The ATLAS High-Granularity Timing Detector for the HL-LHC: project status and results

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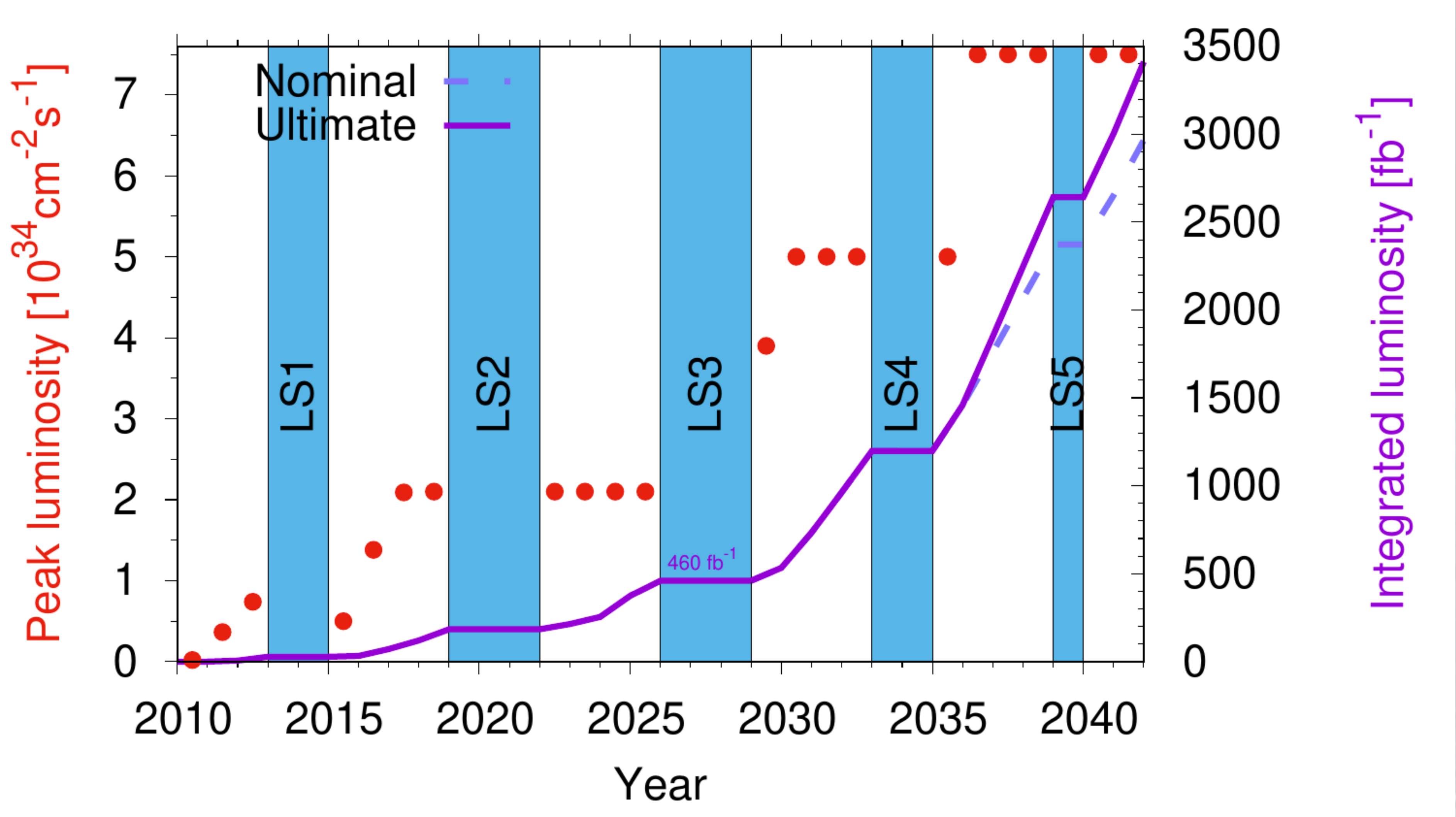
for the ATLAS HGTD Collaboration

The High-Luminosity LHC Phase

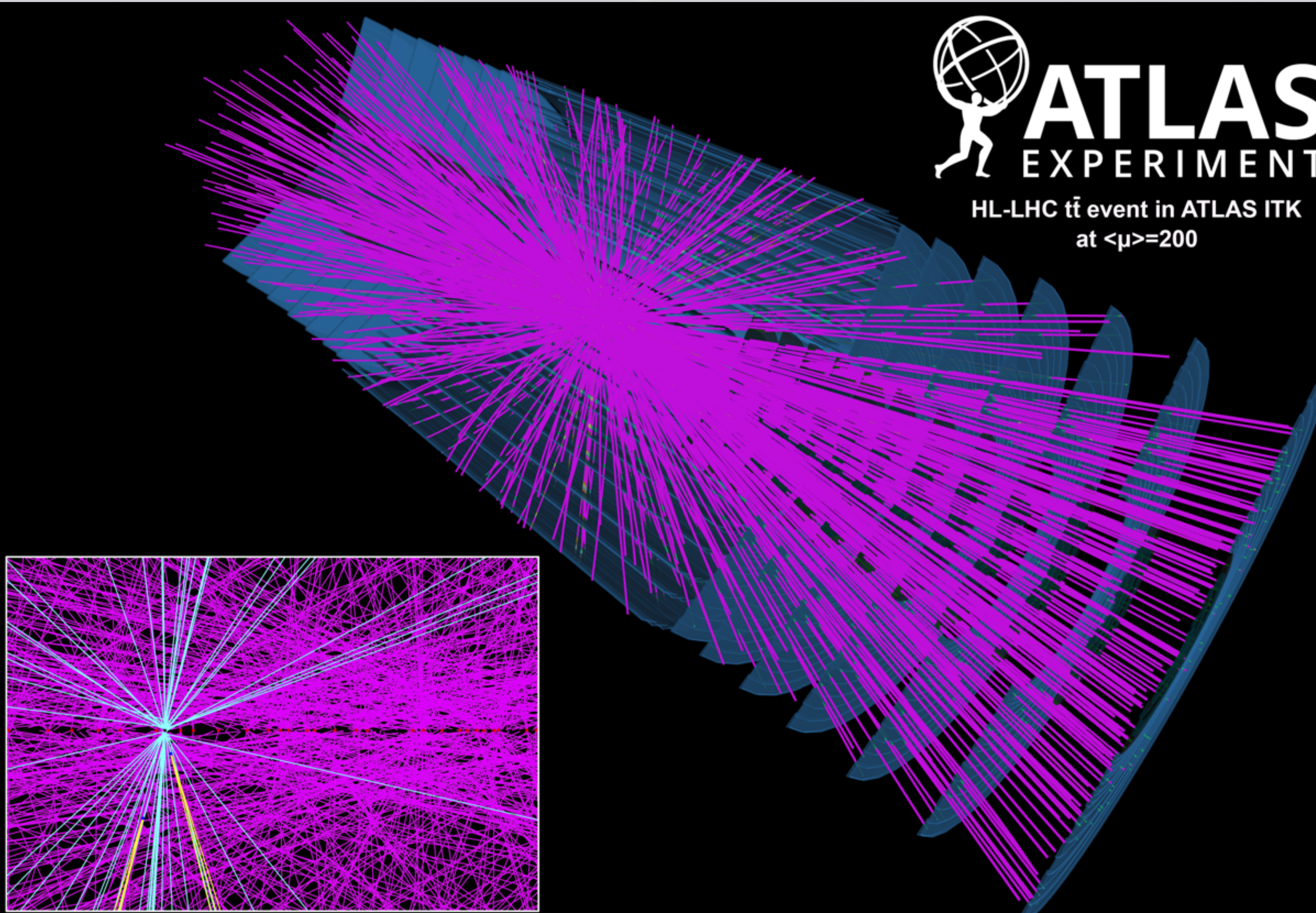


HL-LHC luminosity roadmap (assuming “ultimate” luminosity profile)

Ultimate luminosity to be delivered by the HL-LHC: $7.5 \cdot 10^{34}$ cm^{-2} s^{-1} (total integrated luminosity at least up to 3 ab^{-1})

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

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



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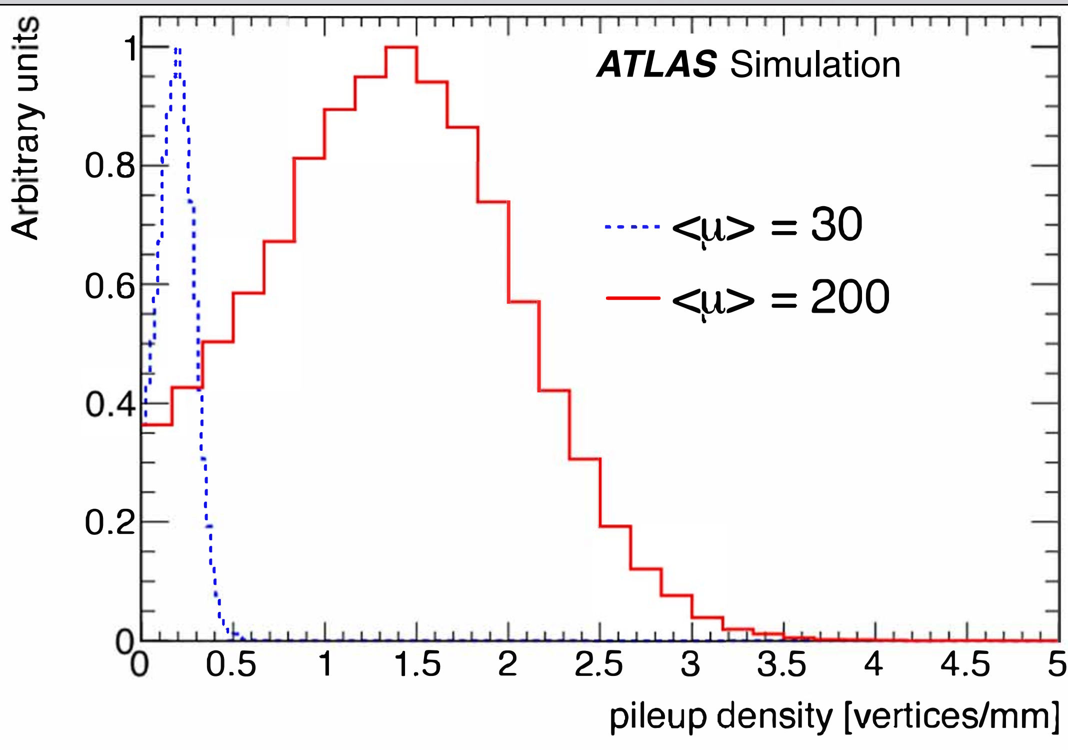

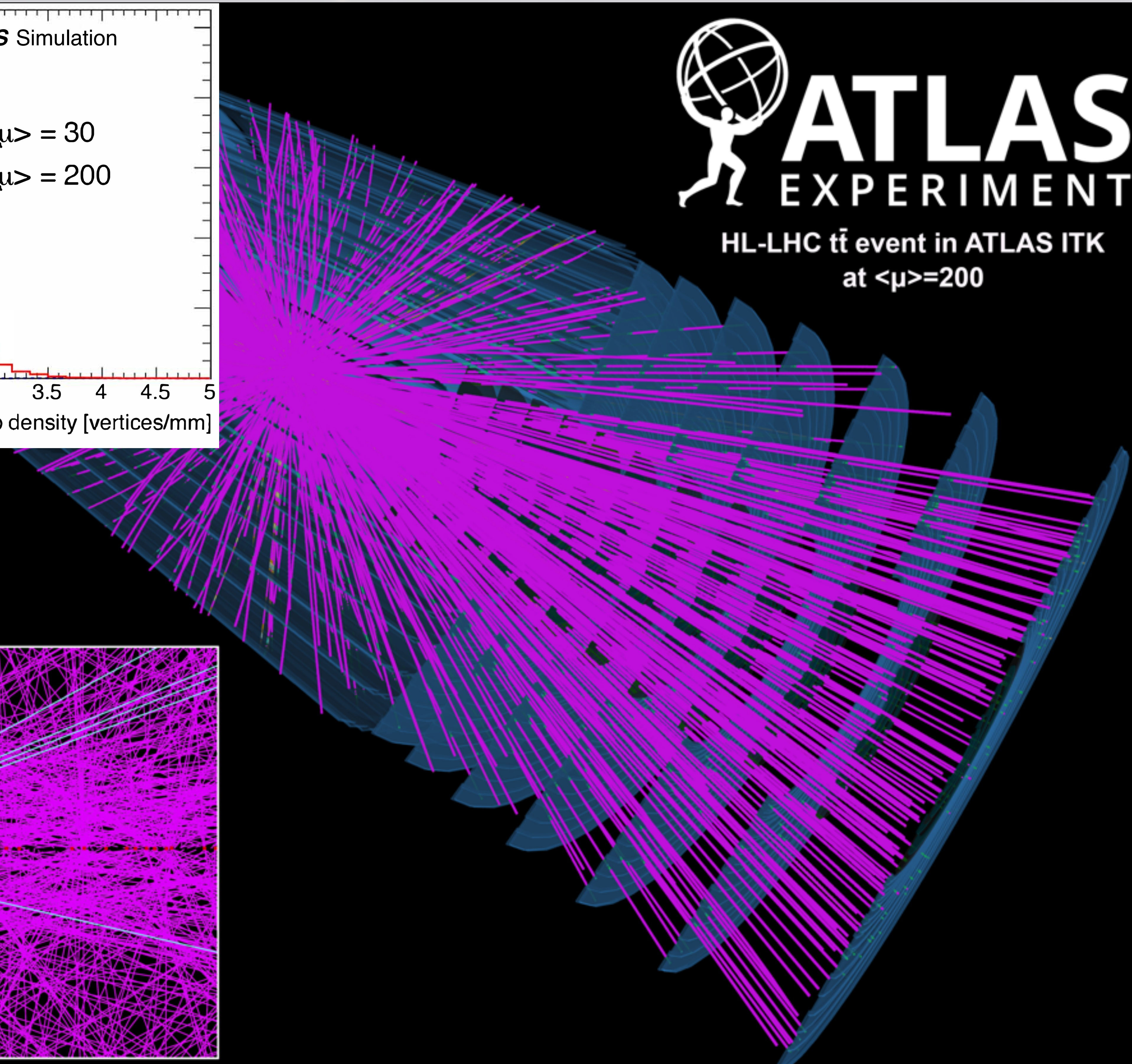

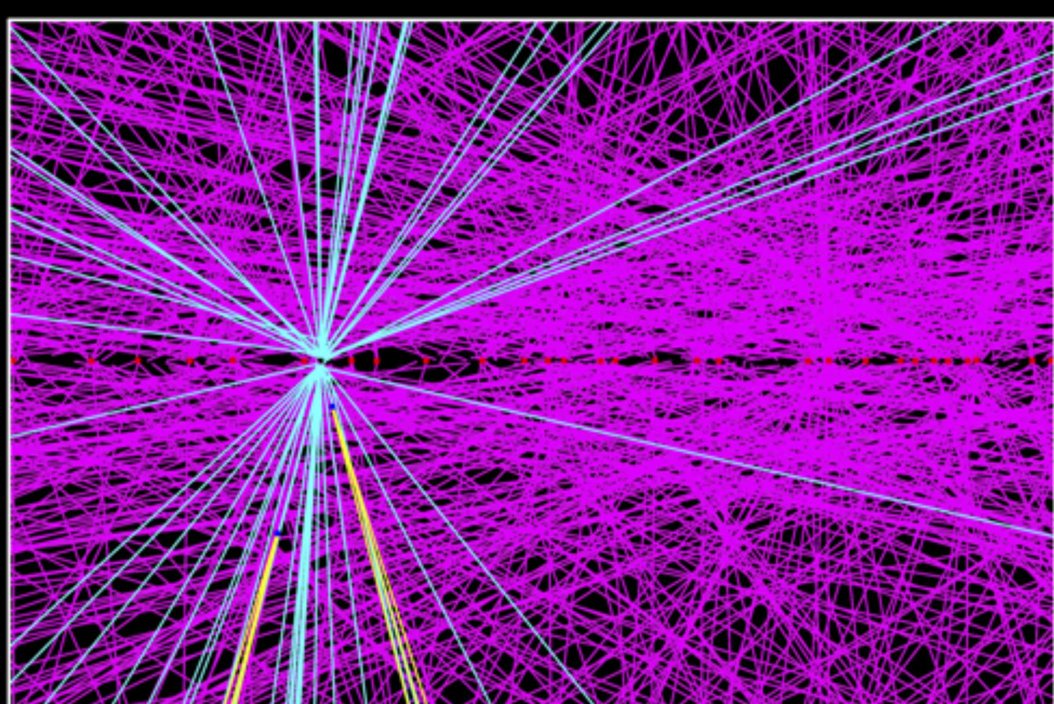

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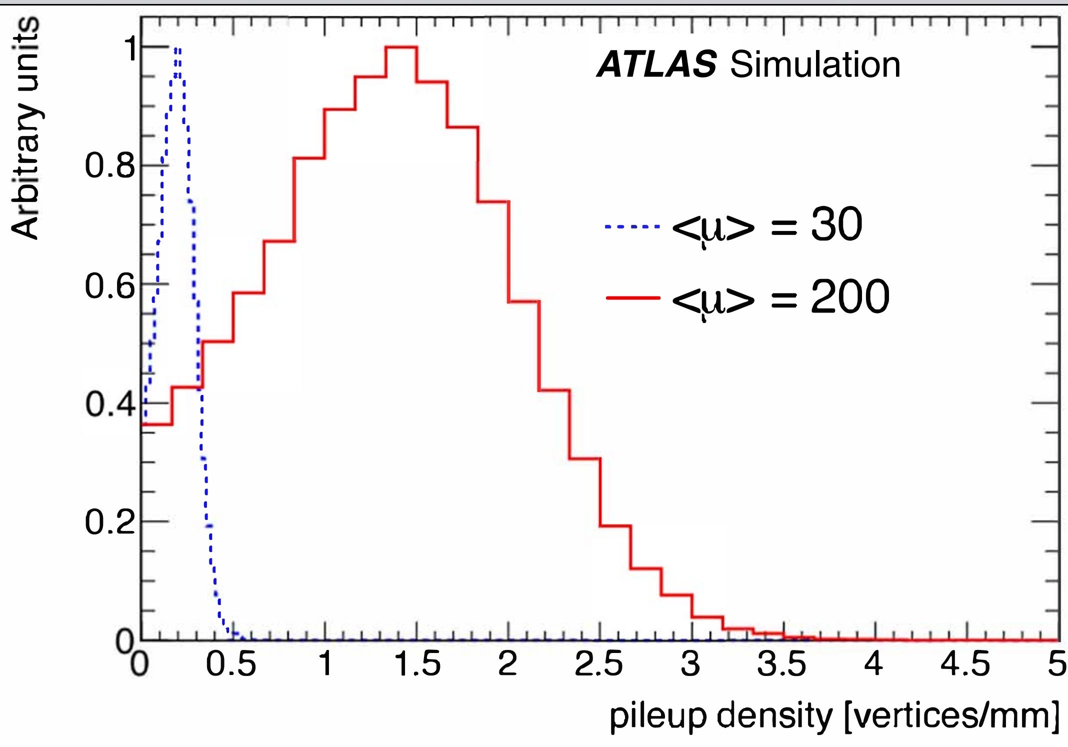
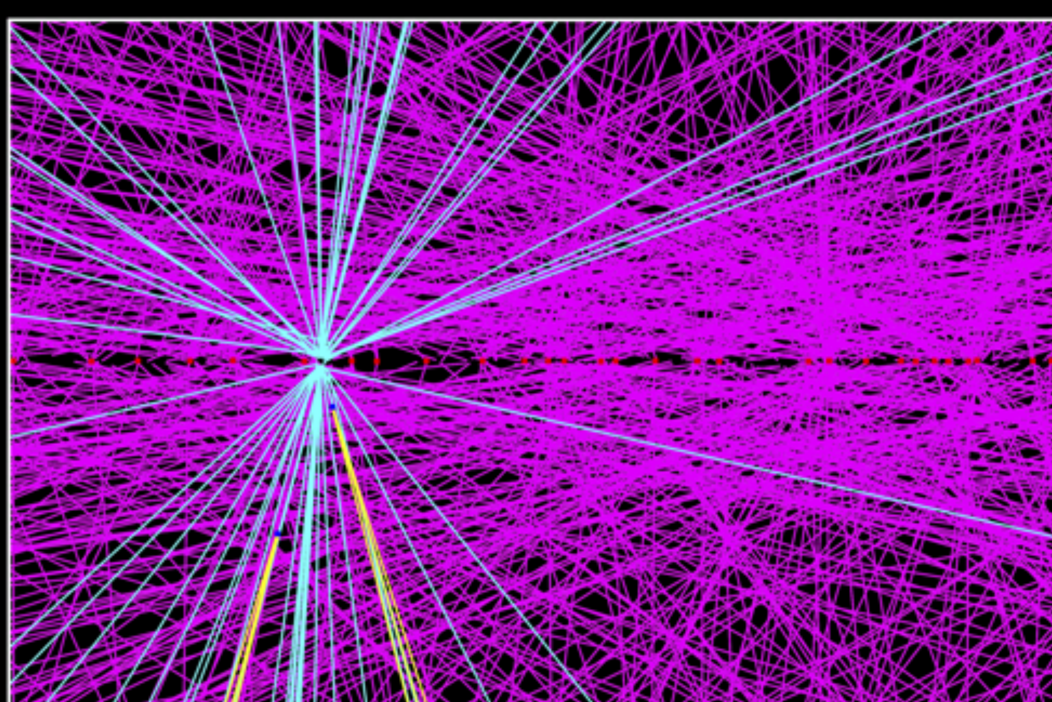
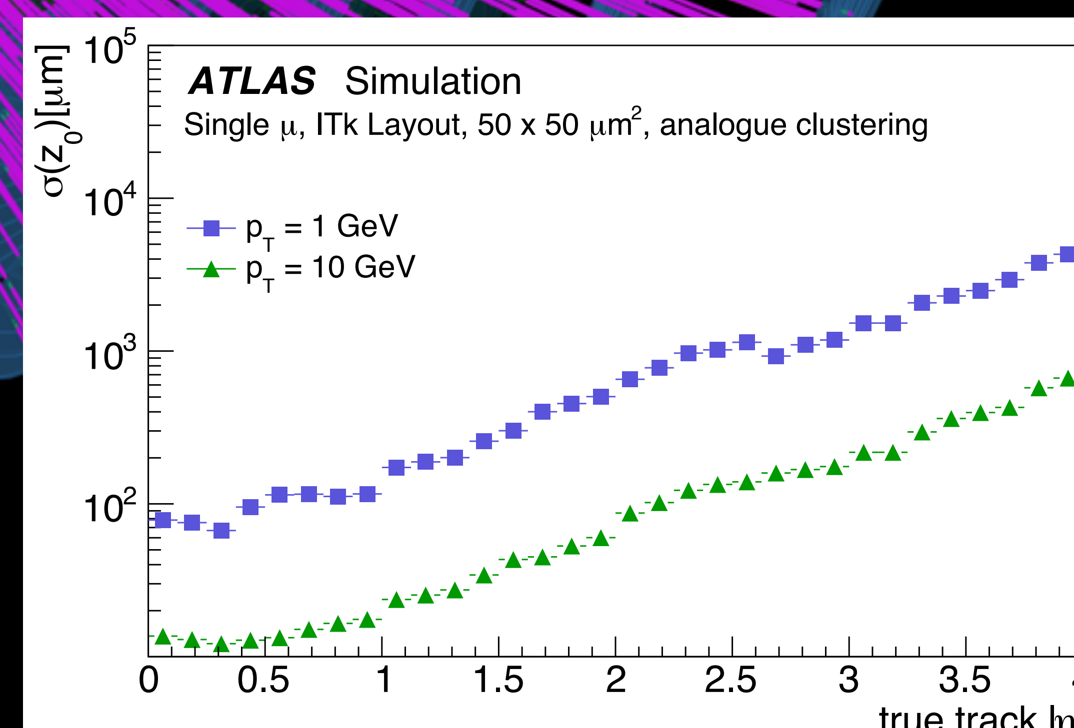
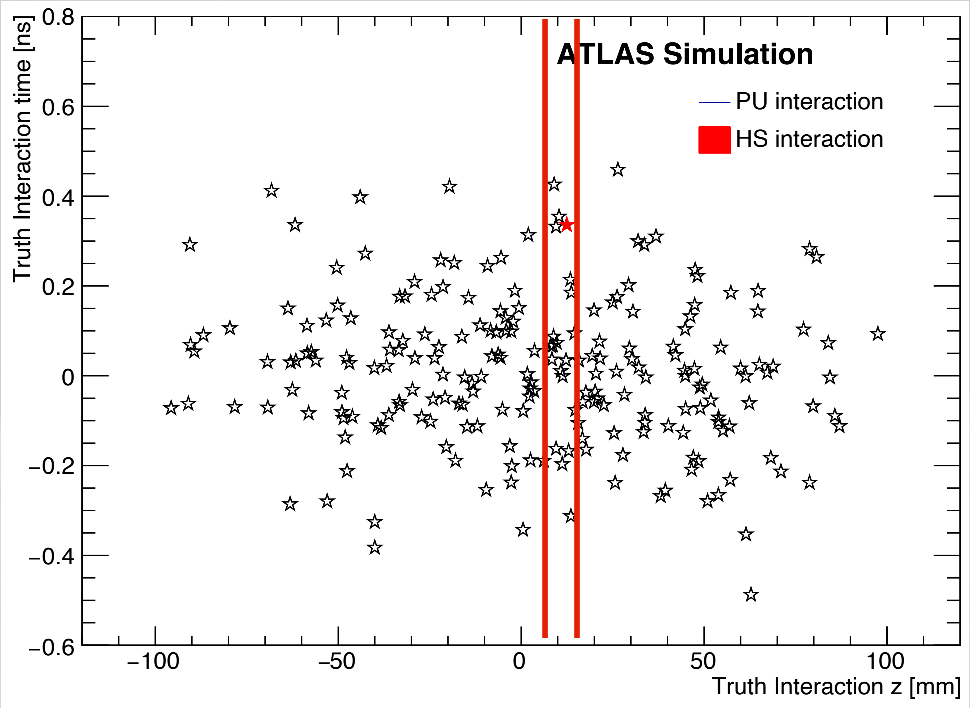
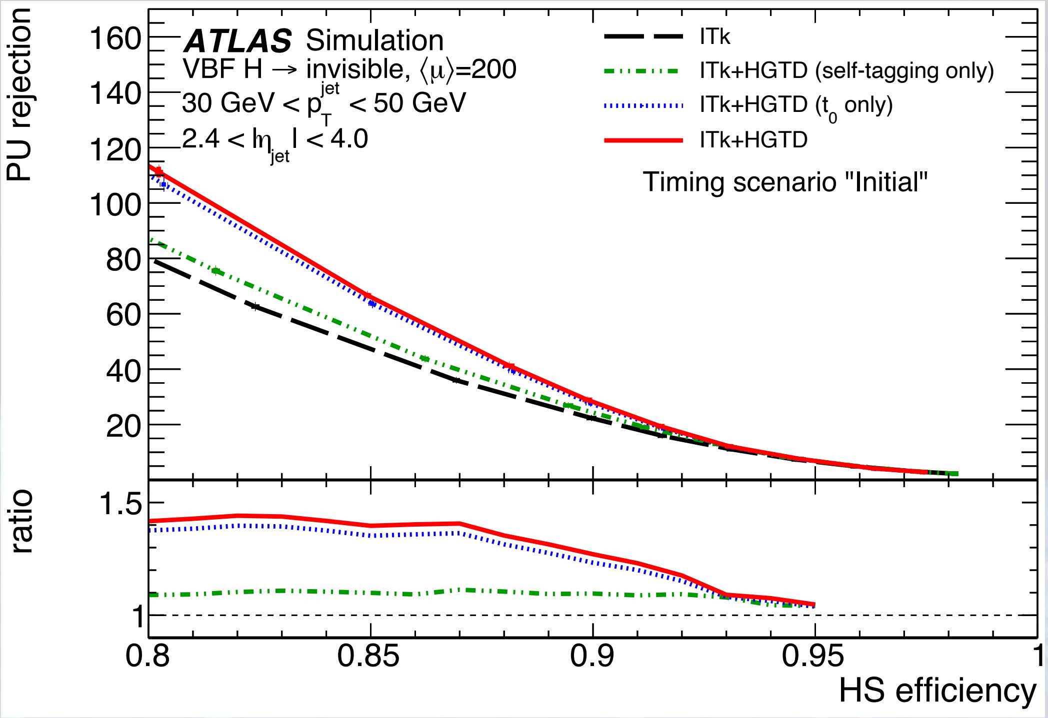






Anatomy of a bunch crossing





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

- also other physics performance improvements expected (e.g. electron isolation criteria)

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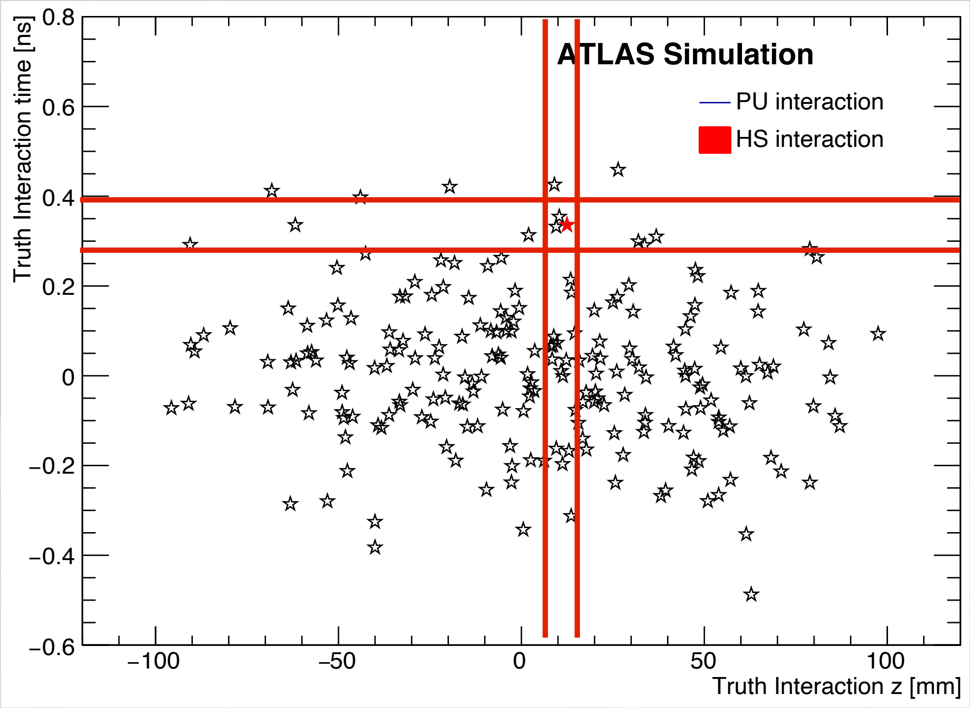

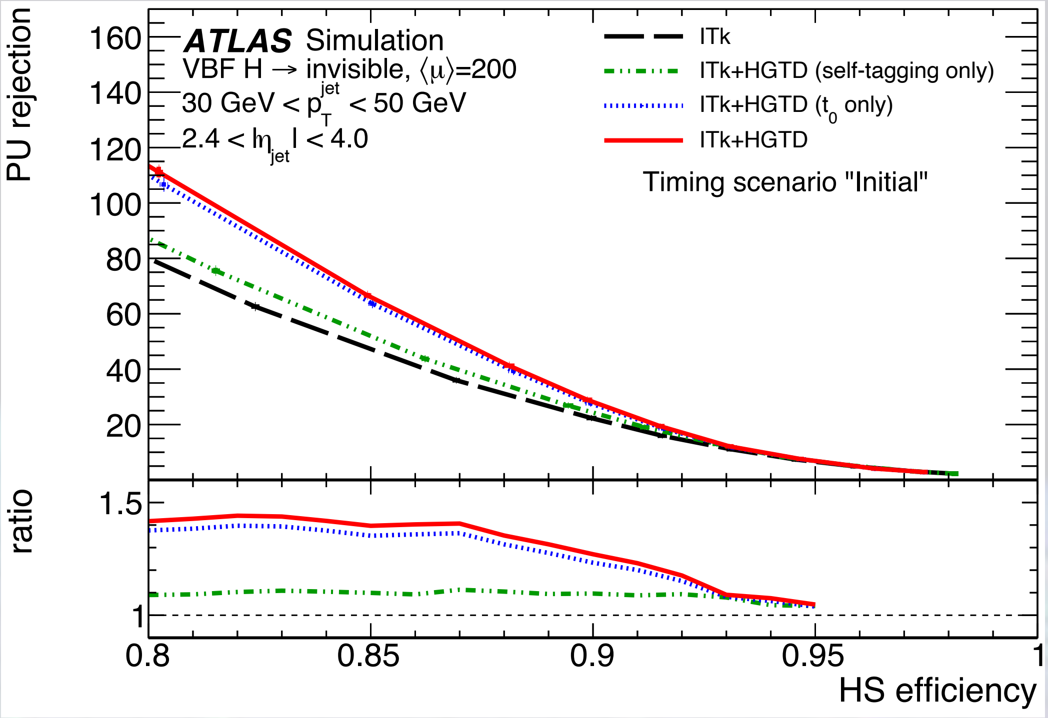

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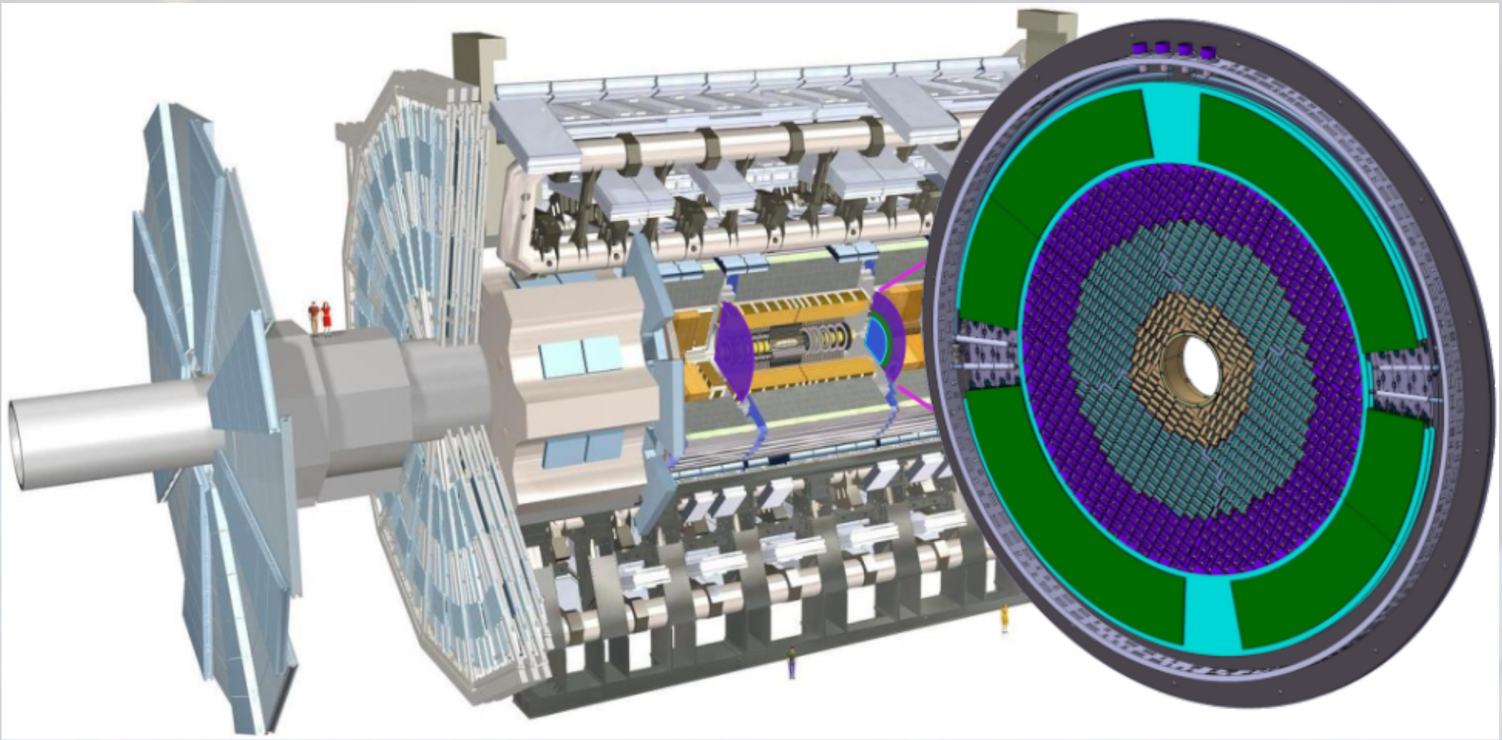
The High-Granularity Timing Detector

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

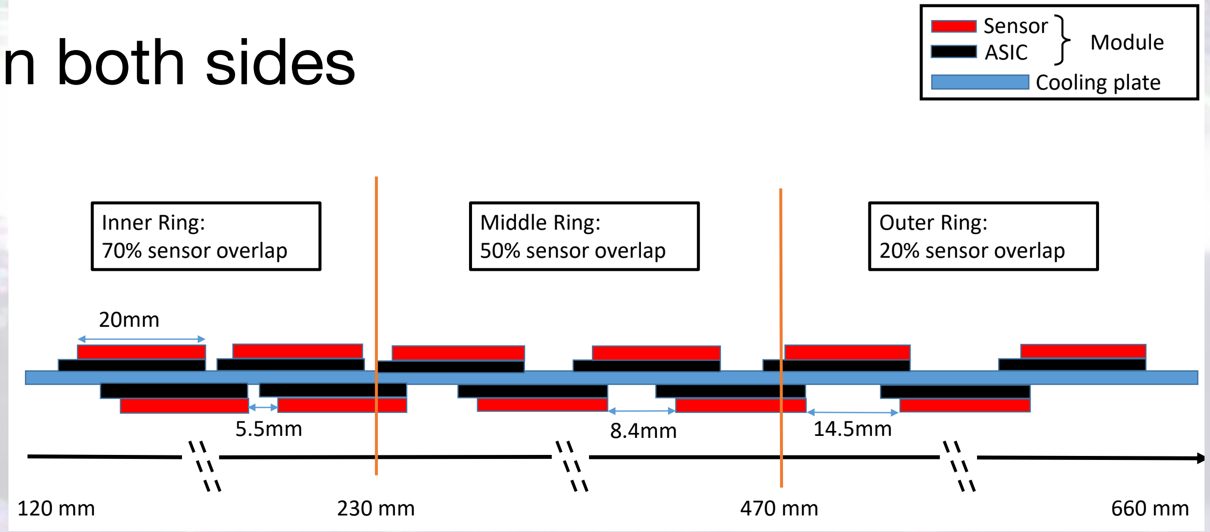
- $|z| = 3.5$ m, $\Delta z = 75$ mm
  - plus moderator (50 mm)
- 120 mm $< r <$ 640 mm



Achieve desired σ_t by up to 4 independent time measurements (~2 on average), each with 45—70 ps resolution

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

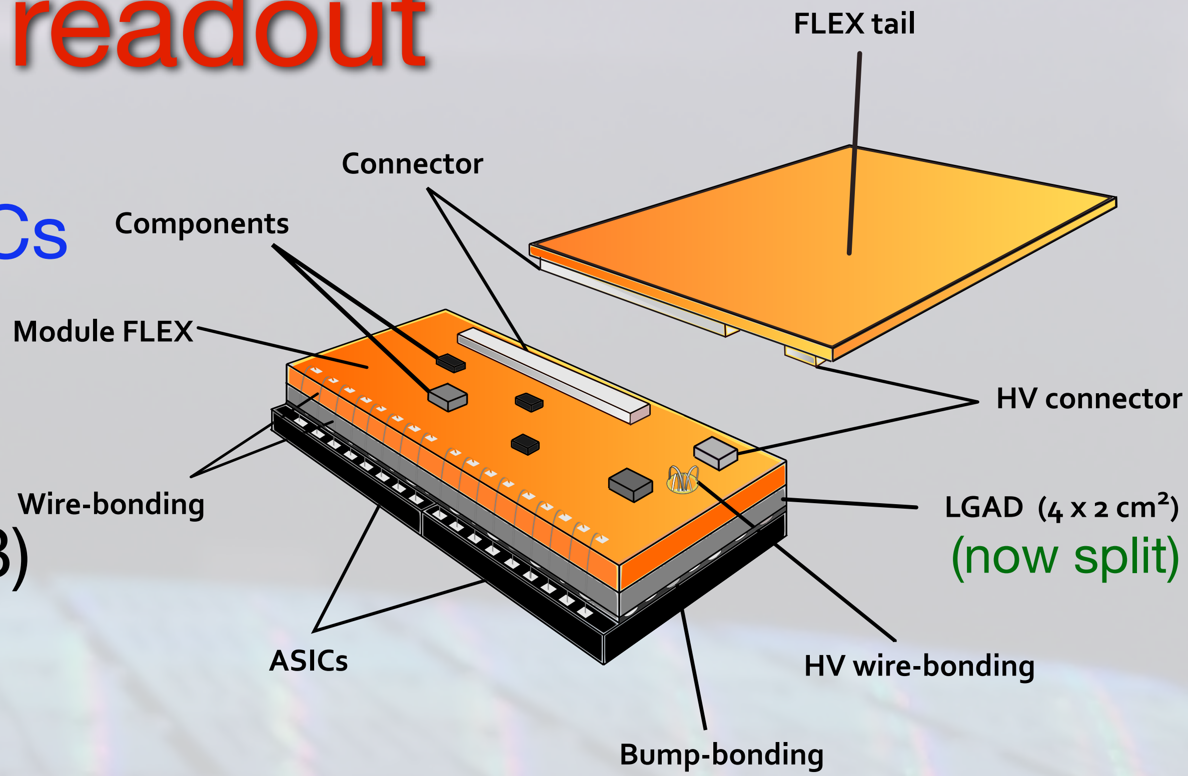
- arranged on 2 disks each instrumented on both sides
- 3.6 M channels; occupancy < 10%
- radiation tolerance: $2.5 \cdot 10^{15}\, n_{eq}$ cm^{-2}, 2 MGy
  - operation @ -30 ˚C
  - arrangement in 3 rings; expect to replace innermost rings in LS4 (in backup)



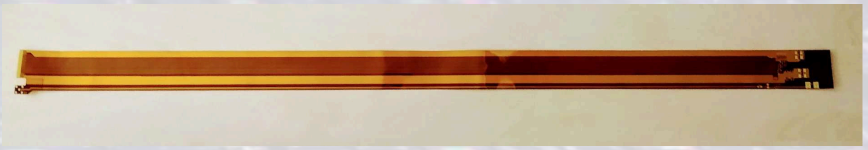
Modules and readout

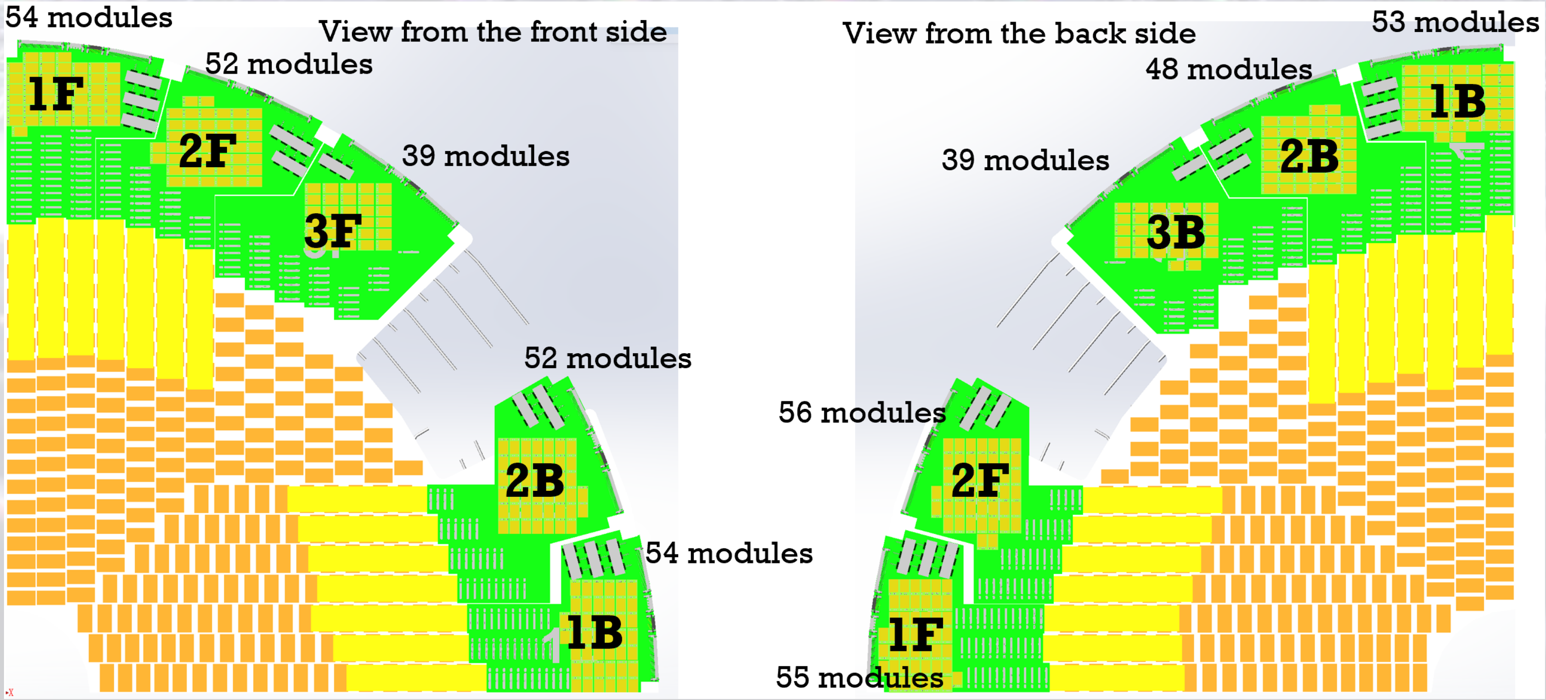
Sensors bump-bonded to ALTIROC ASICs

- 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, to accommodate radial dependence of fluence
- Sensor temperature (-30 ˚C) to be maintained by evaporative CO_2 cooling manifold in disks
  - 6 different PEB types

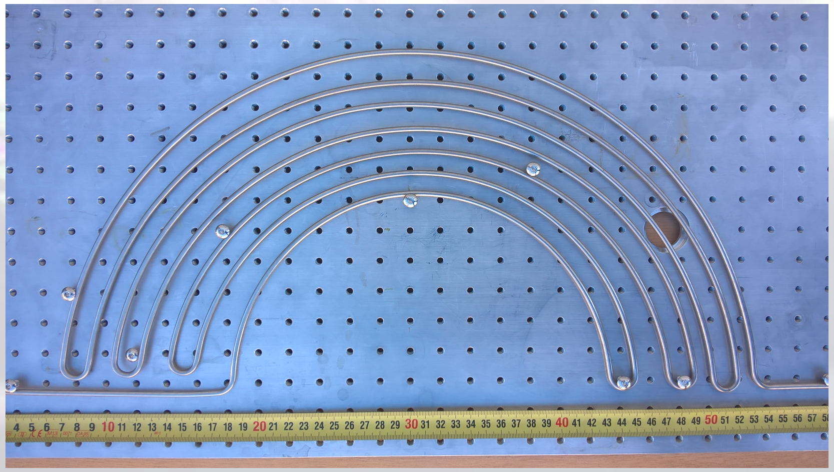


flex tails (up to ~ 70 cm)





prototype cooling serpentine



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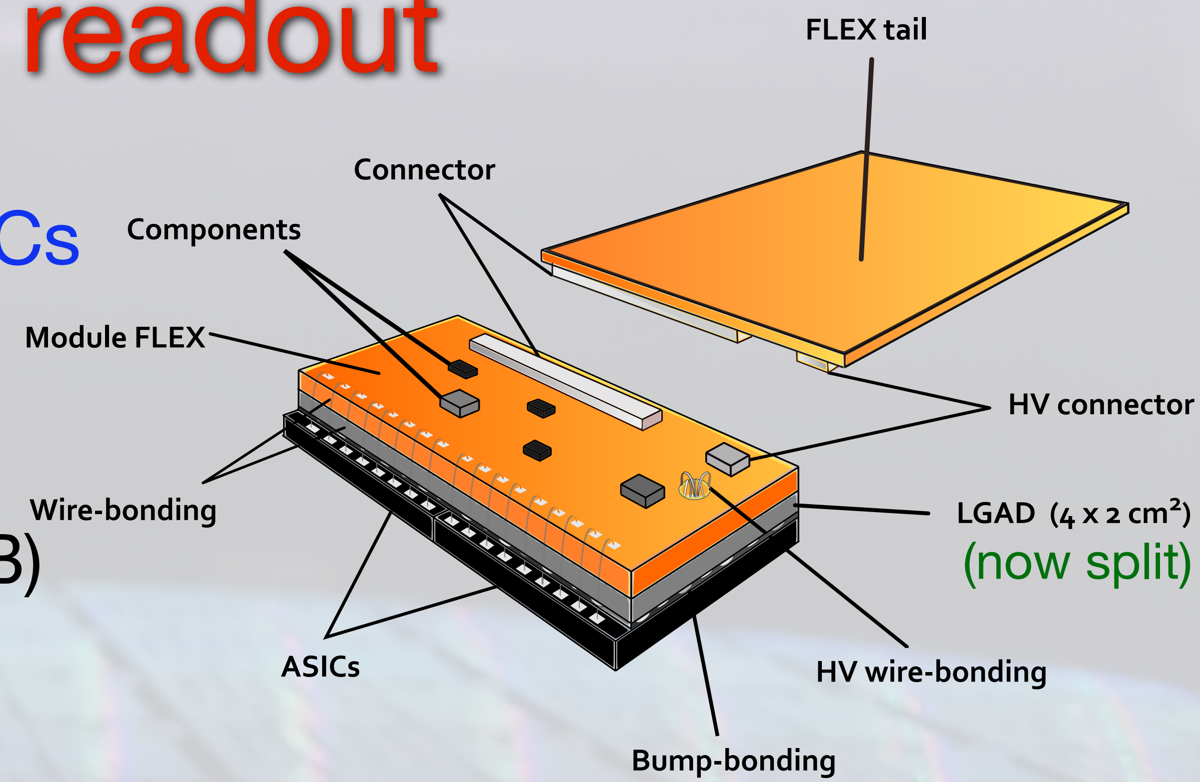
  - 6 different PEB types
    - PEB-1F produced and used in tests
    - detailed design of other types ongoing



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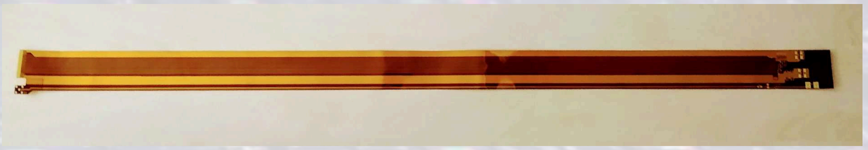

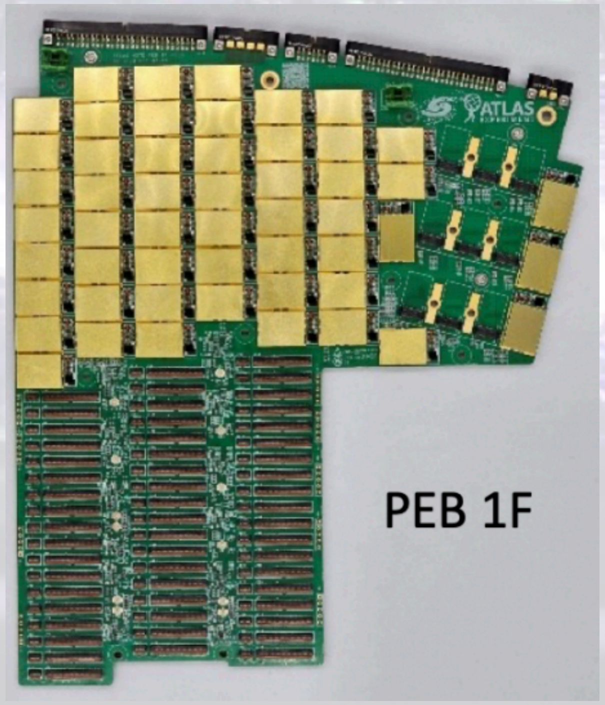

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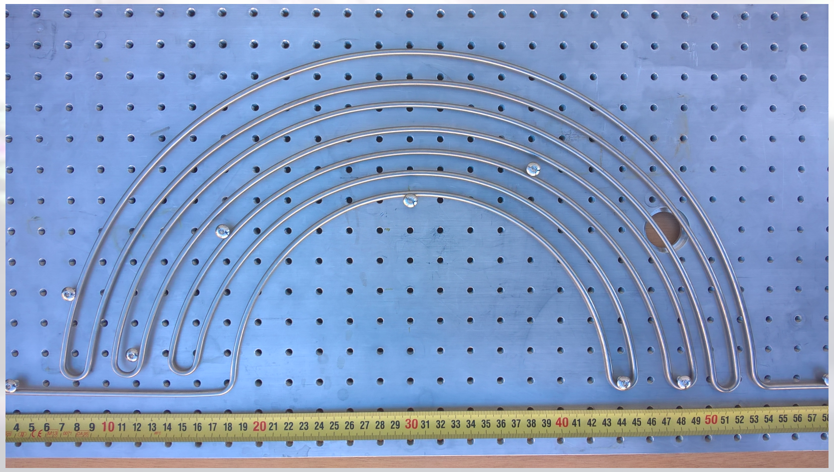
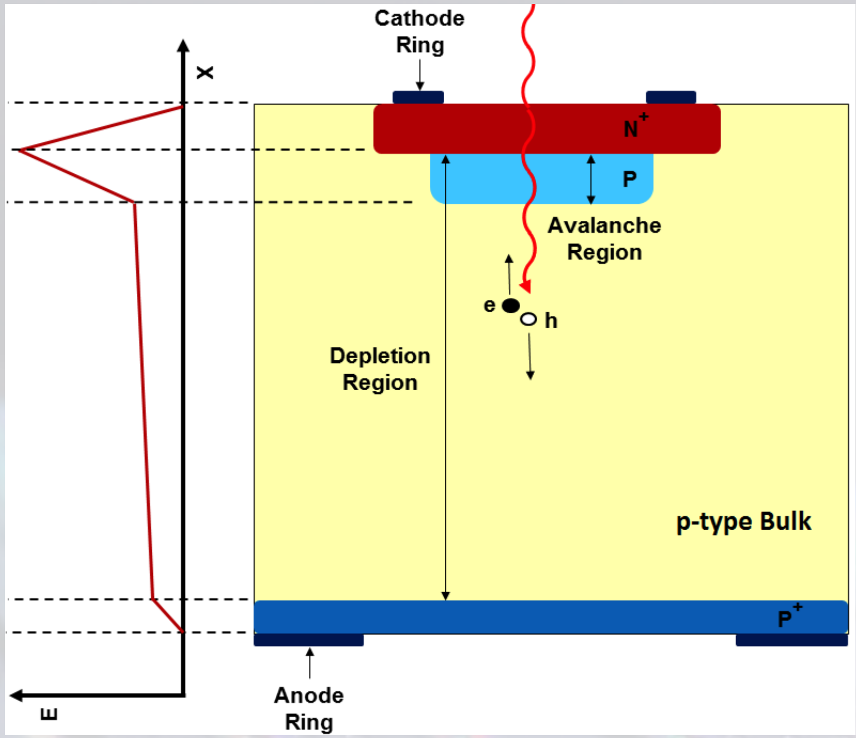


Sensors

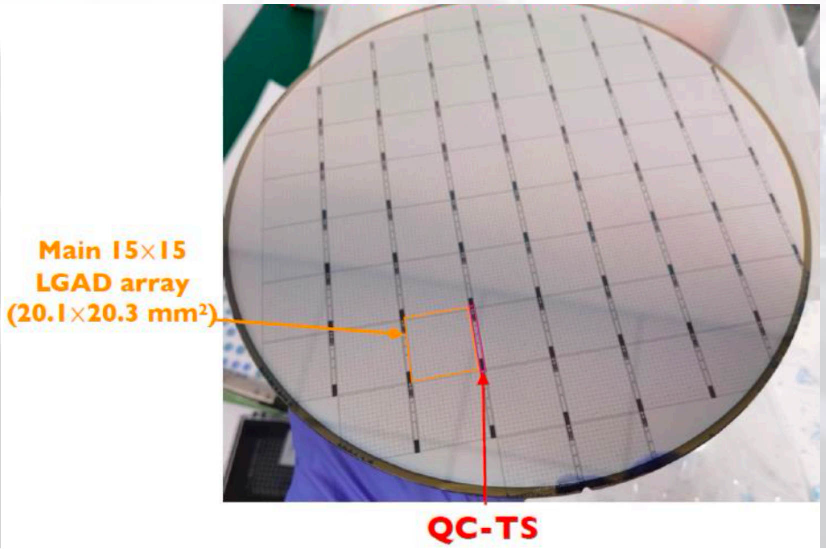
Low-gain avalanche detectors (LGADs):

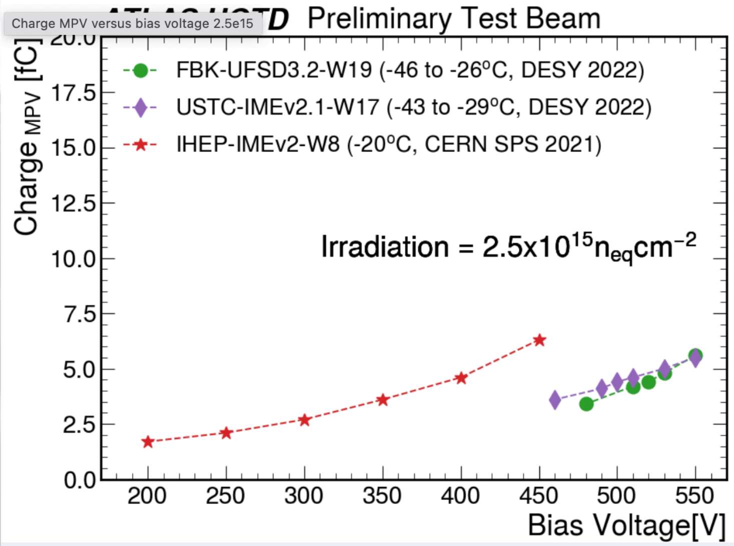
- $\sigma^2 = \sigma^2_{\text{Landau}} + \sigma^2_{\text{tw}} + \sigma^2_{\text{j}} + \sigma^2_{\text{TDC}}$ (arXiv:1704.08666)
- pad size (1.3 × 1.3 mm²) and thickness (50 μm) compromise between rise time, capacitance, fill factor
- requirement: × 20 gain (10 fC) before, × 8 gain (4 fC) after irradiation

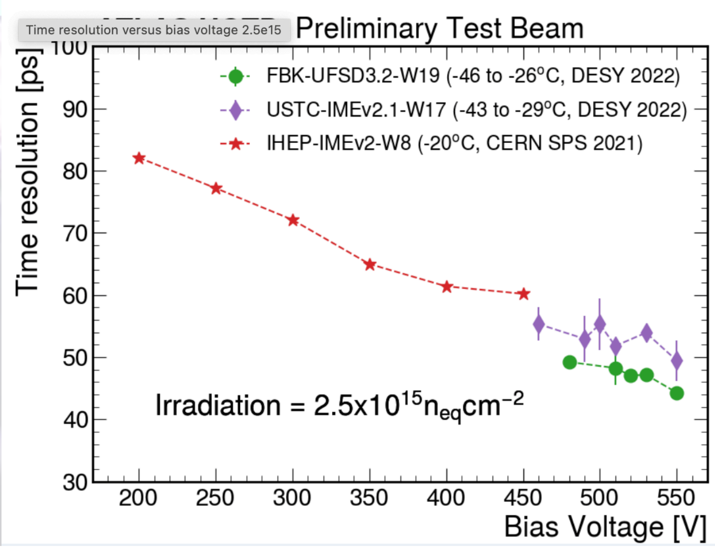


Series production by IME (China) has started

- QC done by probing wafer (V_{bd}, I_{leak}), then on test structure adjacent to each sensor







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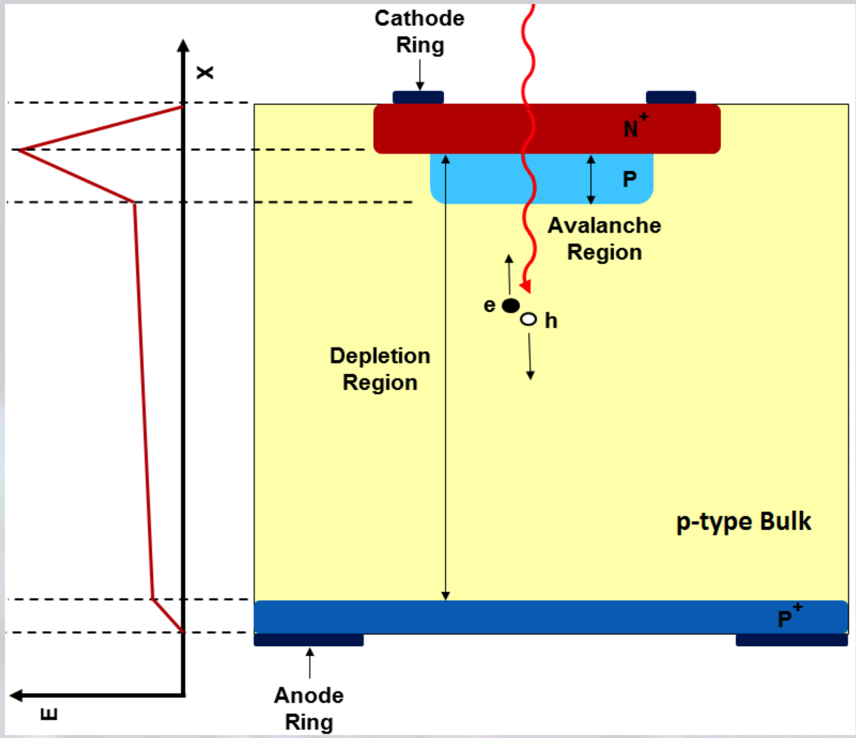

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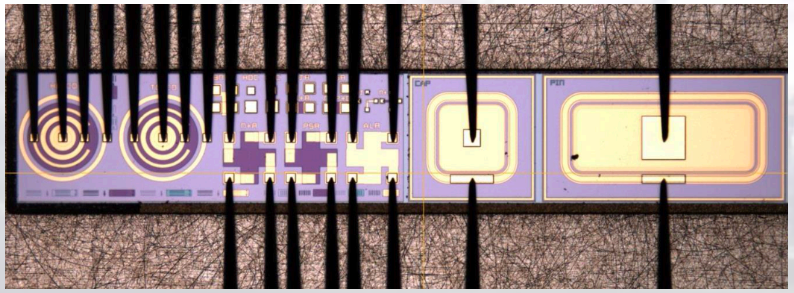
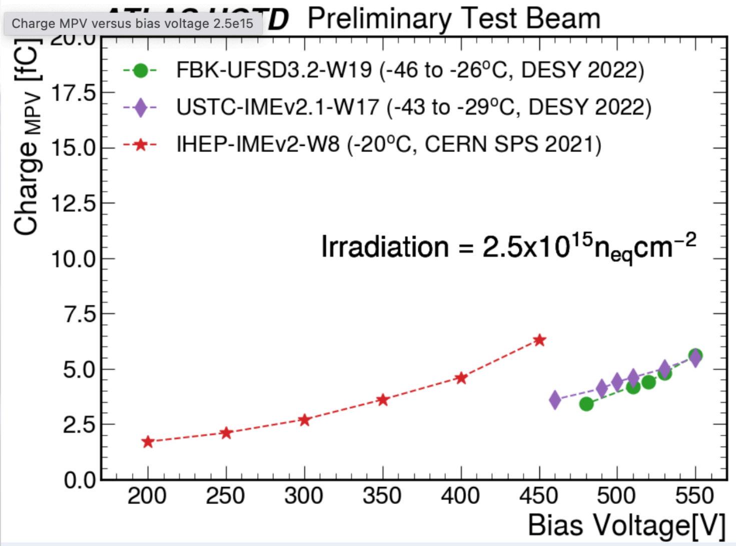
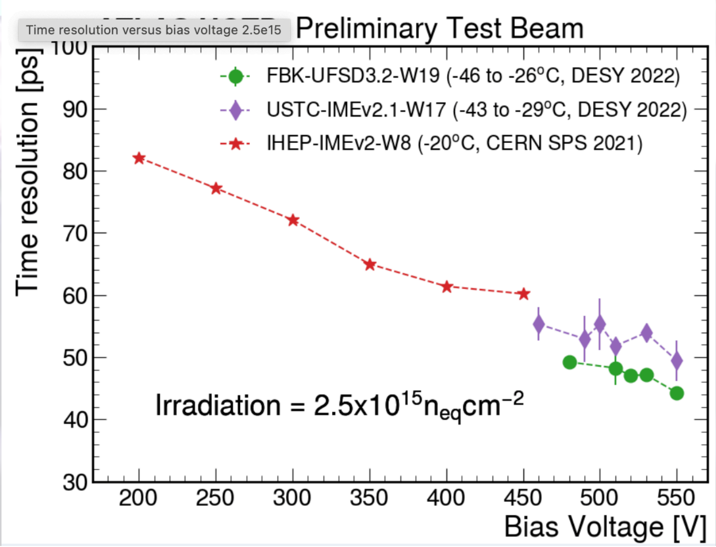
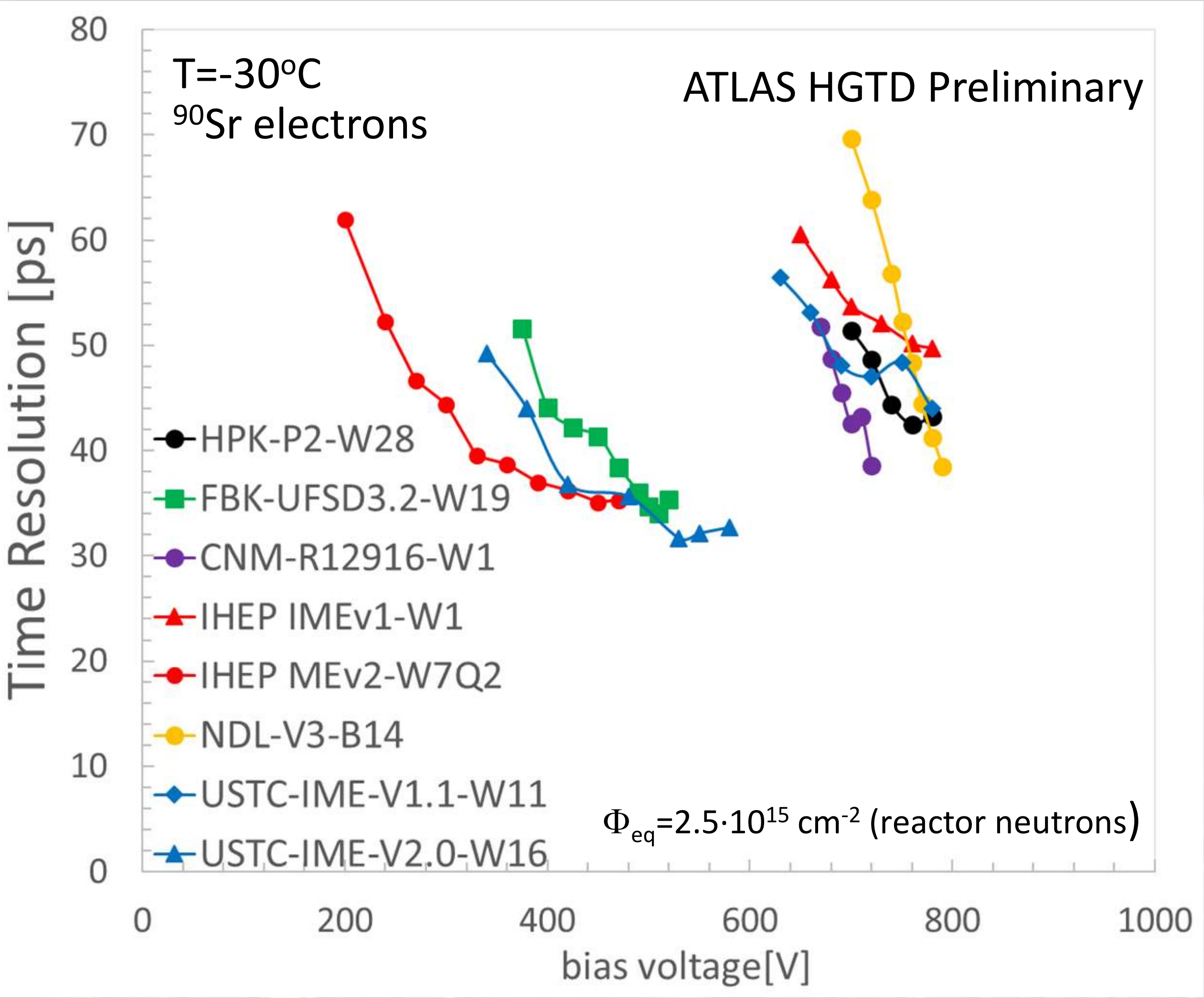




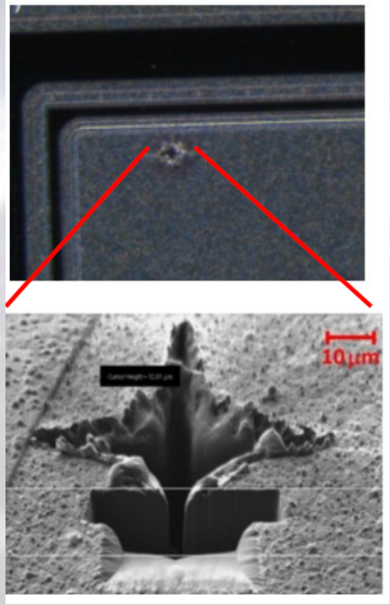


Sensor testing

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



- need to maintain average electric field < 11 V/μm to avoid single-event burnout ➠ V_{bias} not to exceed 550 V
- more information in backup



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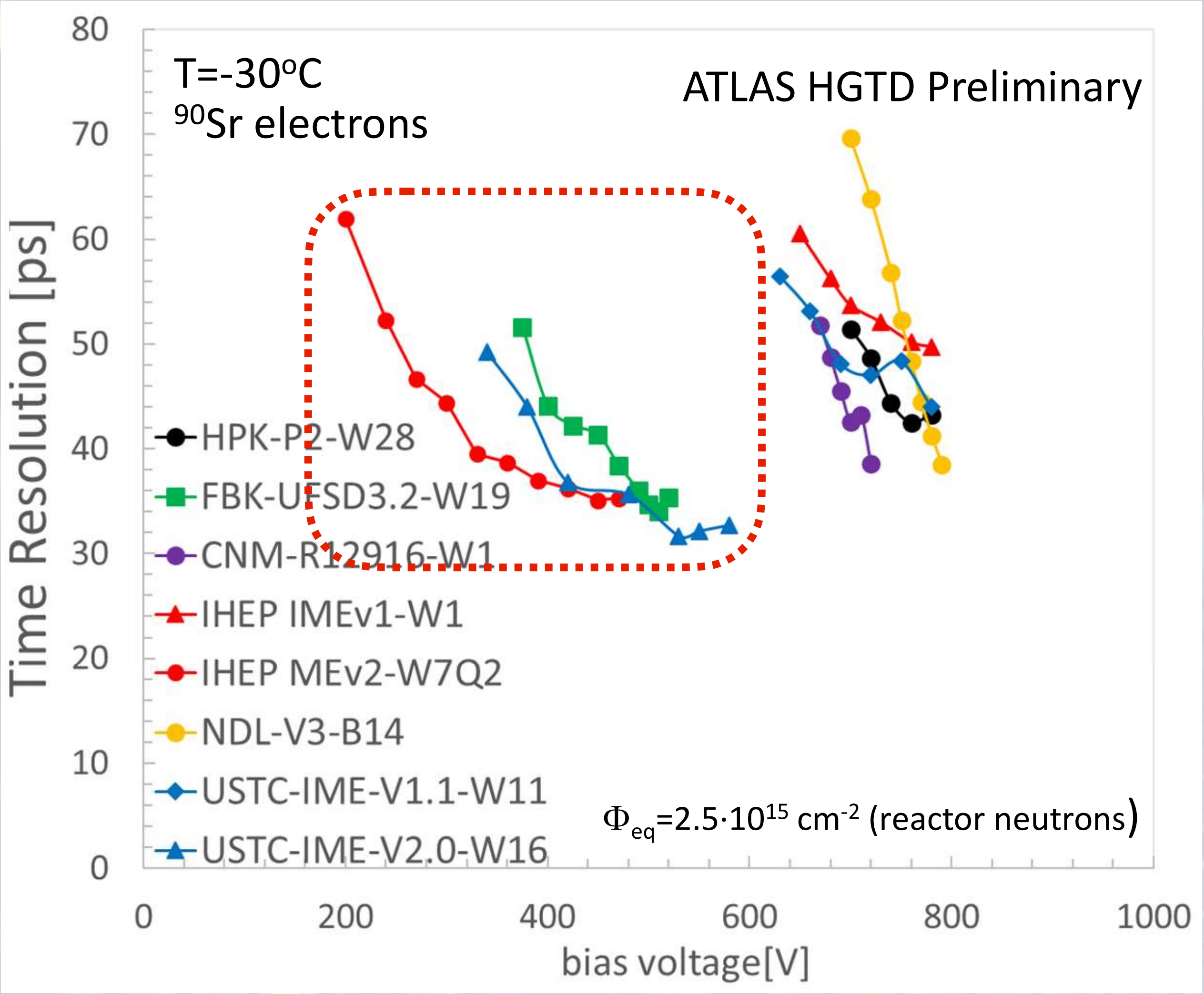

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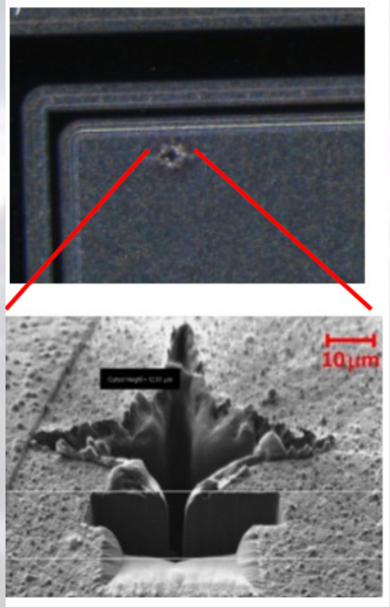
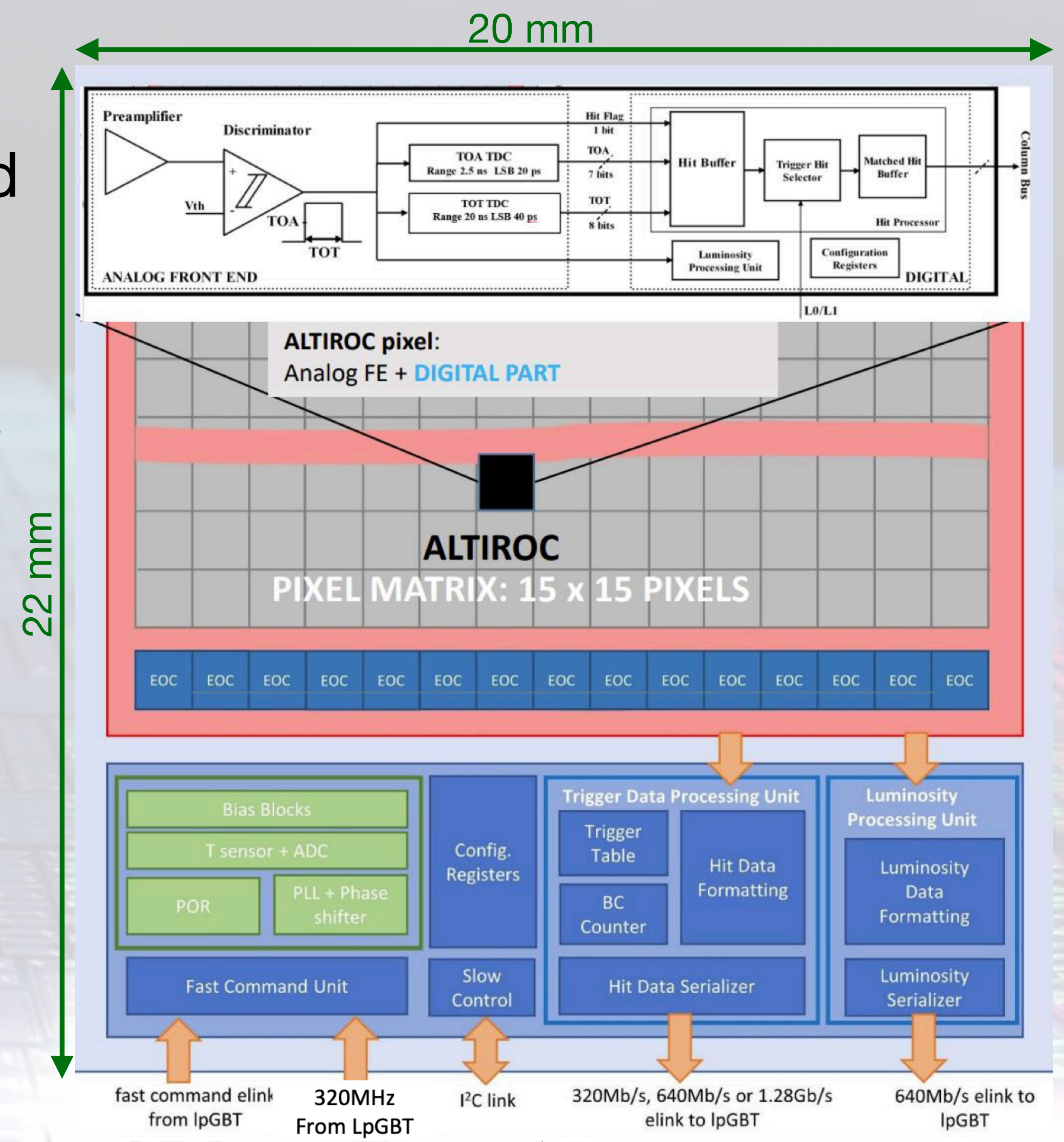


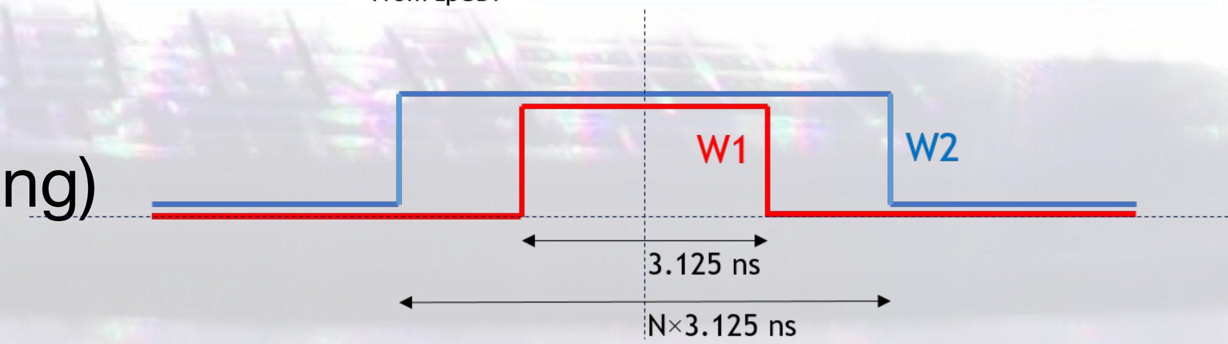
ATLAS LGAD Timing Integrated ReadOut Chip

ALTIROC asic (TSMC 130 nm CMOS):

- time-of-arrival (TOA) + time-over-threshold (TOT) data per channel, transmitted upon L1 trigger
  - Vernier delay lines (120 ps, 140 ps) 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 at system level
  - < 300 mW cm^{-2} (+ sensor: < 100 mW cm^{-2}) to satisfy cooling power budget (20 kW/side)



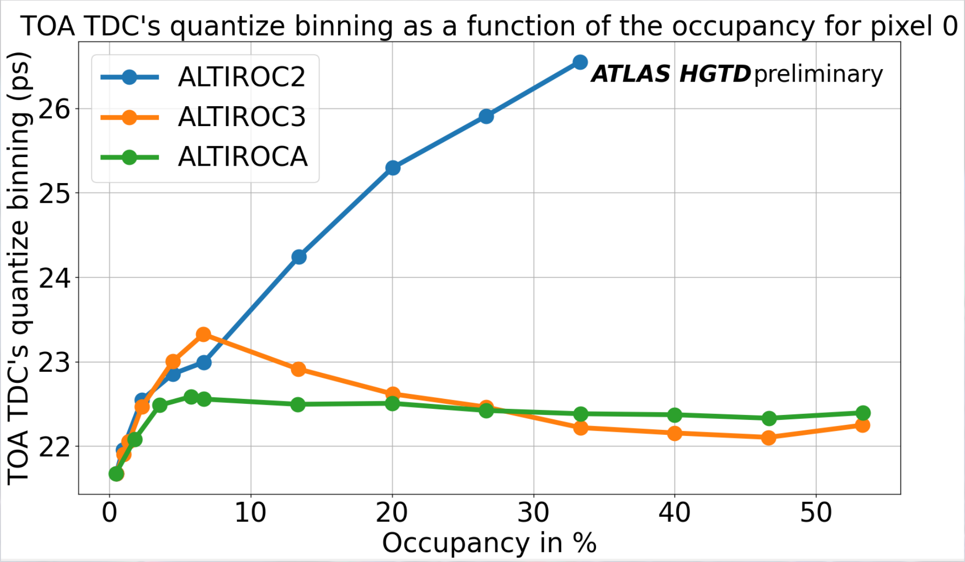
- per-sensor hit multiplicity @40 MHz, for luminosity counting (only used in outer ring)
  - separate readout path



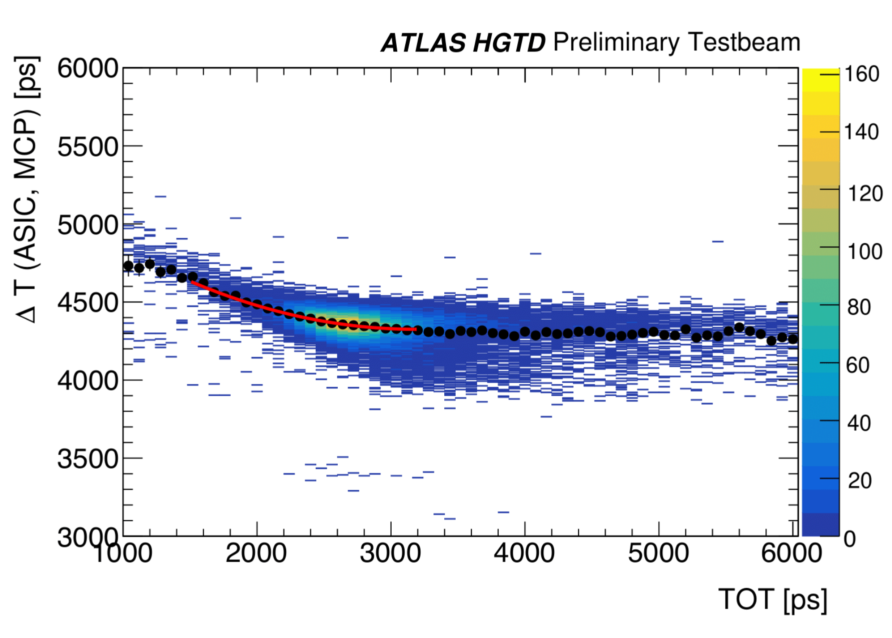
ALTIROC status

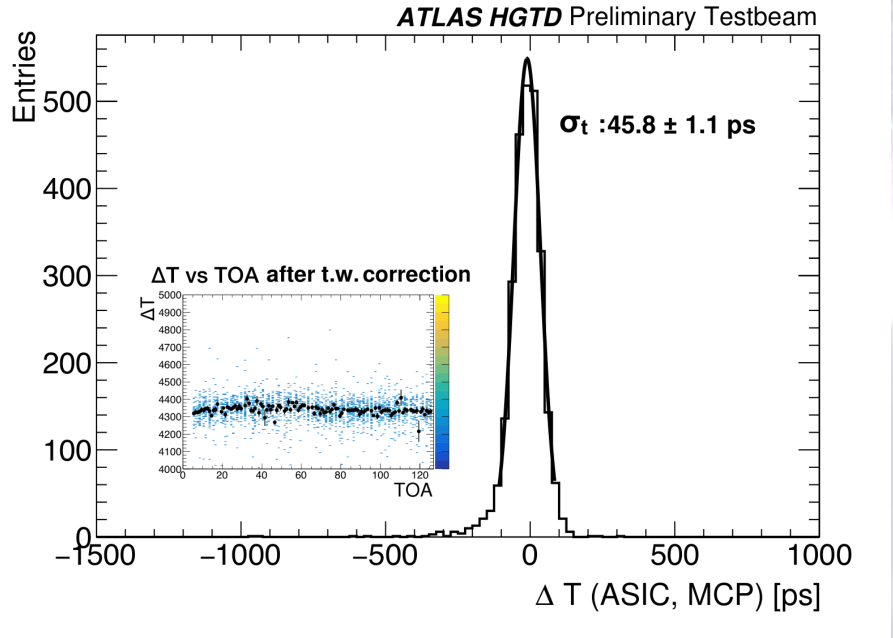
Series production of ALTIROC-A asic about to start; wafer probing QA/QC criteria

- compared to previous versions, this exhibits a much better controlled TOA "bin size"
  - lengths of wire bonds minimised to limit I*R voltage drops
  - cross-talk between TOA_busy and TDC lines removed



- test beam studies carried out using TOT for time-walk correction
  - ~ 46 ps reached for tracks in the central part of the pad
  - ~ 50 ps without this selection of tracks
- verified luminosity hit counting

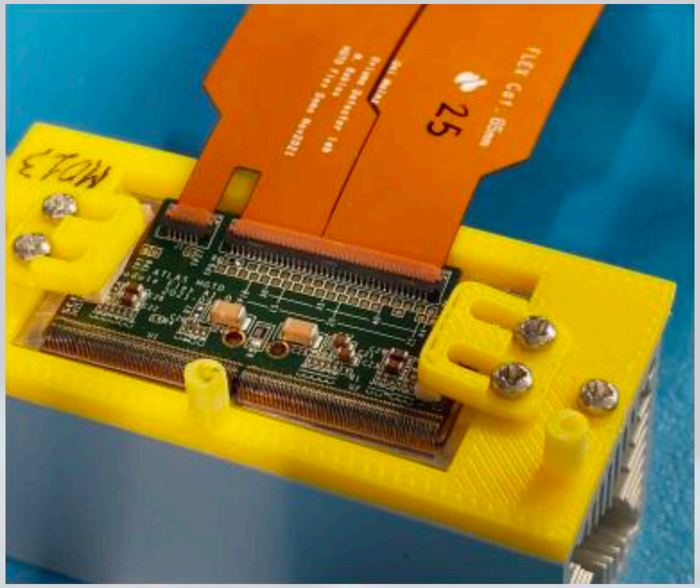




Module and detector unit production

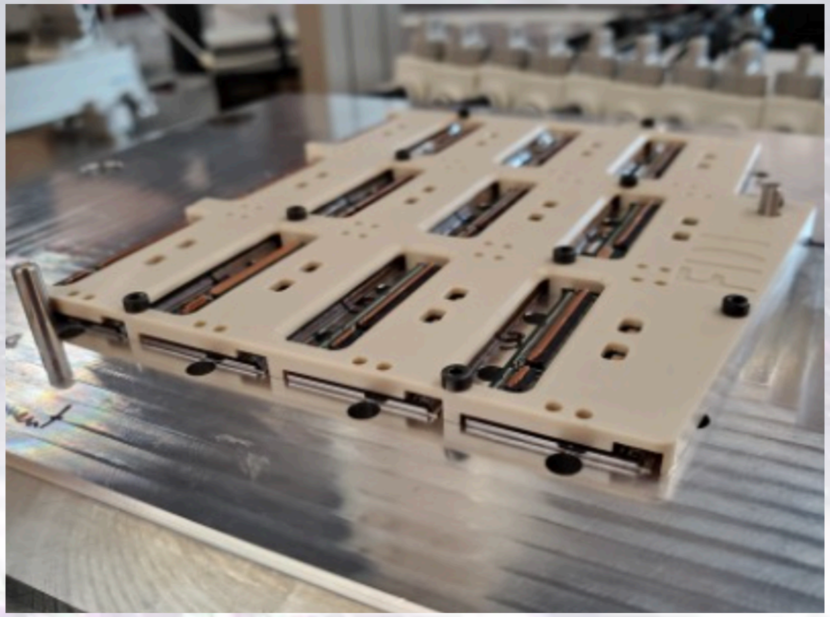
Module construction:

- bump-bonding sensor to asic
- wire-bonding two asics to module flex (distribution of power & control to asics, collection of digitised data, low-pass filtering of bias voltage)



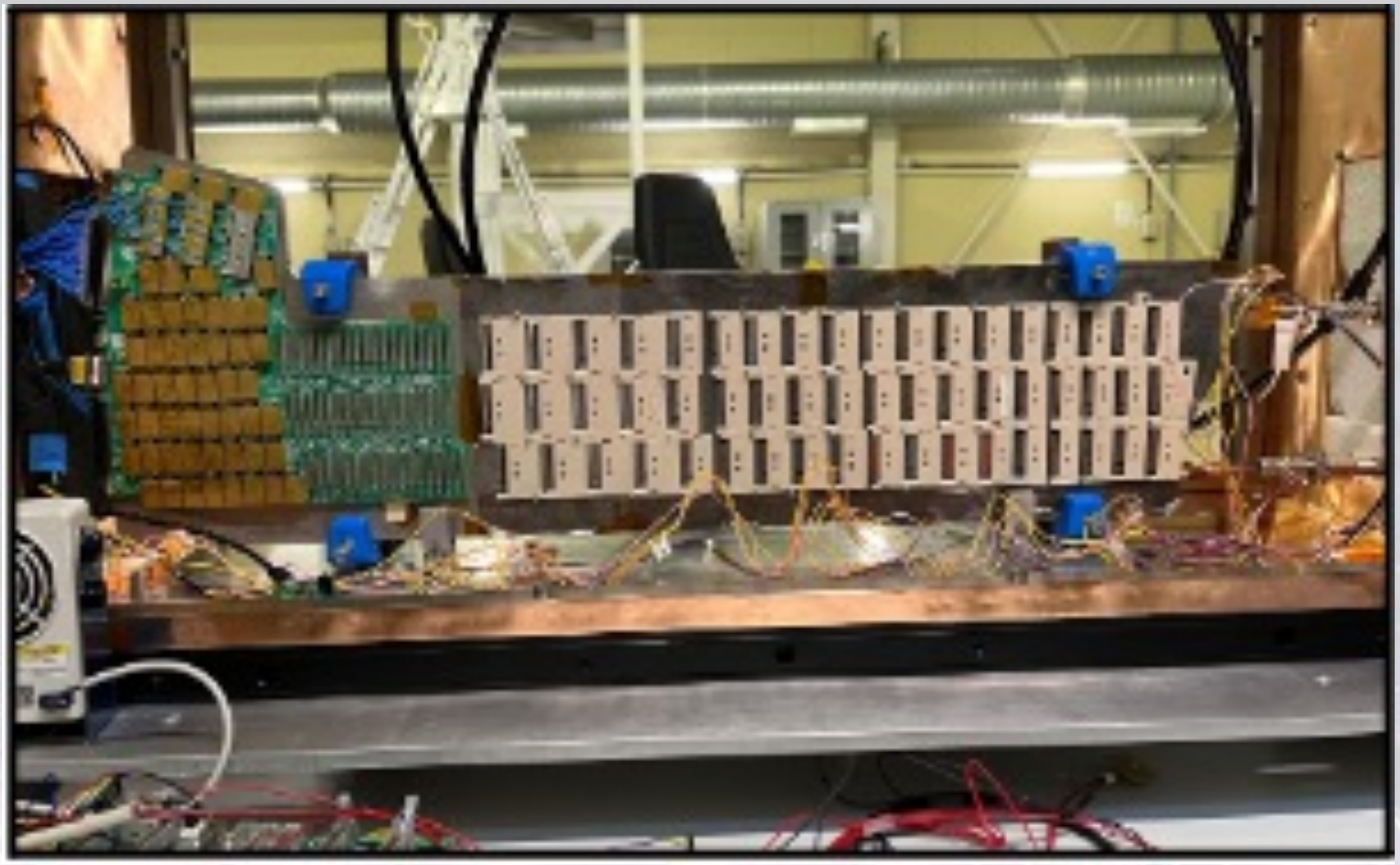
Detector Unit construction:

- mounting of individual modules under support structures
- completed DUs to be fixed to support disks (cooling plates)



Demonstrator & test beam efforts

Aim: first test of full system slice (LV + HV + PEB + ALTIROC2/3 DUs + cooling + preliminary detector control system) in cold box (T = -30 ˚C)



Preparing for second iteration in summer

- representative enclosure (Faraday cage), grounding & shielding tests, ALTIROC-A performance tests

To be followed by Module-0 construction (1/4 disk) in early 2026

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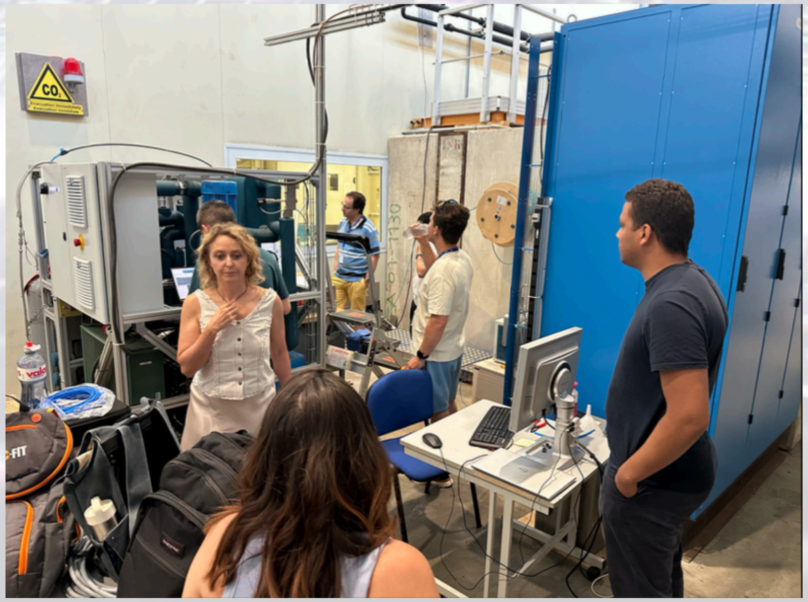
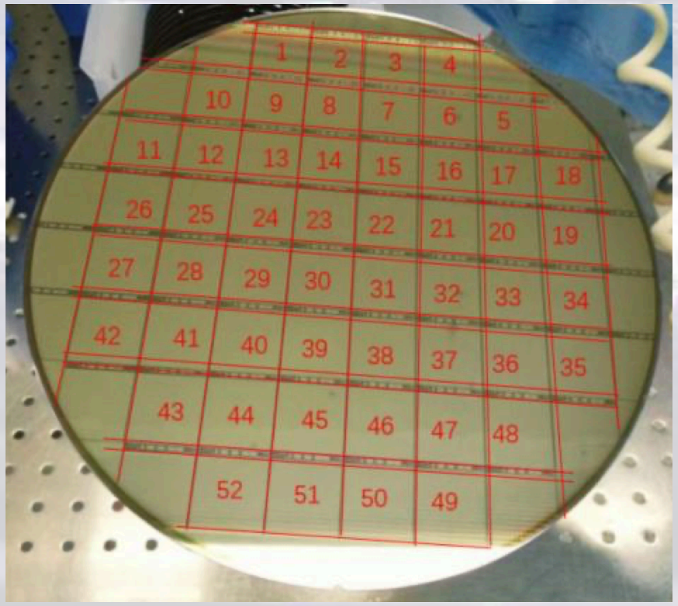
Conclusion & outlook

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
- also provides an independent measurement of bunch-by-bunch instantaneous luminosity

The project has mostly left its development stage, and has entered the (pre-)production stage for its critical elements: busy (construction) times ahead!

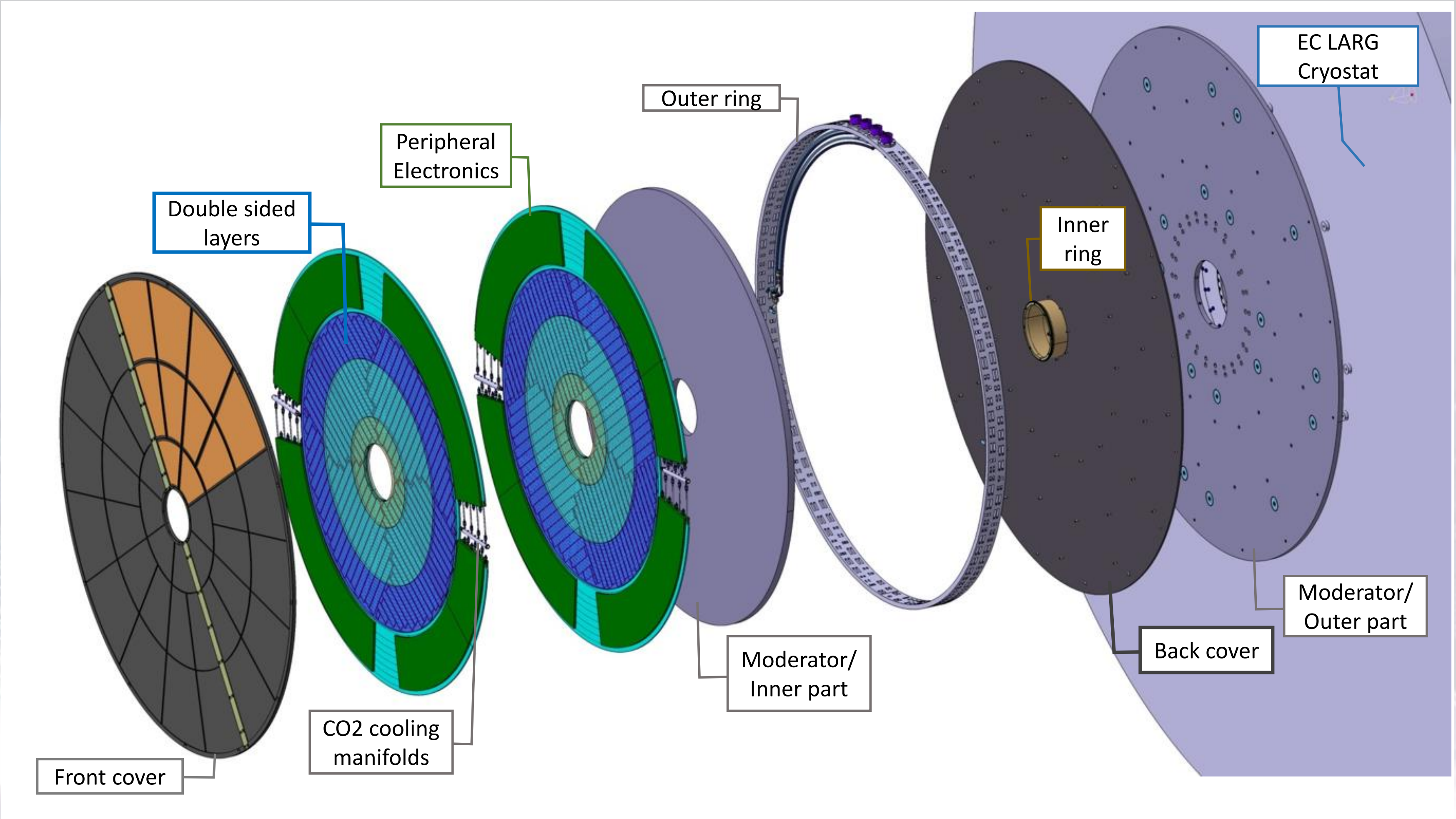




Bonus

HGTD in ATLAS

Assembly

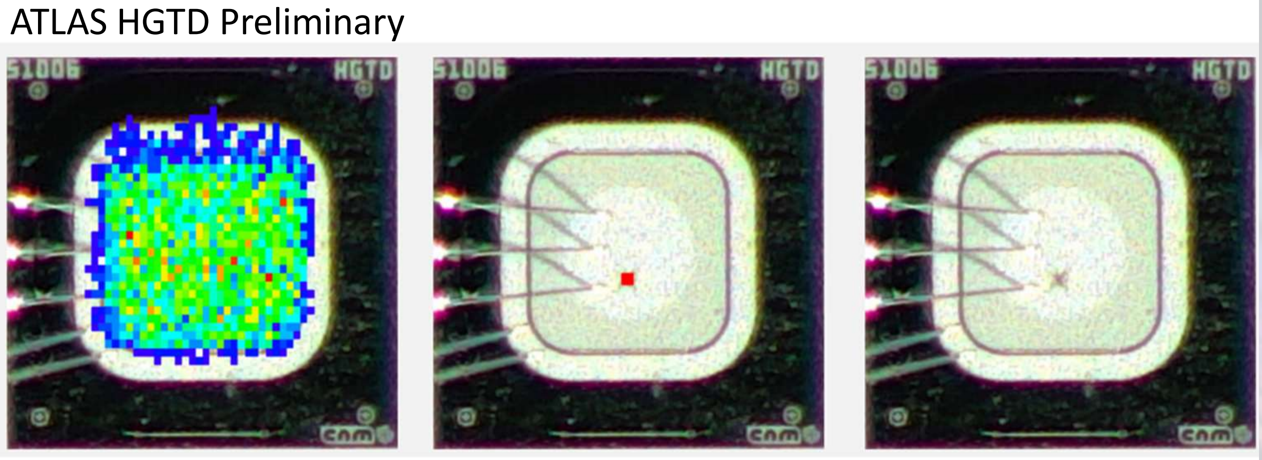


Single-Event Burnout

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

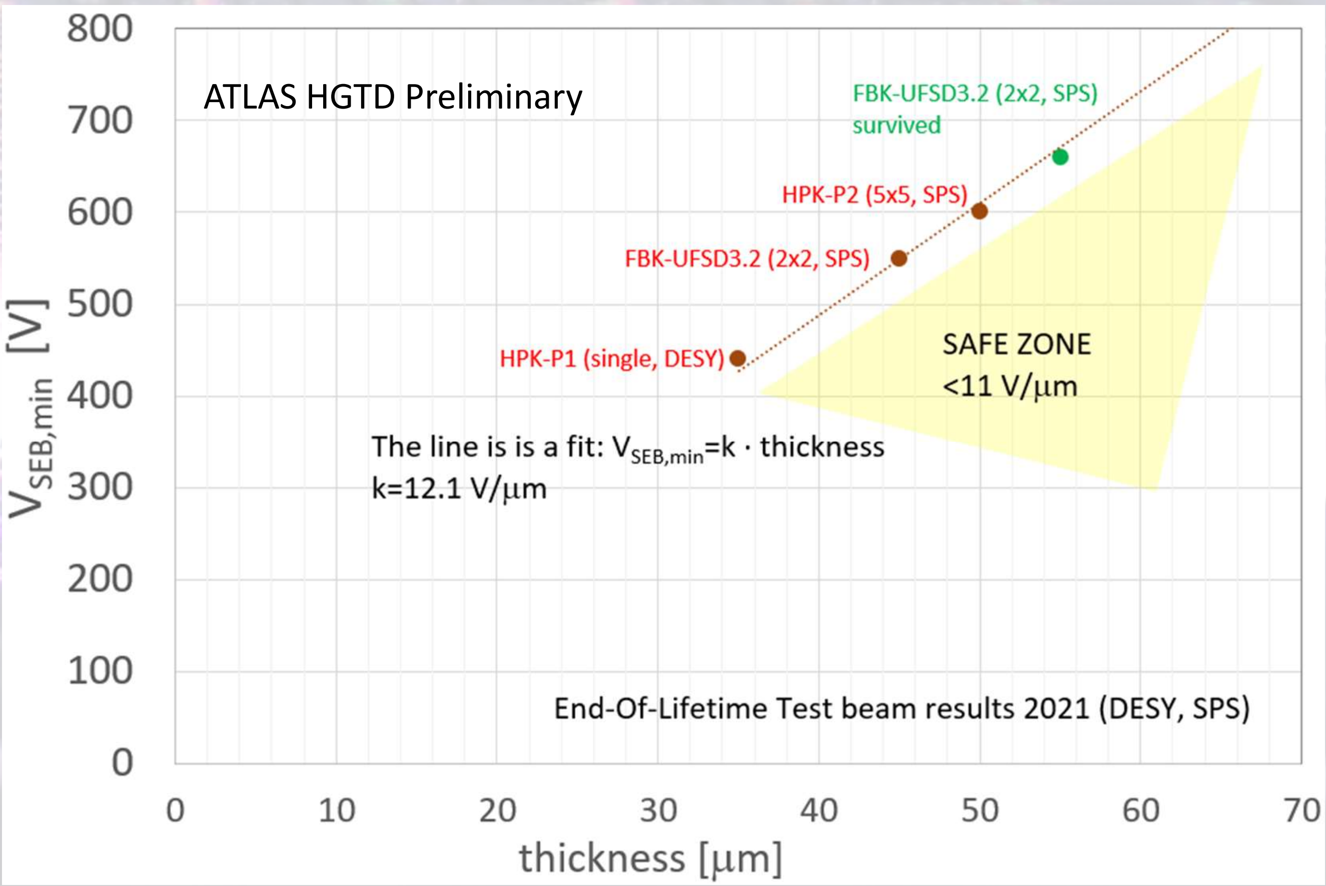
- associated with anomalously high energy deposits (Landau fluctuations) by *single* tracks

(2019 DESY TB: 5 GeV e^-)



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

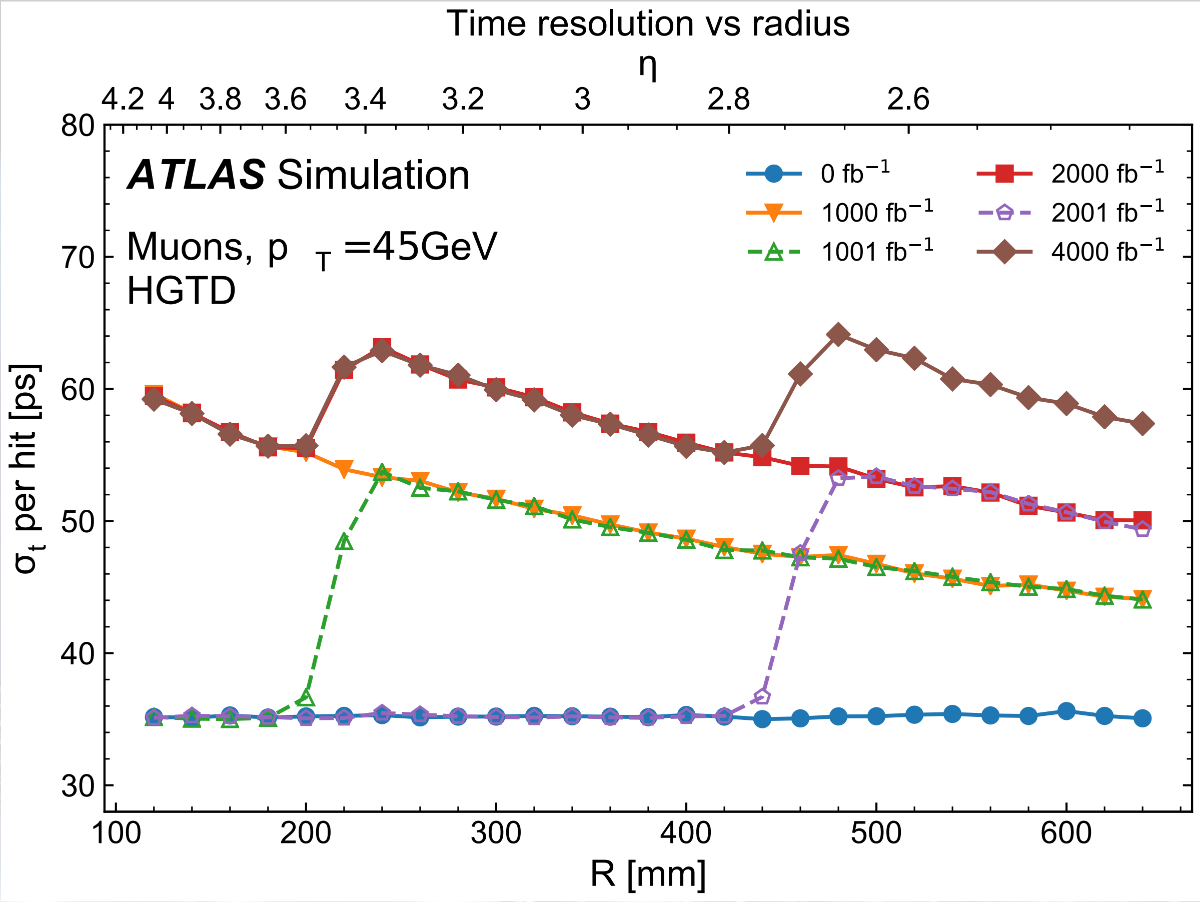
- ~ 80 sensors
- identified "safe zone" as having average electric field < 11 V/μm



Time resolution versus radius

Replacement plan (before elimination of long LS5)

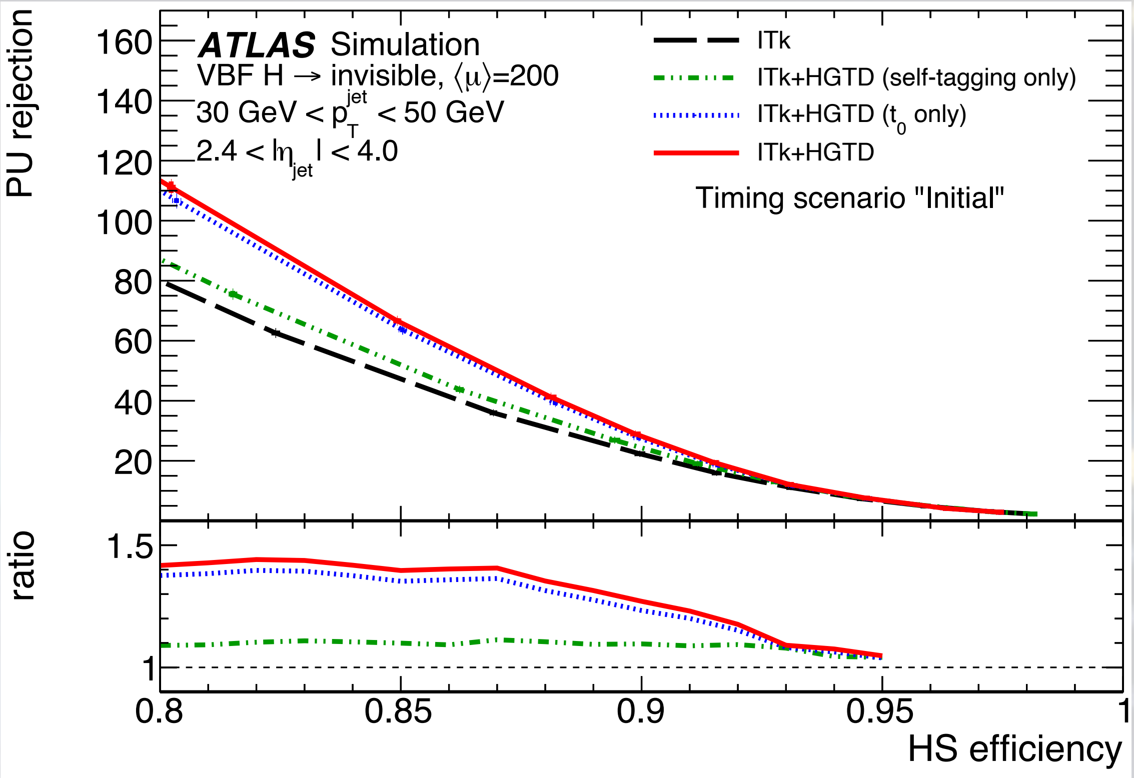
- innermost ring replaced after 1 ab^{-1}, 2 ab^{-1}
  - anticipate technology improvement
- middle ring replaced after 2 ab^{-1}

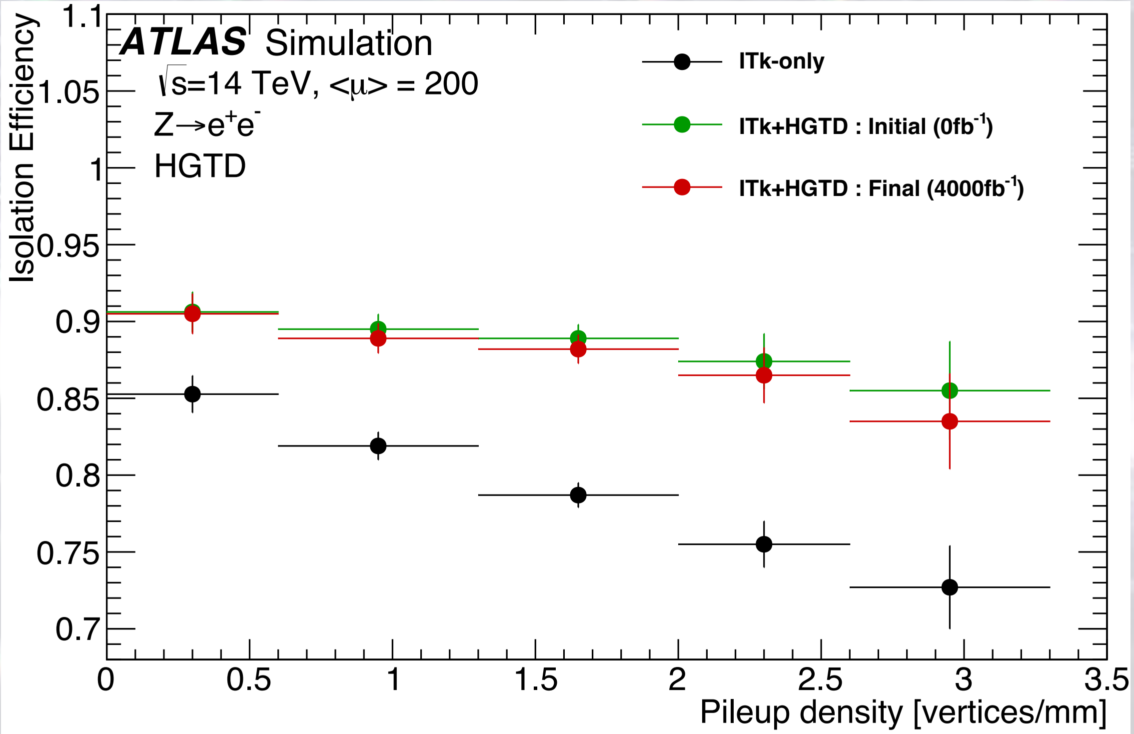


Present understanding:

- LS4 occurs after ~ 750 fb^{-1}
- replacement strategy to be revised

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