The ATLAS High Granularity Timing Detector

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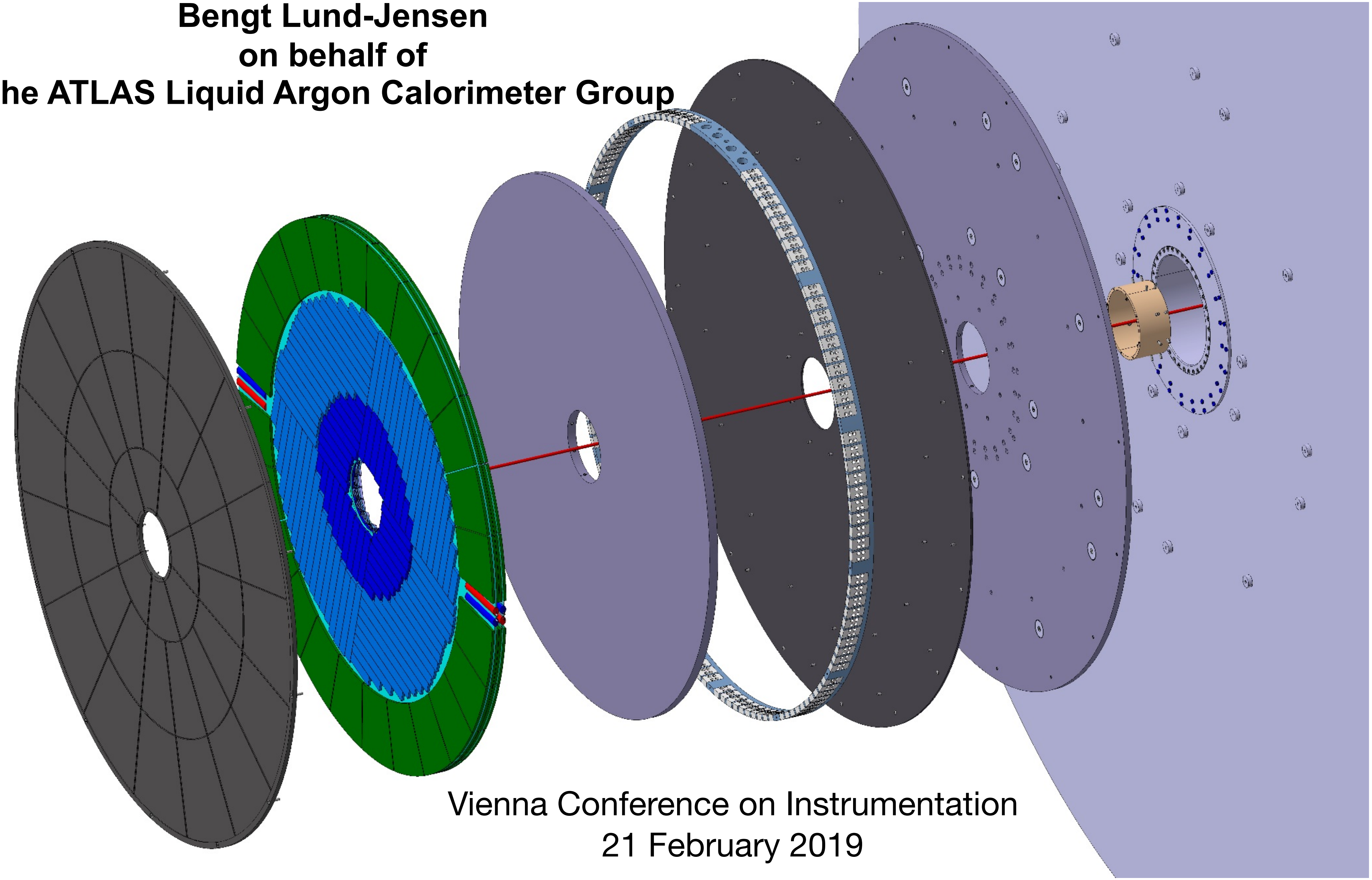
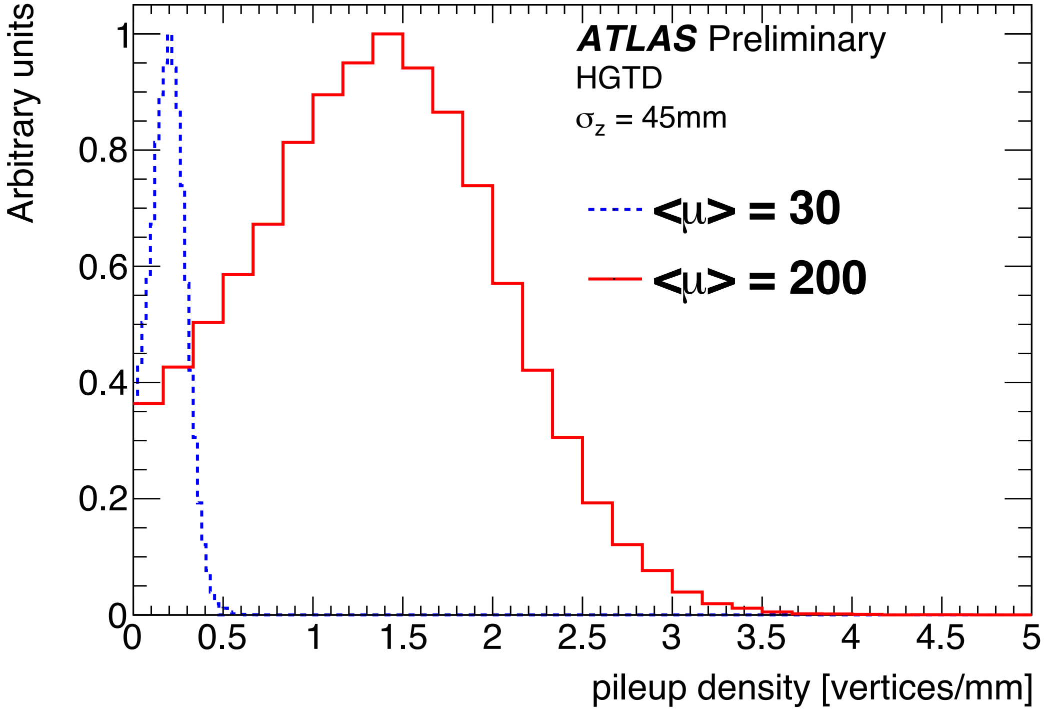
on behalf of
the ATLAS Liquid Argon Calorimeter Group



Vienna Conference on Instrumentation
21 February 2019

HGTD Motivation

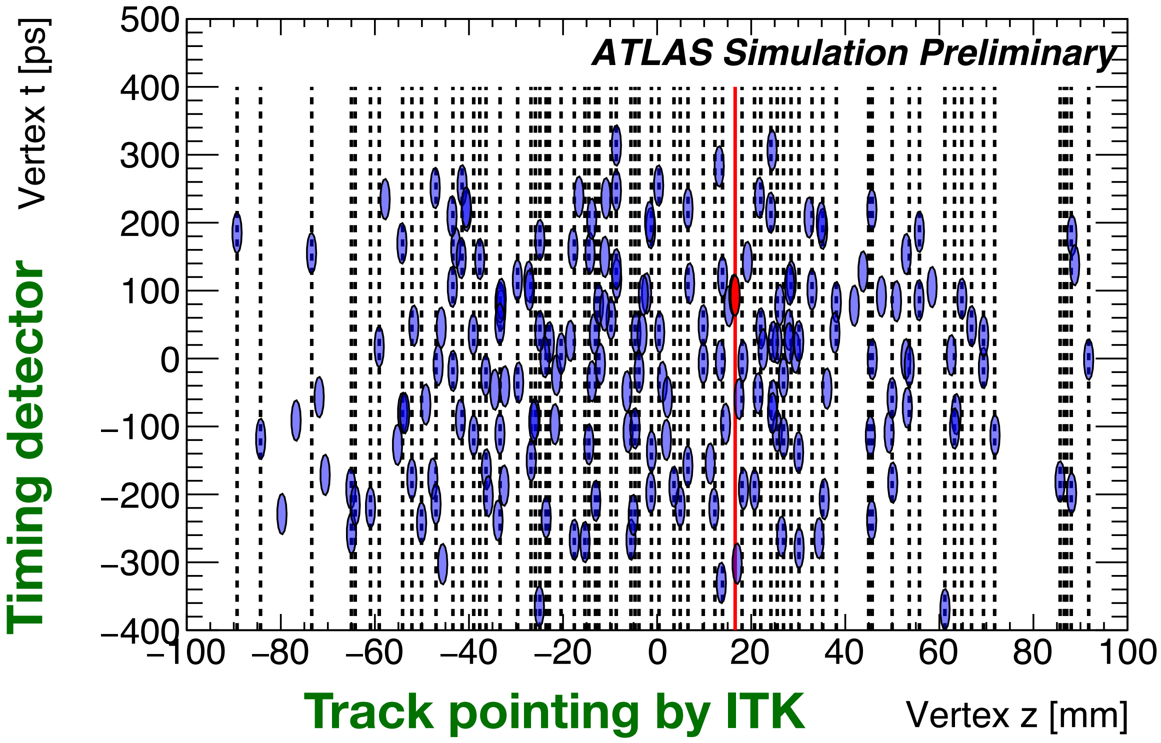
- LHC will be upgraded in 2024-2026 to High Luminosity LHC (HL-LHC)
  - Instantaneous luminosities up to $L \simeq 7.5 \times 10^{34} cm^{-2} s^{-1}$ about 5 times the current
  - Pile up $< \mu > \simeq 200$ simultaneous interactions per bunch crossing
  - On average 1.5 vertex/mm along beam line att collision point



- In the forward region the tracker (new ATLAS tracker ITK) has less longitudinal resolution → degraded vertex resolution

HGTD Motivation

- A new layer of silicon detectors with precise timing, High Granularity Timing Detector (**HGTD**), in front of the liquid argon end-cap calorimeters improves performance by combining
  - HGTD precise timing
  - ITK position information



2 dimensions: z and time

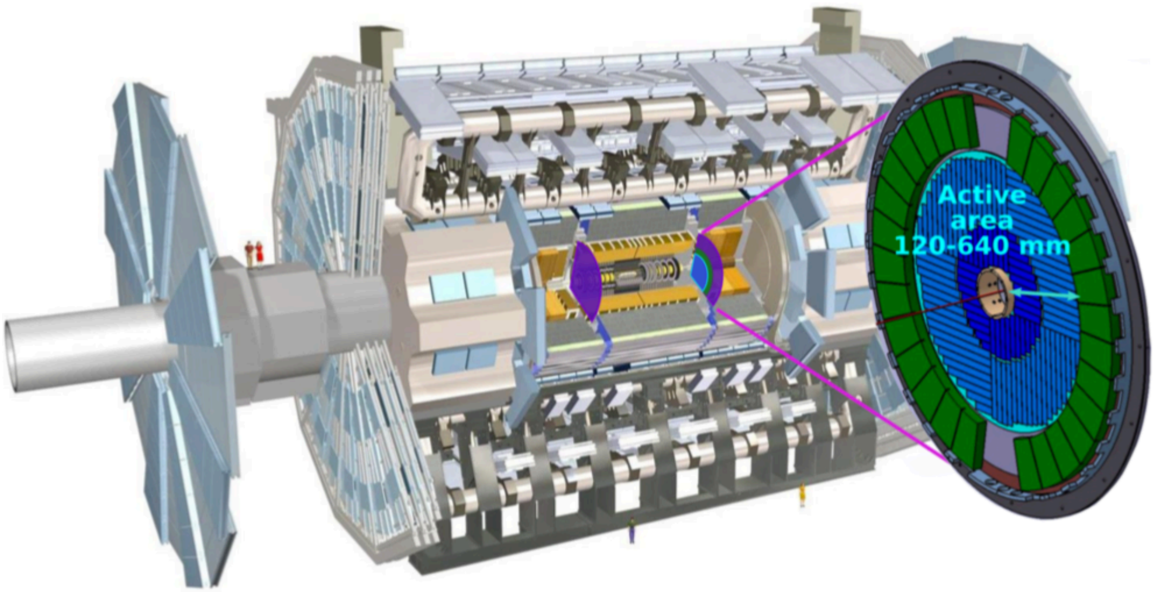
HGTD Requirements

- Two endcap disks at z = ±3.5 m
- $6.3m^2$ active rea: 120mm<R<640mm
  ⇒ $2.4 < |\eta| < 4.0$
- Time resolution better than 30 ps per track (50 ps per hit in a 2 layer geometry)
- Sensors on both sides of two cooling plates with varying overlap ⇒

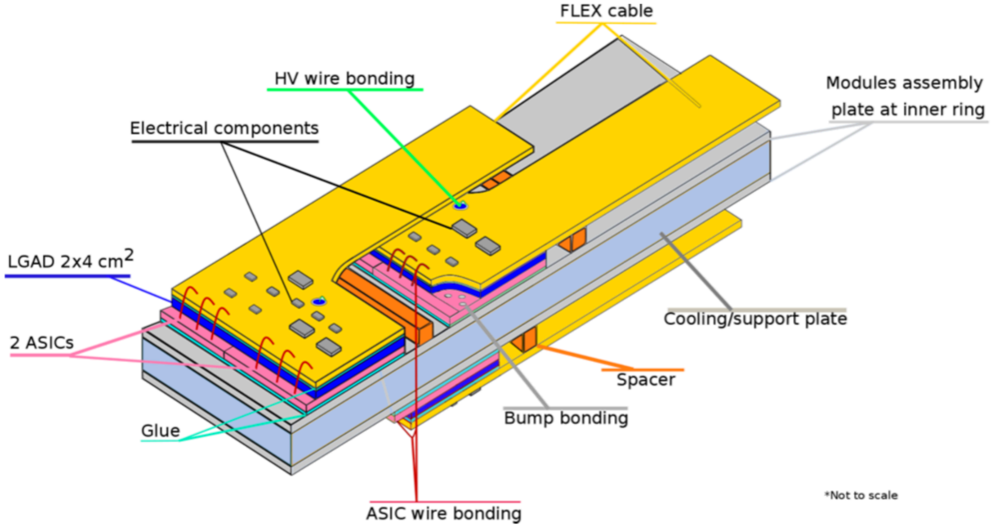
$\langle n_{hits} \rangle$=3 for R<320mm (80% overlap)

$\langle n_{hits} \rangle$=2 for R>320mm (20% overlap)

- Requirement of occupancy < 10%
  ⇒ 1.3 mm × 1.3 mm pixels
- 15x30 pixel sensors
- Sensors bump bonded to readout ASIC (ALTIROC) (15x15 chip)
- Wire bonded to flex cable
- Intotal 3.59 M channels



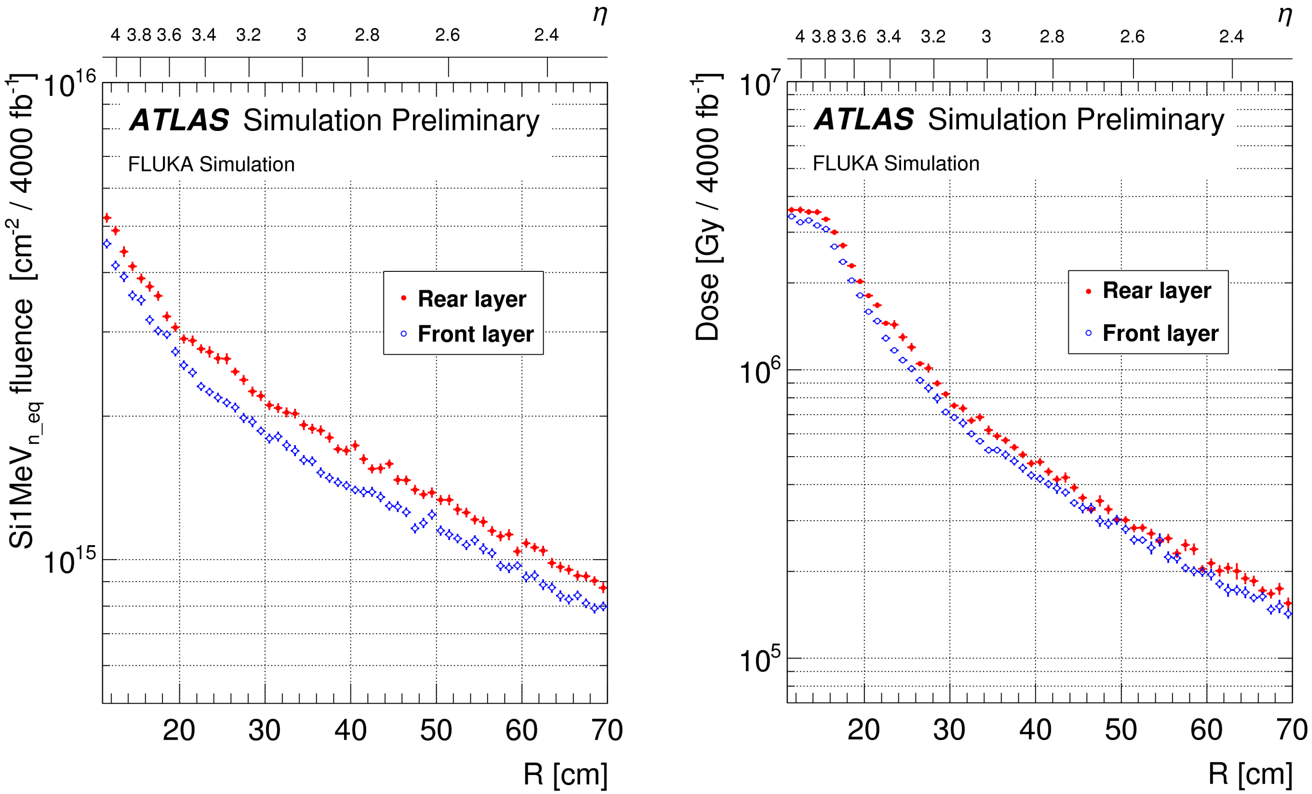
Constrained by available space and harsh environment



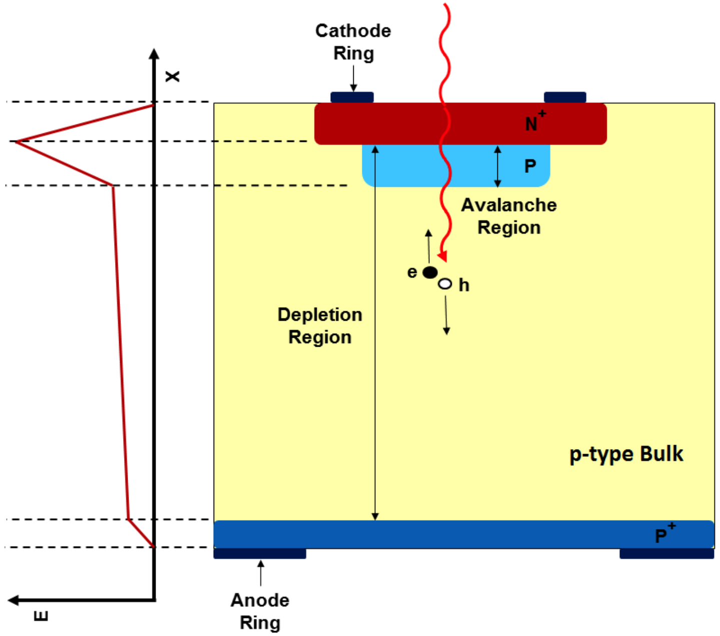
Radiation levels

- Total fluence (n_{eq}) and dose to be sustained
  (new updated numbers compared to fig):
  - R < 32 cm → 5.1×10^{15} n_{eq}/cm^2 and 4.7 MGy
  - R > 32 cm → 3.9×10^{15} n_{eq}/cm^2 and 1.9 MGy
- A safety factor 1.5 for n_{eq} (sensor) and 2.25 for dose (ASIC) and replacement of inner wheel < 32 cm) (~32% of sensors and ASICs) at mid run of HL-LHC are taken into account

- Sensors will be operated at -30 °C using shared CO_2 cooling system with ITK



HGTD sensors: LGADs

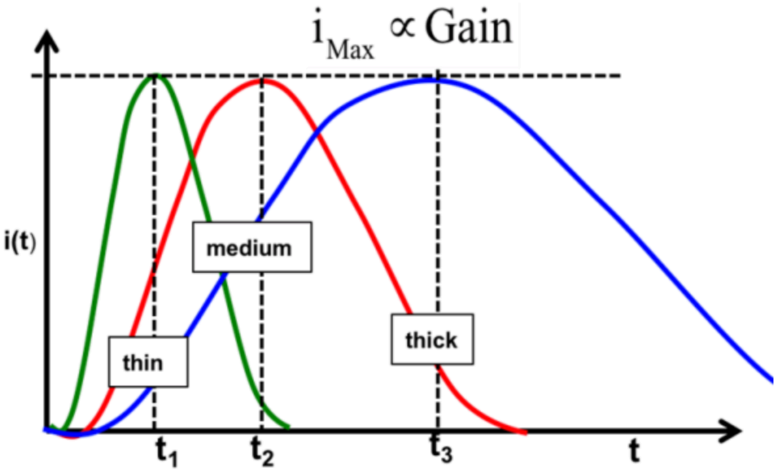


R&D program to provide sensors with required time resolution, radiation hardness and fine segmentation

- New doping materials, substrates and geometries
- Prototypes tested from CNM, HPK, BNL, FBK
- >1000 single pad sensors tested
- Several 5x5 and 15x15 sensors tested. Very uniform leakage current and breakdown voltage

Low Gain Avalanche Detectors (LGADs)

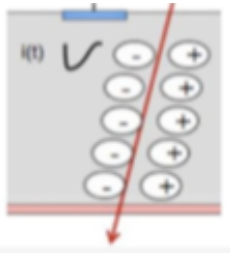
- n-on-p planar silicon layer with additional p-layer for moderate gain (10-50) (increases signal, limits noise)
- Time resolution < 30 ps before irradiation
- Thin (base line 50μm) => small t_{rise}



CNM LGAD for HGTD

Contributions to timing resolution

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

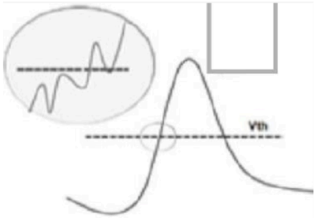


- Landau term: < 25 ps, reduced for thin sensors (35-50 μm)

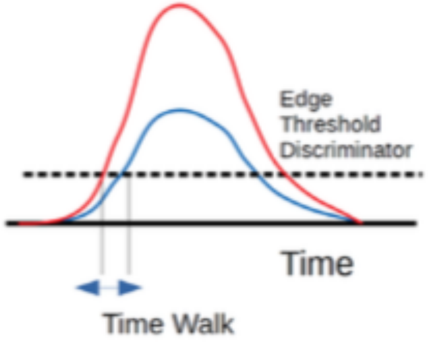
< 25 ps

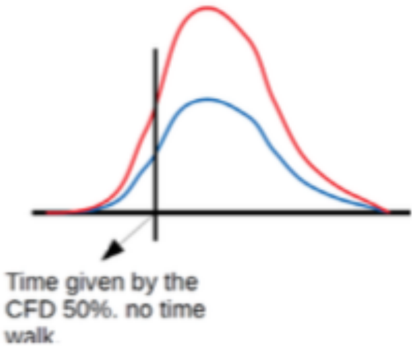
- Jitter term

  $$\sigma_{jitter} \approx \frac{t_{rise}}{S/N}$$



- Time walk, minimised by correcting for time over threshold (or for beam tests using constant fraction discriminator (CFD))



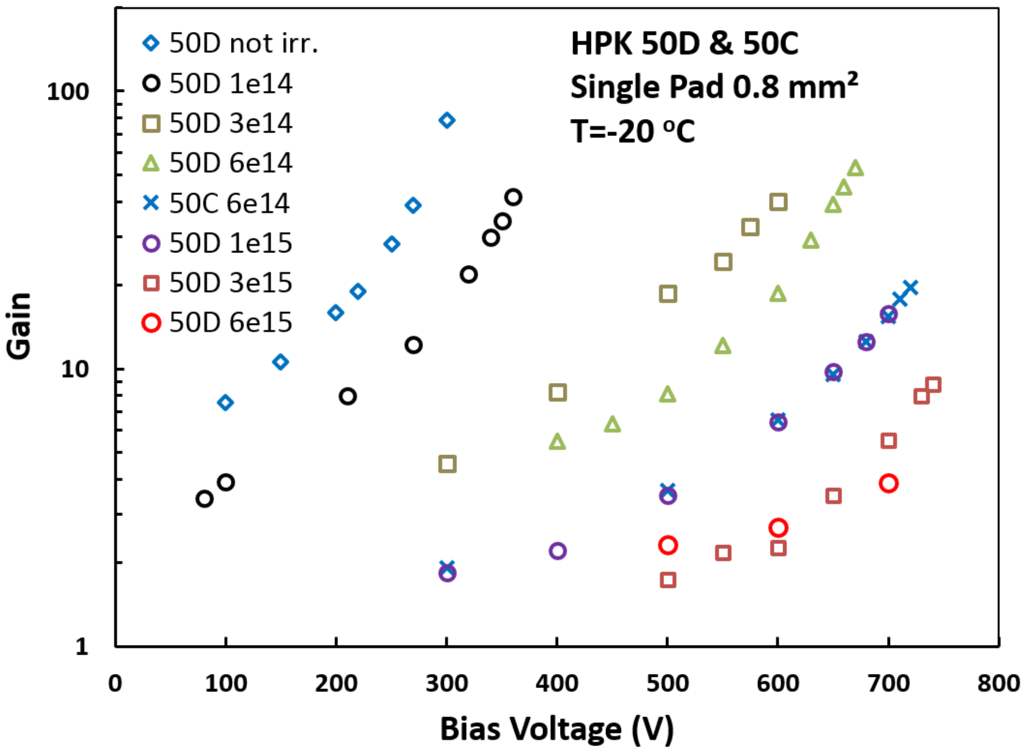


- Digitisation granularity ~ 5ps

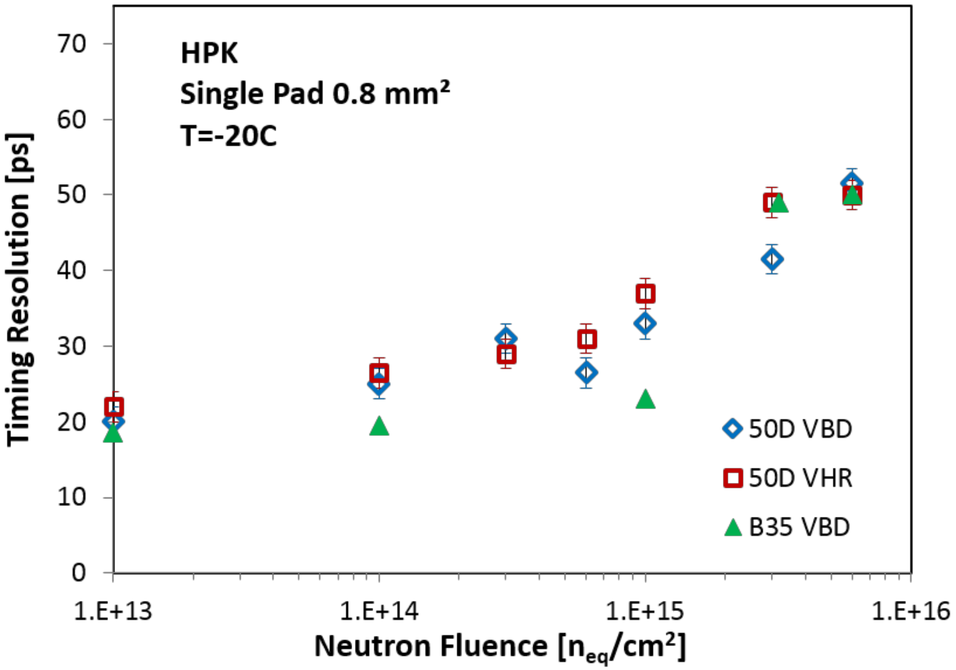
- Clock distribution < 10 ps

Radiation damage on LGADs

- Sensors have been irradiated at with neutrons at IJS (Lubiana) and protons at PS-IRRAD (CERN):
  - From 1×10^{14} to 1×10^{16} n_{eq}/cm^2 (3.7×10^{15} n_{eq}/cm^2 need for HGTD)
- Reduction of gain partially compensated by increasing bias voltage (higher breakdown voltage)



Z. Galloway et al, arXiv:1707:04961
and Y. Zhao et al arXiv: 1803:02690

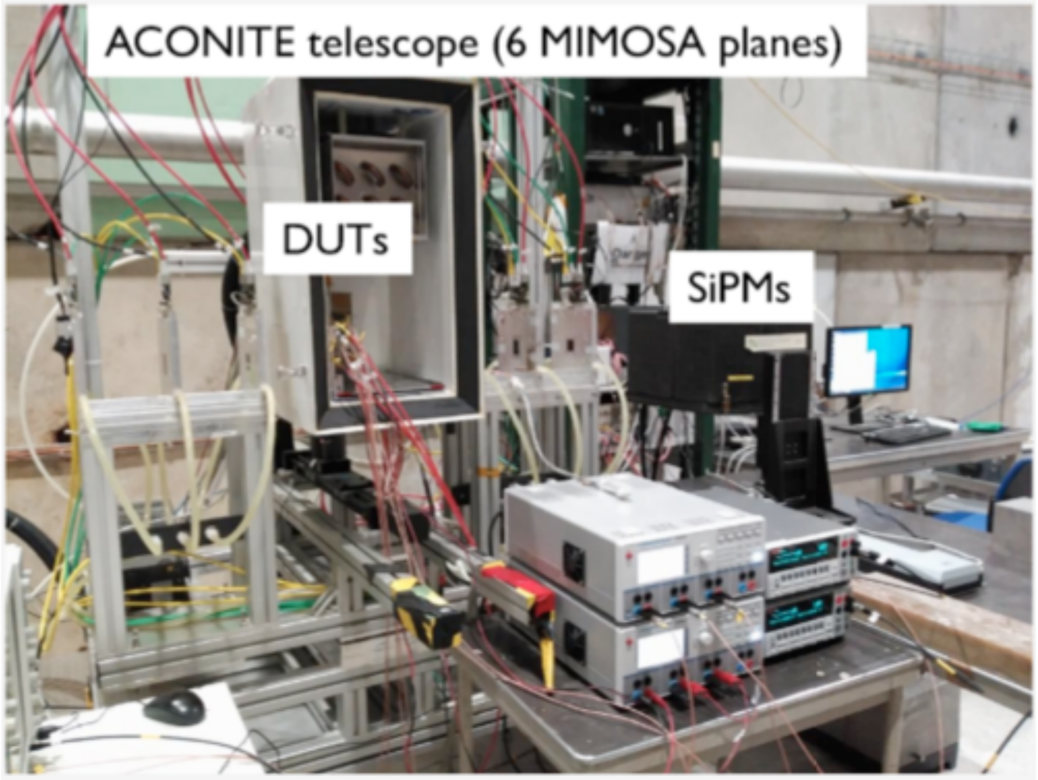


Test beam measurements

Hit efficiency and timing resolution has been studied with pion beams at CERN SPS North Area

~ 50 sensors tested so far

- Un-irradiated sensors CNM, HPK, BNL
- Irradiated sensors (neutron & proton) CNM and HPK
- 2×2 array sensors
- 2×2 array sensors with ALTIROC0_v2
- Arrays with different inter-pad gaps

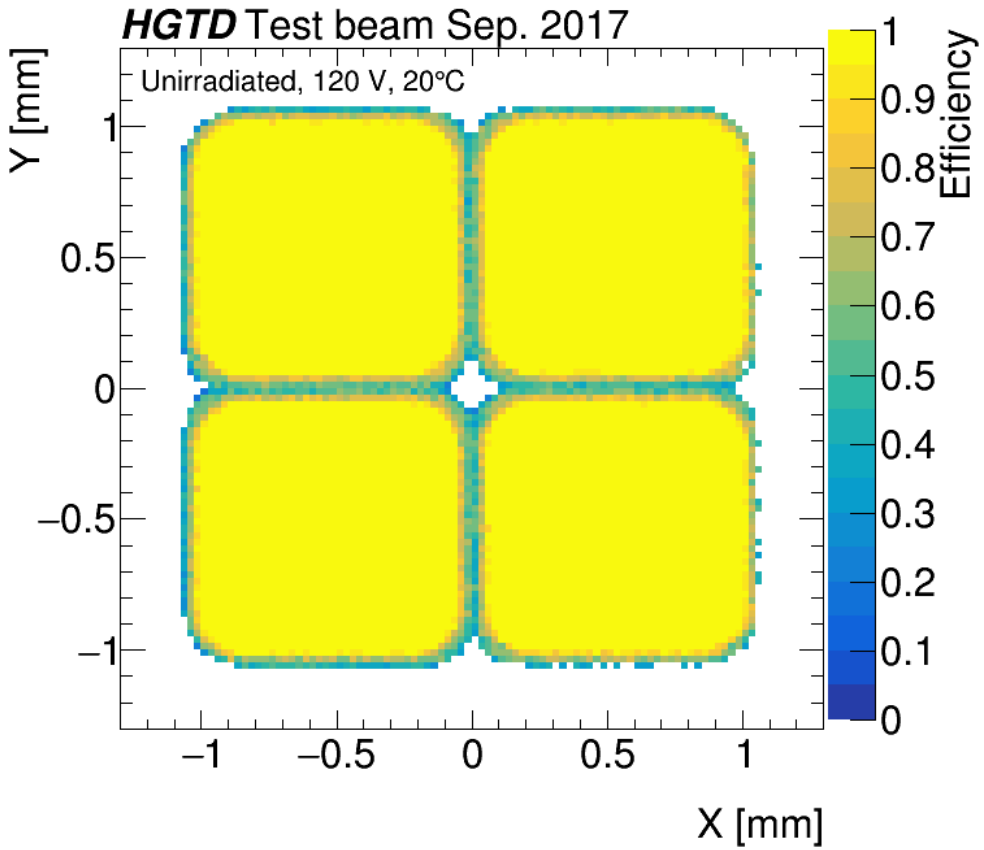


Beam tests have also been performed at Fermilab and SLAC and in future also DESY

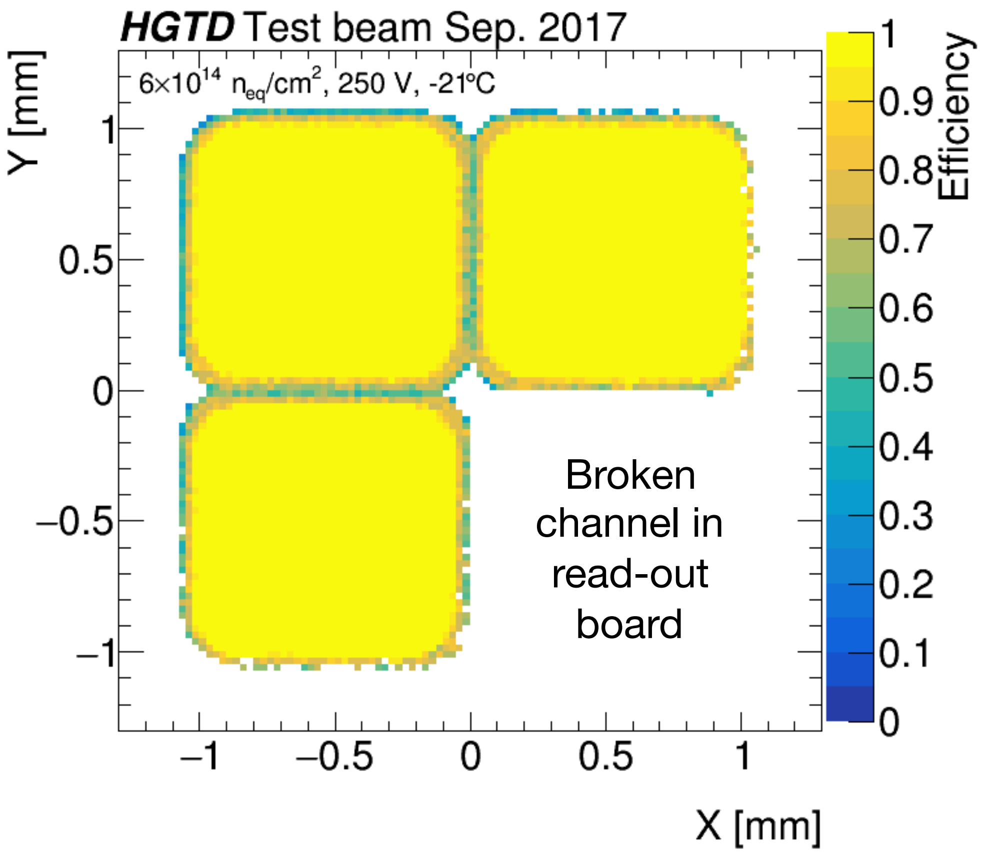
Results from test beam measurements

Hit efficiency

Before irradiation



After 6×10^{14} n_{eq}/cm^2



Broken channel in read-out board

Efficiency still ~100% in center

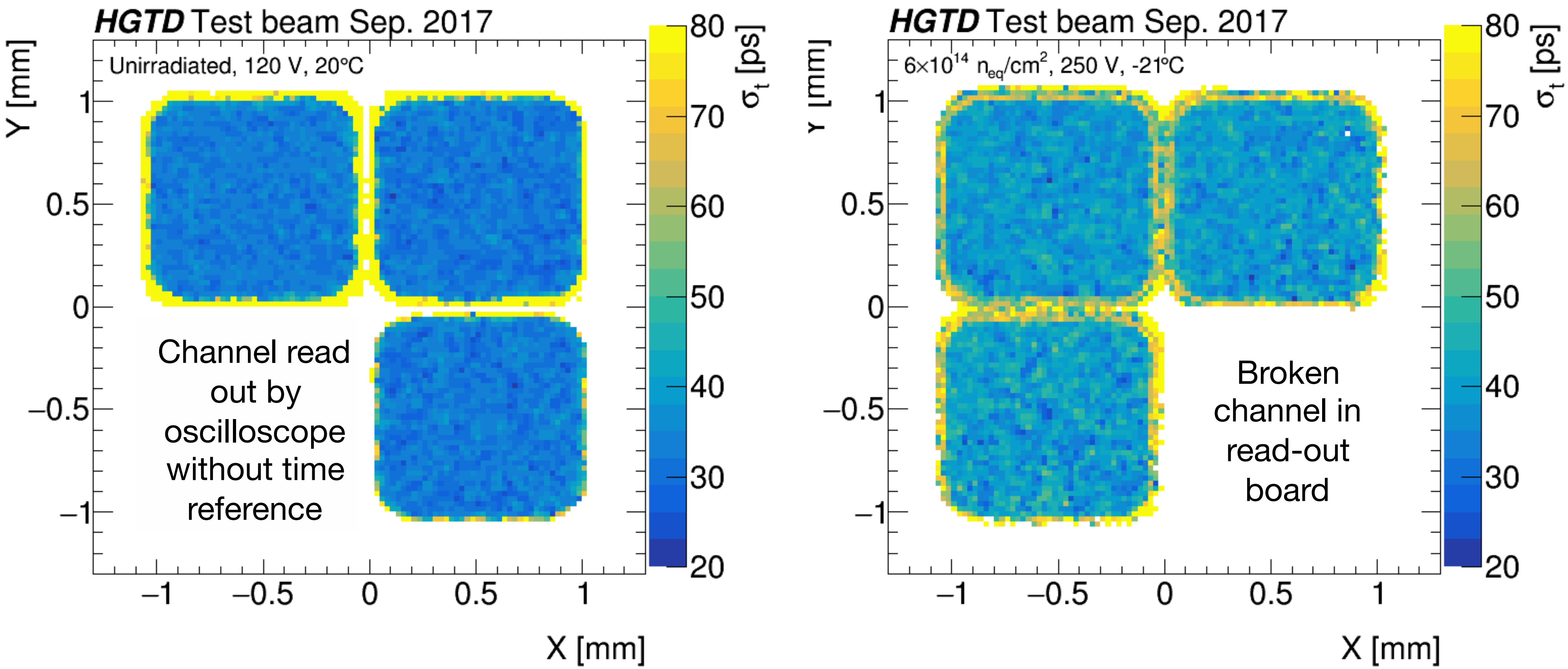
Results from test beam measurements

Timing resolution

A SiPM is used as time reference. Its 40 ps contribution is subtracted.

Before irradiation

After 6×10^{14} n_{eq}/cm^2



Channel read out by oscilloscope without time reference

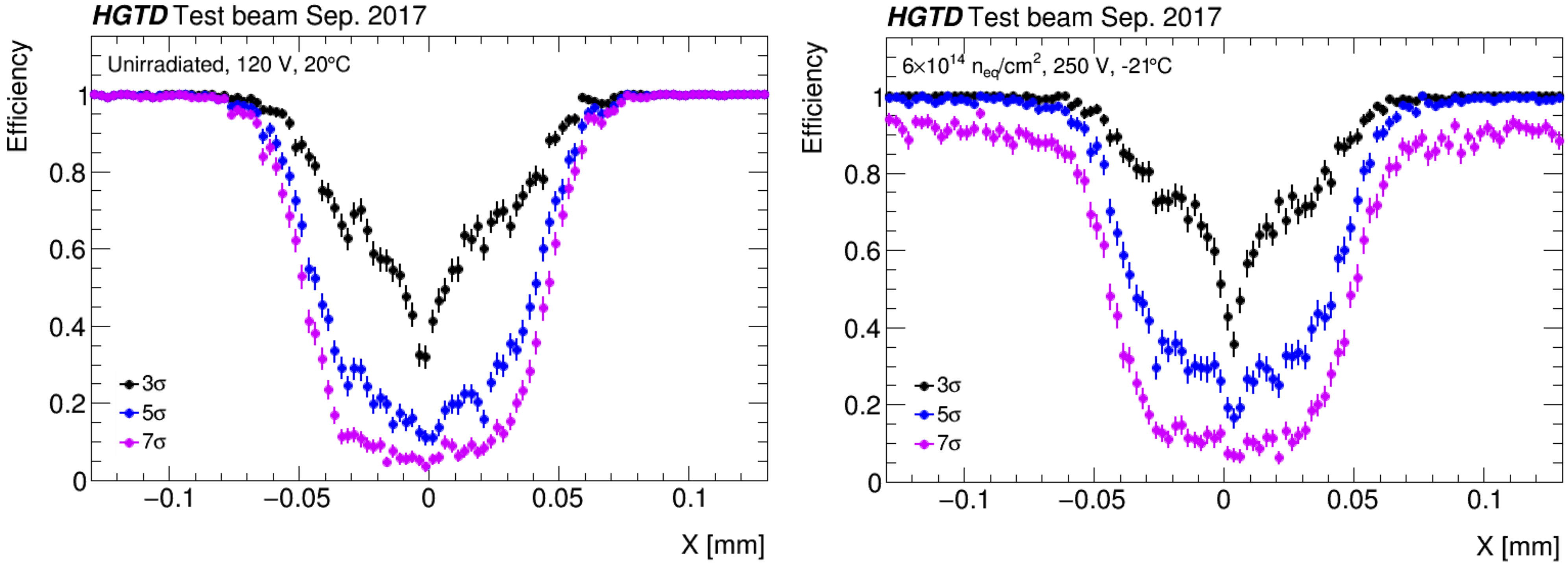
Broken channel in read-out board

Timing resolution slightly worse after radiation

Results from test beam measurements

Signal efficiency in the interpad region

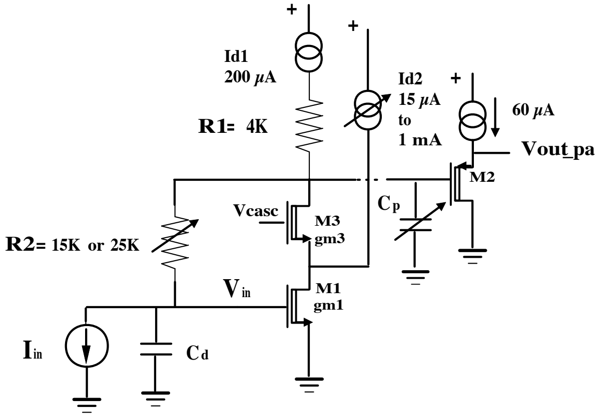
as function of X (mm) for 3 different voltage thresholds



Before irradiation

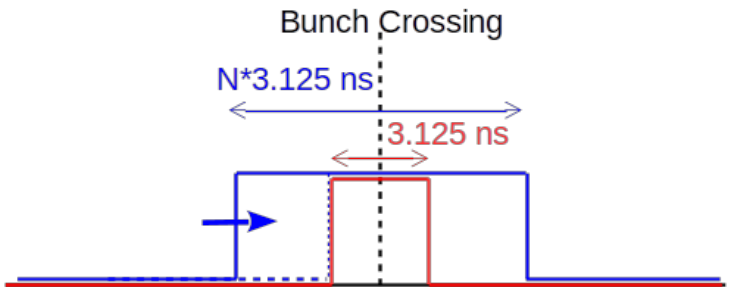
After 6×10^{14} n_{eq}/cm^2

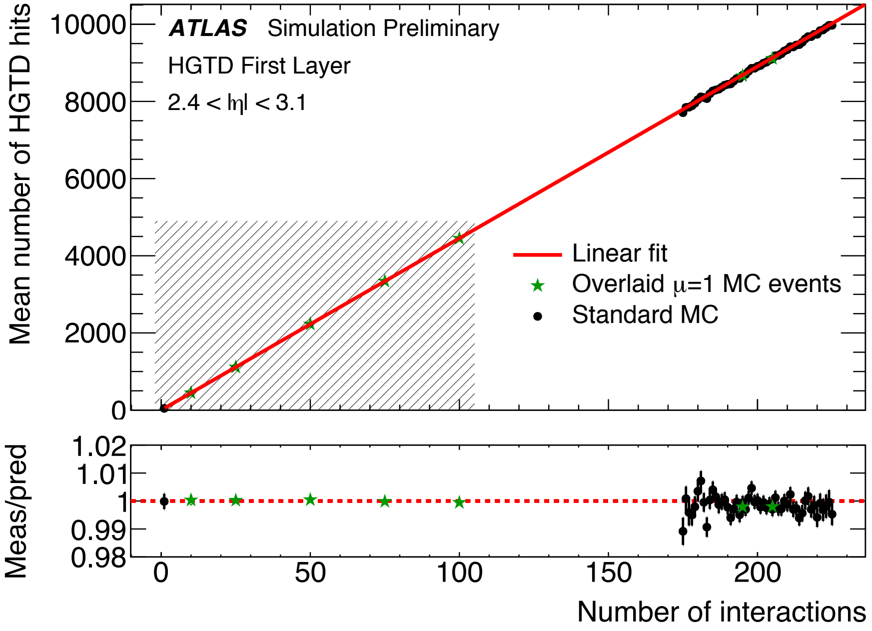
ALTIROC Readout ASIC



ATLAS LGAD Timing Integrated ReadOut Chip (**ALTIROC**)

- Broad band voltage pre-amplifier
  - Input transistor size chosen to minimize noise and power consumption
  - Provide TOA (9 bits, 20 ps bins) and ToT (7 bits, 40 ps bins)
  - Rise time ~0.5-1 ns (as sensor) to minimise jitter
  - Designed for 5 μA sensor leakage current





Bunch by bunch luminosity measurement capability

- Sums hits in two time windows to evaluate luminosity and background per ASIC
- Only ASICS at R> 320 mm will use luminosity readout

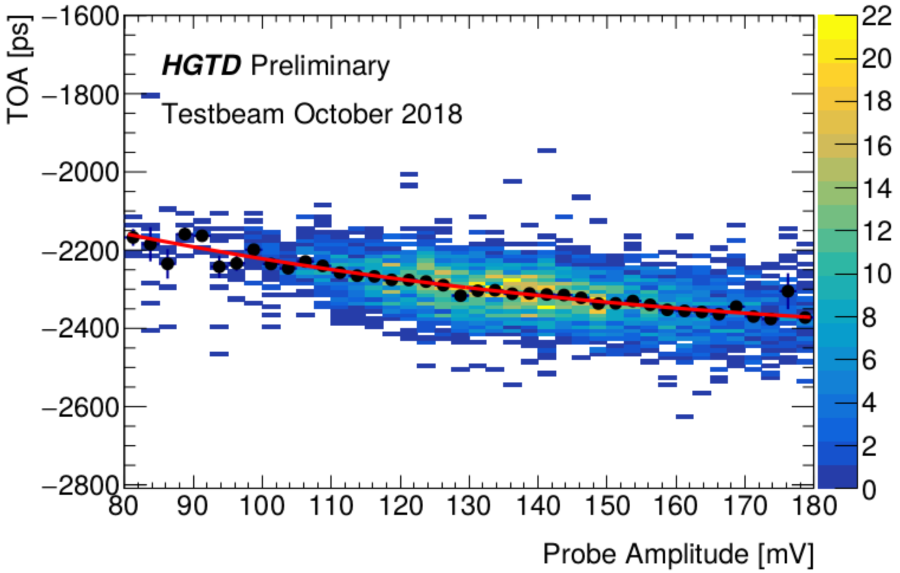
ALTIROC Readout ASIC

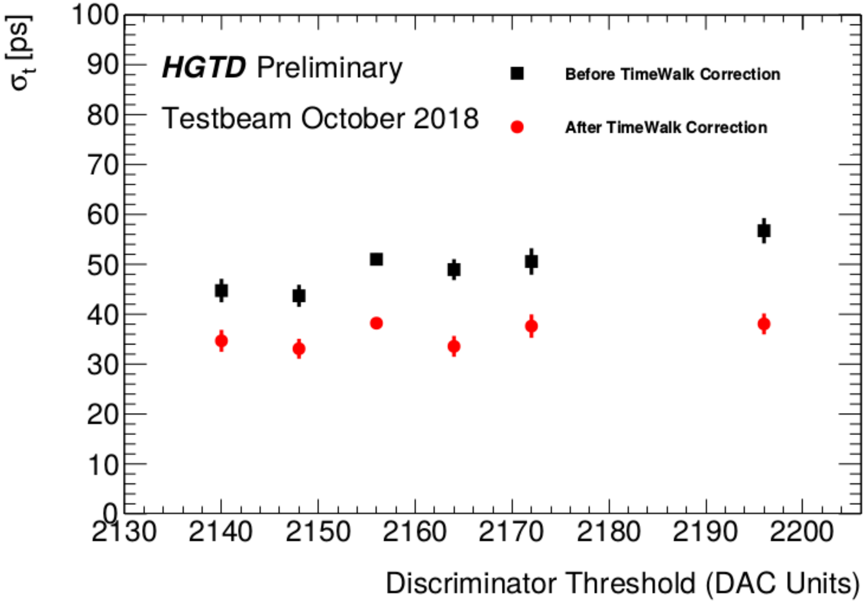
Developed in phases:

- ALTIROC0: single pixel analog readout (pre-amp + discri)
  - test bench measurements satisfactory
  - Beam tests → see next slides
- ALTIROC1: full single pixel (analog + TDC) readout in 5×5 array
  - Test bench measurements on-going
    (preliminary results show similar behaviour as ALTIROC0)
  - Irradiation and beam tests in Q1 2019
- ALTIROC2: final 15x15 version.
  - Submission expected end 2019

ALTIROC0_v2 Test beam results

- ALTIROC0_v2 bump bonded to an un-irradiated CNM 2×2 LGAD array
  - TOA of signal corrected for time walk (using probe amplitude)
- Best achieved time resolution after correction: 35 ps

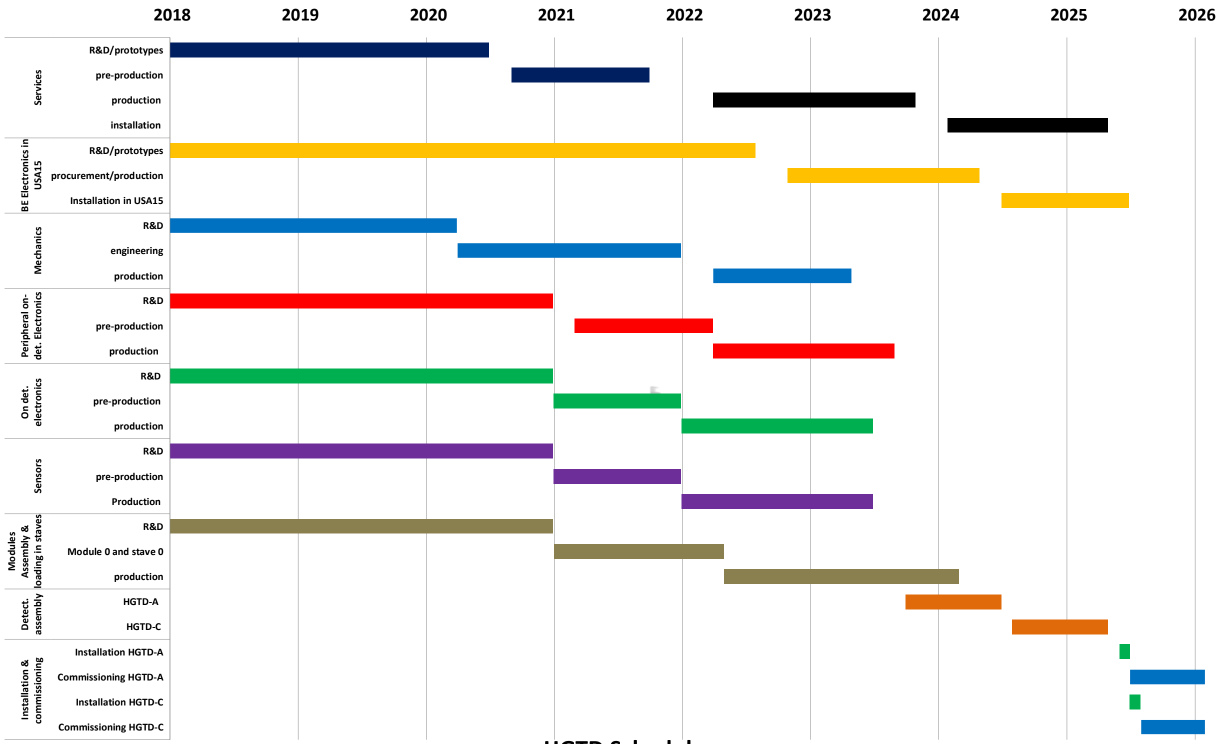




Summary and perspectives

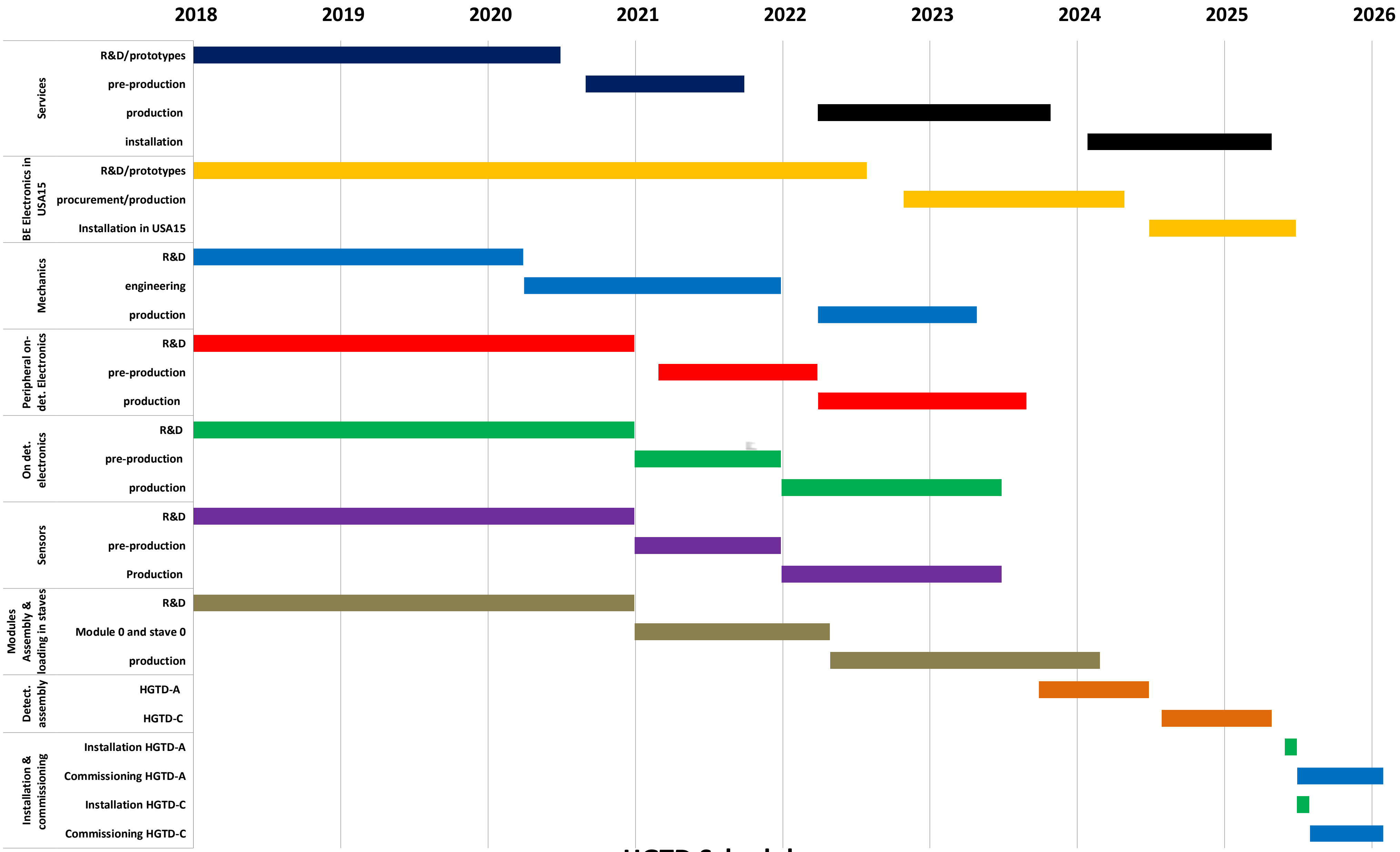
- The HGTD will mitigate pile-up effects and improve performance in the ATLAS forward region
- Technical proposal was approved 2018
- After a fluence of 6×10^{14} n_{eq}/cm^2
  - Efficiency in bulk is still ~100%
  - Time resolution of 40-50 ps is achieved

    Link to HGTD beam test paper
- Intense R&D program during 2019-2020
- New sensors are under tests, including 5x5 and 15x5 arrays
- Technical Design Report (TDR) under preparation (5 April)



HGTD Schedule

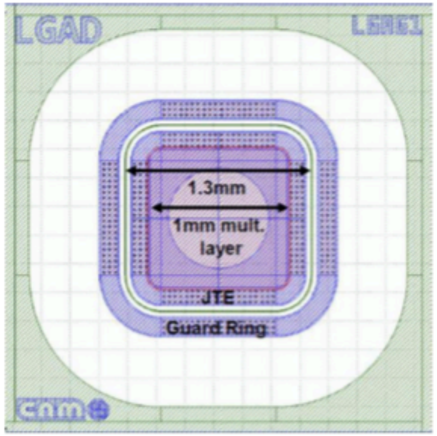
Backup: HGTD Schedule

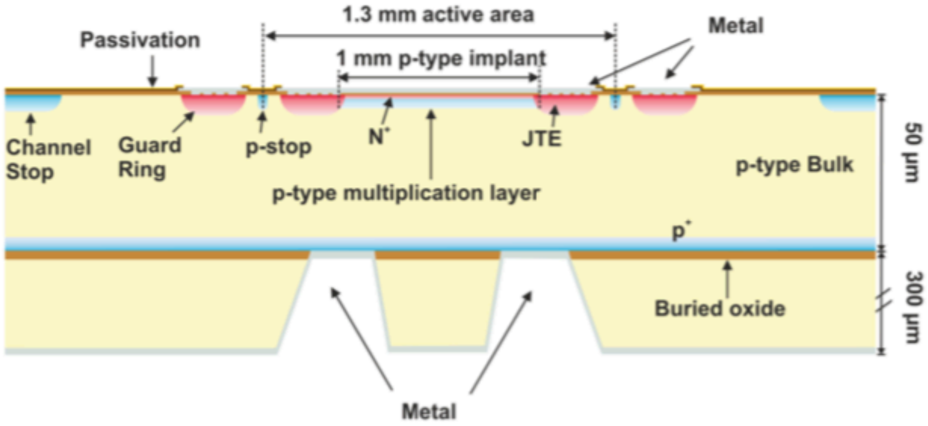


HGTD Schedule

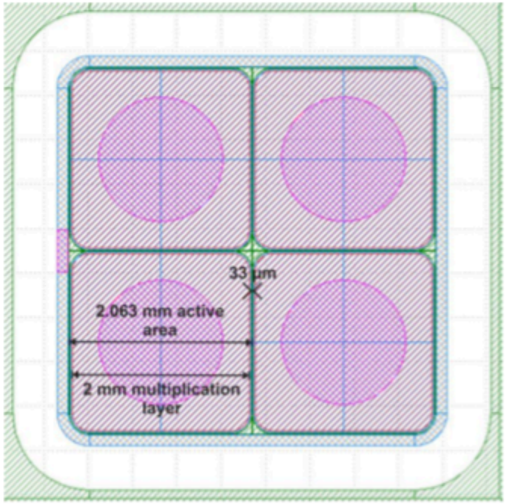
Backup

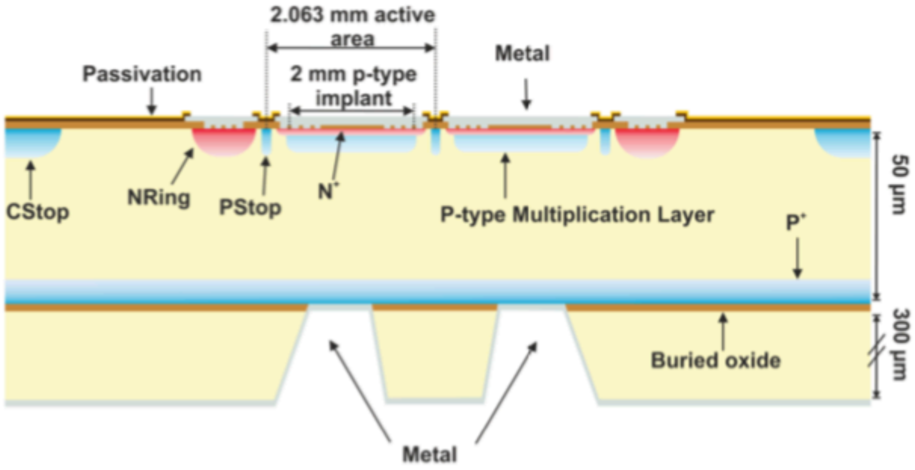
Single Pad LGA



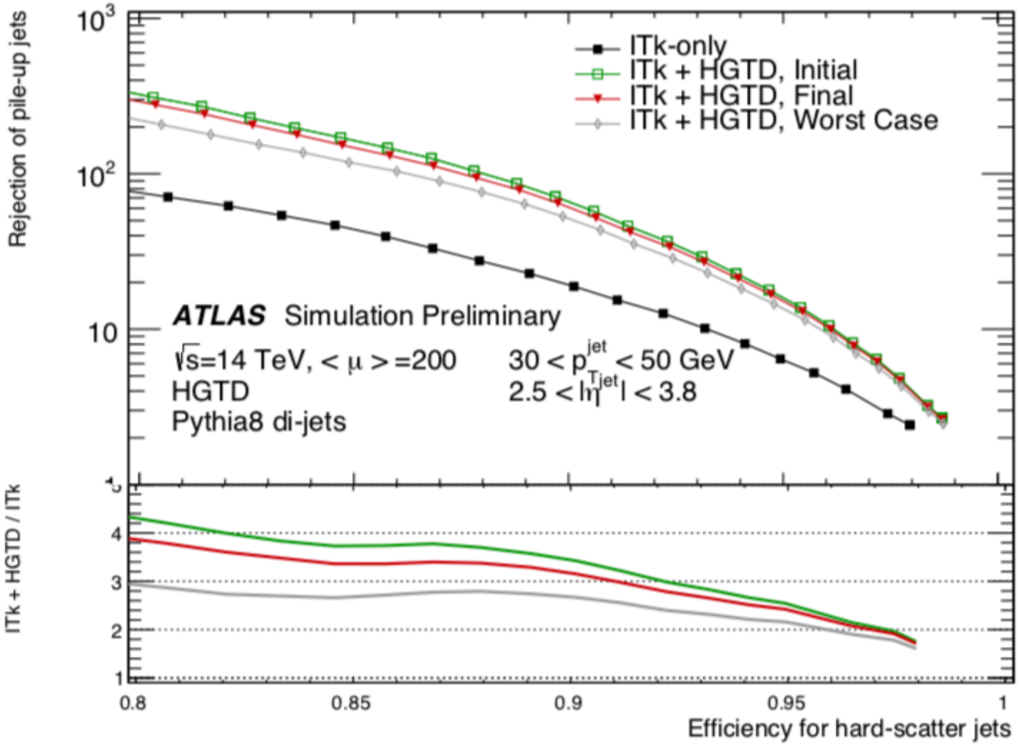


2x2 Pad Array





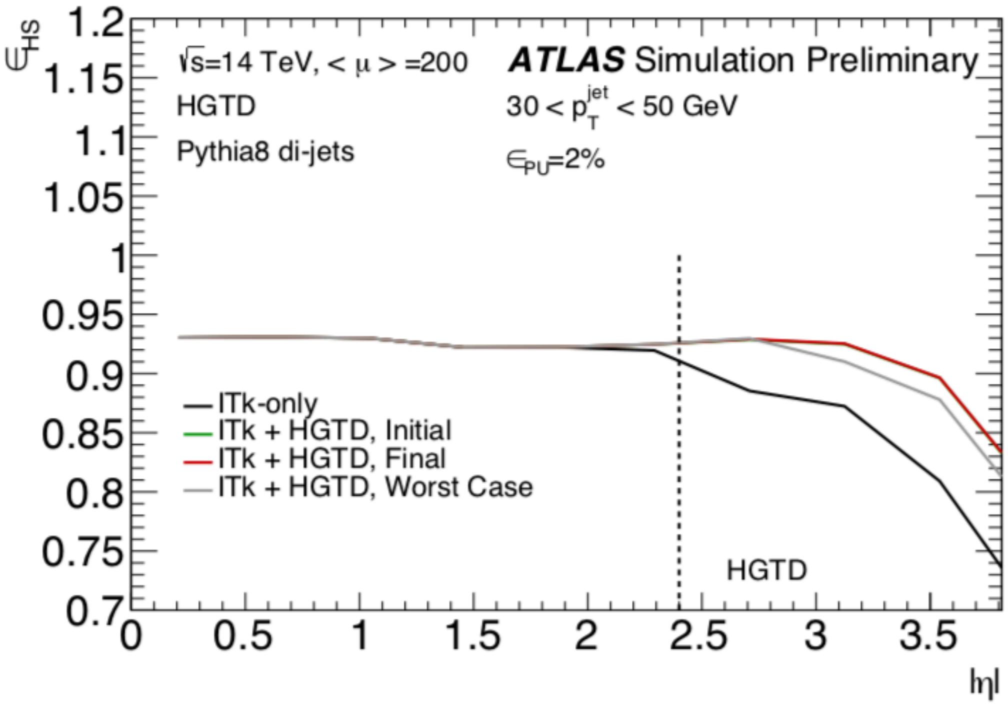
Backup: Pile-up rejection



With initial and final timing resolution ($\sigma(t) = 30$ ps), rejection improved by factor of 1.6-4

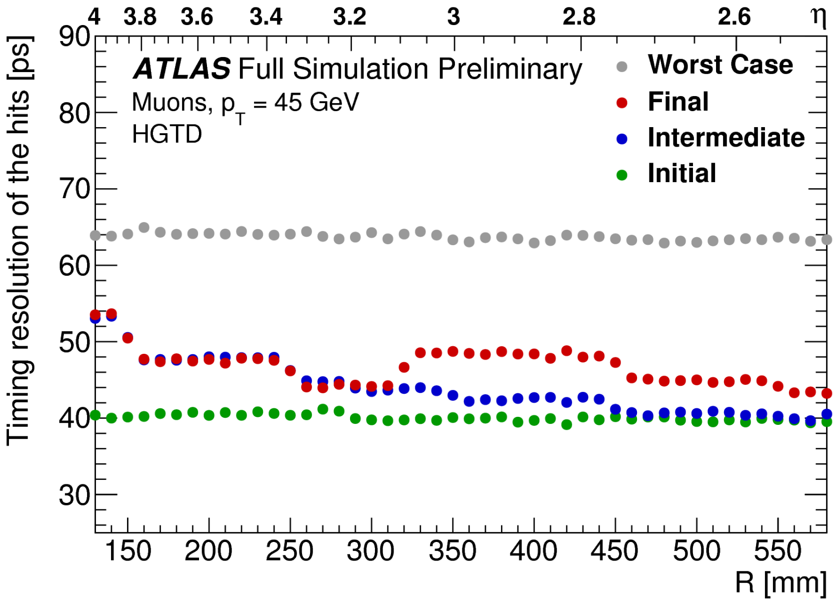
- Pileup-jet rejection as a function of hard-scatter jet efficiency in forward region
- No HGTD (black) and HGTD with different $\sigma(t)$

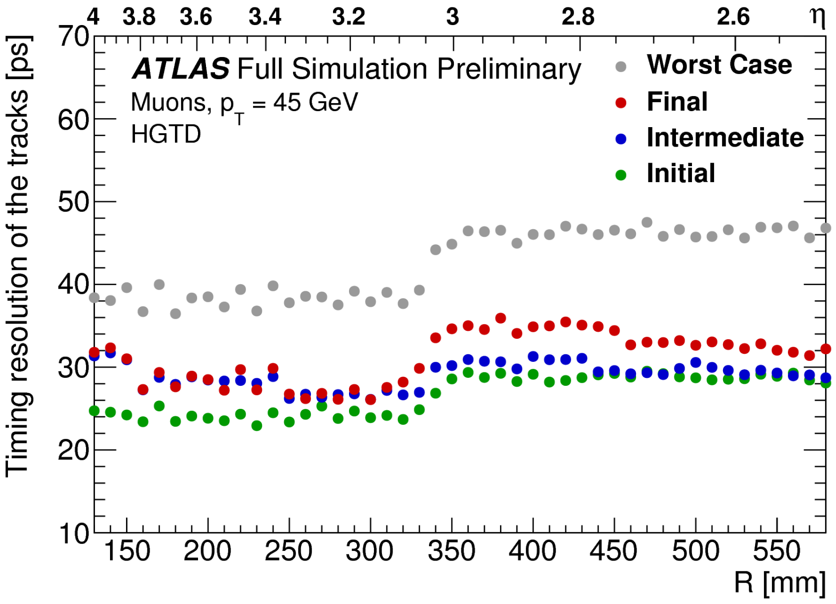
Backup: Pile-up rejection



Fixed pileup-jet eff of 2%, HS eff vs η

Backup





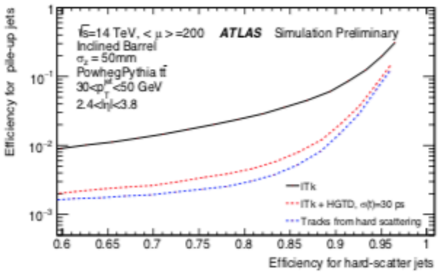
Time resolution worsens with radiation (higher dose at lower radius)

Compensated by more hits/track at lower radius. ($\geq$ 3 hits at R<320 mm, $\geq$2 hits at > R)

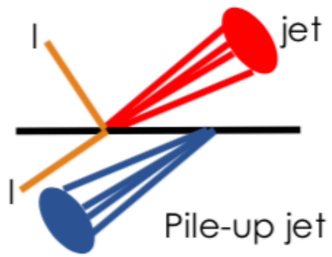
Backup: Physics use-cases

Examples:

forward pile-up suppression

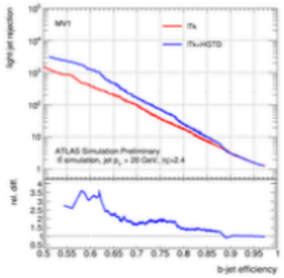


VBF final states



$VBF\ H \rightarrow \tau\tau$

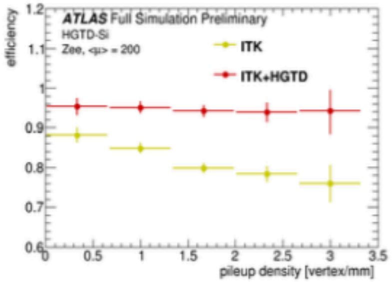
forward b-tagging



Searches and measurements with **forward b-quarks**

$t(H \rightarrow bb)$

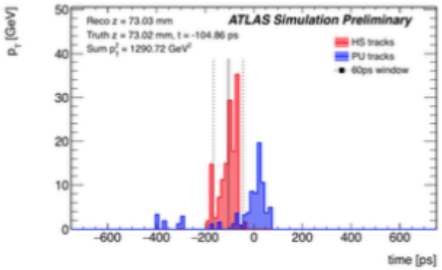
forward lepton isolation



Searches and measurements with **forward leptons**

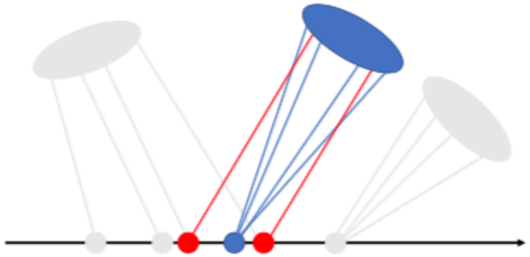
$sin^2\theta_W$

Timing measurements



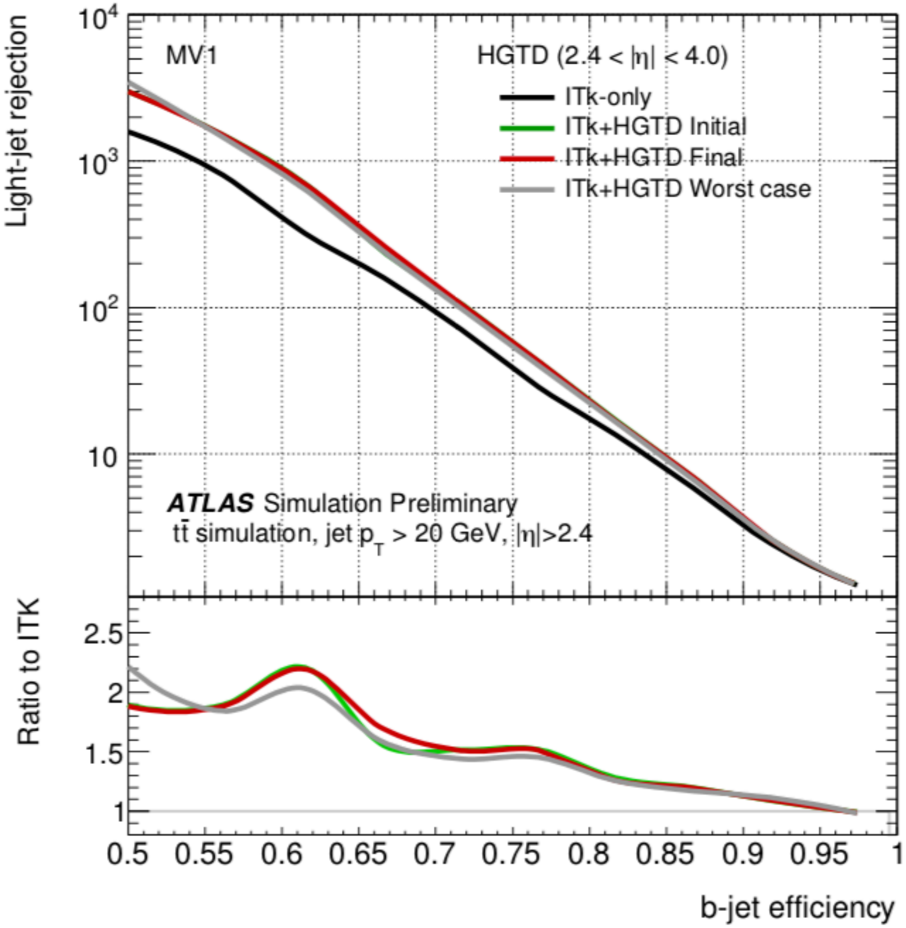
Long-lived slow particles

Backup: Physics use-cases

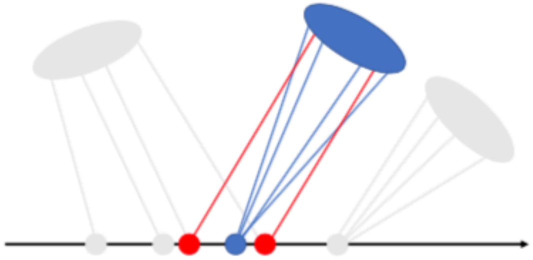


- Light-jet rejection versus b-jet efficiency within the HGTD acceptance →
- At 70% WP, light-jet rejection improved by a factor of ∼1.6

Particularly useful for physics with reducible bg from mis-tagged light jets!

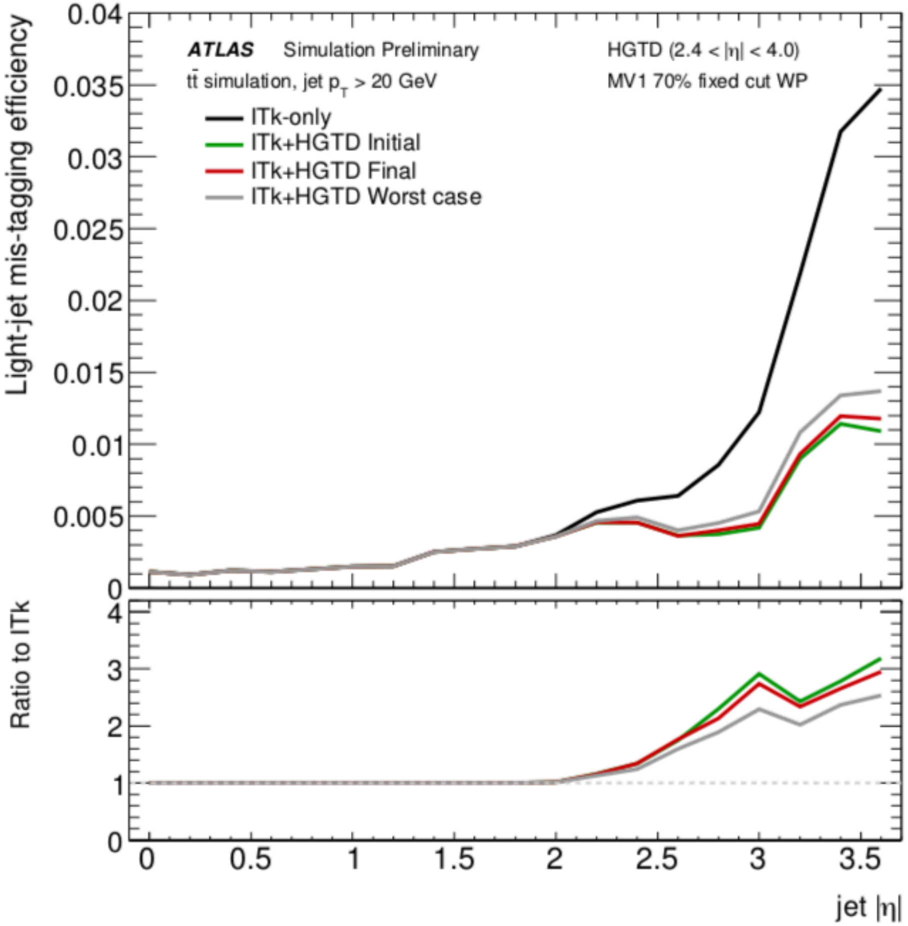


Backup: Physics use-cases

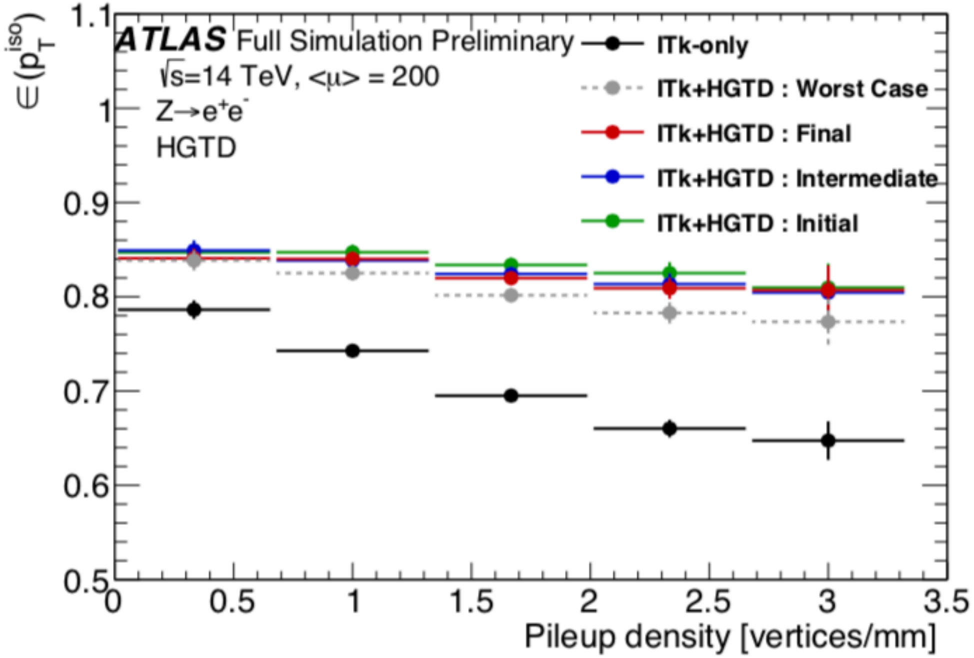


- Light-jet rejection versus b-jet efficiency within the HGTD acceptance →
- At 70% WP, light-jet rejection improved by a factor of ∼1.6
- At high η rej. improved by factor ∼3

Particularly useful for physics with reducible bg from mis-tagged light jets!



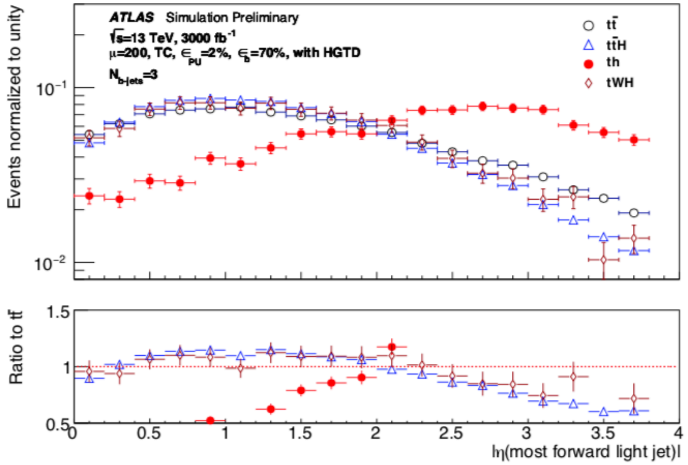
Backup: Physics use-cases



- Efficiency for **electron isolation** selection as a function of pileup vertex density
- No HGTD (black) and HGTD with different $\sigma(t)$ scenarios
- HGTD removes the majority of the effects of pileup, recovers 15% for average HL-LHC vertex density
- $\sigma(t) < 30$ ps does not help much

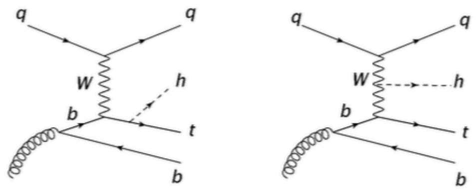
Backup: Physics use-cases

Physics: Impact on tH (final state with ≥ 2 b-tagged jets)



$|\eta|$ for most forward light-jet shown in the $3b$ region for tH followed by $H \to b\bar{b}$ and the backgrounds from $t\bar{t}$ and $t\bar{t}H$ production

- Probes sign of top-Yukawa coupling directly (left, if negative $\Rightarrow \sigma(tH)$ x10), complementary to $t\bar{t}H$



- Sensitivity to tH increased by 11% using HGTD
- Primarily due to improved b-tagging