A High-Granularity Timing Detector (HGTD) for the Phase-II upgrade of ATLAS

Detector concept, description and R&D and first beam test results

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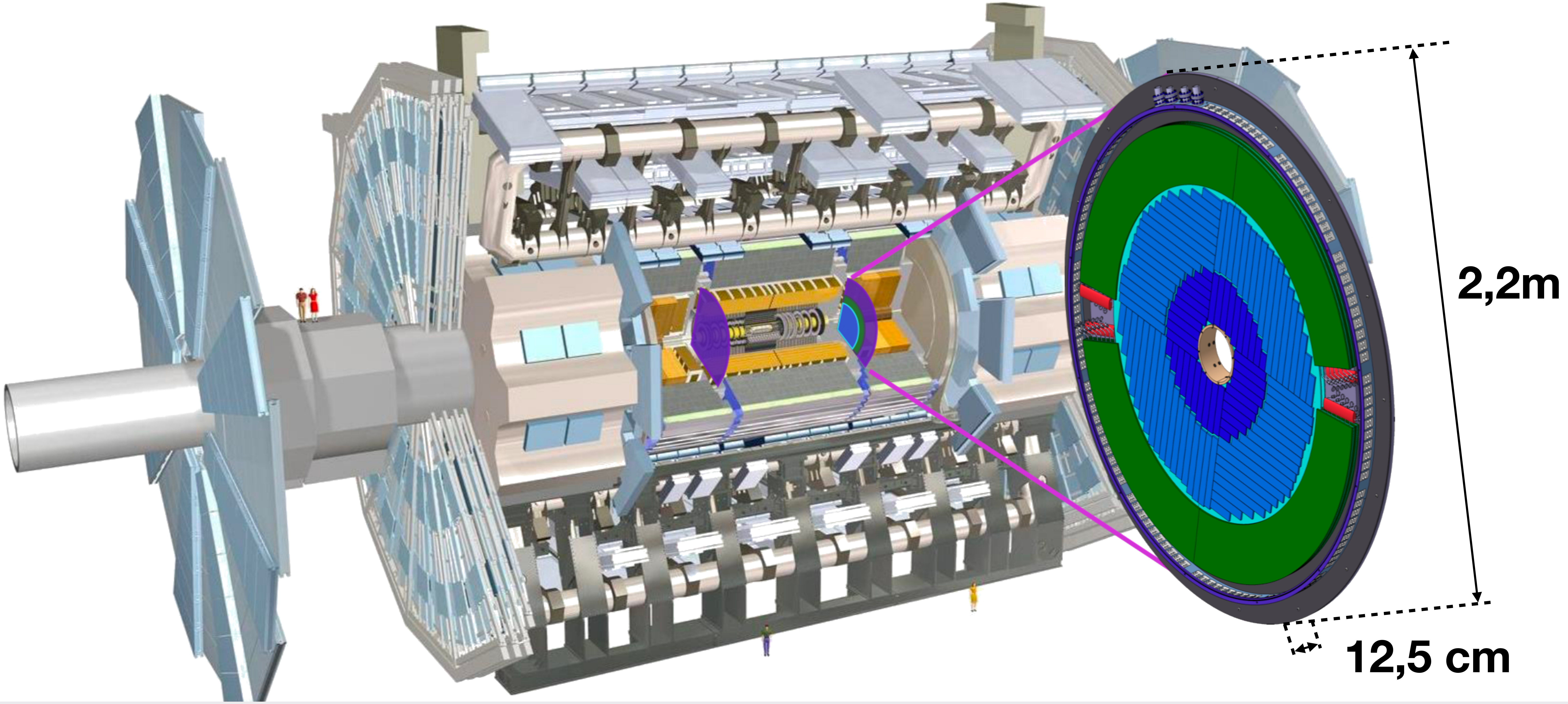
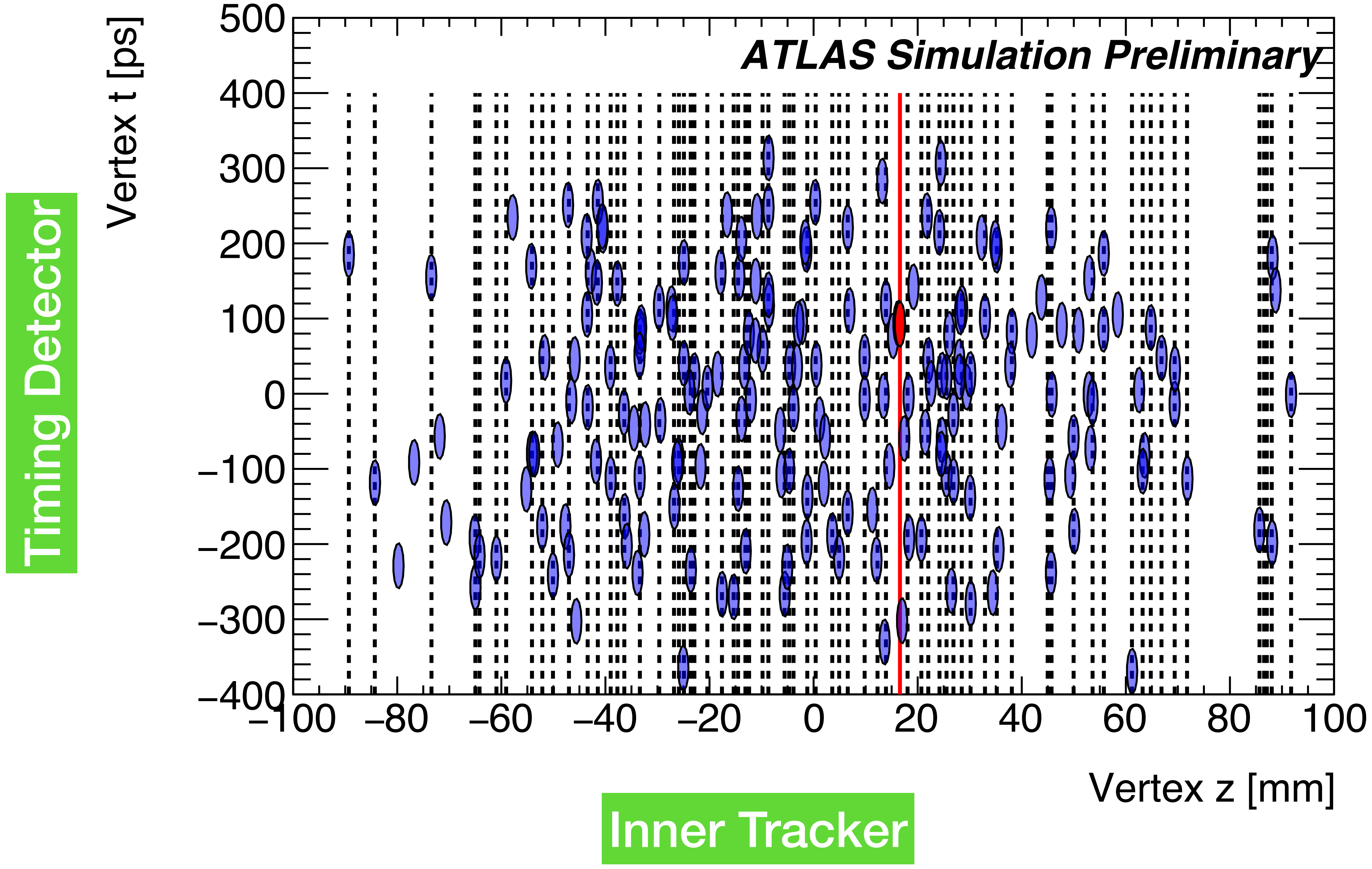
High-Granularity Timing Detector

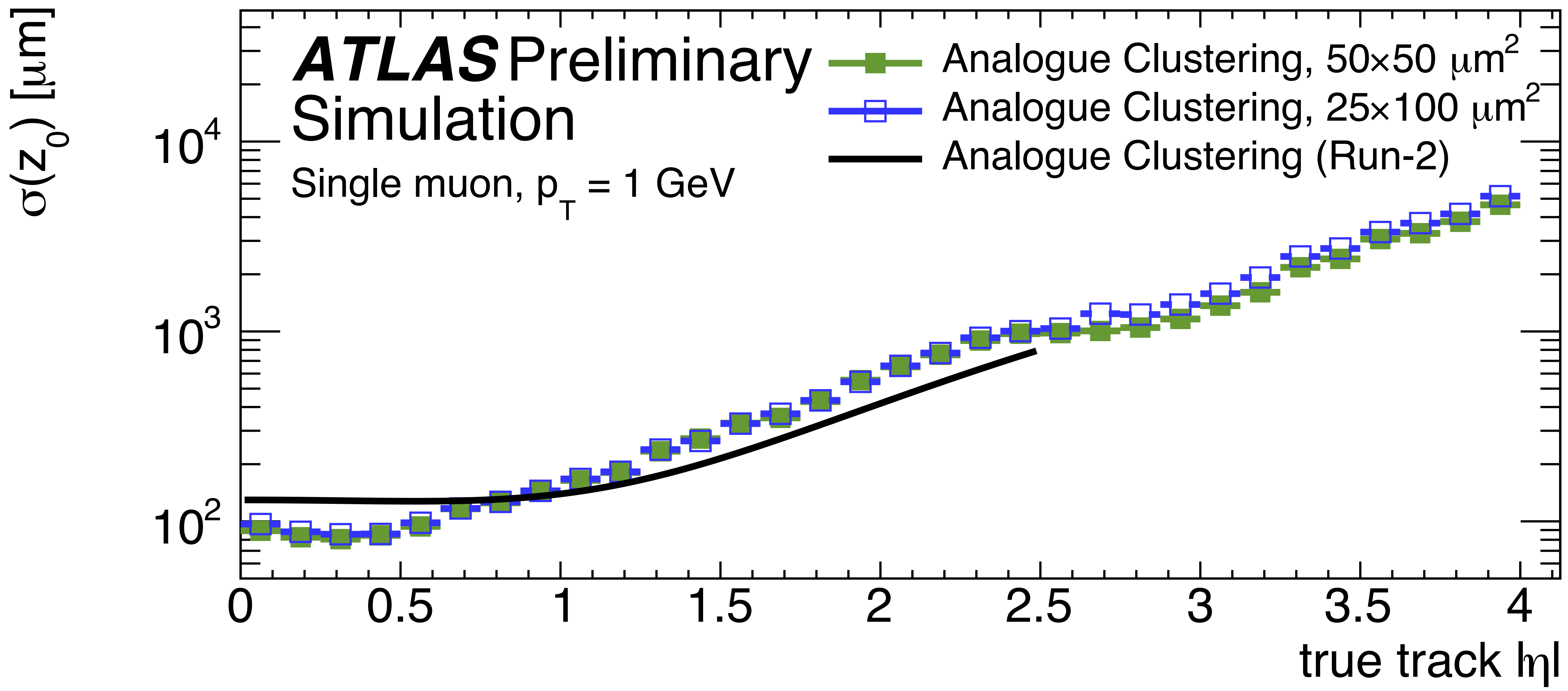
- ATLAS upgrade detector for the high luminosity - LHC
- uses LGAD sensors to measure time with **σ_t~30-50ps per track** until end of HL-LHC
- covers range **$2.4 \leq |\eta| \leq 4.0$**
- two disks positioned at z = ±3.5m from the interaction point



Motivation

- at HL-LHC (average pile-up (PU) of 200 p-p collisions per bunch crossing) expecting average vertex density of ~1.4 vertices/mm
- in very forward region track-vertex association with the inner tracker (ITk) alone becomes ambiguous
- HGTD takes advantage of spread in time of collisions (~180ps)





Basic idea:

★ Tag particle tracks with a time

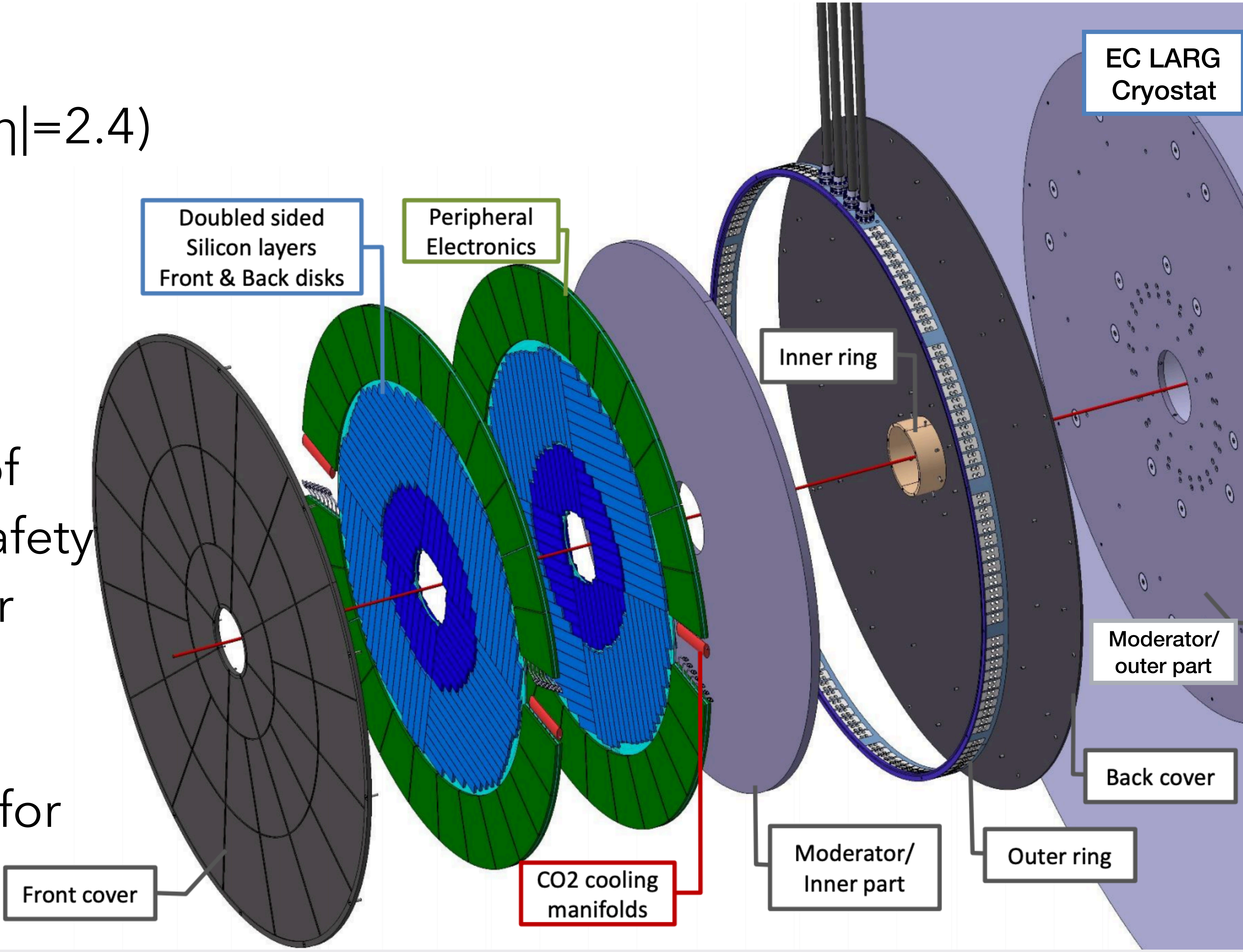
★ Assign a time to the HS interaction

★ **Remove tracks that are out of time** relative to this reference to *reduce pile-up*

★ application in PU-jet rejection, b-tagging, lepton isolation, …

Detector Layout - overview

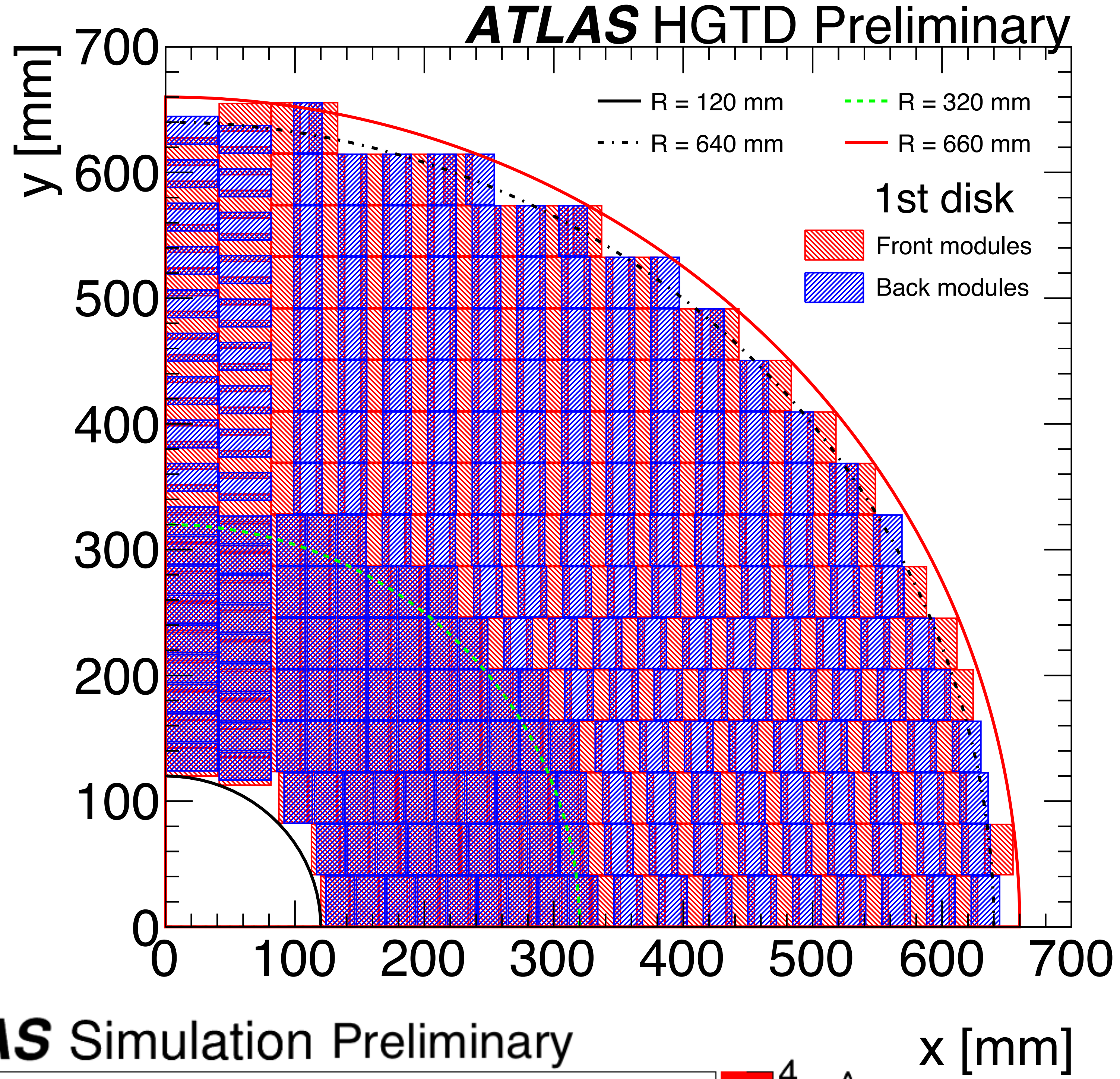
- active area:
  120 mm (|η|=4) < r < 640 mm (|η|=2.4)
- overall thickness of **12.5 cm**
- **3.59 M** channels
- active area 6.4 m^2
- occupancy <10%
- max. expected radiation levels of **5.1×10^{15} n_{eq}/cm^2** (including safety factors and replacement of inner ring at 2000 fb-1)
- N_{hits} transmitted in reduced eta range (2.4 < |η| < 3.1) at 40MHz for online luminosity measurement



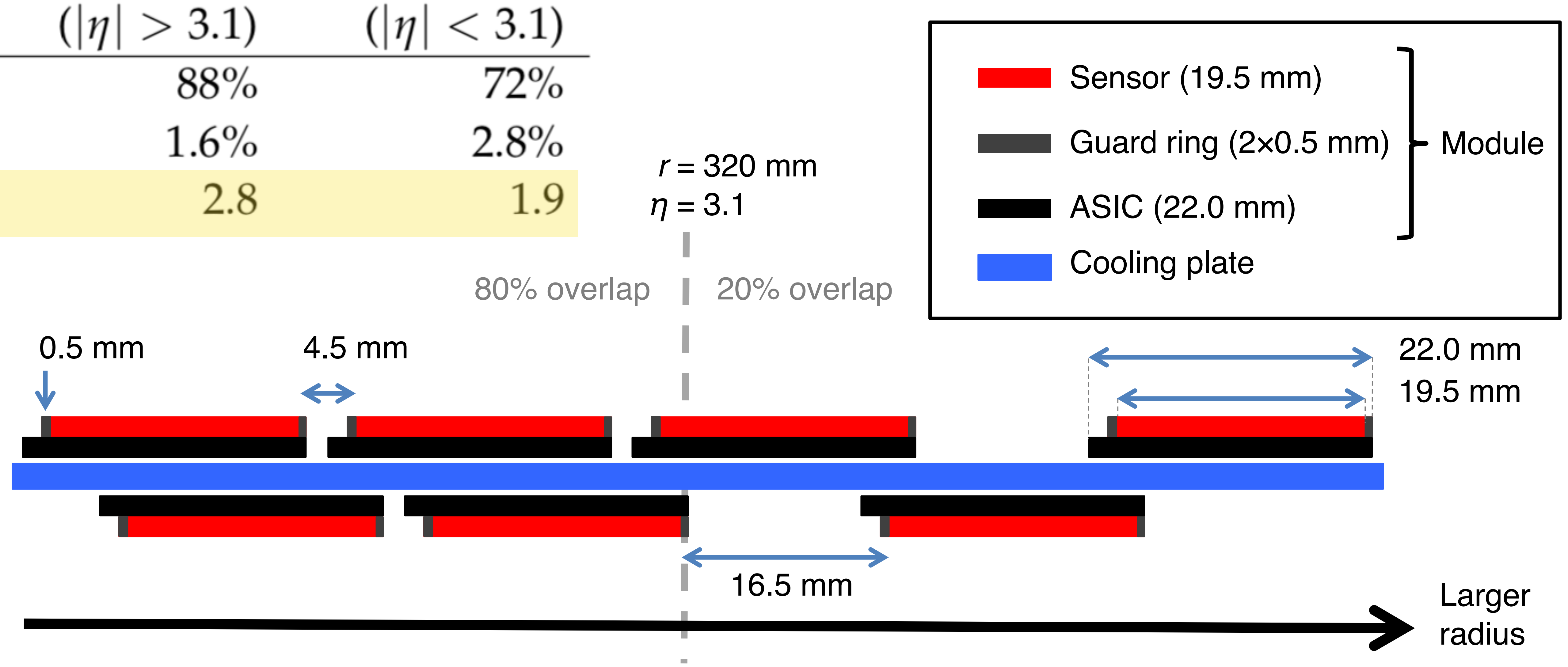
Detector Layout - active area

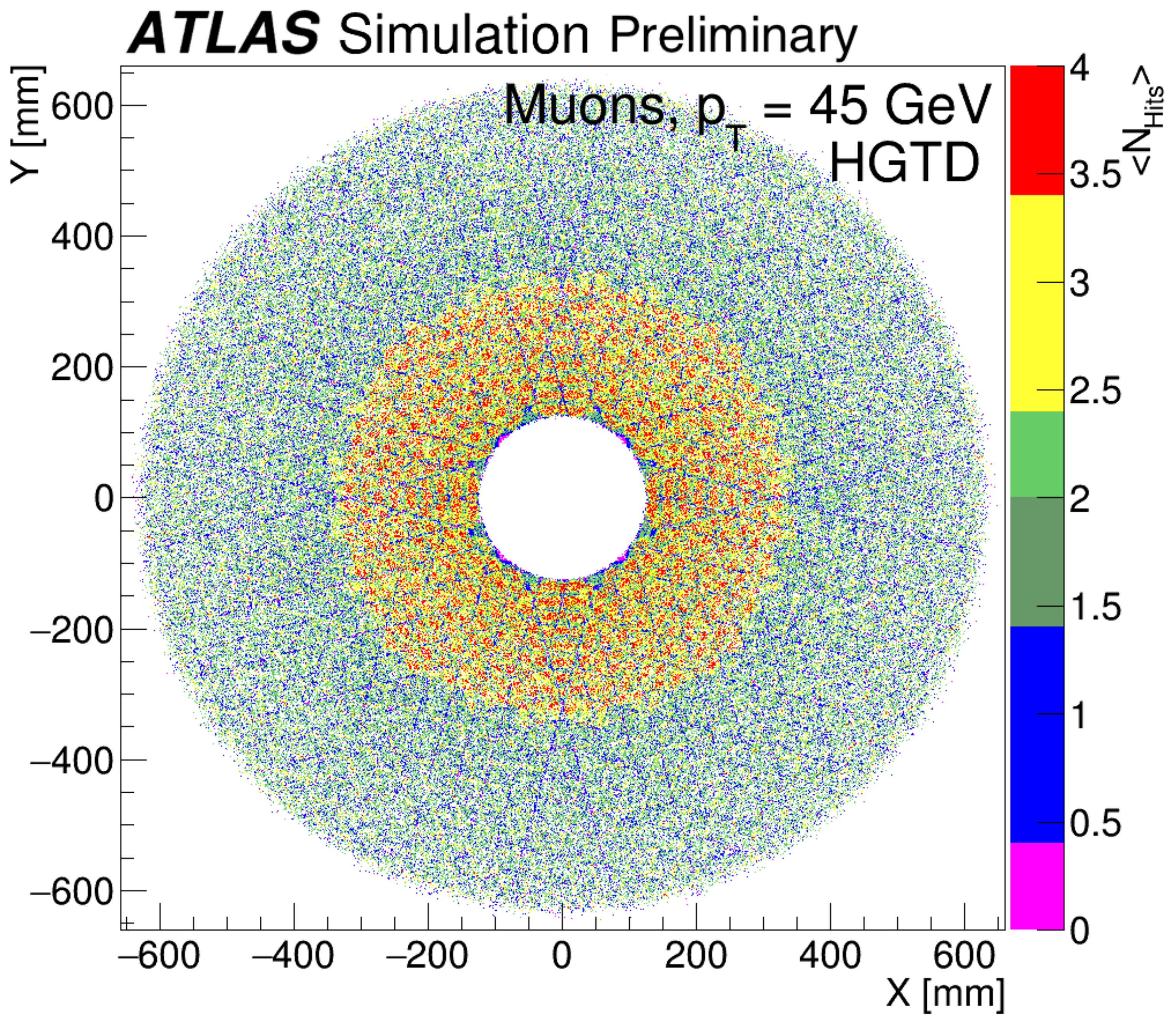
- detector consists of two double sided layers in each end cap
- overlap of sensors on the front- and backside of the respective layers of 80% (20%) for |η|>3.1 (|η|<3.1)

- time resolution of **σ_t ~ 40-85 ps per hit** until end of HL-LHC
- track time resolution target requires 2 hits per track on average
- better coverage and more homogeneous response achieved by rotating layers by 15° in opposite direction



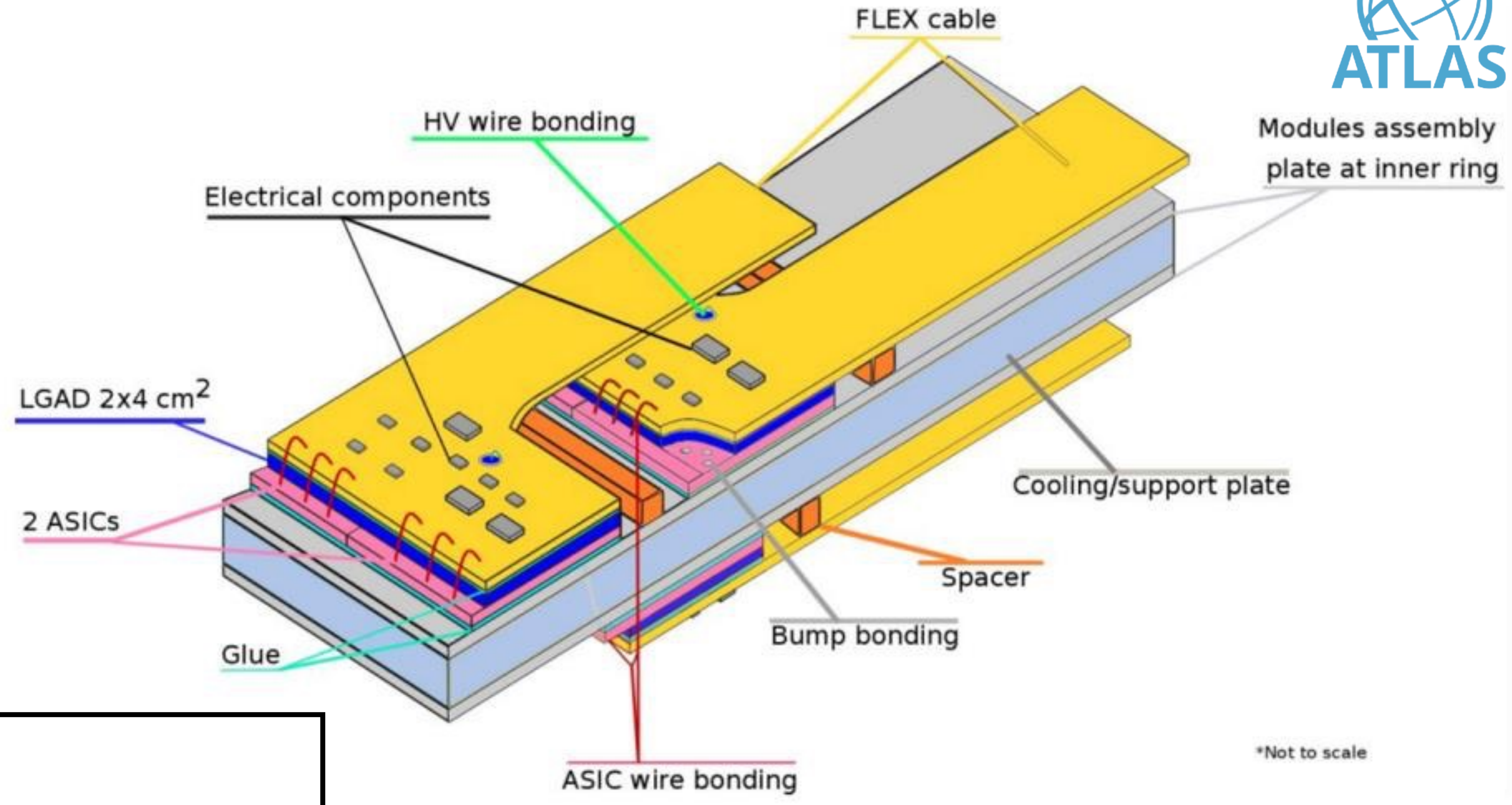
	$R < 320$ mm ($\lvert\eta\rvert > 3.1$)	$R > 320$ mm ($\lvert\eta\rvert < 3.1$)
$N_{hits} \geq 2$	88%	72%
$N_{hits} = 0$	1.6%	2.8%
$\langle N_{hits} \rangle$	2.8	1.9





Modules

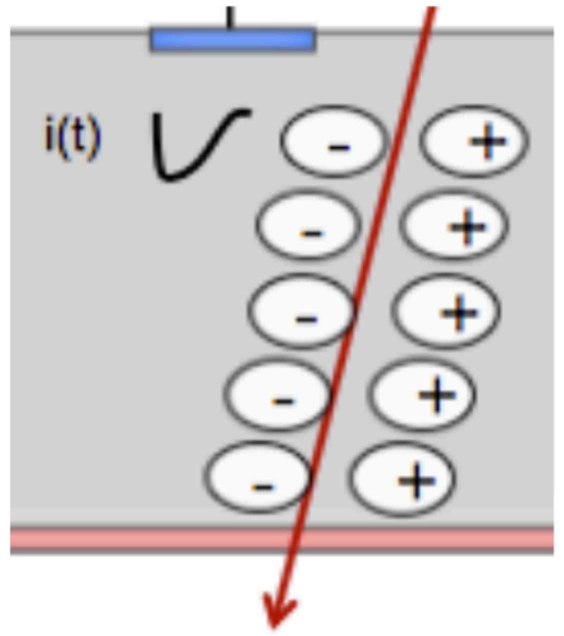
- 1 **LGAD** sensor
- 2 **ALTIROC** readout chips bump bonded to sensor
- 1 **FLEX** cable glued to bare module, wire-bonded to ASIC (signals, low and high voltage)



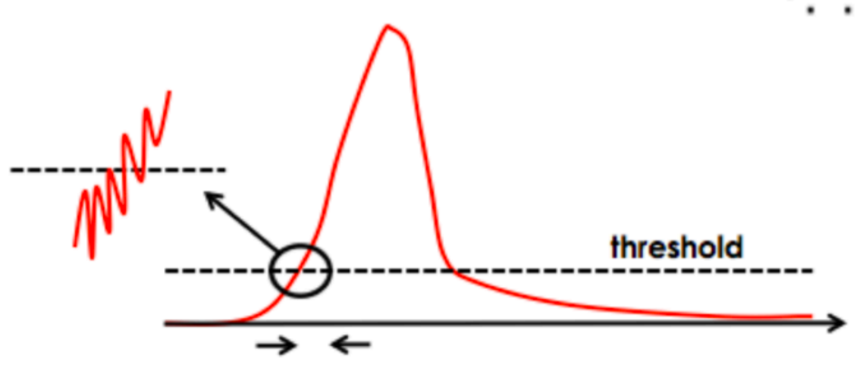
overview of contributions to the time resolution:

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

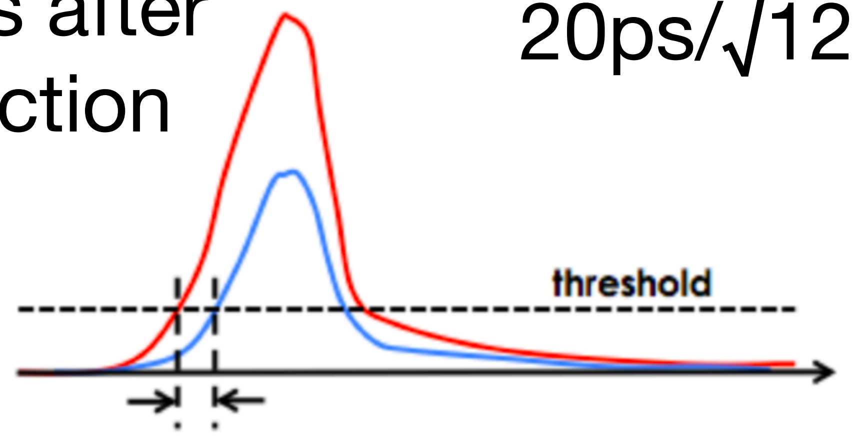
~25 ps (thin sensor)



<25 ps at large gain



<10 ps after correction



bin width, 20ps/√12

from clock distribution, <10ps

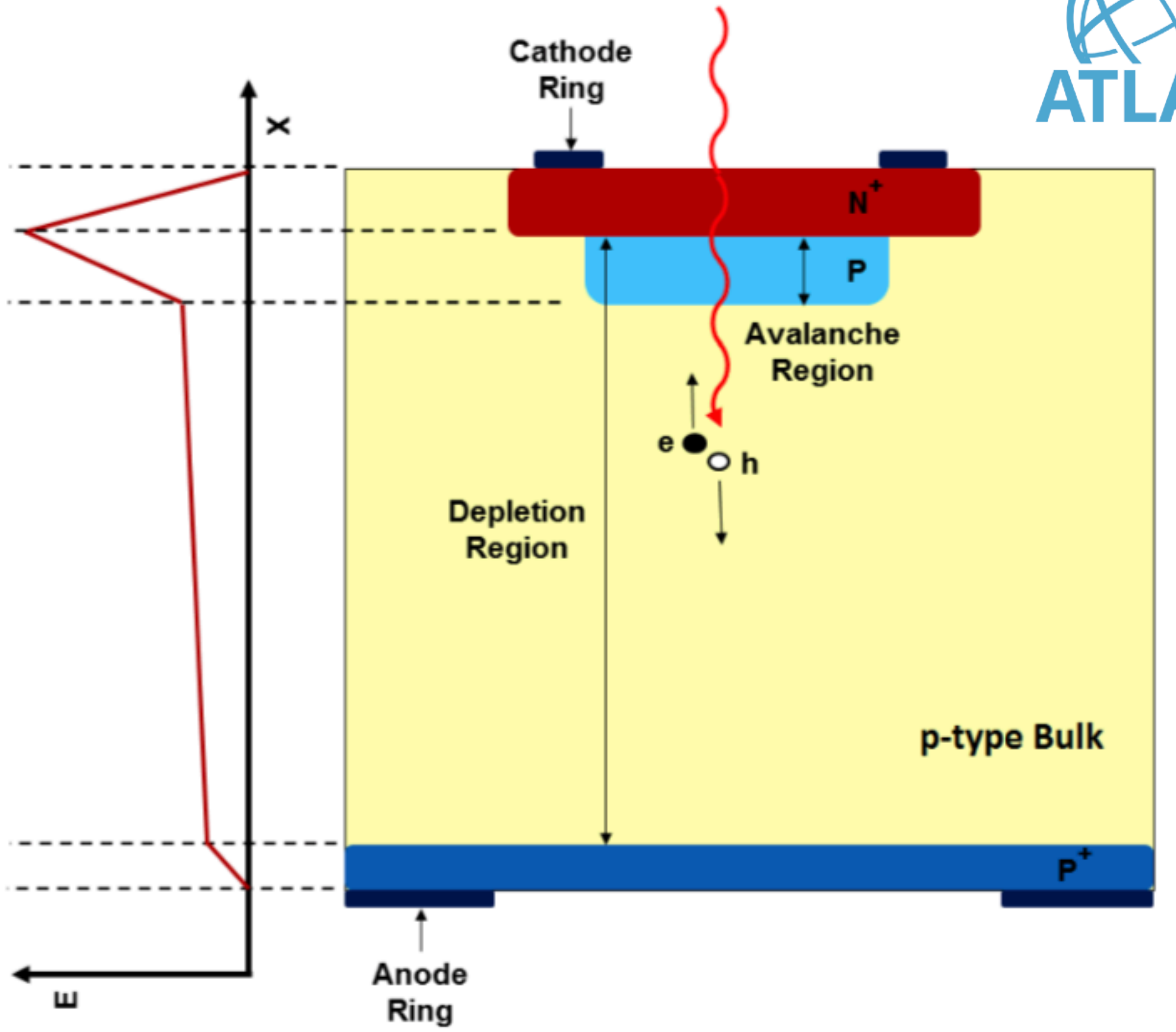
- **7984** modules
- total thickness of ~1mm
- glued to support plates (staves and rings)
- plates screwed to cooling plate

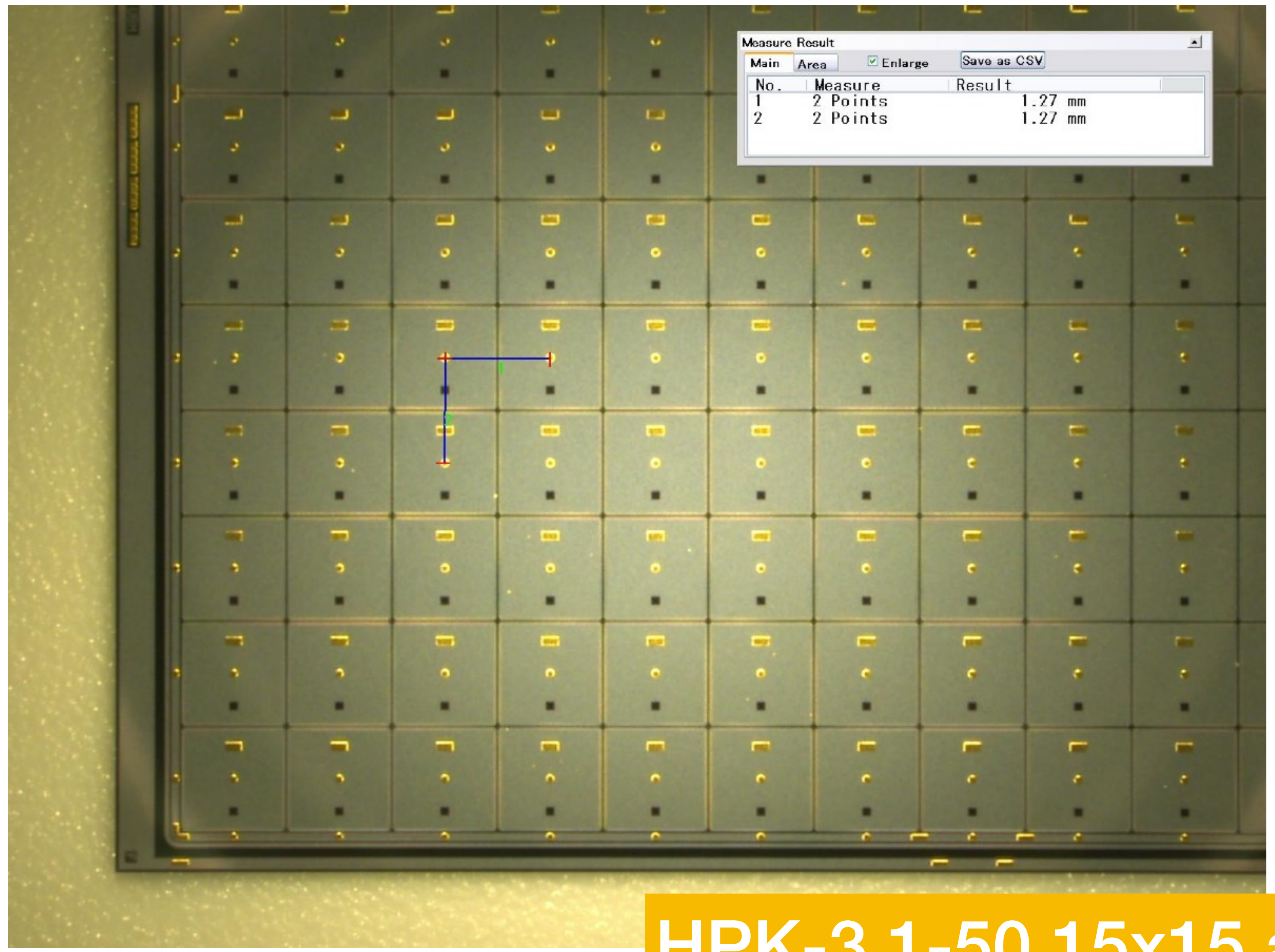
Sensor (LGAD)

- Low Gain Avalanche Detector
- n-on-p silicon detector with extra highly doped p-layer
  ↠ internal amplification

- sensor size of **2x4 cm²**
- per sensor **450** pixels with a pitch size of **1.3x1.3 mm²**
- Thickness of <300 μm, active thickness of 50 μm
- allows for a **gain of 20** before irradiation

- target time resolution **σ_t < 40ps** at start of operations, and **70-85** ps at end of lifetime
- sustain radiation levels of up to **5.1 x 10^{15} n_{eq}/cm^2**
- maximum leakage current of 5 μA



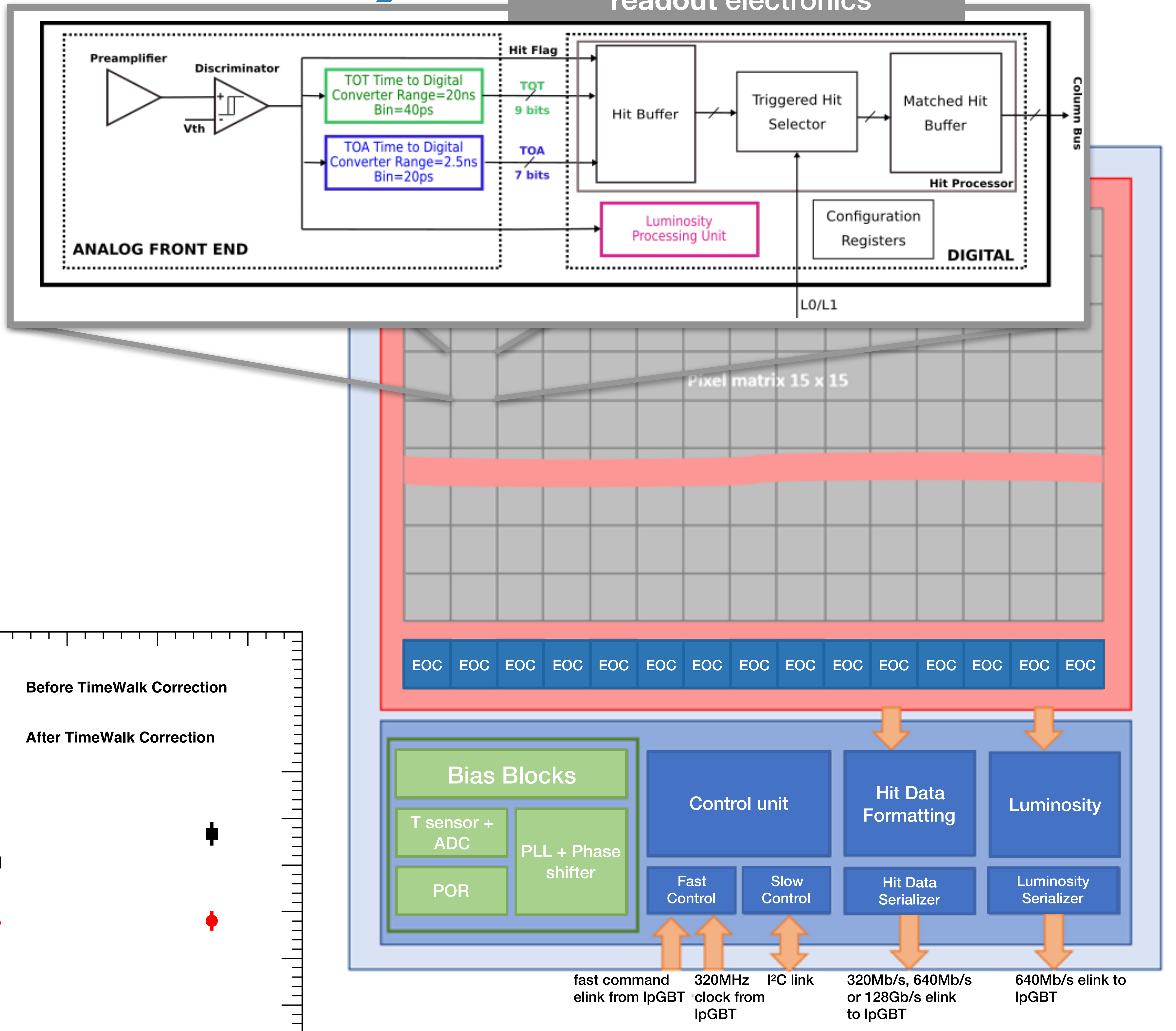

HPK-3.1-50 15x15 array

Front-end ASIC (ALTIROC)

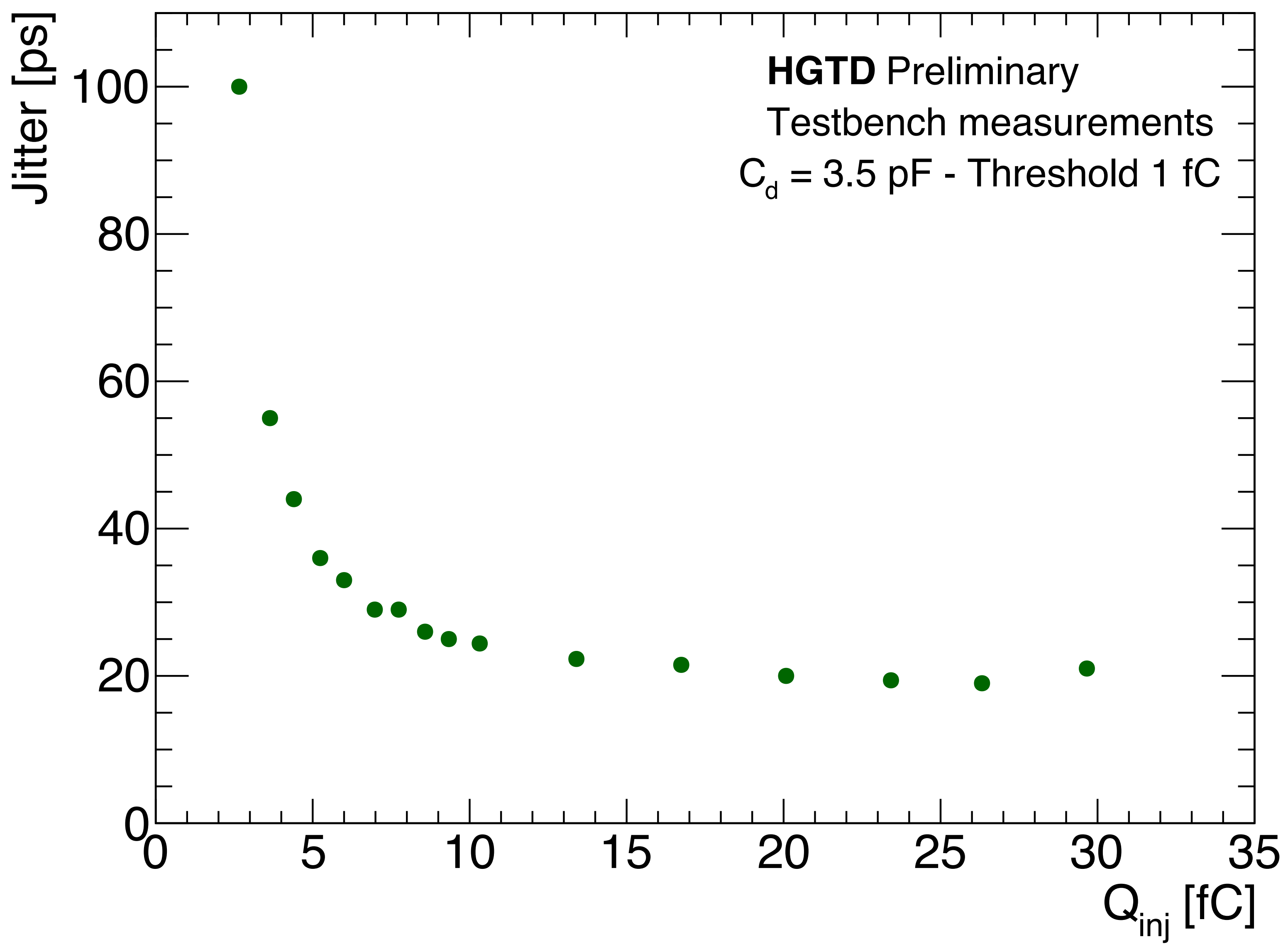
- 225 readout channels per ASIC , 2 ASICs per module
- bump bonded to LGAD sensor
- sends digitised output to peripheral electronics

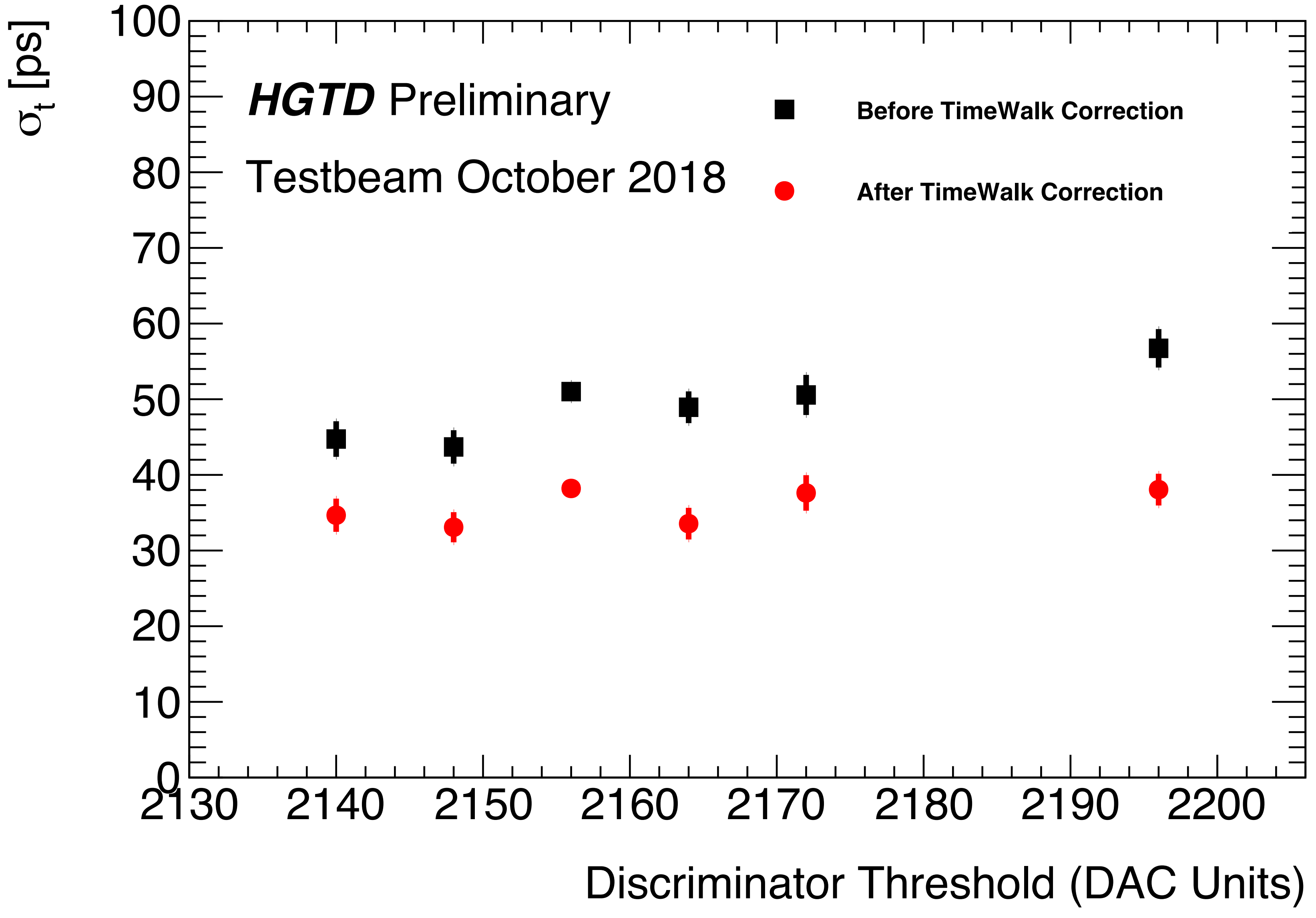
- measures **time of arrival** (TOA), **time over threshold** (TOT) and **number of hits**

Schematic of the single-channel readout electronics



common digital part: transmit digitized data, receive slow control, generate and align clocks





Sensor performance

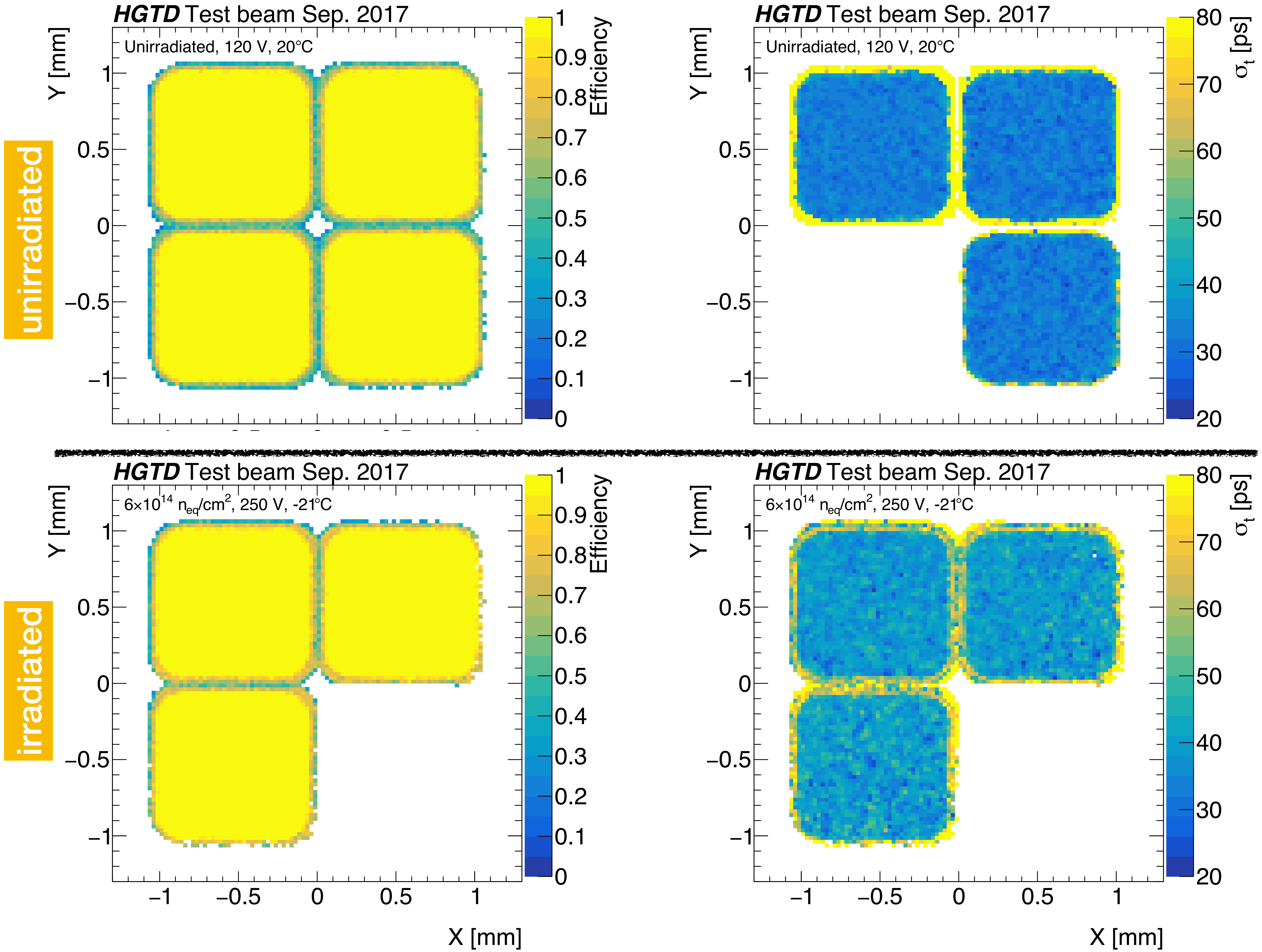
2D maps showing efficiency and time resolution before and after irradiation

in pad center:

<eff>$_{unirr}$ ~ 99%

<eff>$_{irr}$ > 95%

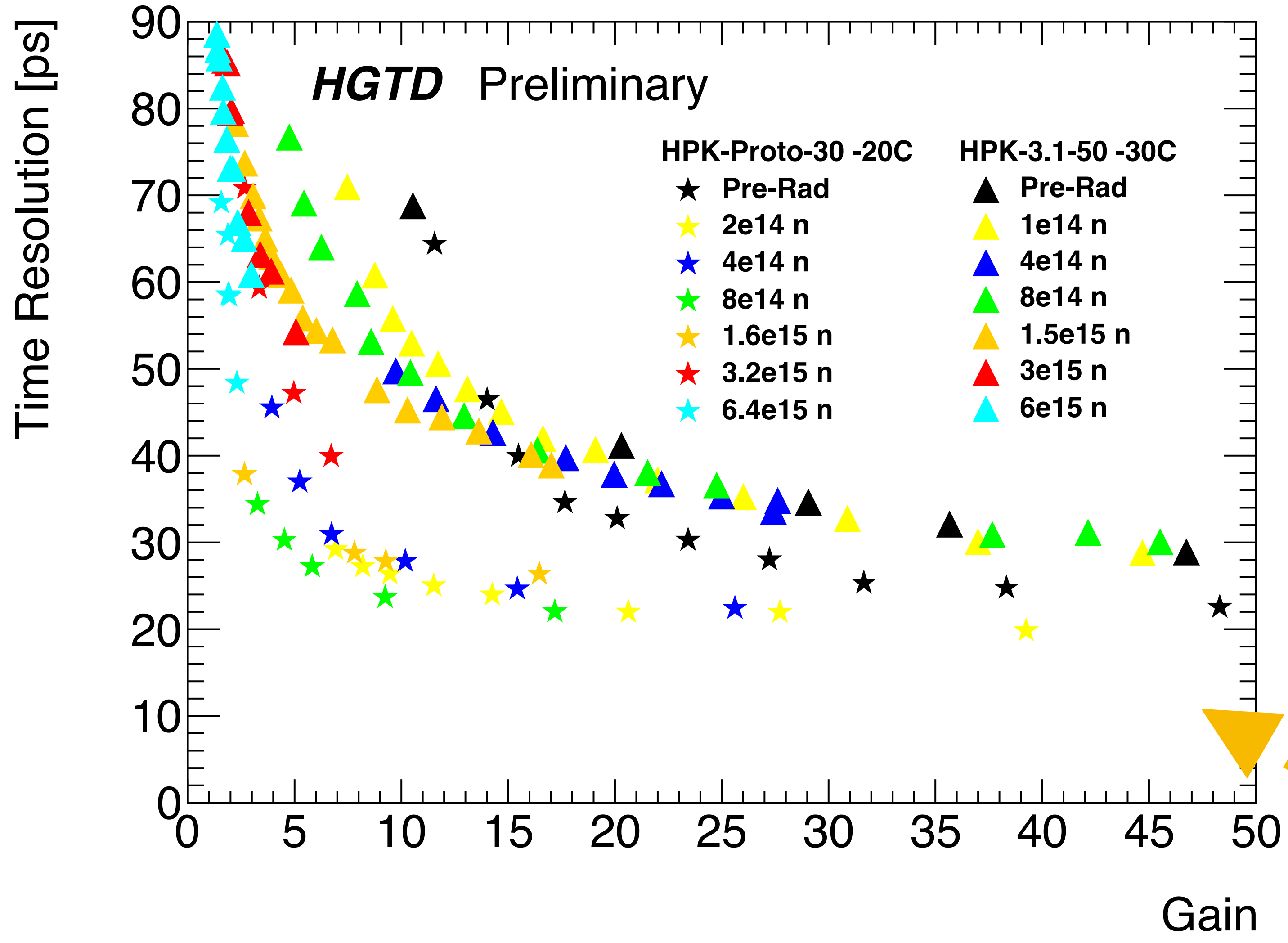
very homogeneous time resolution over the sensor pad

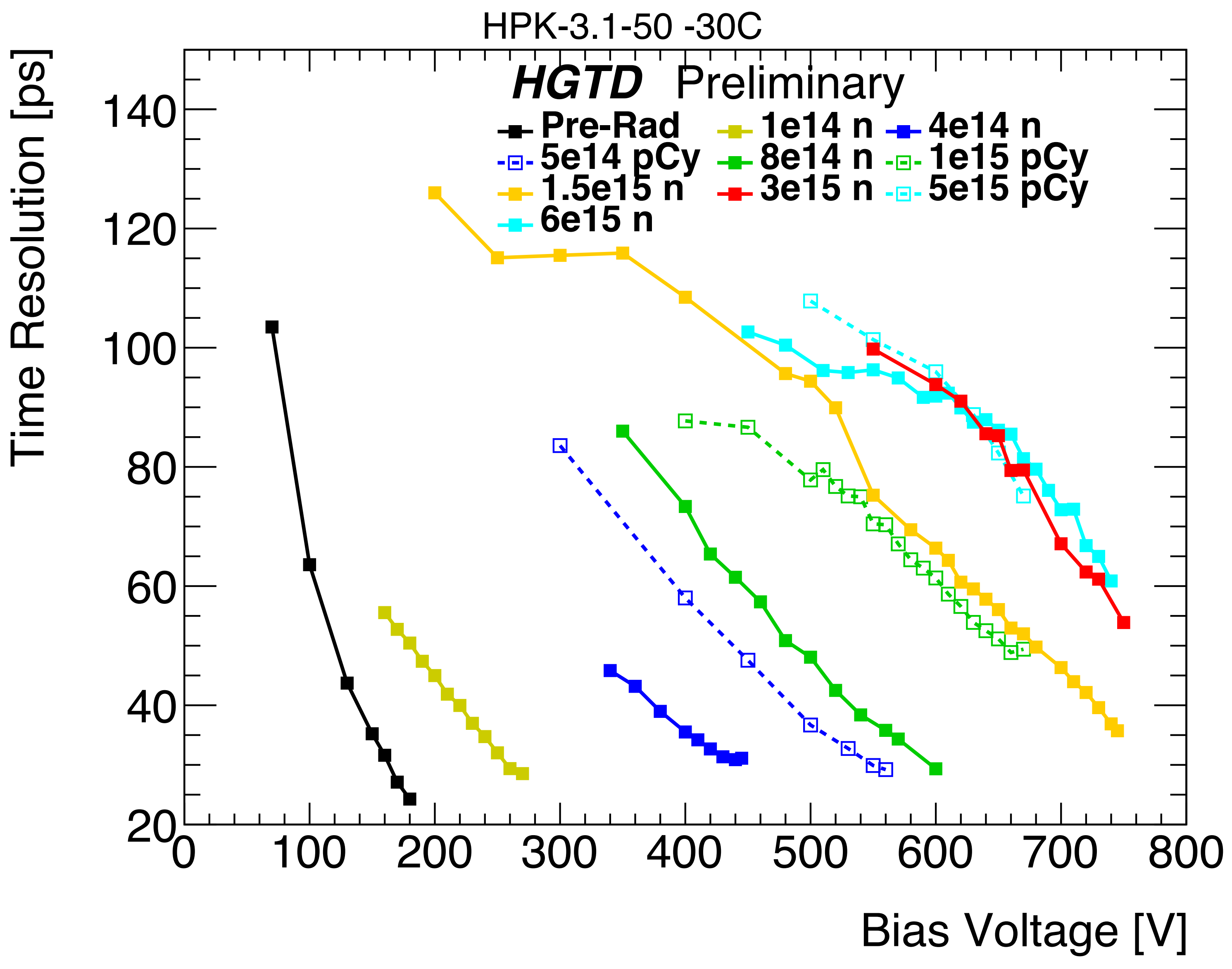


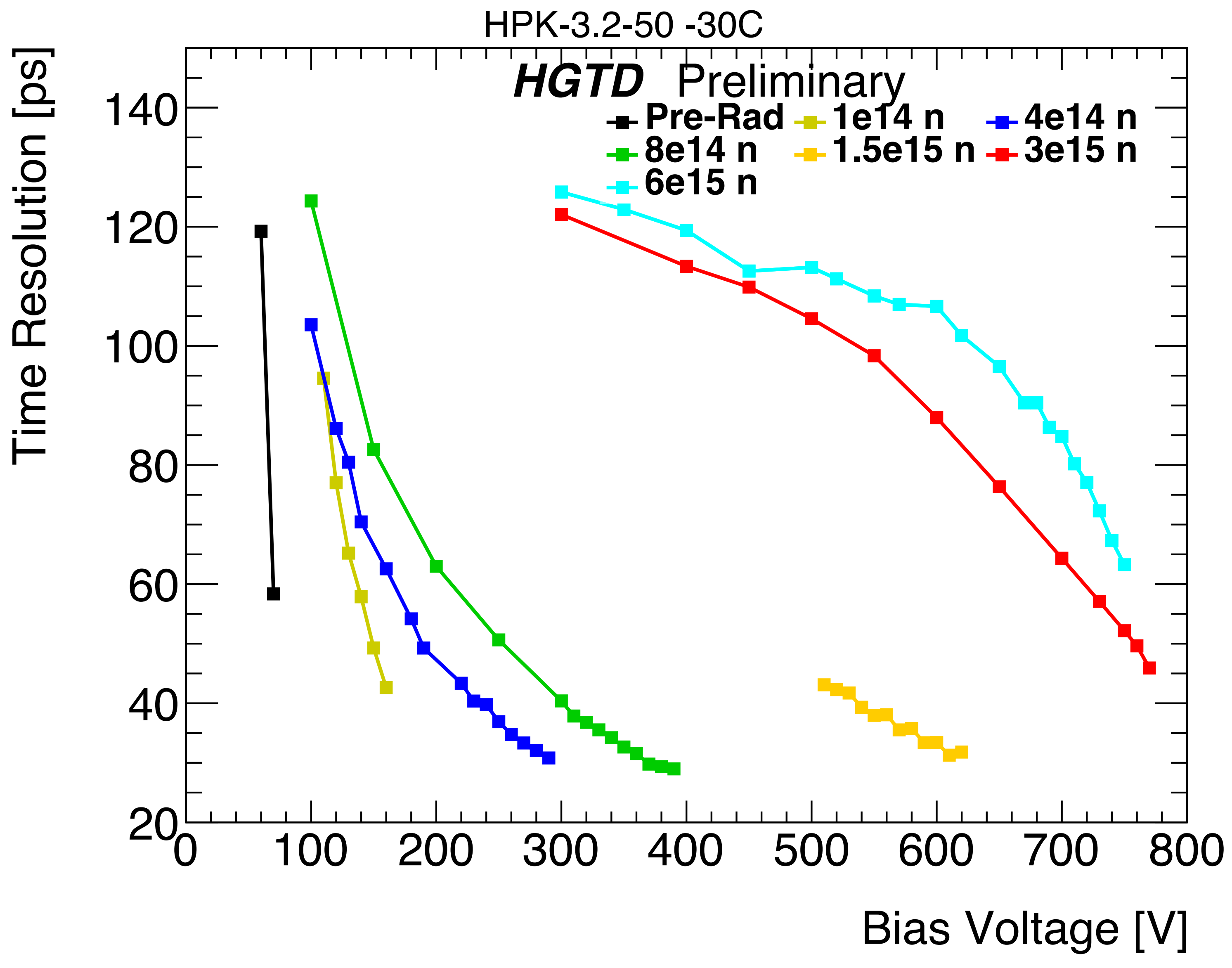
Time resolution

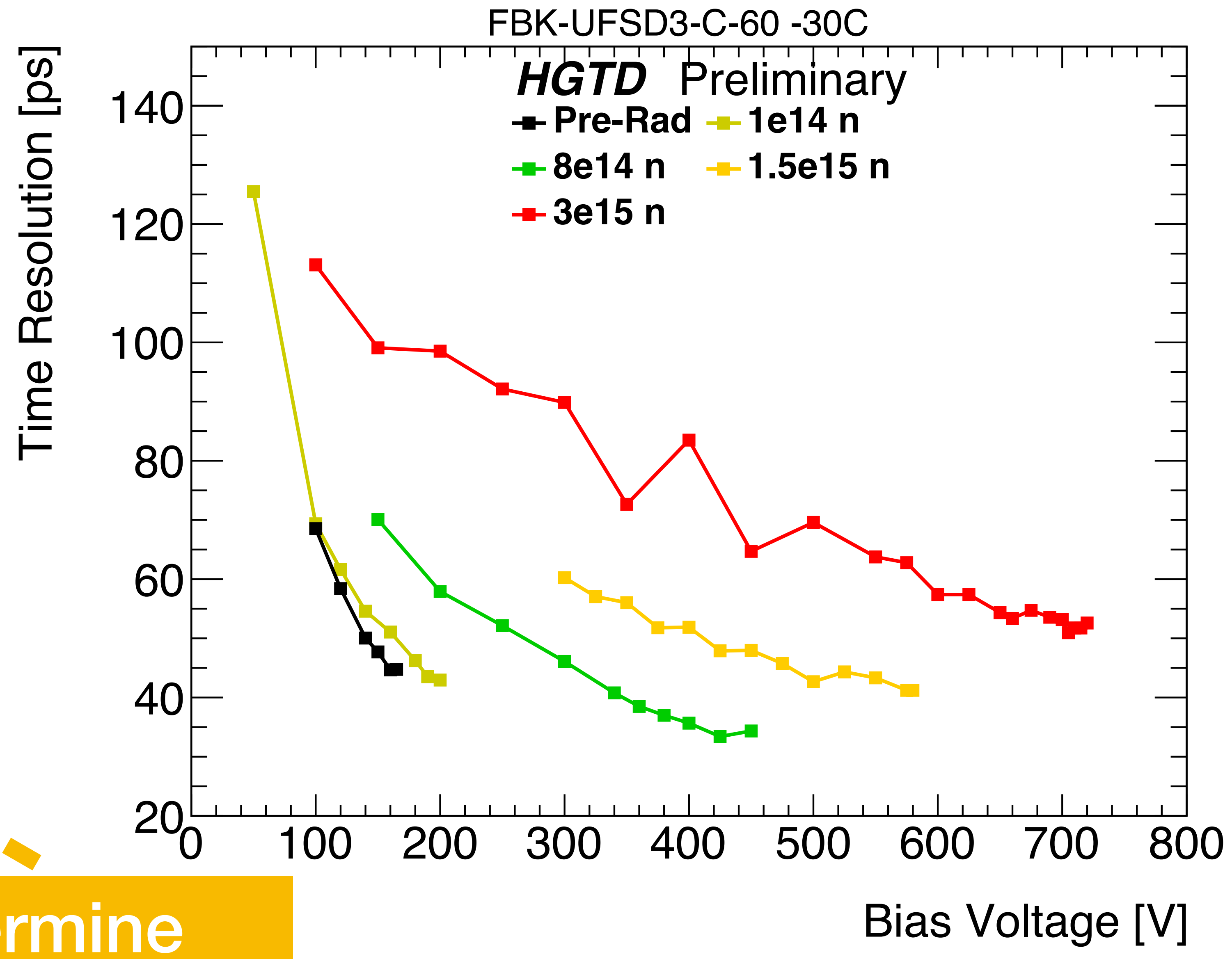
σ_t depending on the bias voltage for *different fluence* levels (4 different sensors)

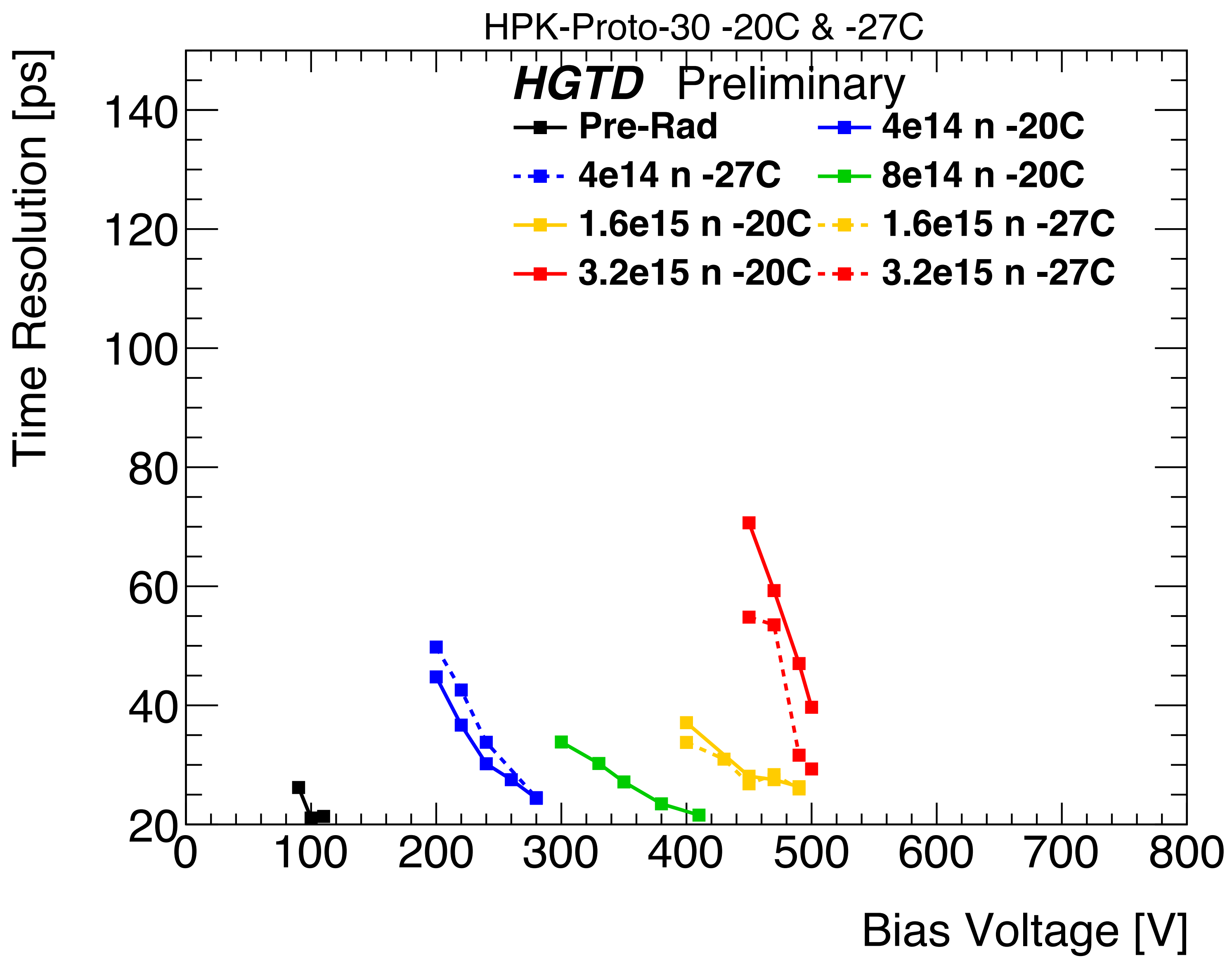
can achieve σ_t < 35 ps up to $1.5\times10^{15}\ n_{eq}/cm^2$







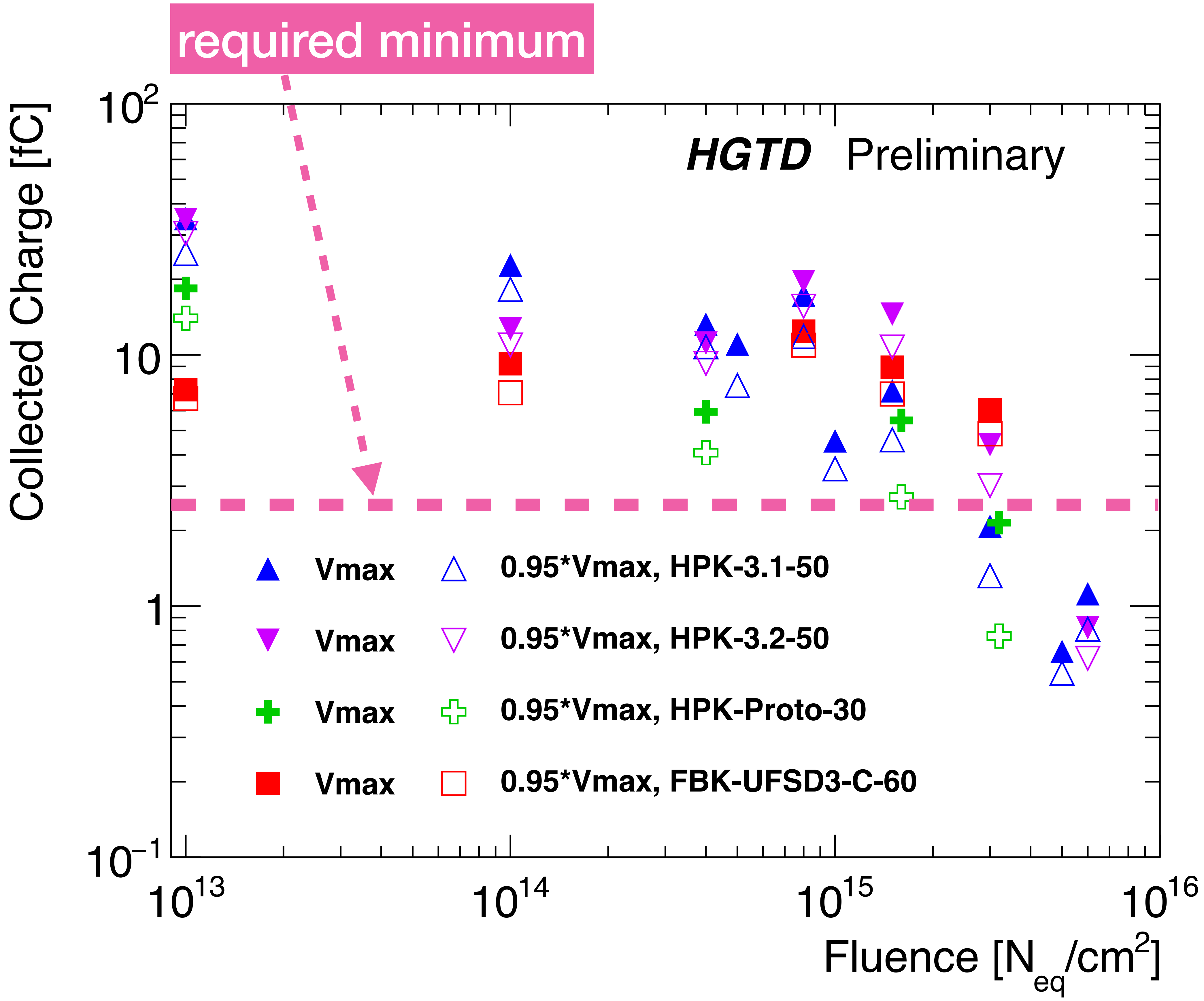


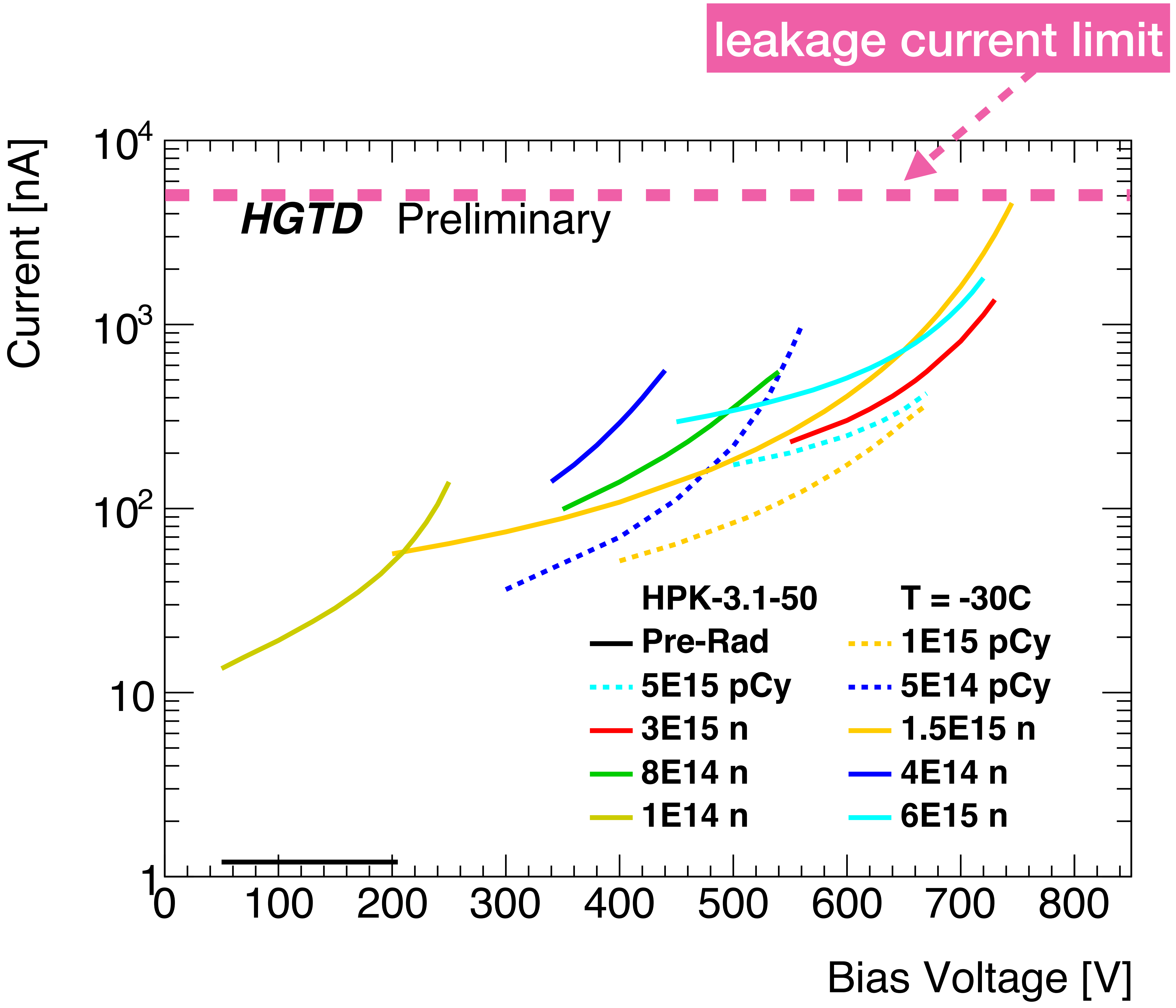


Landau fluctuations determine maximum reachable time resolution

Collected charge and leakage current

- minimum required collected charge of **2.5 fC**
- maximum tolerated leakage current **5 µA**

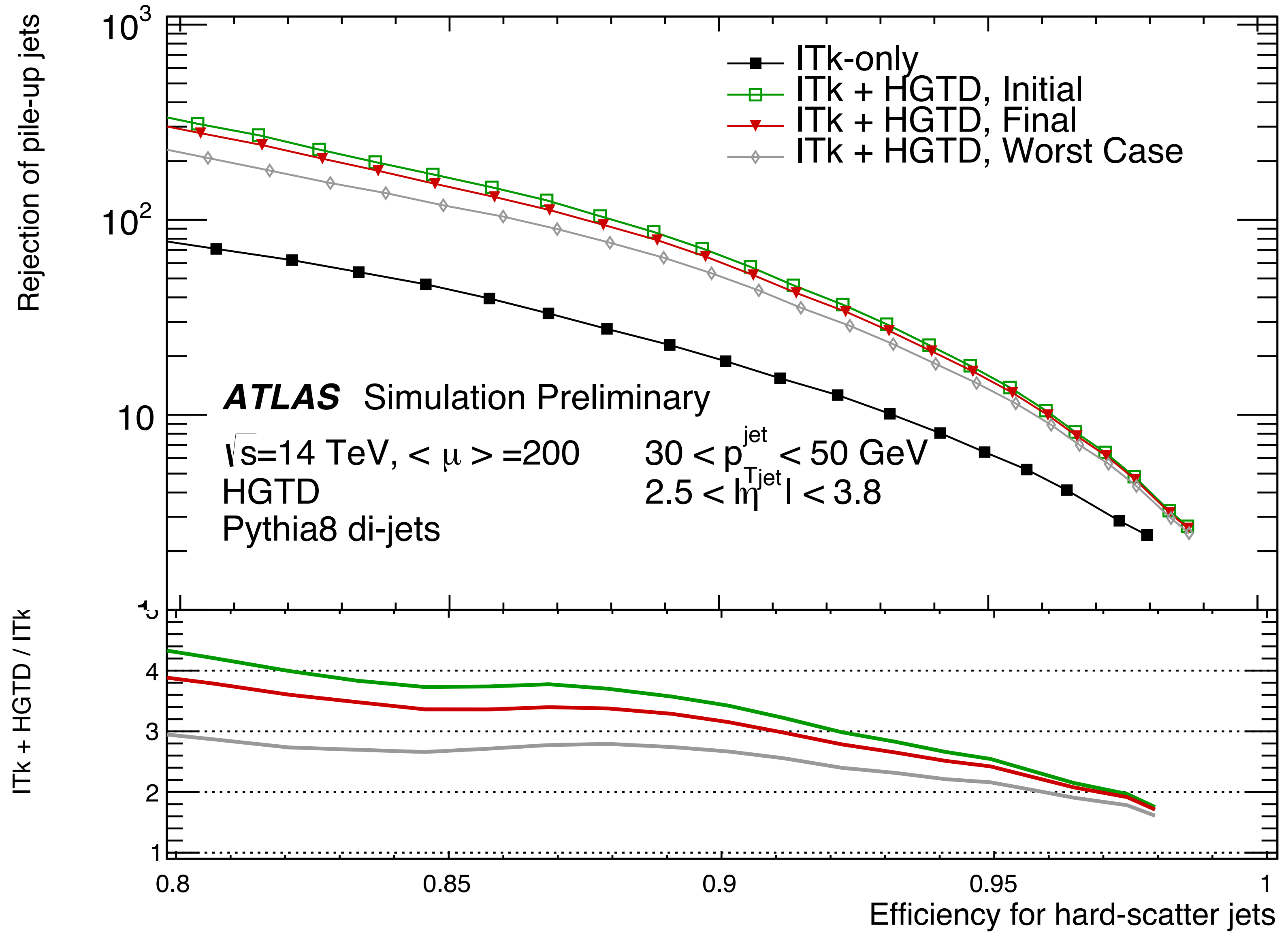


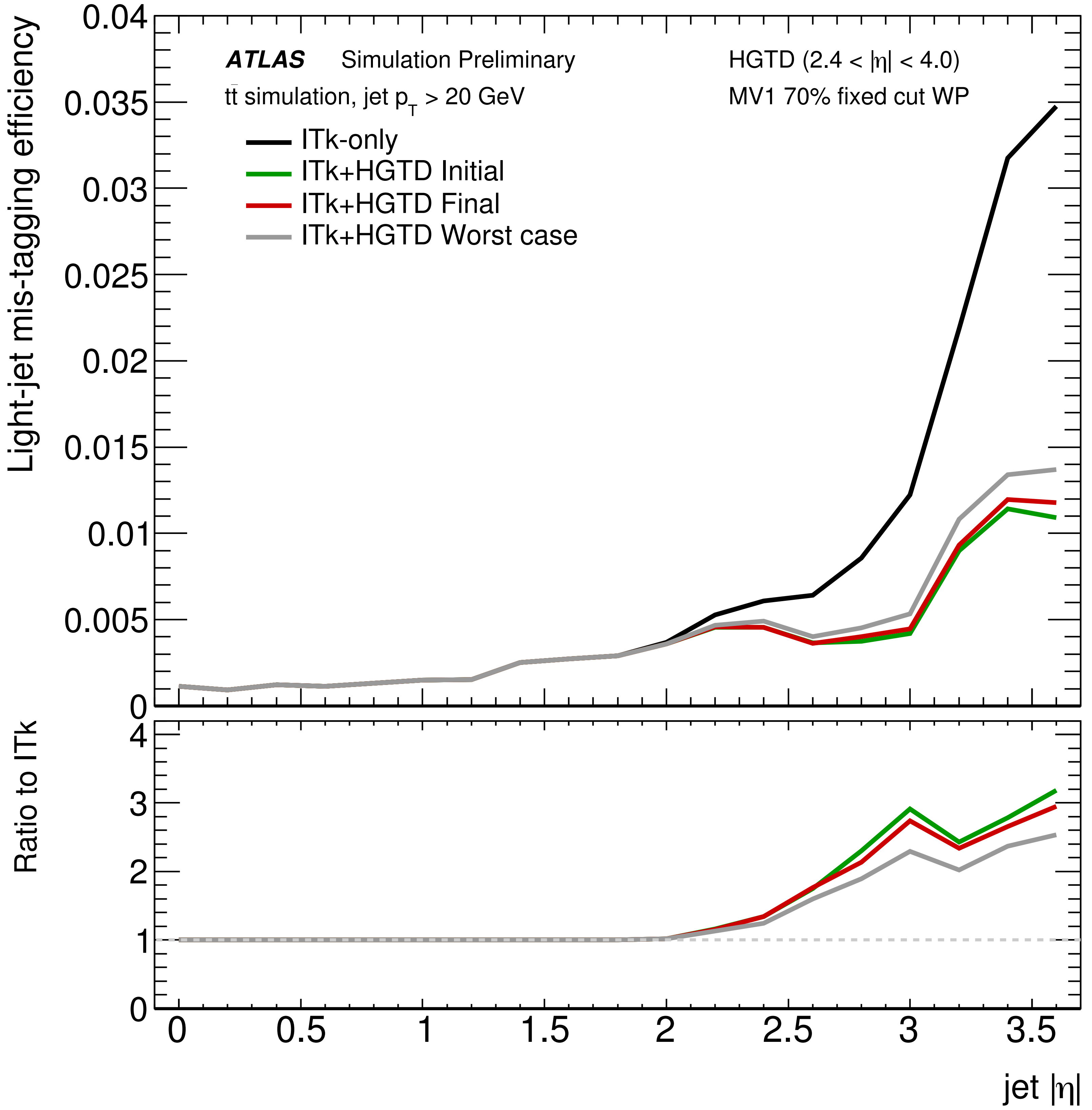


Physics performance - selection

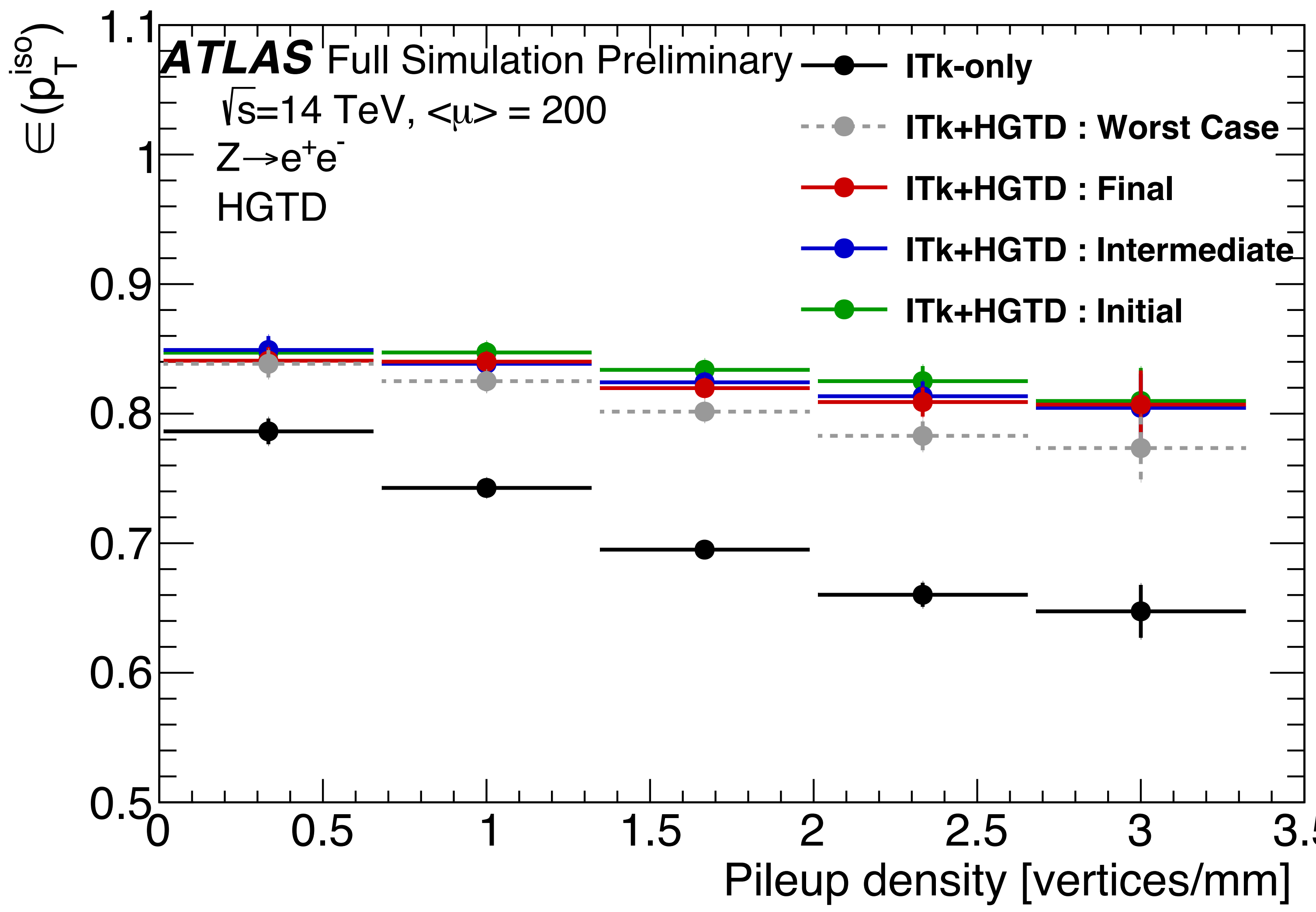
B-tagging

Pile-up jet suppression





Lepton isolation

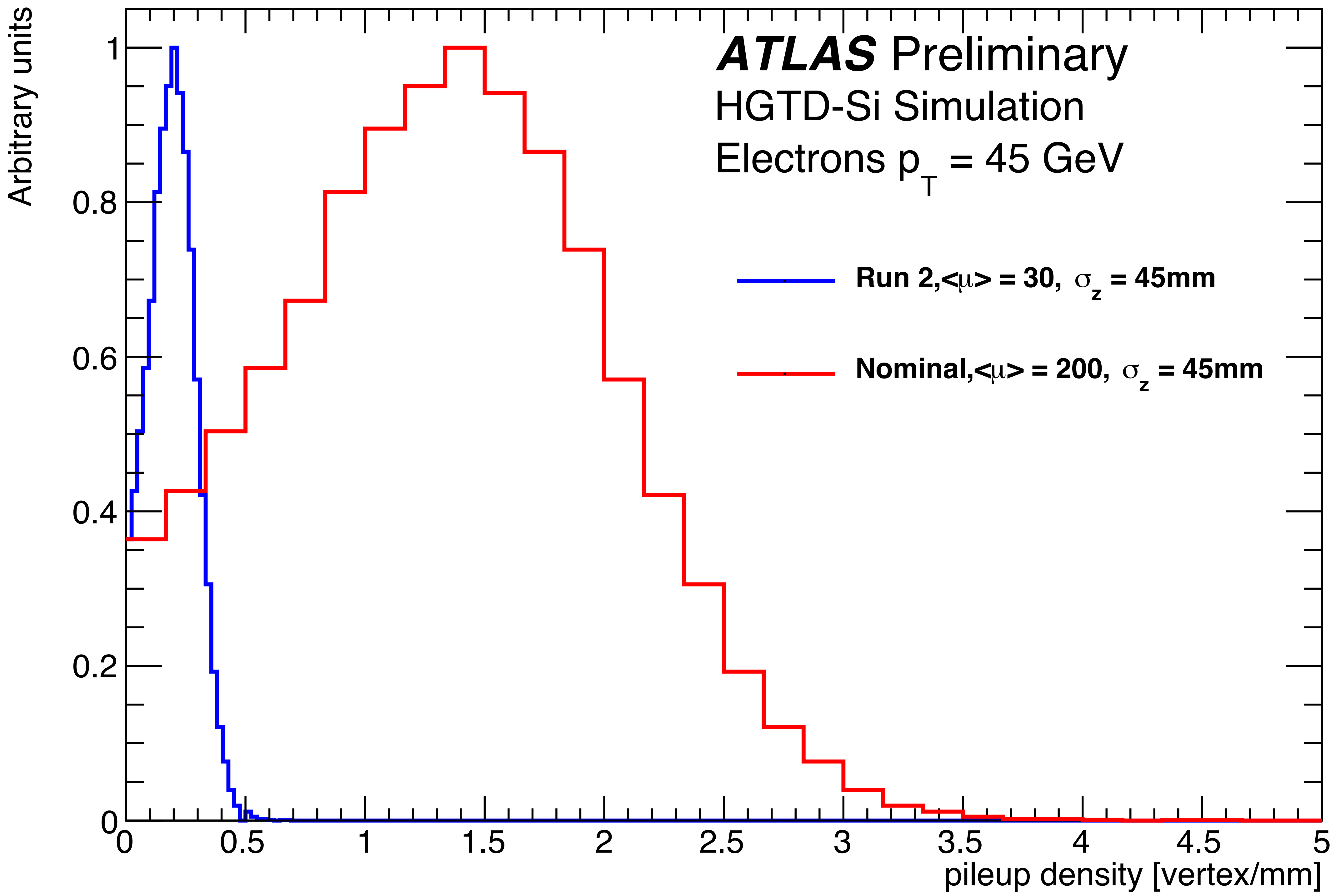


Summary

- conditions at HL-LHC make track-vertex association a very challenging task, especially in the forward region
- HGTD adds time measurements to tracks in order to mitigate pile-up in the forward region
- extensive R&D of sensors and electronics to achieve the targeted performance goals, testing in lab and under beam conditions
- HGTD Technical Proposal approved by LHCC and the Technical Design Report is planned for April 2020
- currently re-optimising the layout with 3 rings to mitigate the max. radiation levels to 3×10^{15} n_{eq}/cm^2 (2 to 3 replacements of the most inner rings during HL-LHC)

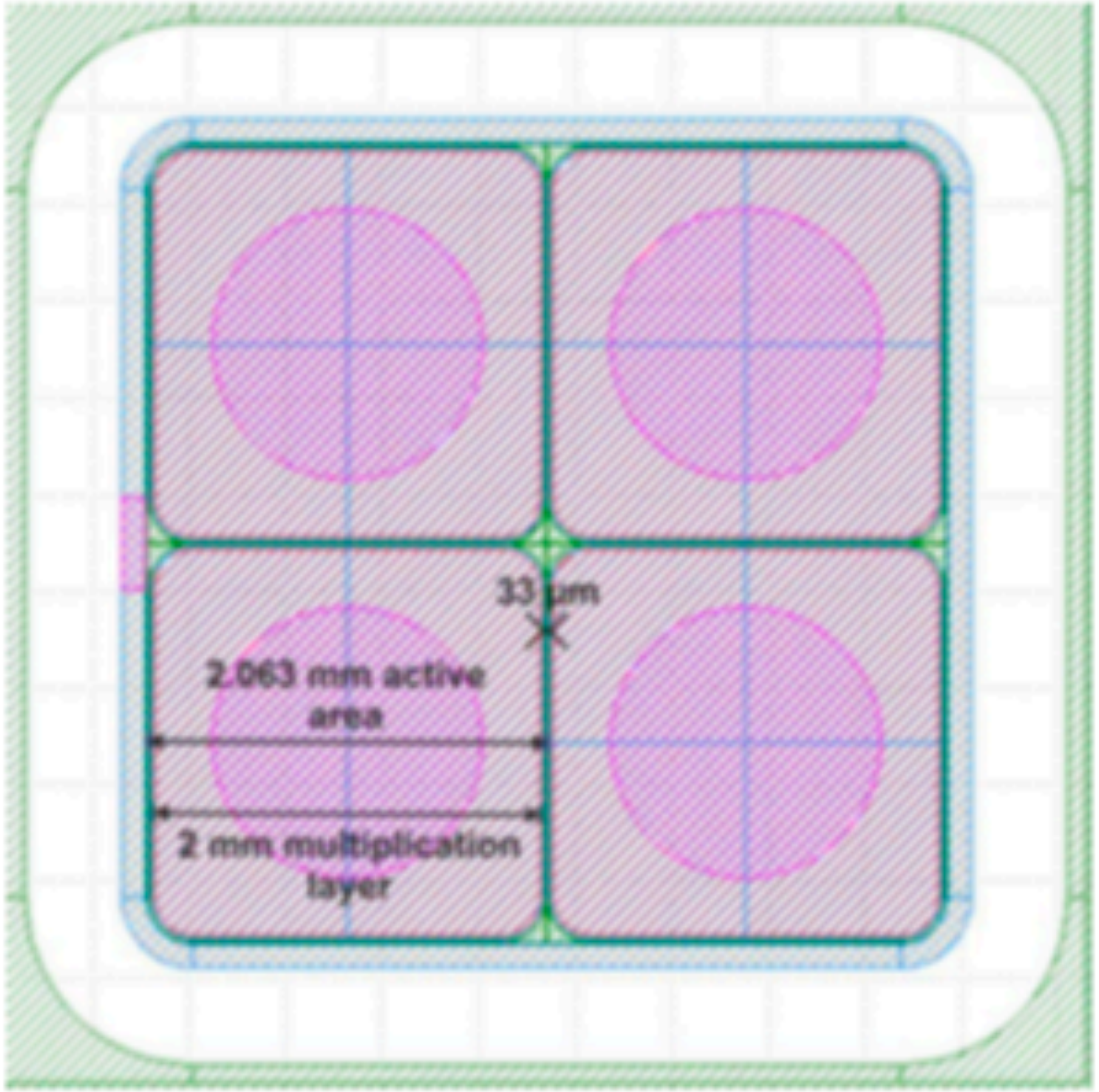
BACKUP

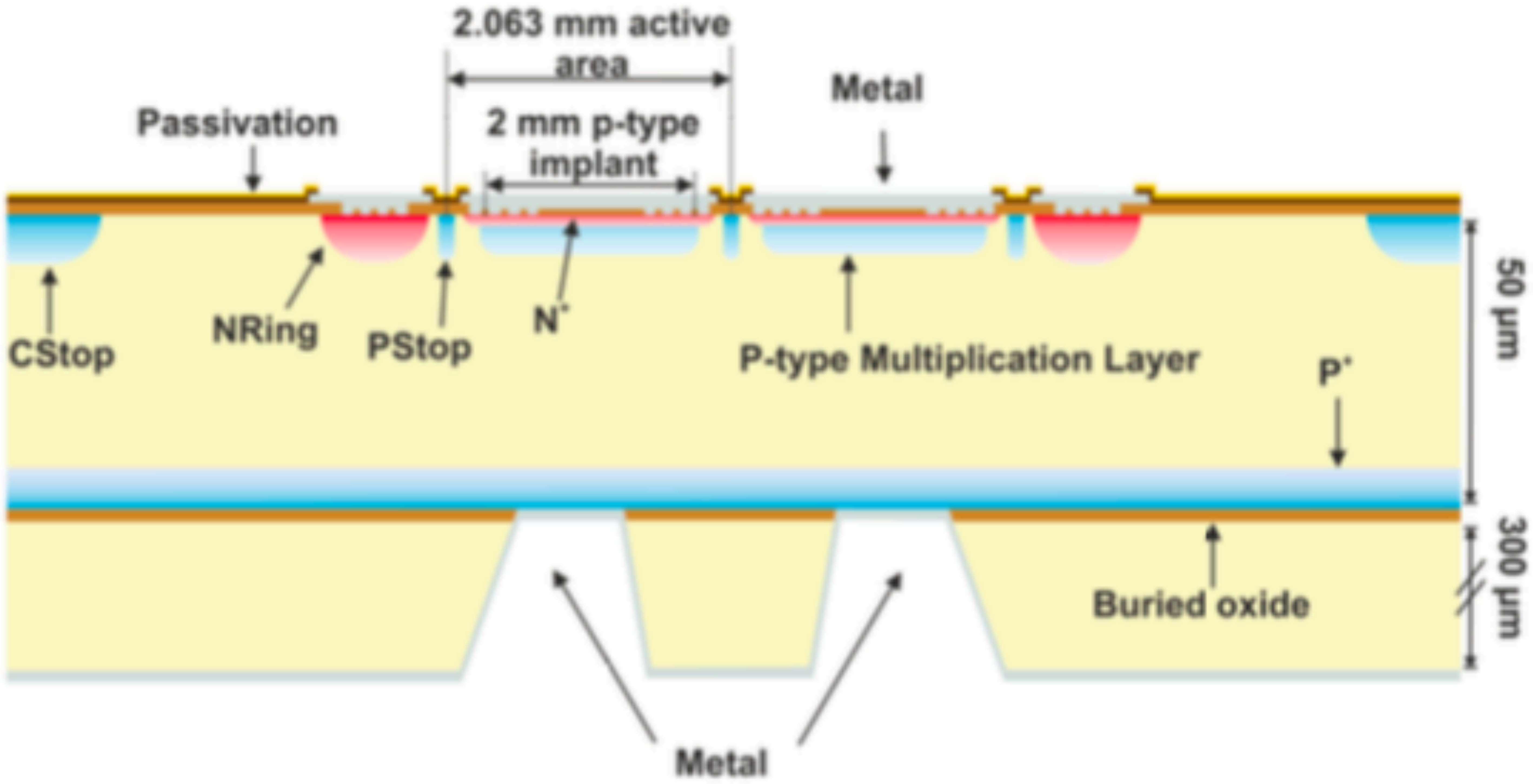
Pile-up density



2x2 LGAD array

2x2 Pad Array





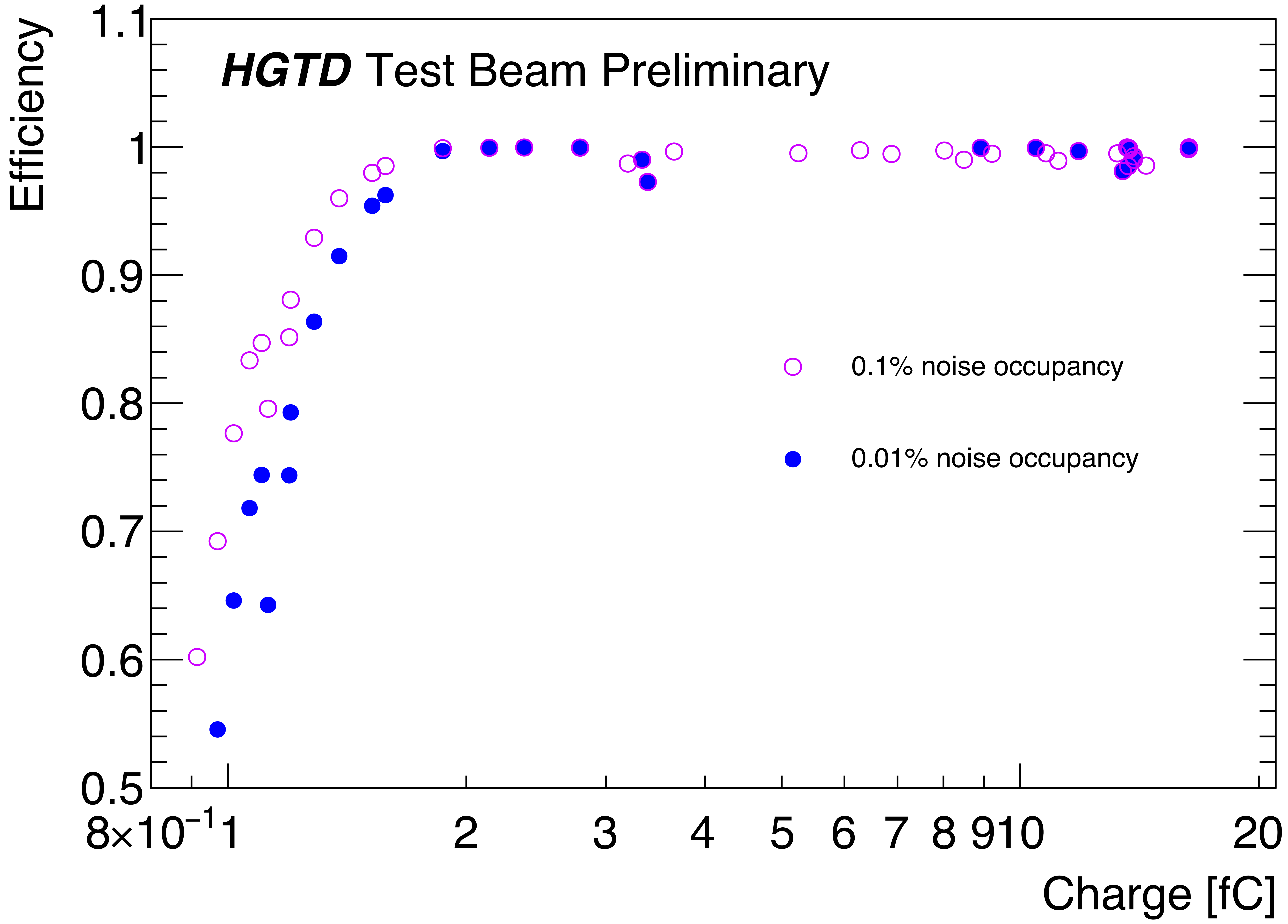
taken from arxiv 1804.00622

Sensors for testing

Manu-facturer	Name	Thickness [μm]	Gain layer dopant	C implant	Gain layer depth [μm]	Gain layer depletion [V]
HPK	HPK-3.1-50	50	Boron	No	1.6	40
HPK	HPK-3.2-50	50	Boron	No	2.2	55
HPK	HPK-PROTO-30	30	Boron	No	1.6	50
FBK	FBK-UFSD3-C-60	60	Boron	Yes	0.6	20
CNM	CNM-AIDA-50	50	Boron	No	1.0	45

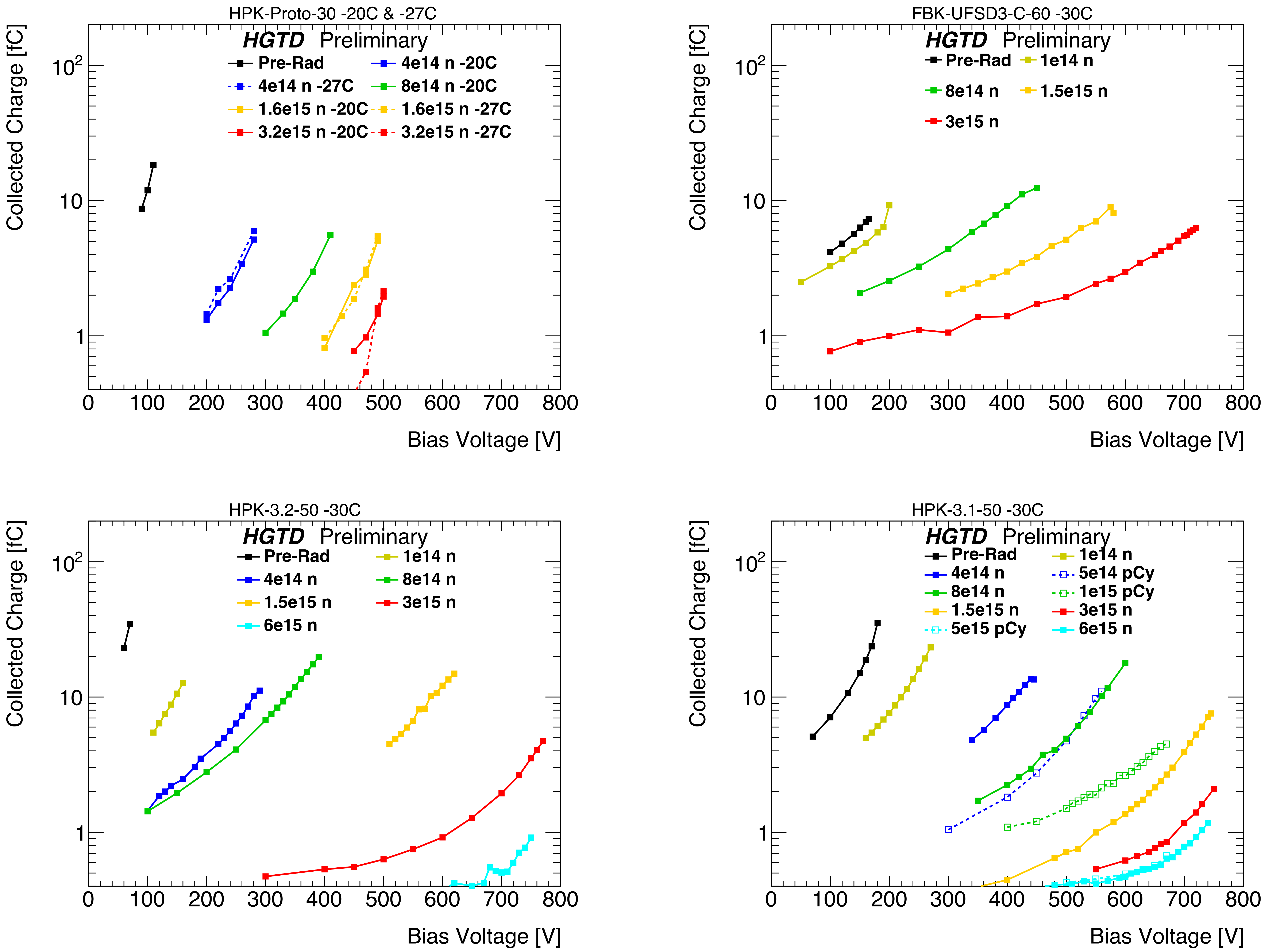
Manu-facturer	Name	Full depletion [V]	V_{BD} −30 °C [V]	Nominal IP [μm]	Nominal edge[μm]	Max. Array Size
HPK	HPK-3.1-50	50	200	30→95	200→ 500	15 × 15
HPK	HPK-3.2-50	65	70	30→95	200→ 500	15 × 15
HPK	HPK-PROTO-30	75	110	-	-	Single
FBK	FBK-UFSD3-C-60	25	170	37	200→ 500	5 × 5
CNM	CNM-AIDA-50	50	220	37→57	200→ 500	5 × 5

Efficiency

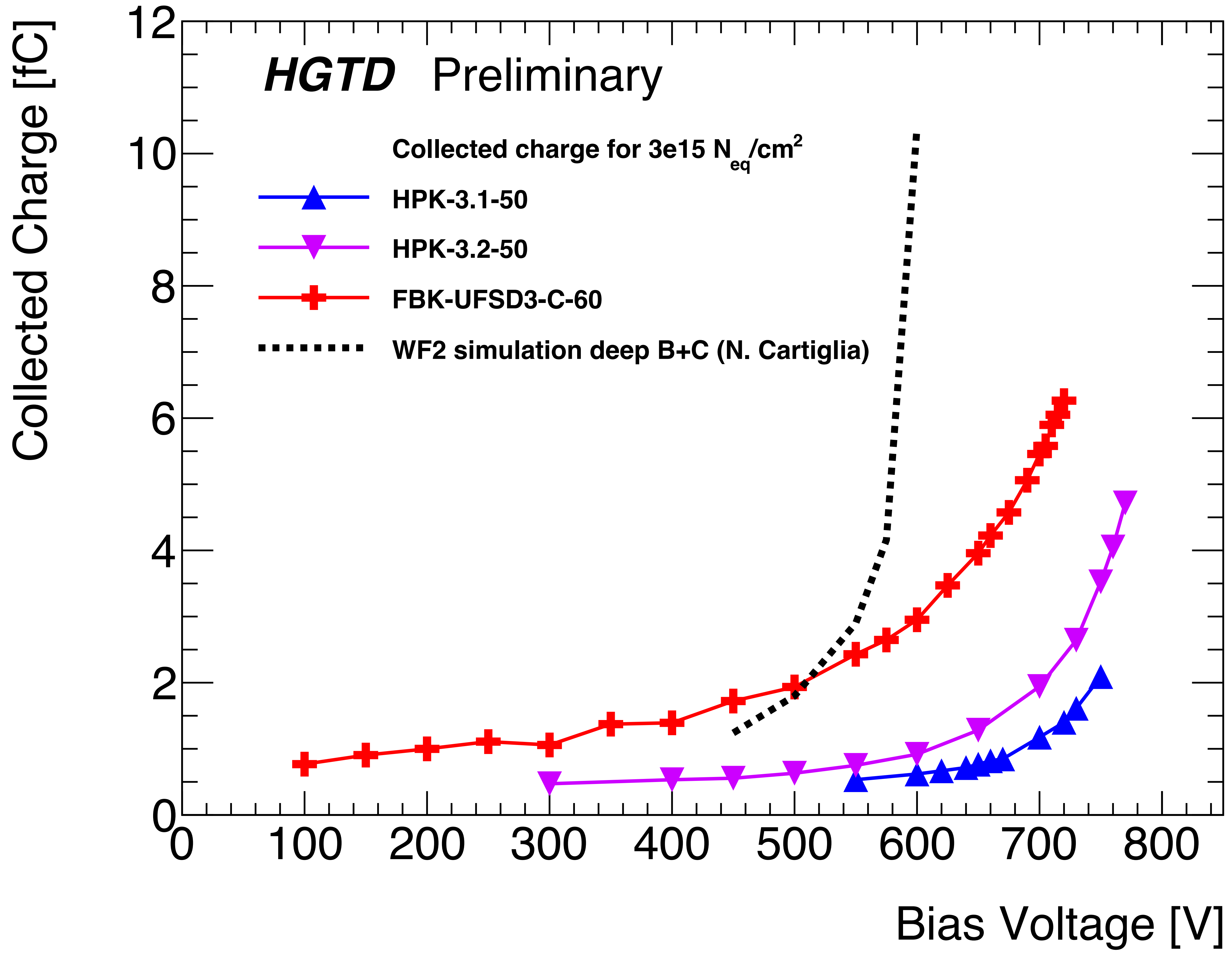


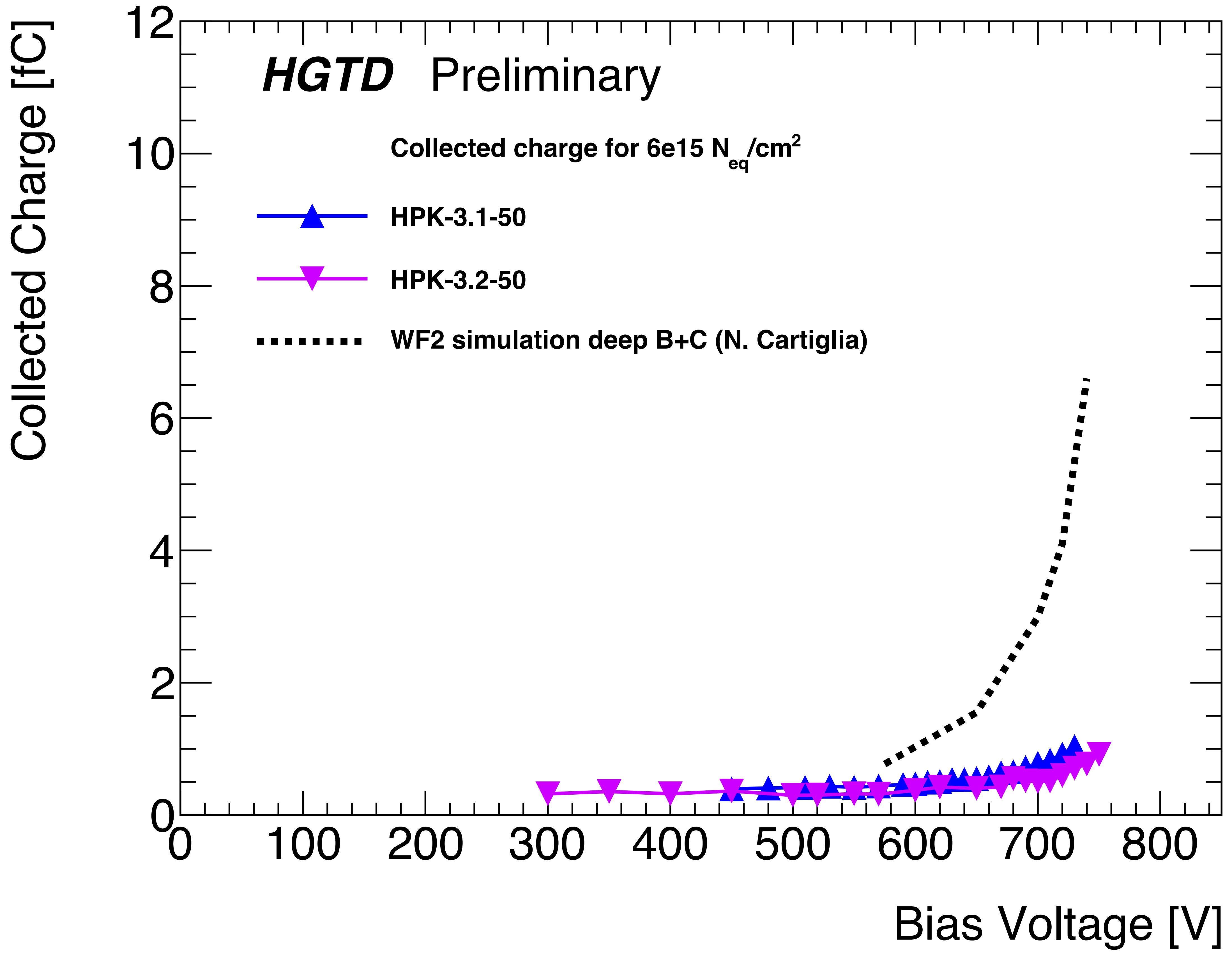
Efficiency
1.1
1
0.9
0.8
0.7
0.6
0.5
HGTD Test Beam Preliminary
0.1% noise occupancy
0.01% noise occupancy
8×10^{-1} 1 2 3 4 5 6 7 8 9 10 20
Charge [fC]

Collected charge



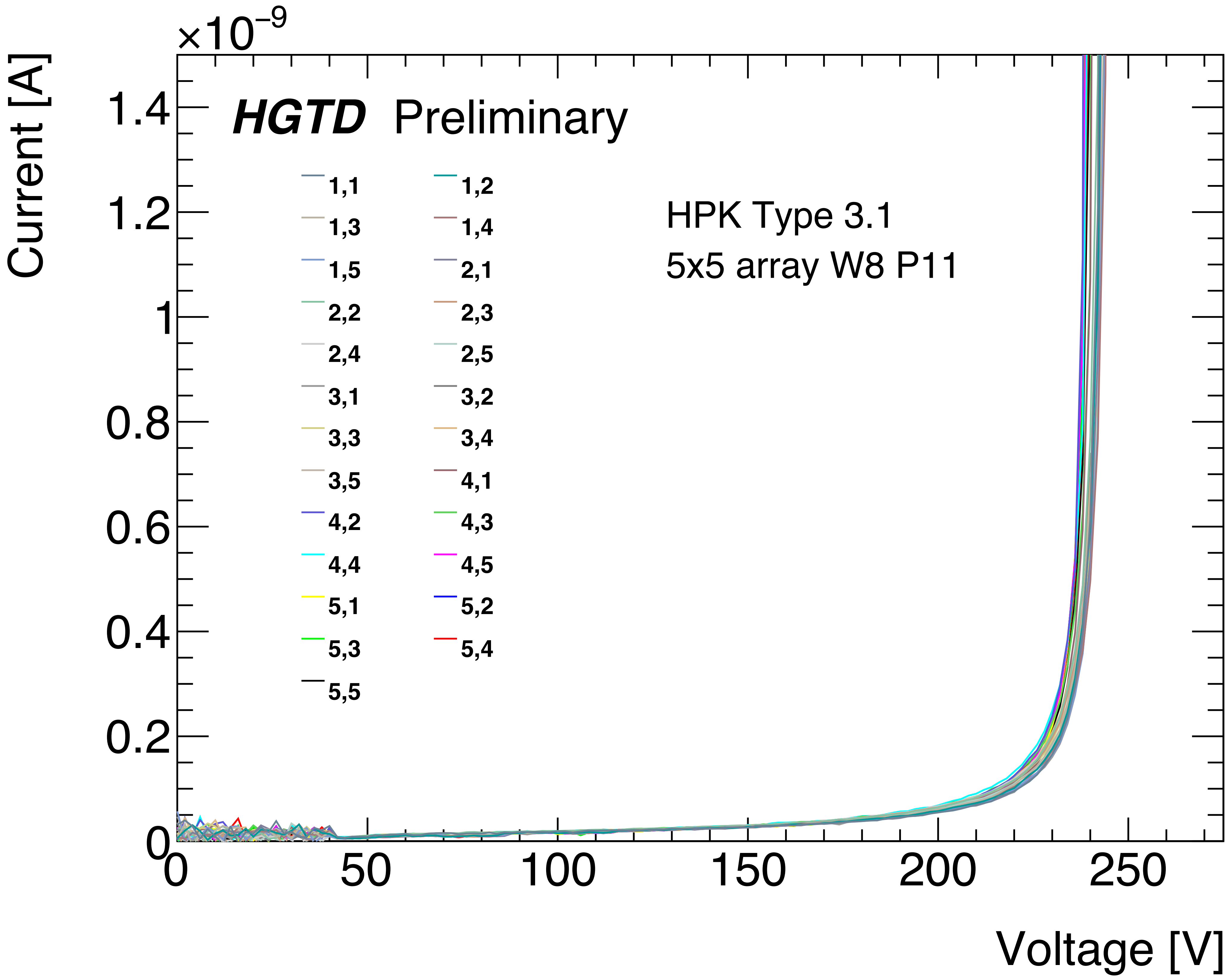
Collected charge

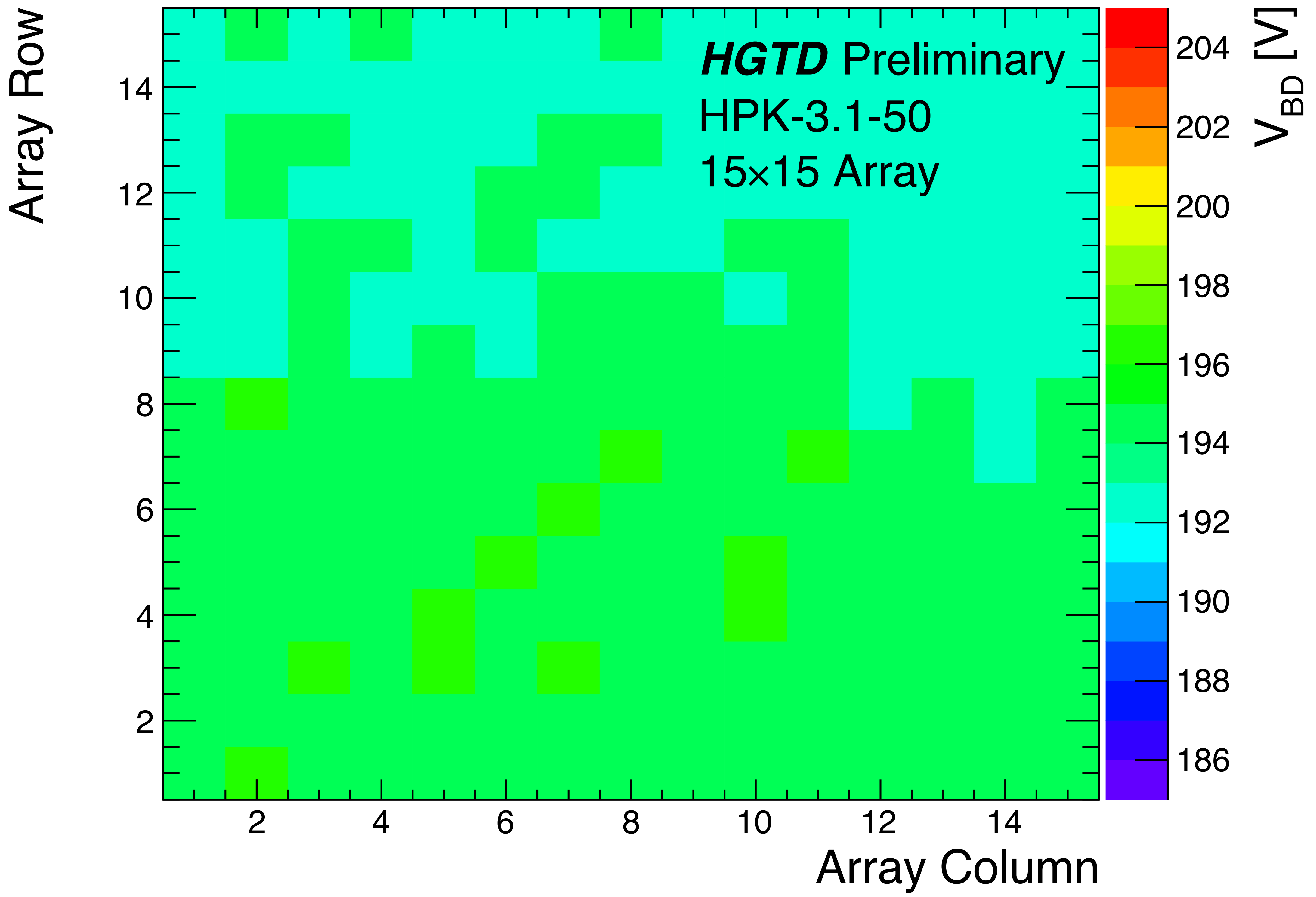




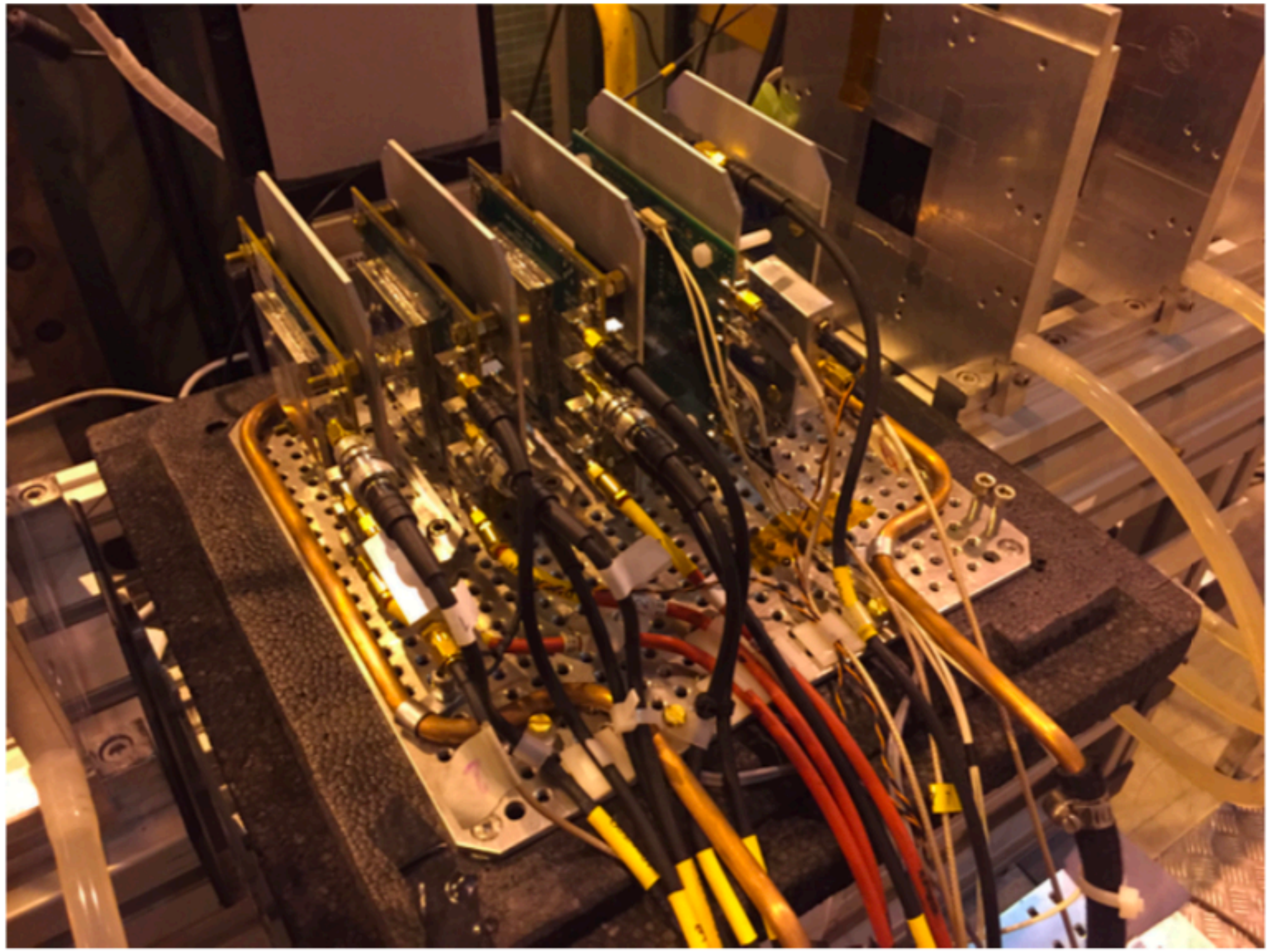
Array measurements

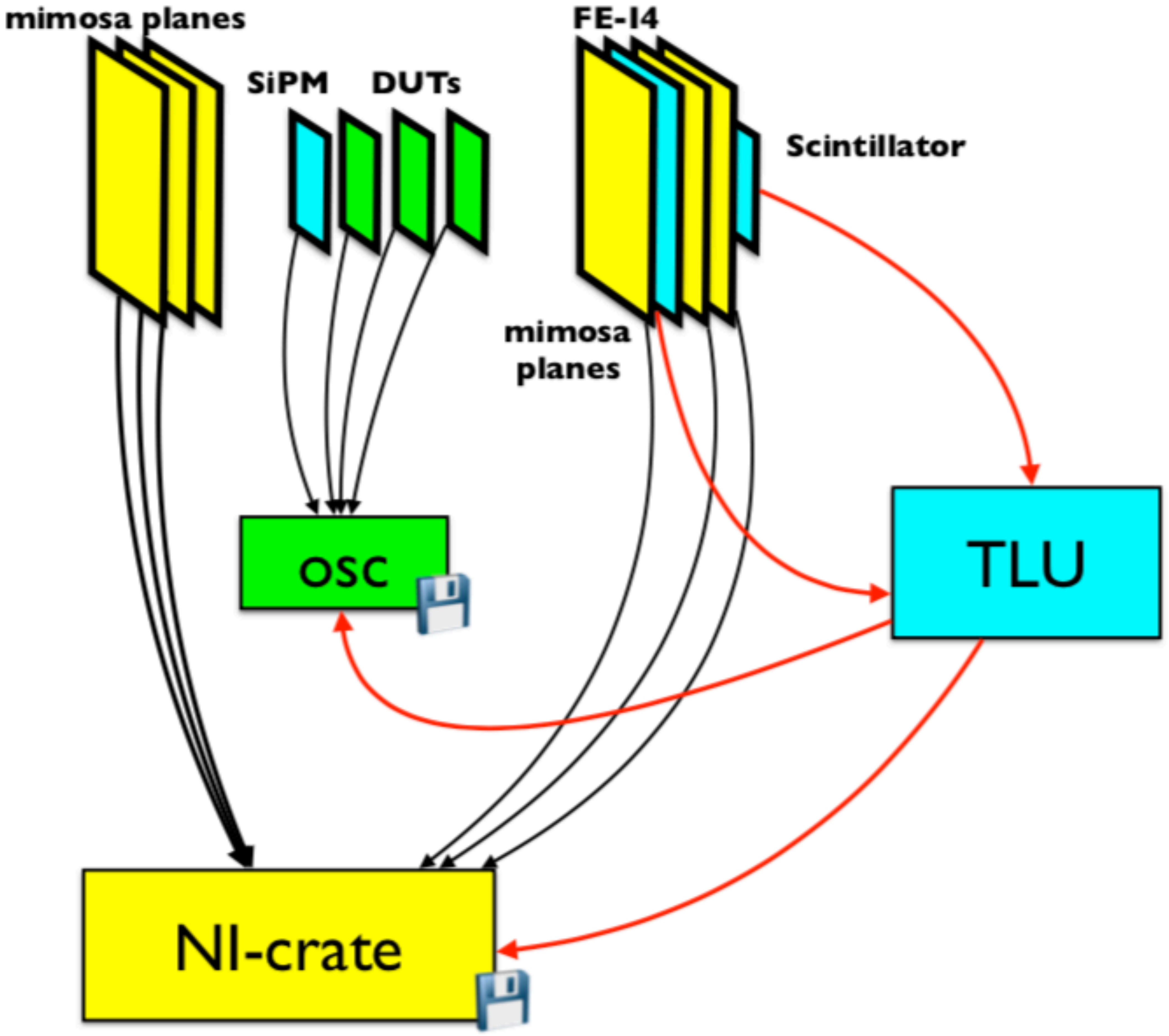
ATLAS





Test beam setup





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