -30 ˚C
  - arrangement in 3 rings; expect to replace innermost rings



Time resolution versus radius

Replacement plan:

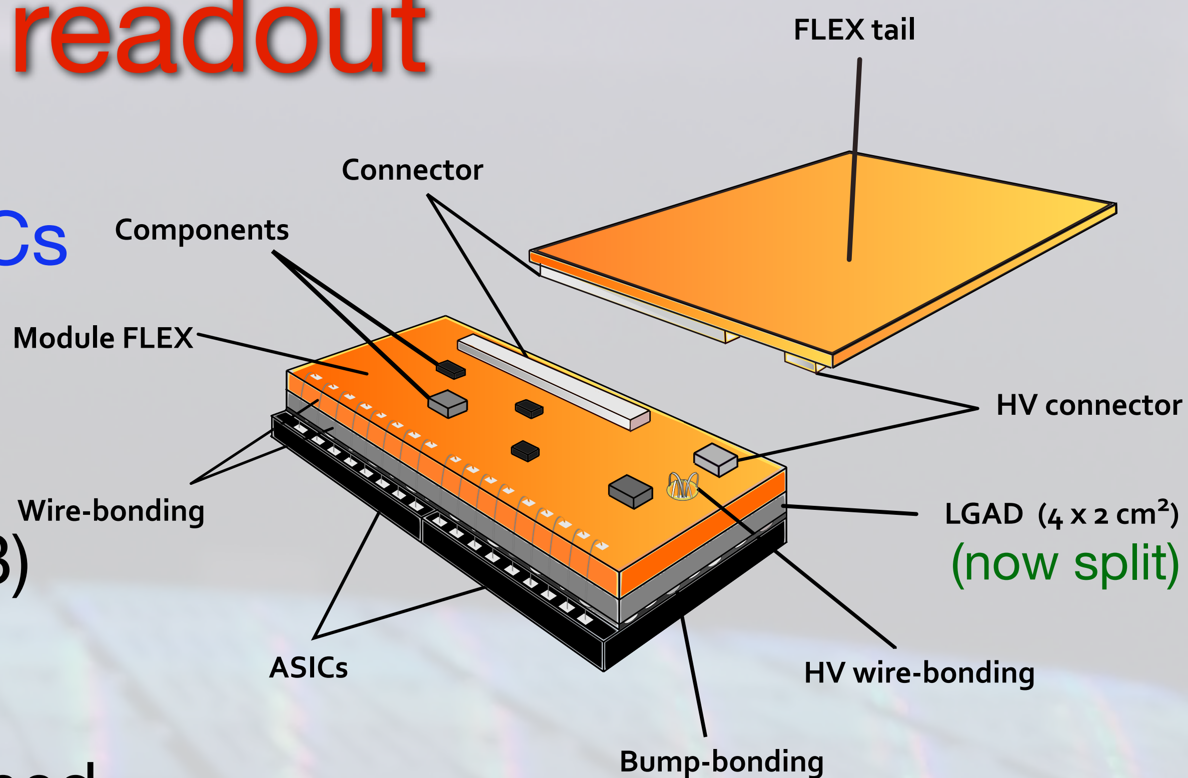
- innermost ring replaced after 1 ab^{-1}, 2 ab^{-1}
  - anticipate technology improvement
- middle ring replaced after 2 ab^{-1}



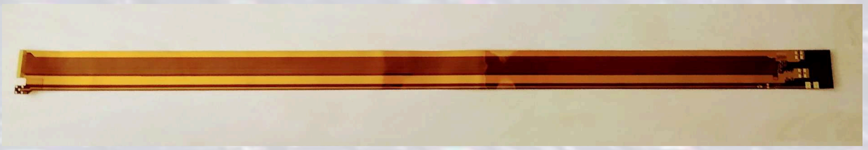
Modules and readout

Sensors bump-bonded to ALTIROC ASICs

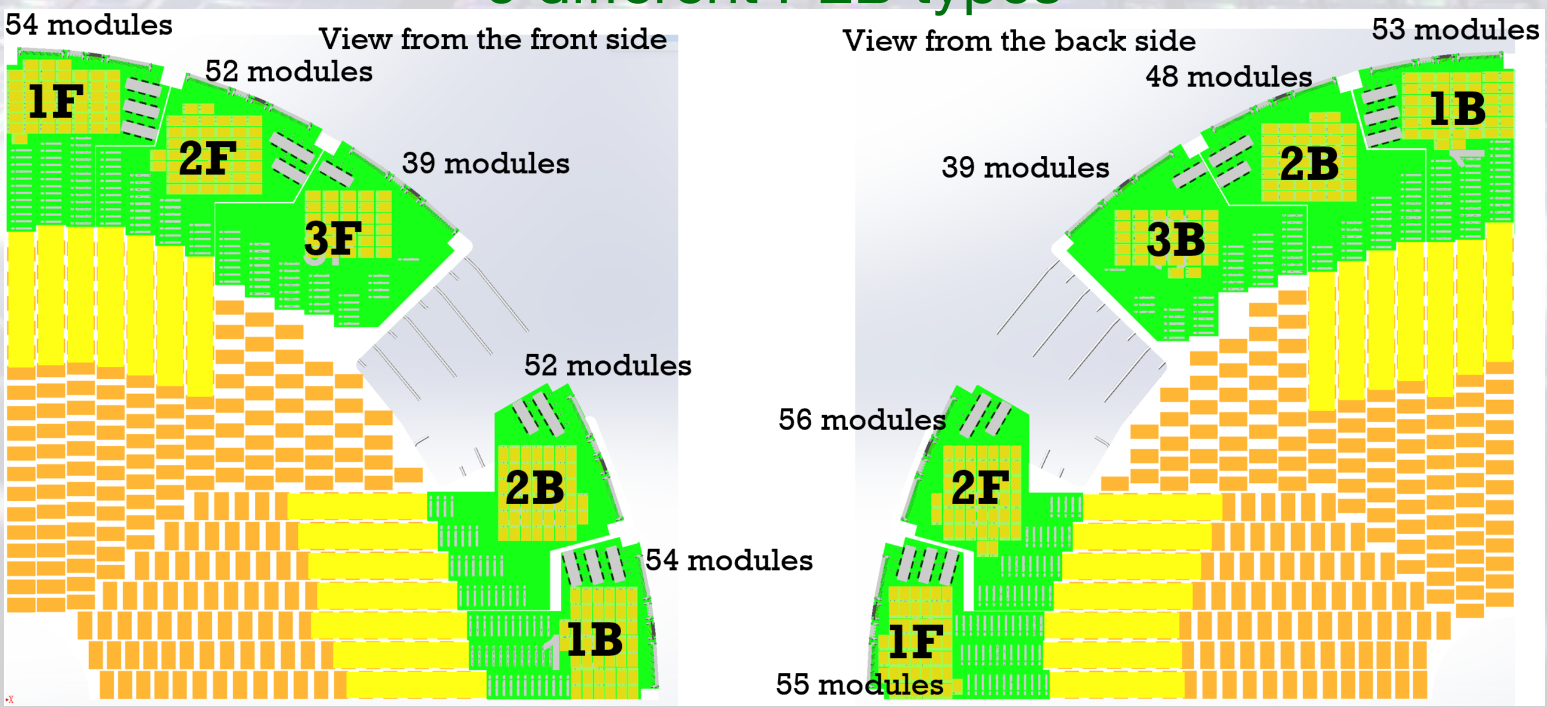
- 8032 modules: 2 sensors + 2 asics + flex
- flex tails carrying HV, LV and signals to/from peripheral electronics boards (PEB)
  - HV set individually for each module
- Sensor temperature (-30 ˚C) to be maintained by evaporative CO_2 cooling manifold in disks



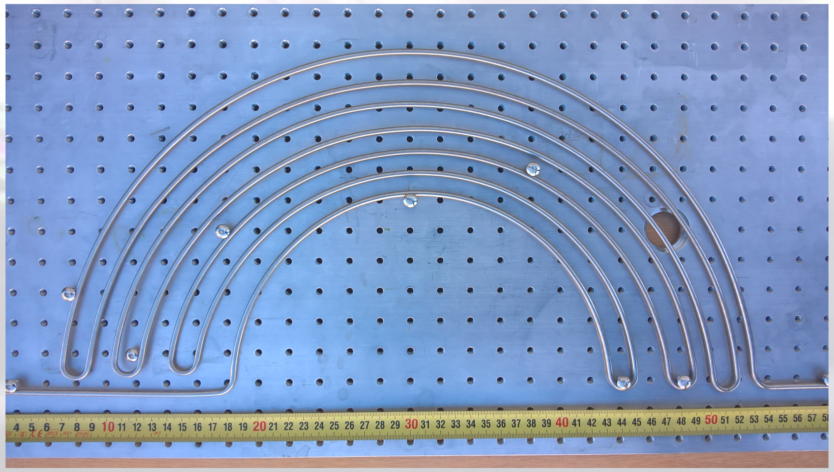
prototyping flex tails



6 different PEB types



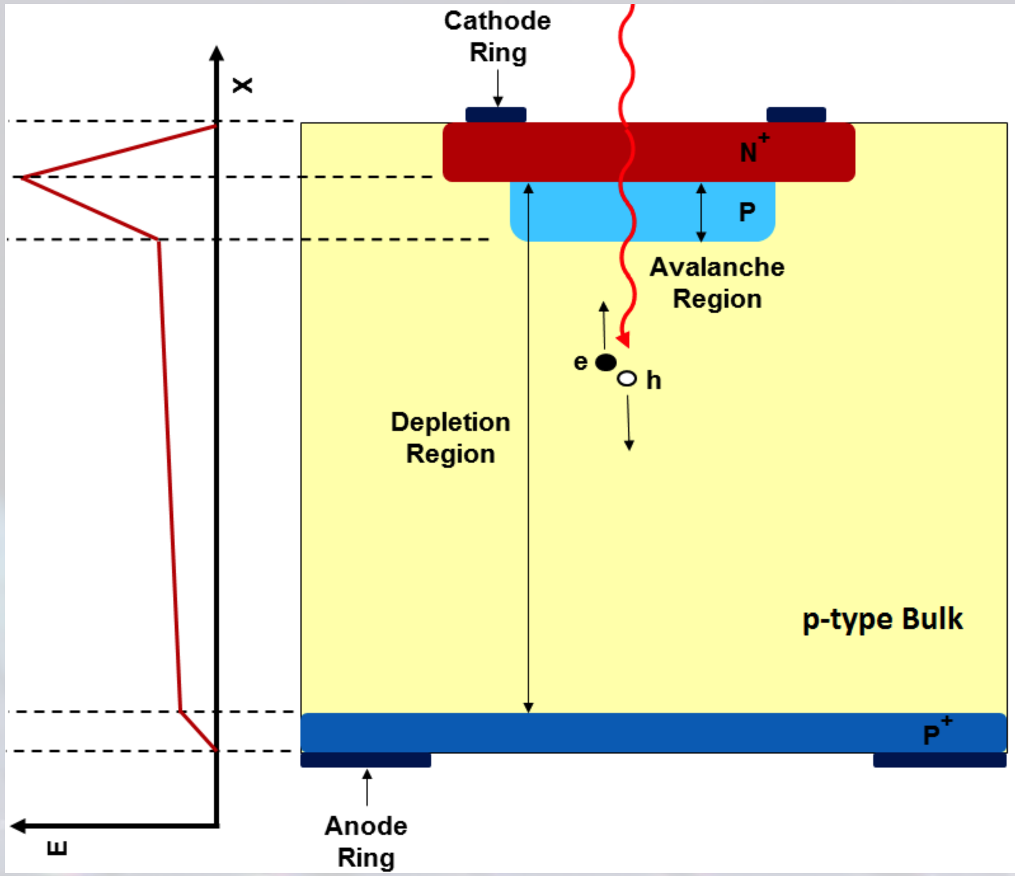
prototyping cooling serpentine



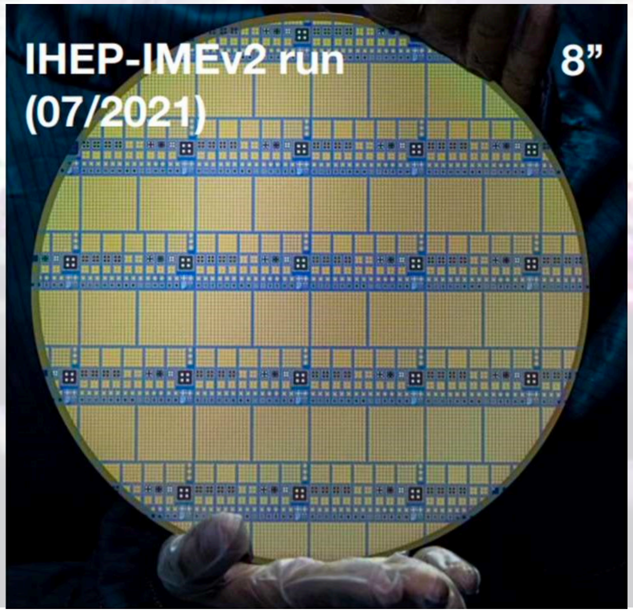
Sensors

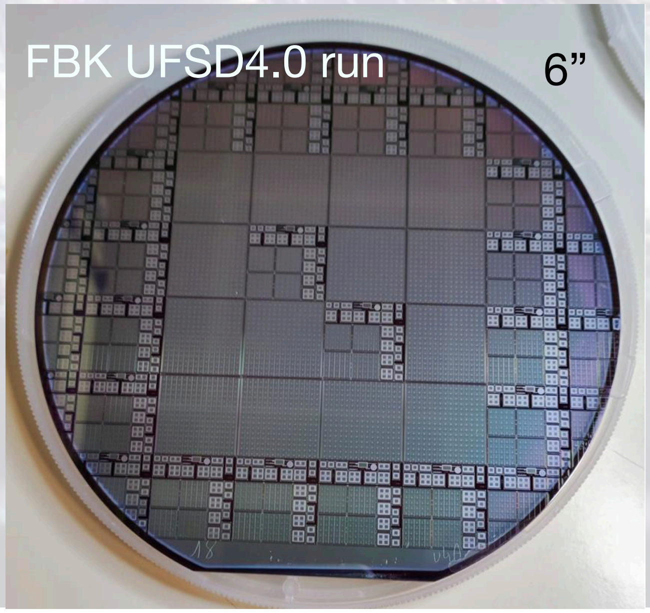
Low-gain avalanche detectors (LGADs):

- $\sigma^2 = \sigma_{\text{tw}}^2 + \sigma_{\text{j}}^2 + \sigma_{\text{TDC}}^2$
- pad size (1.3 × 1.3 mm^2) and thickness (50 μm) compromises between rise time, capacitance, fill factor, …
- requirement: 10 fC (× 20 gain) before, 4 fC (× 8 gain) after irradiation

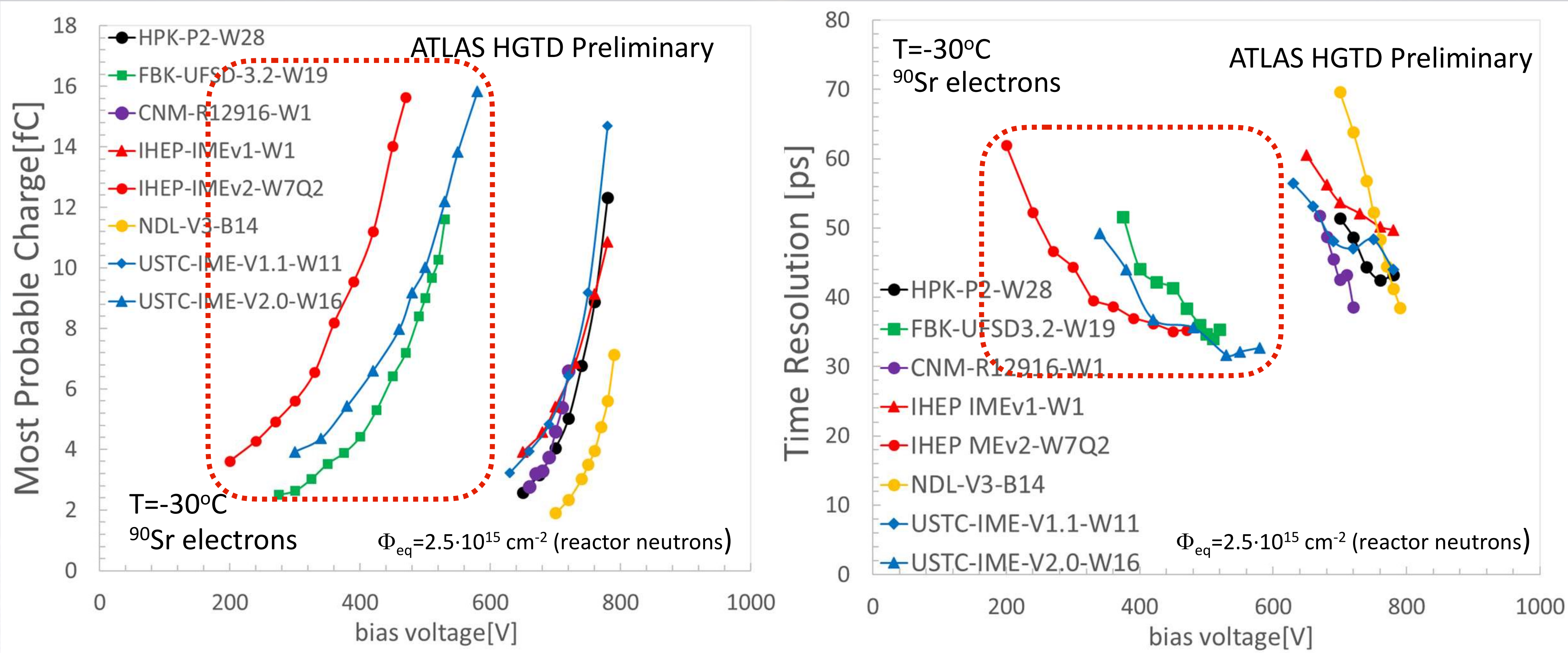


15×15 sensors now available from HPK (Japan), IME (China), FBK (Italy), NDL (China); CNM (Spain) expected soon





Sensor testing



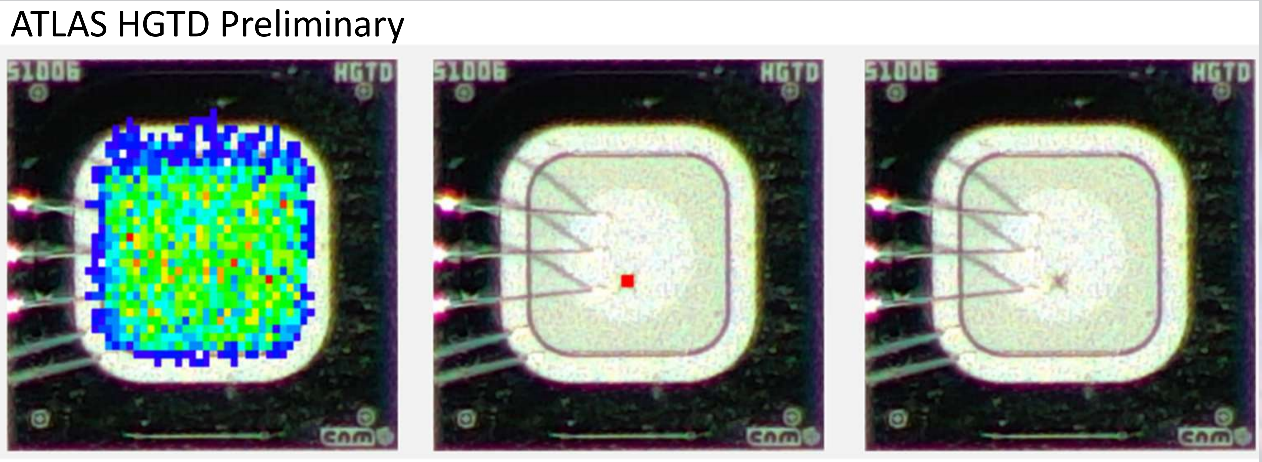
Laboratory tests using ^{90}Sr e^-: carbon-enriched gain layers allow to satisfy requirements after irradiation at much lower bias voltages than non-enriched gain layers

Single-Event Burnout

Sensor mortality observed in test-beam campaigns (*not* in laboratory measurements):

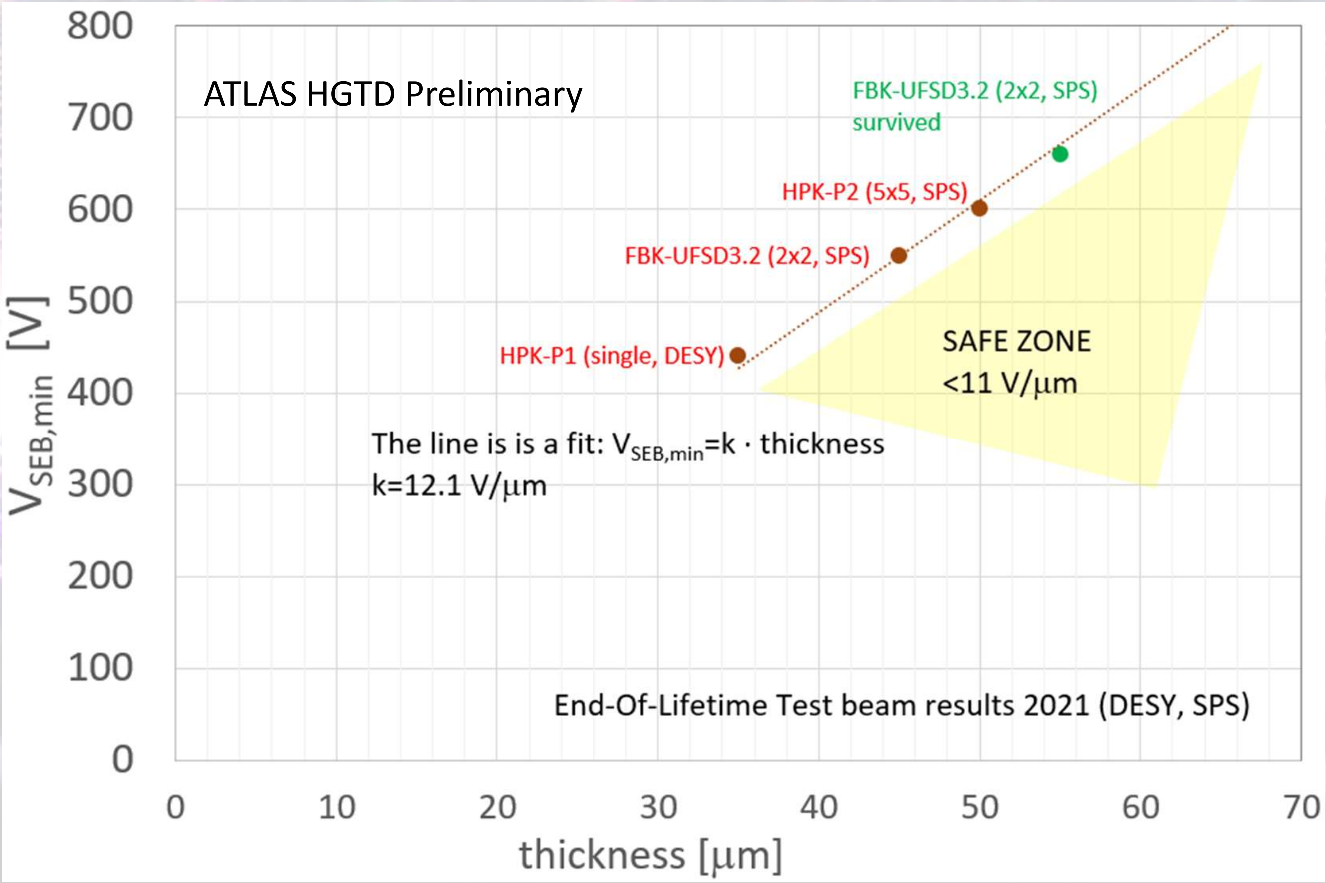
- associated with anomalously high energy deposits (Landau fluctuations) by *single* tracks

(2019 DESY TB: 5 GeV e^-)



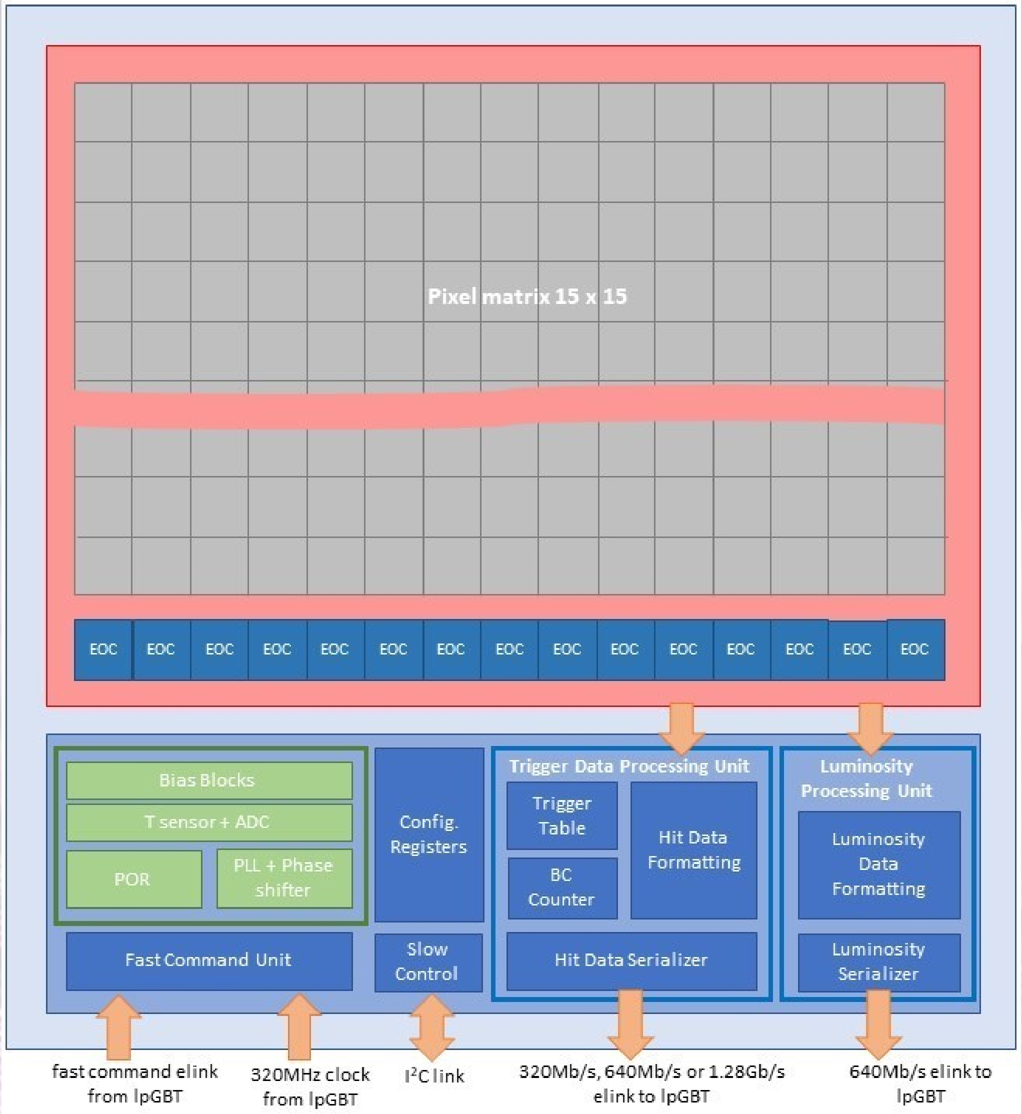
From subsequent tests ("mortality test-beam"):

- ~ 80 sensors
- identified "safe zone" as having average electric field < 11 V/μm
  - also aided by carbon enrichment



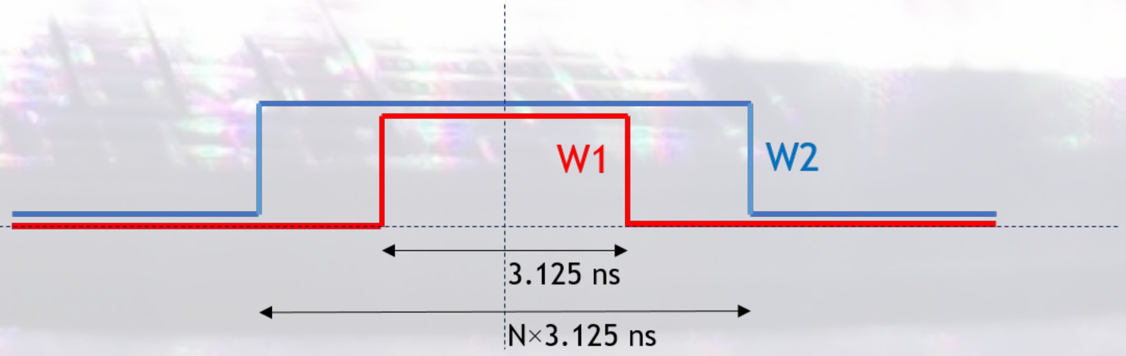
ATLAS LGAD Timing Integrated ReadOut Chip

ALTIROC asic (TSMC 130 nm CMOS):



- time-of-arrival (TOA) + time-over-threshold (TOT) data per channel, transmitted upon L1 trigger
  - Vernier delay line TOA TDC
  - TOT for time-walk correction
  - requirement for jitter to σ_t: < 25 ps
  - integrated temperature measurement with $\sigma_T = 0.2$ K + calibration between fills to maintain resolution @ system level
  - < 300 mW cm^{-2} (+ sensor: < 100 mW cm^{-2}) to satisfy cooling power budget (20 kW/side)

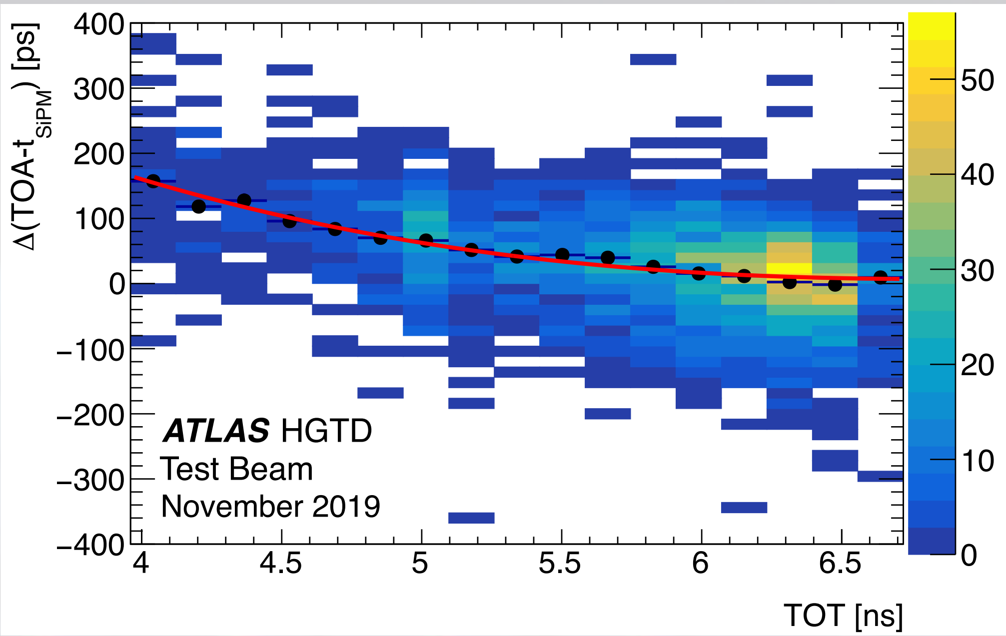
- per-sensor hit multiplicity @40 MHz, for luminosity counting (only used in outer ring)
  - separate readout path

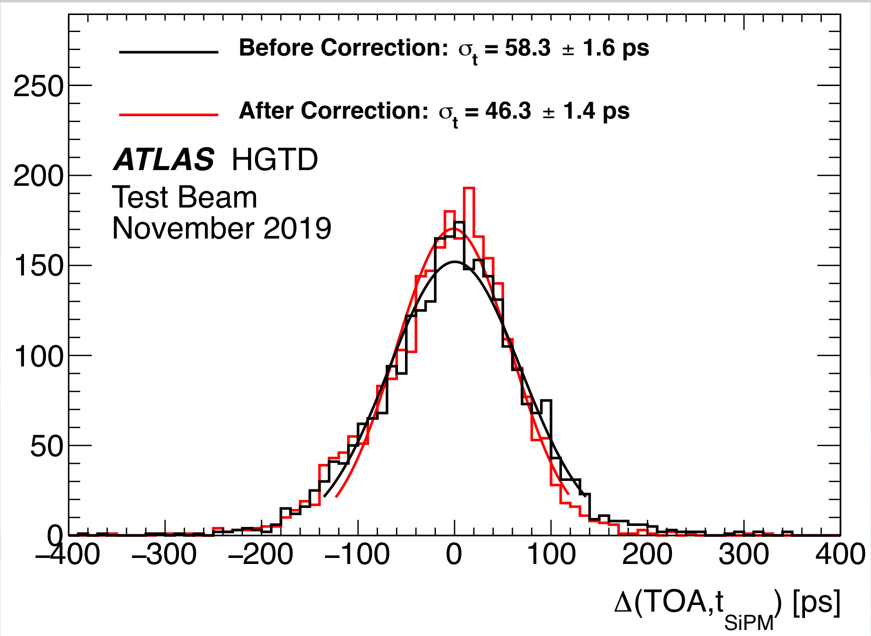


ALTIROC progress

ALTIROC v0,1 (2016—present): focus on performance of analogue electronics only

- $\sigma_t \approx$ 46 ps after time-walk correction
- $\sigma_j = \sigma_t \ominus \sigma_{\text{land}} \approx$ 39 ps



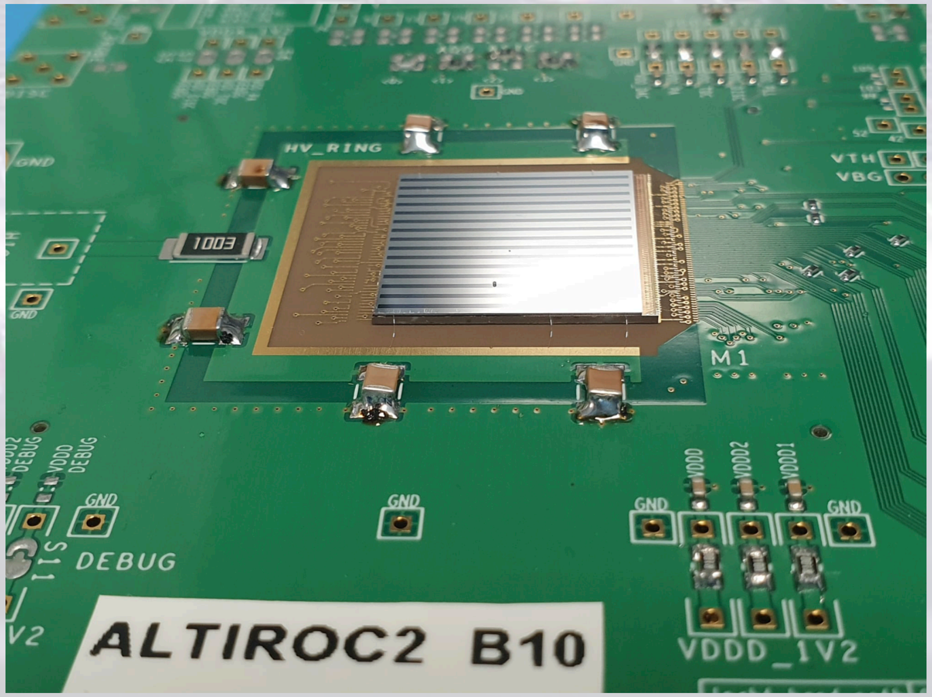


- > required 25 ps due to (external) noise from readout system ➟ will improve

ALTIROC v2 diced in Q4 of 2021, presently under test

- addition of full digital electronics functionality

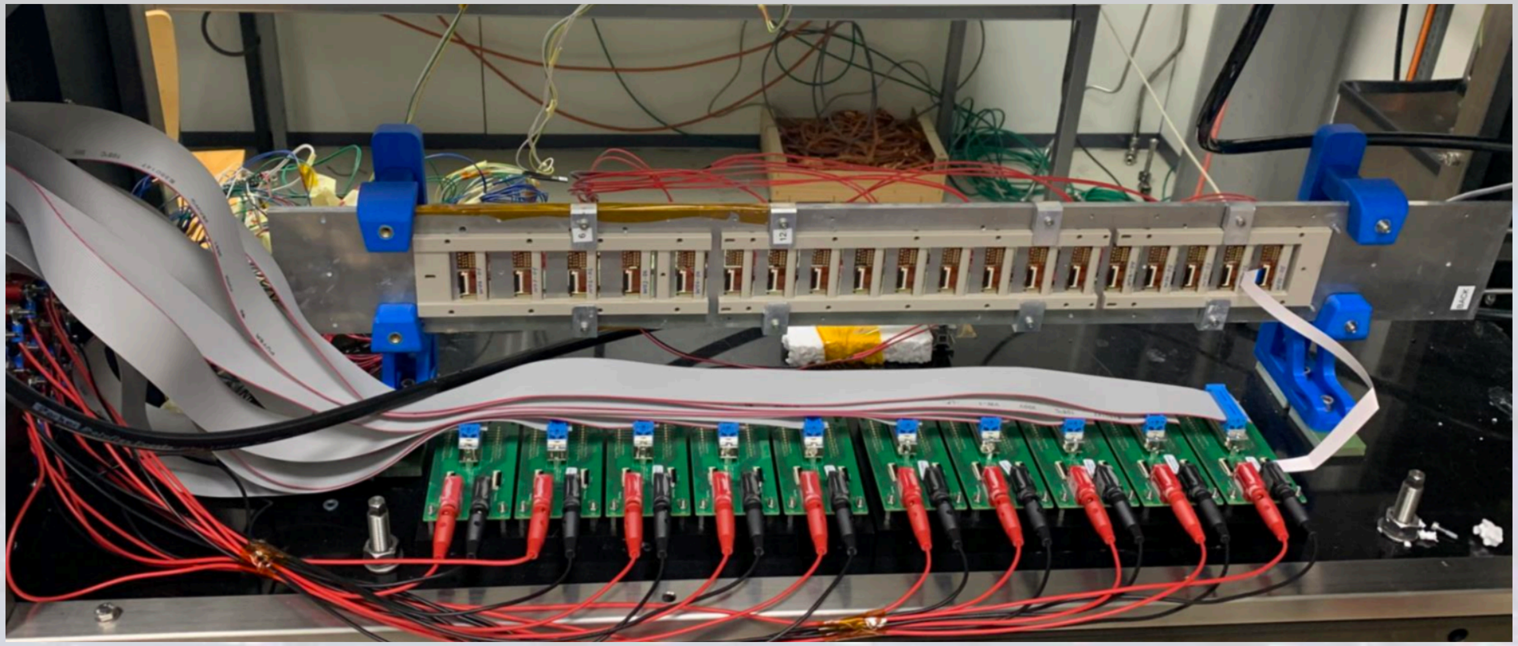
Design of final ALTIROC v3 (radiation-hard version) expected this summer



Demonstrator project

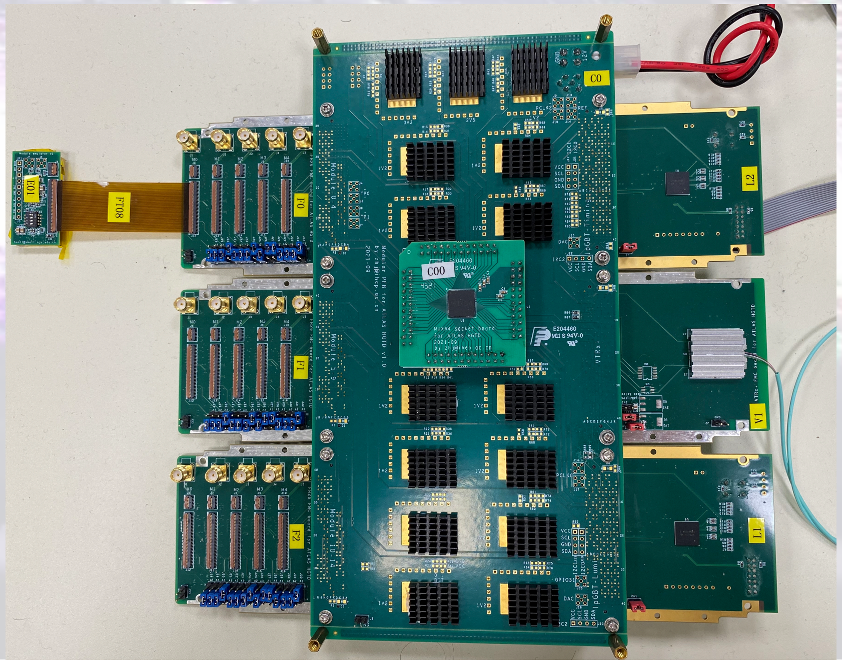
Aim: test (a slice of) the full system, starting with cooling

- thermal contact between cooling manifold, modules is critical to maintain $T =$ -30 °C



Preparing to test communication and readout: "modular" PEB, using dummy inputs

- gradually replace with actual modules, flex tails and PEB



Conclusion & outlook

The HGTD will yield track time measurements with a resolution of 30—50 ps in the forward region $2.4 < |\eta| < 4$

Expect important benefits from suppression of pile-up tracks & jets

Great progress has been made in the development of both LGAD sensors & readout asics

The coming year will be an exciting one, with

- design of the final ALTIROC asic
- construction of a complete “slice” demonstration
- verification of timing performance at system level

Bonus

HGTD in ATLAS

Assembly