A High-Granularity Timing Detector for the Phase-II upgrade of the ATLAS Calorimeter system: detector concept, design, and readout

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on behalf of the ATLAS Collaboration

Pile-up at HL-LHC

HL-LHC will deliver ~4/ab of pp collisions

Main HL-LHC challenge: **pile-up**

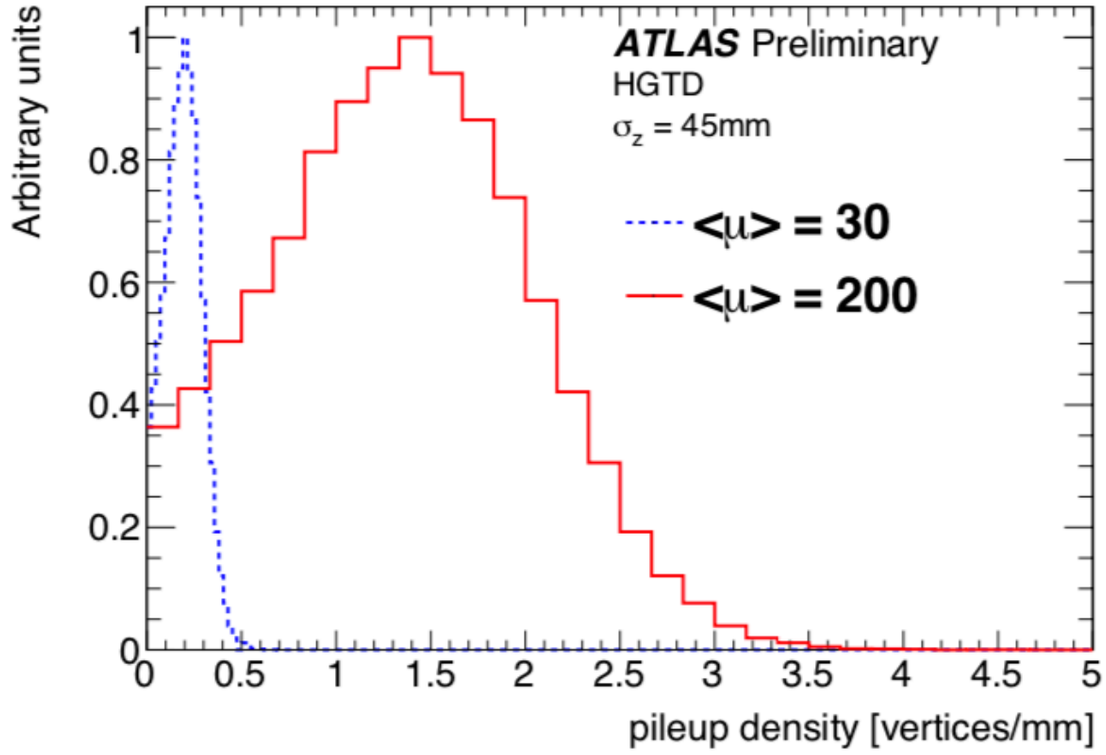
- e.g. 200 pile-up interactions with 30–60 mm RMS in z
- Much effort going to maintain excellent Run-1/2 performance in these more challenging conditions

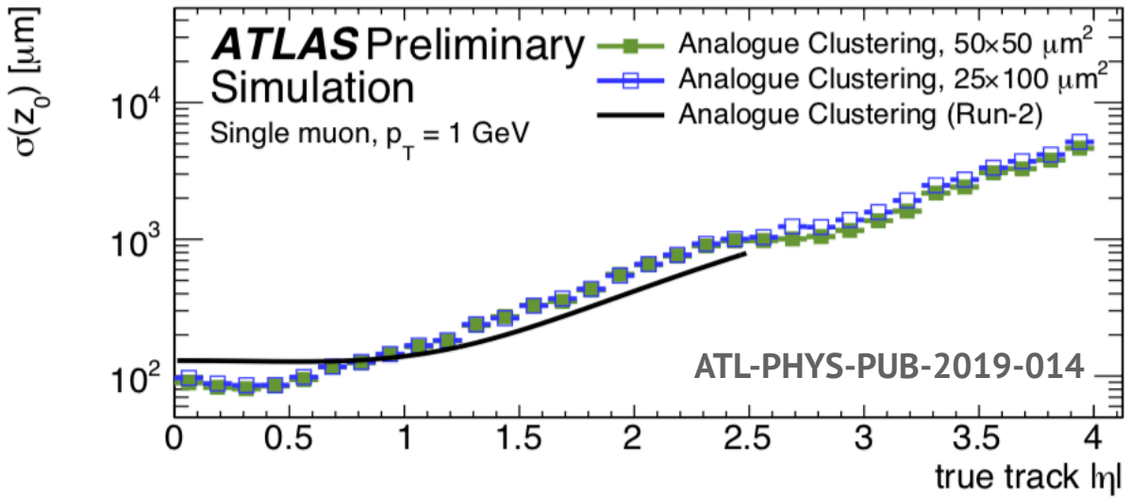
Charged particle tracking is key to address pile-up

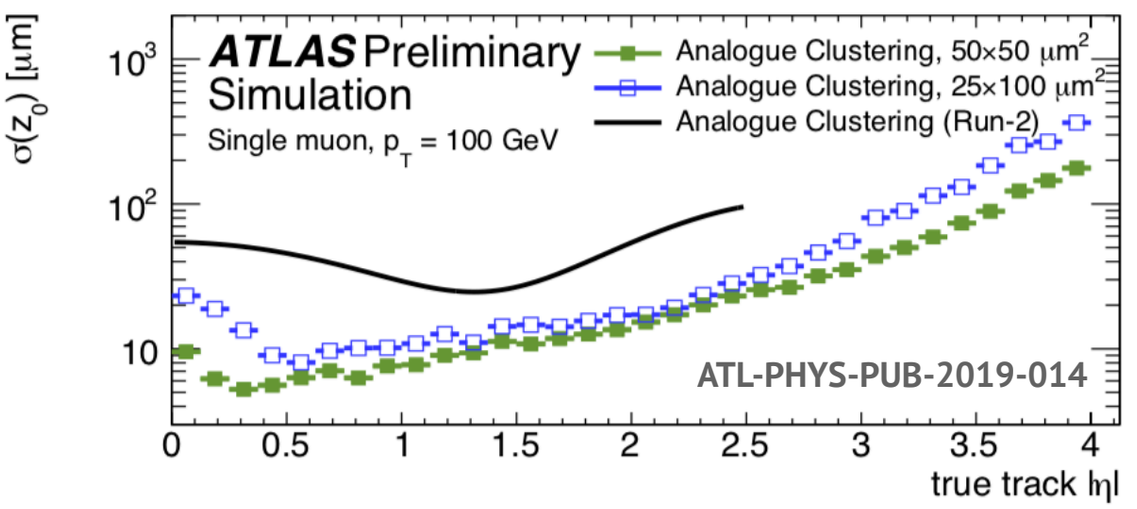
- ITK provides tracking for $|\eta| < 4$

Powerful pile-up rejection possible when track can resolve individual vertices in z

- Expect average PU line density to be around 1.8 collisions/mm, with large uncertainties
- Typical z_0 resolution from upgraded ATLAS silicon tracker (ITk) is far better than needed to resolve these, for central tracks
- But z_0 resolution degrades farther forward





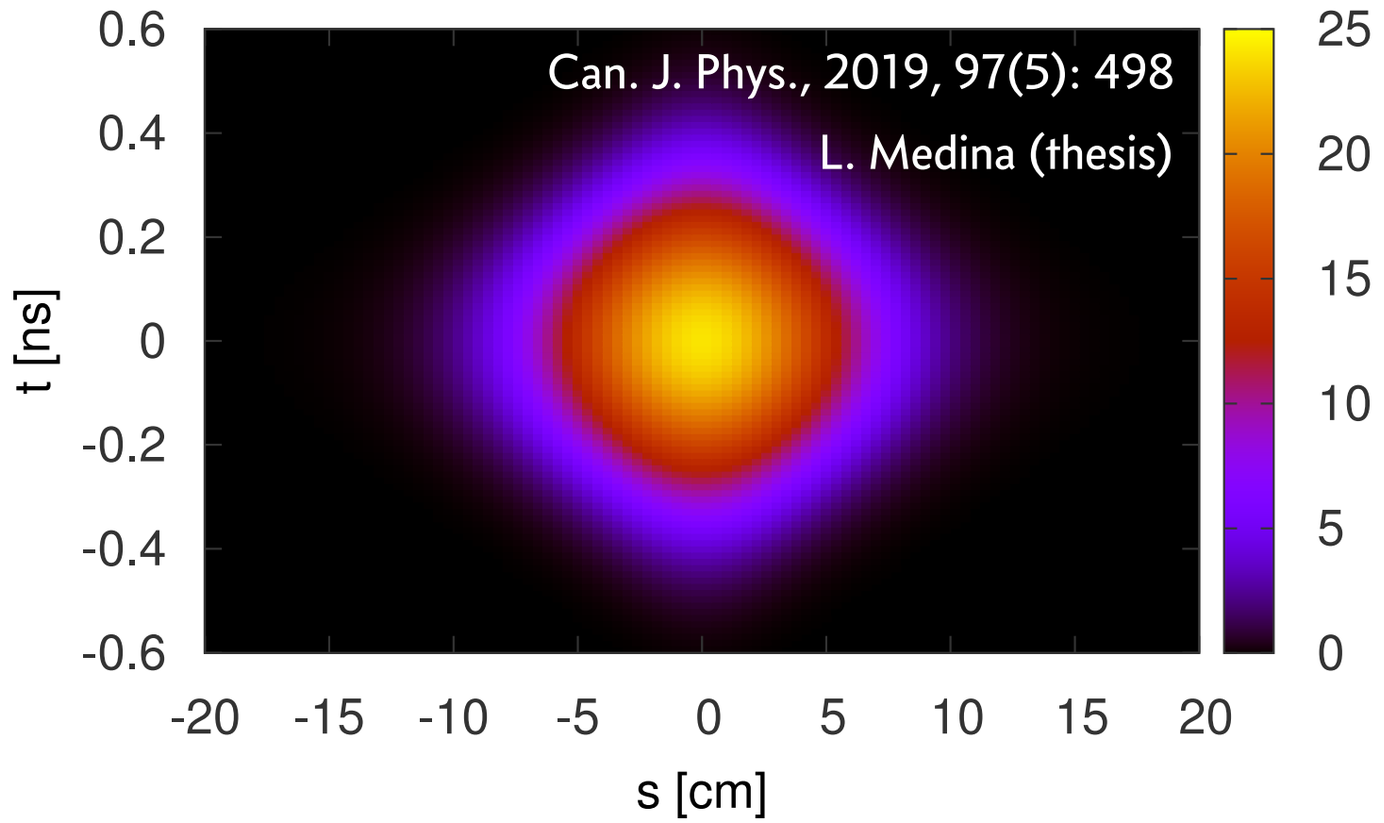


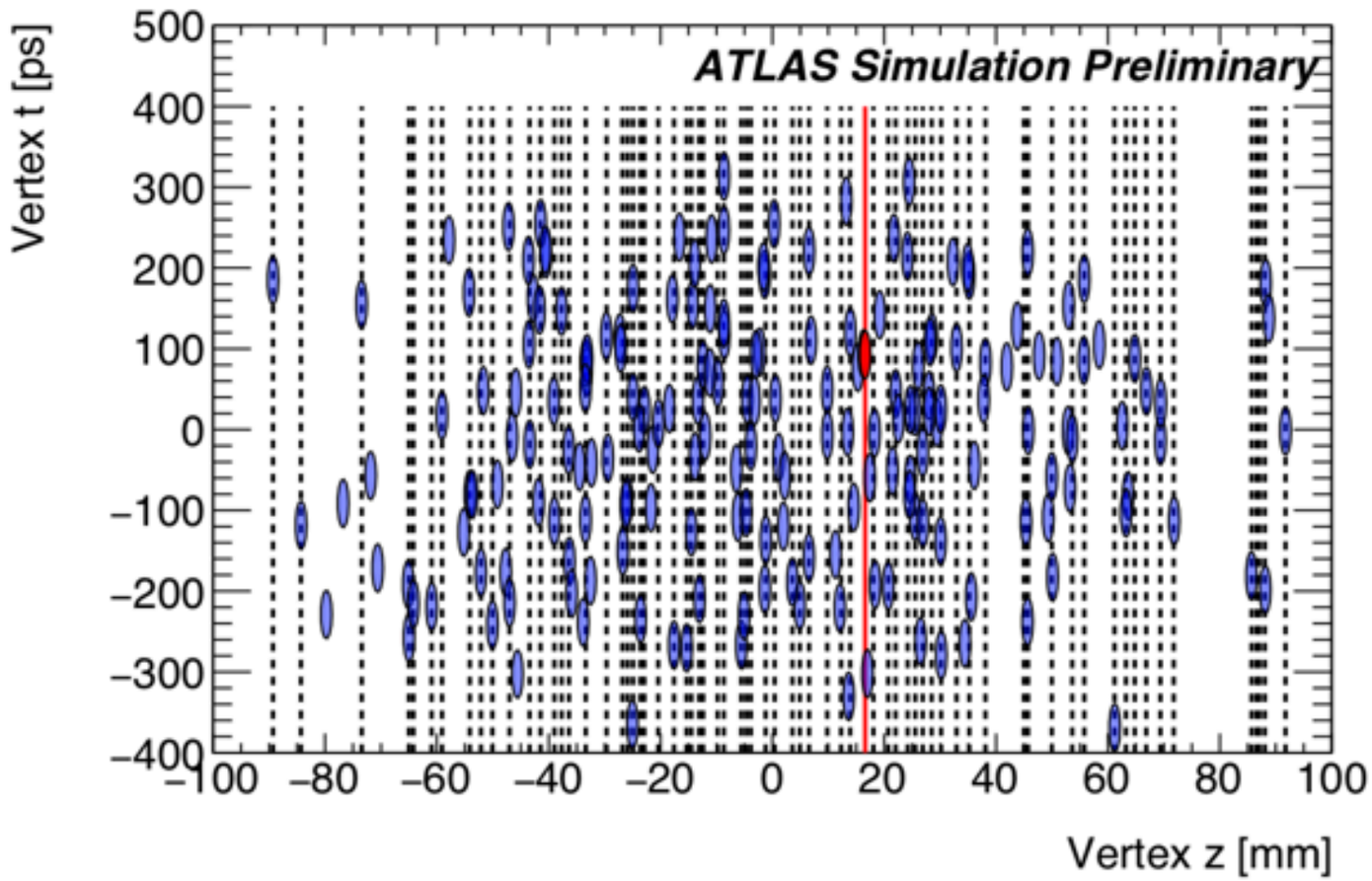
Motivation for HGTD

Goal: capability to exploit both space and time spread of pile-up (175–260 ps RMS)

- Extend great pile-up rejection in central region from ITk to higher eta
- Augment ITk in the difficult high eta region: an additional dimension of information → more flexibility to handle surprises
- Provide counting at 40 MHz for precision luminosity measurement

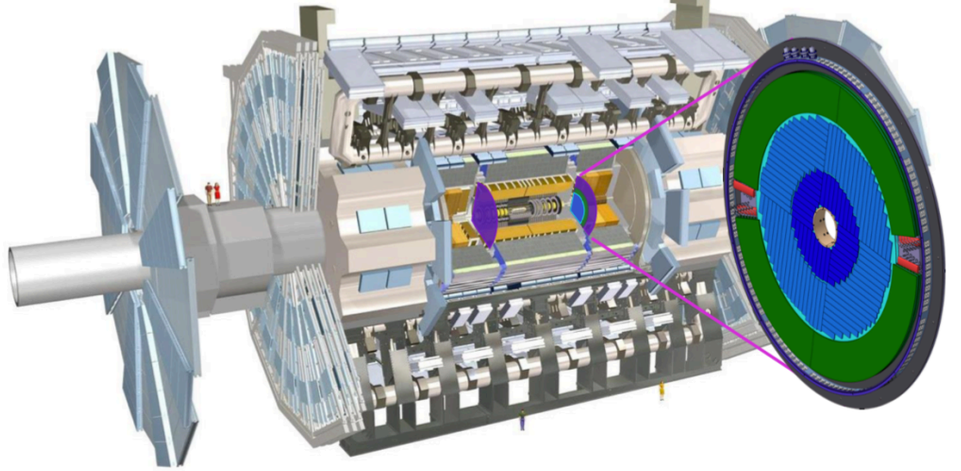
Initial 30 ps per track resolution (→ PU reduction by e.g. a factor of 175/30 → 6, μ~200 as if μ~33)





The High Granularity Timing Detector

Fits in MBTS envelope (unoccupied high η region in HL-LHC)

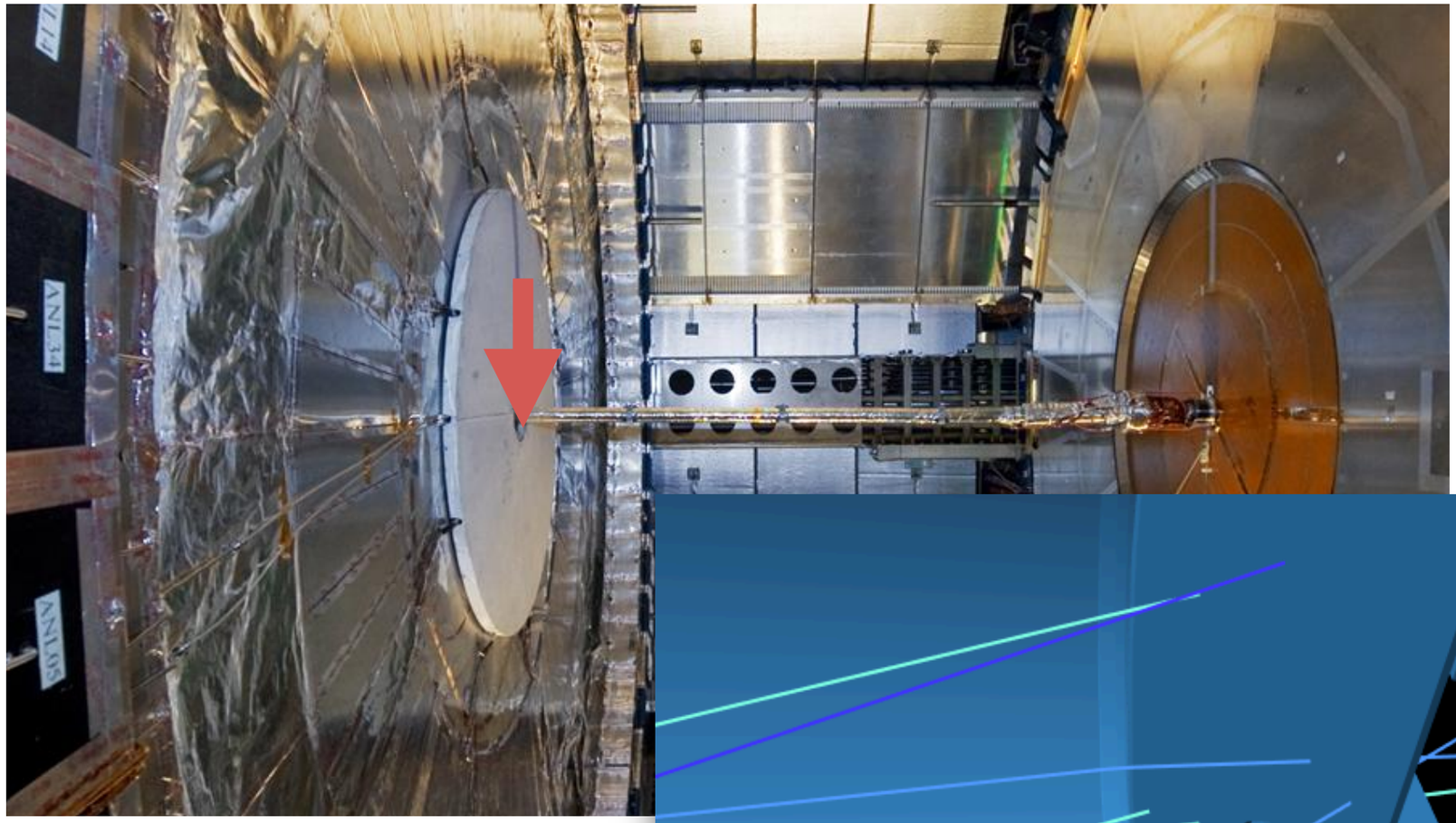


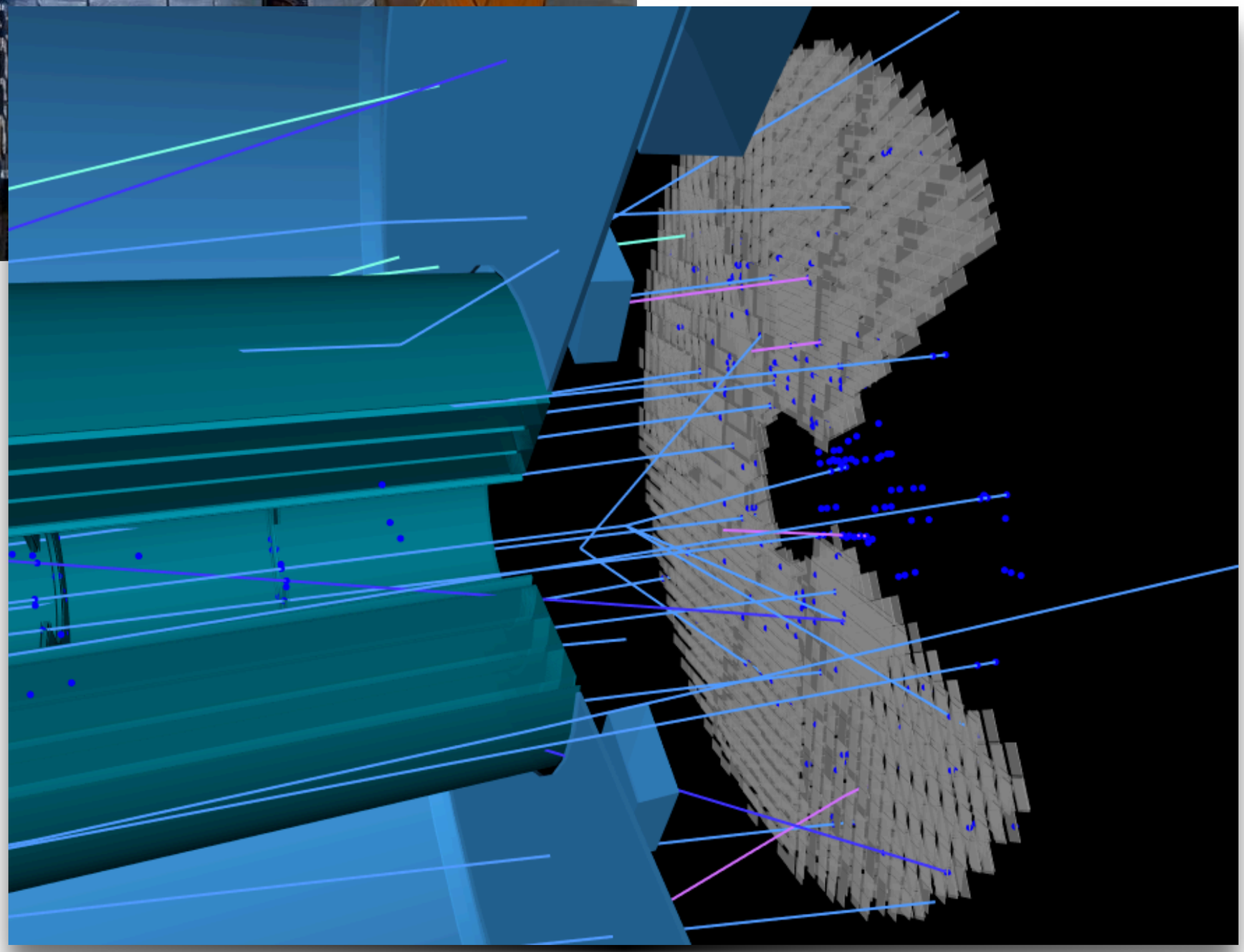
Pseudo-rapidity coverage	$2.4 < \|\eta\| < 4.0$
Thickness in z	75 mm (+50 mm moderator)
Position of active layers in z	$z = \pm 3.5$ m
Radial extension:	
Total	110 mm $< r <$ 1000 mm
Active area	120 mm $< r <$ 640 mm
Pad size	1.3 mm × 1.3 mm
Active sensor thickness	50 µm
Number of channels	3.59 M
Active area	6.4 m^2
Average number of hits per track	>= 2
Average time resolution per track (start and end of operational lifetime)	≈ 30 ps (start) ≈ 50 ps (end)

Design requirements: **excellent time resolution**, **radiation-hard**, **low occupancy**, **modular**

- thin **Low Gain Avalanche Detectors (LGADs):** pixel detector with coarse spatial resolution (→high granularity, **1.3 x 1.3 mm²** for occupancy < 10%) but precision timing (**30–50 ps**)
- 2 double **planar layers** in each endcap
- specially-designed **ASIC ALTIROC** front-end

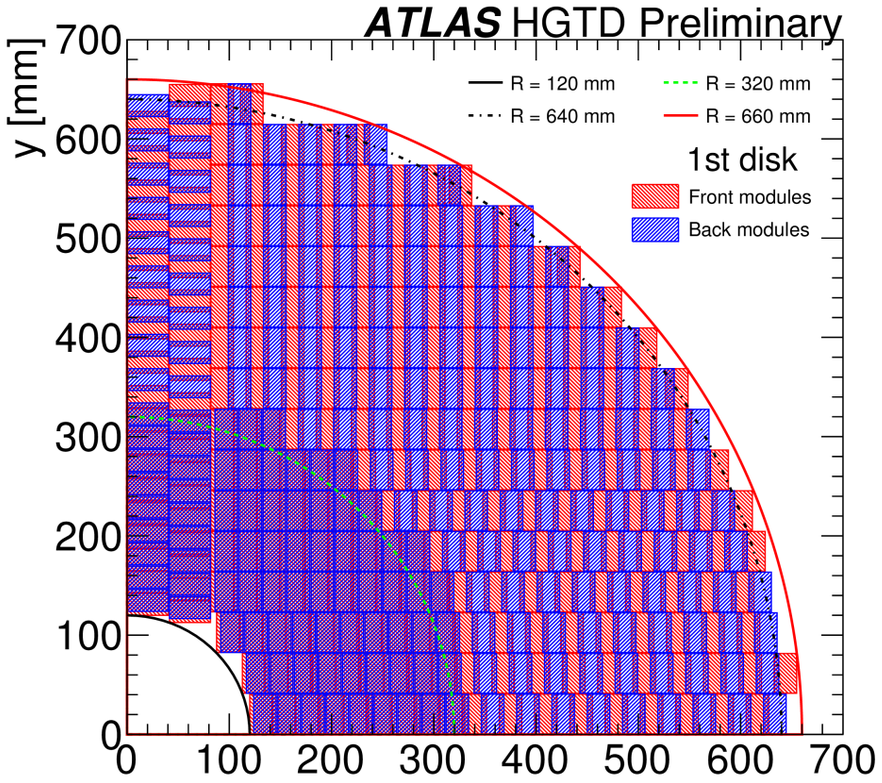
See Zhijun's talk on Monday

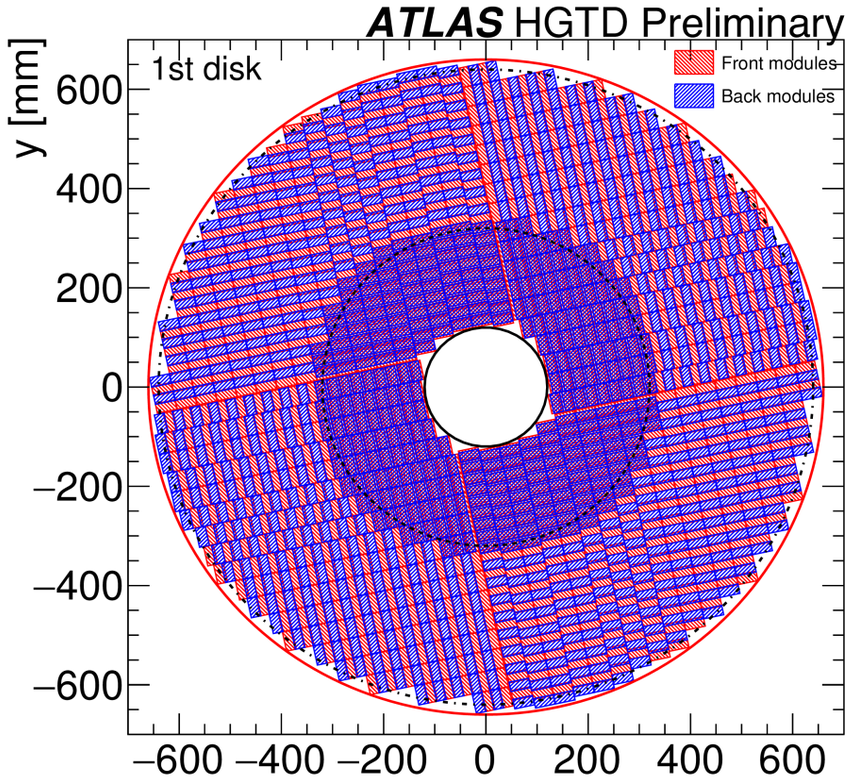

ANL34
ANL55



Detector layout evolution

Design for Technical Proposal (2018)

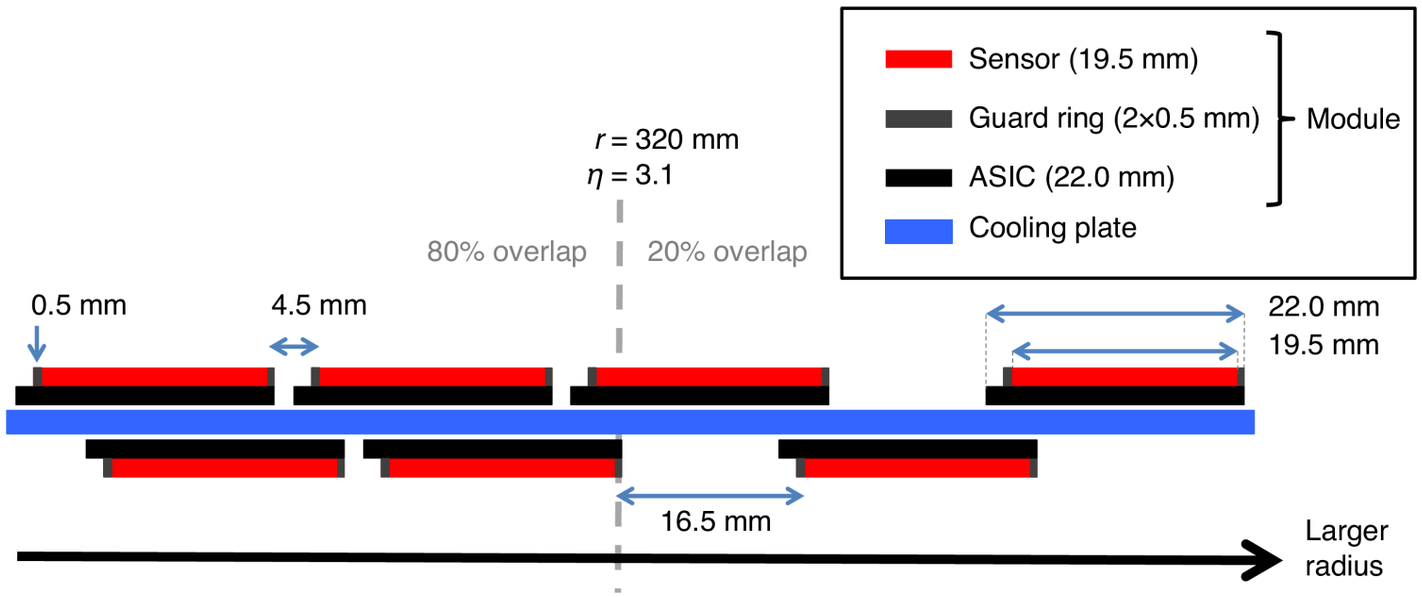


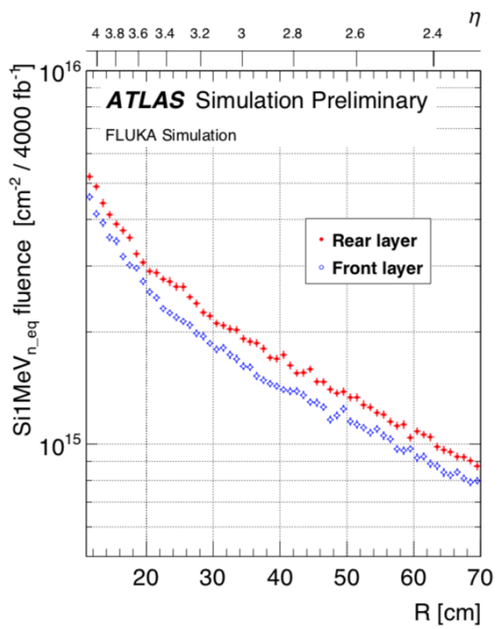


Two rings of modules

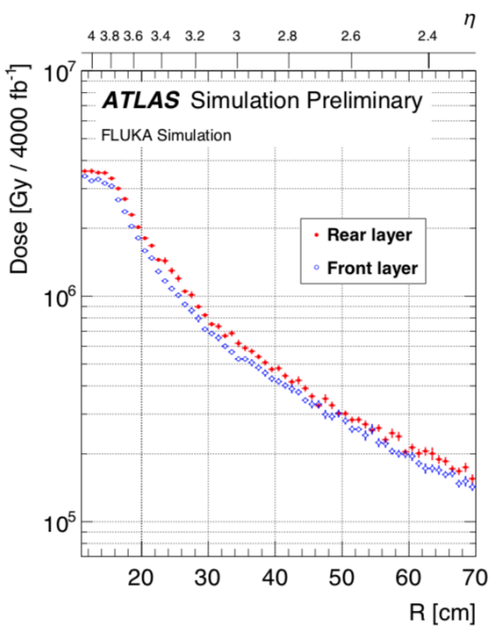
80%,20% overlap fractions to provide average 3 hits/ track in most irradiated region.

Inner ring can be replaced after 2/ab





(a) Nominal Si1MeV$_{n_{eq}}$ fluence for HL-LHC.



(b) Nominal ionising dose for HL-LHC.

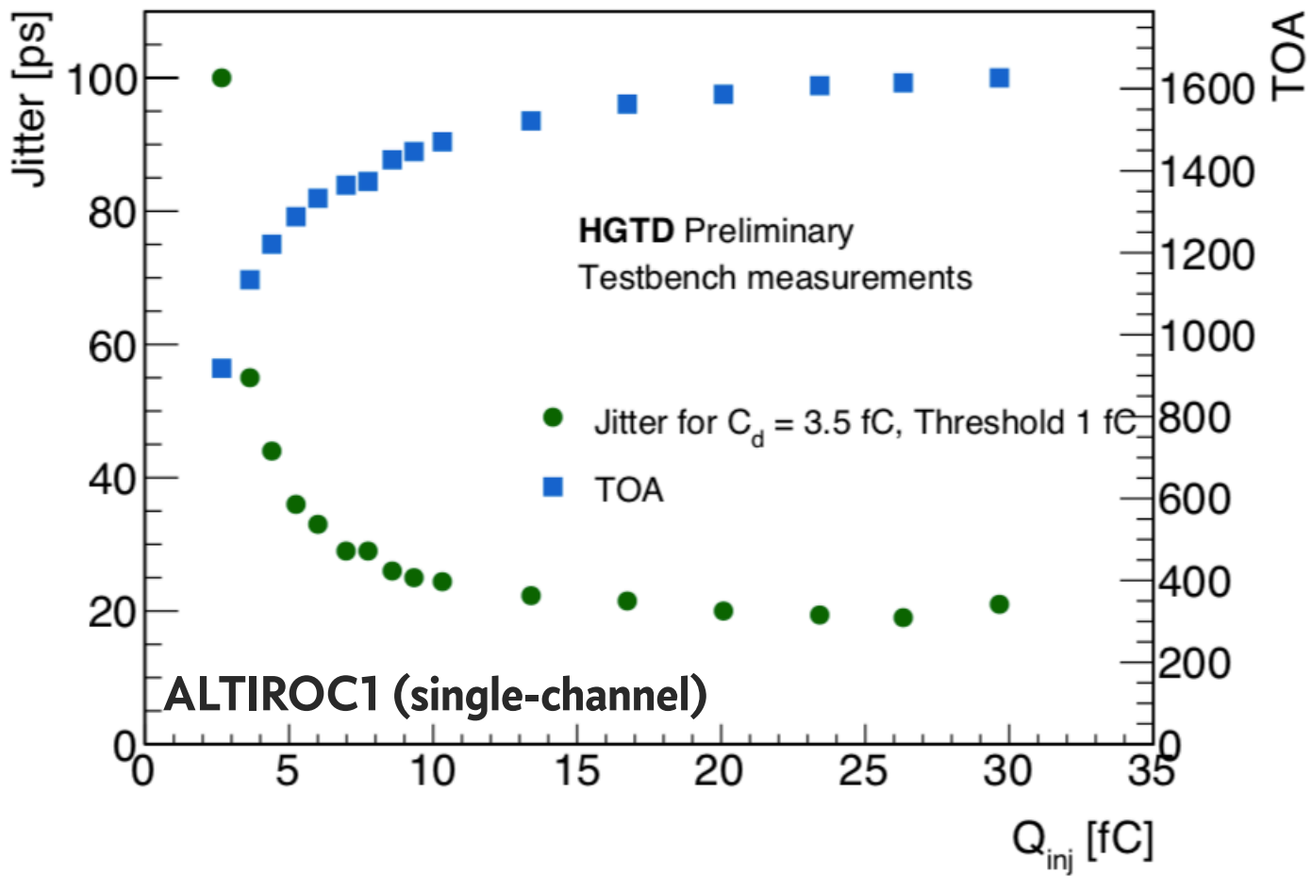
Detector layout evolution

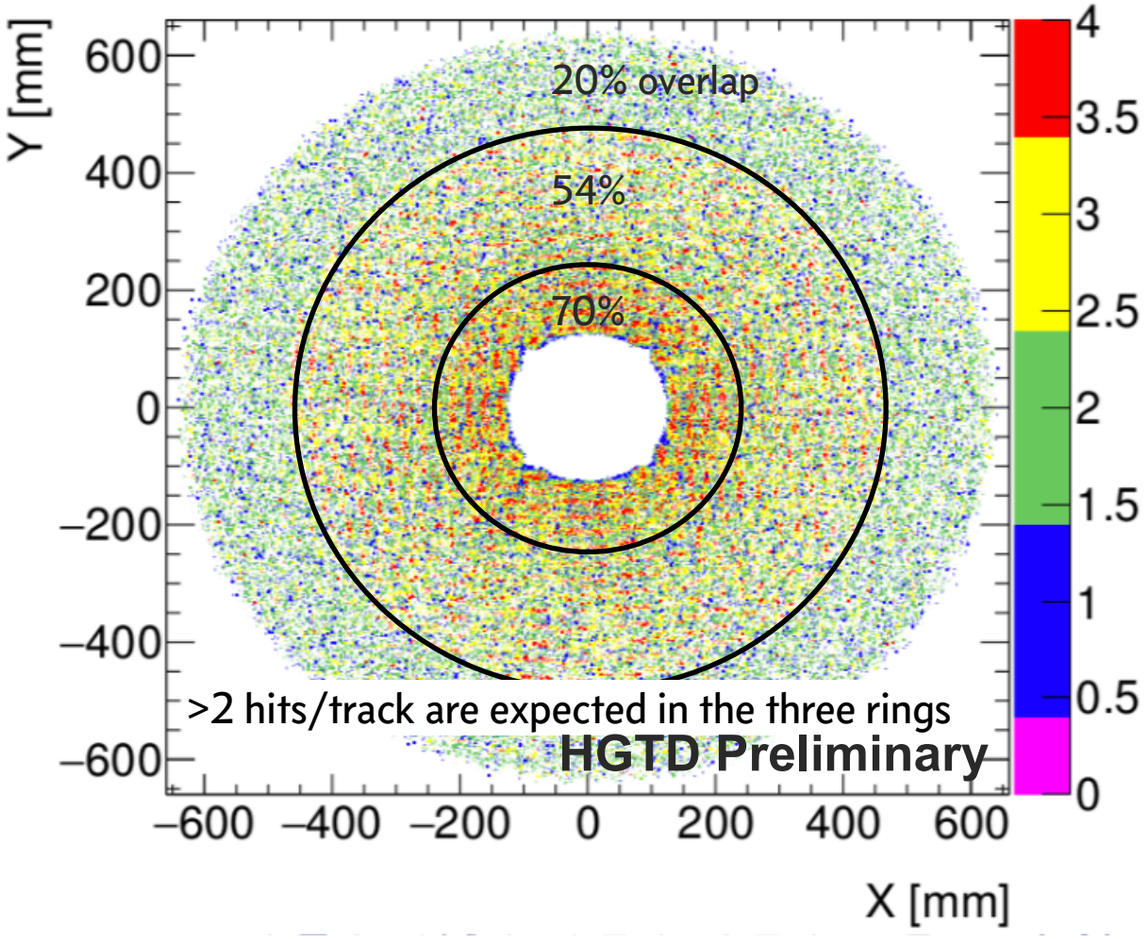
Current R&D does not allow us to reach 5×10^{15} N_{eq}/cm^2 and 3.6 MGy. Mitigate with **three ring** proposal.

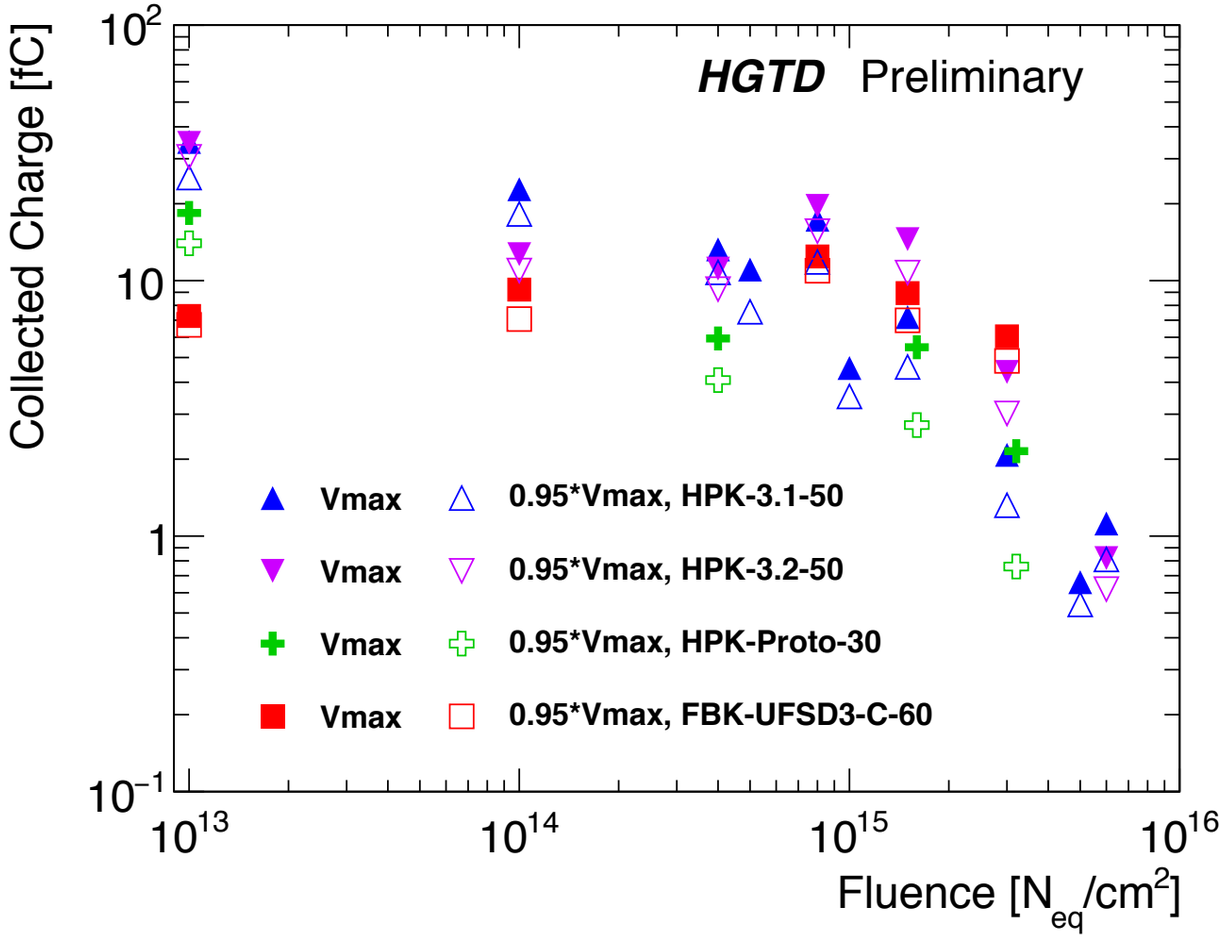
Inner ring replaced after each 1/ab

Middle ring replaced after 2/ab

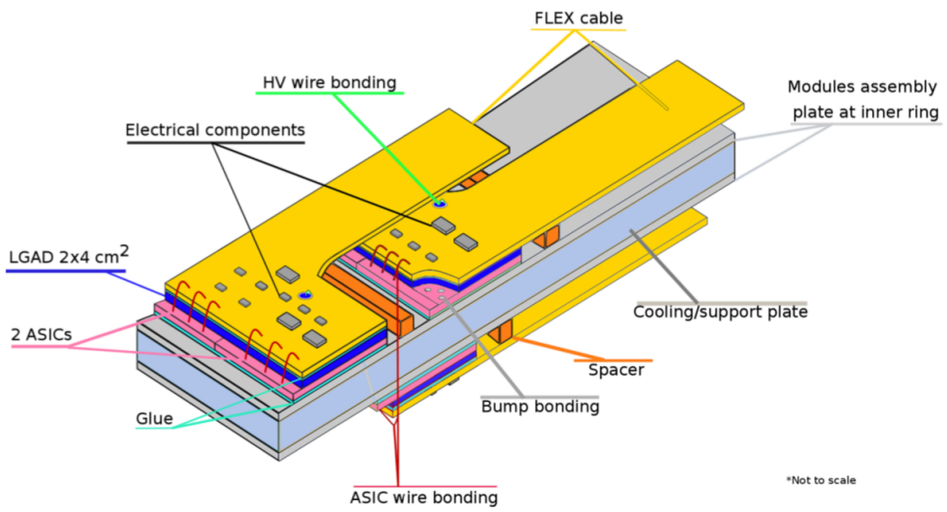
Ensures sensor charge of >= 4 fC
after 2.5×10^{15} N_{eq}/cm^2 and 2 MGy

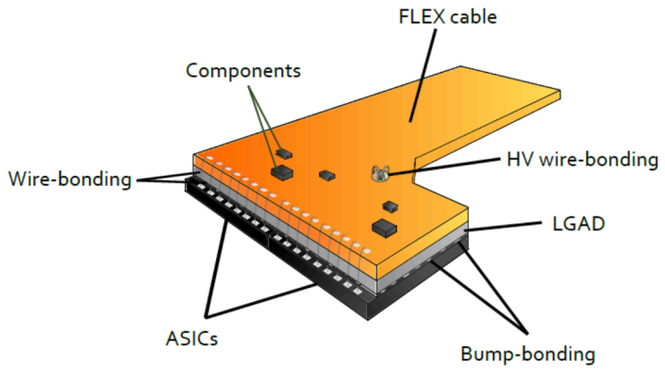


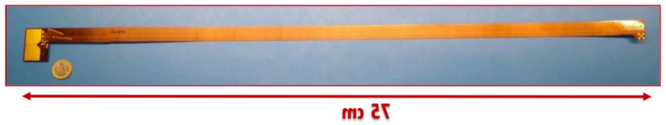


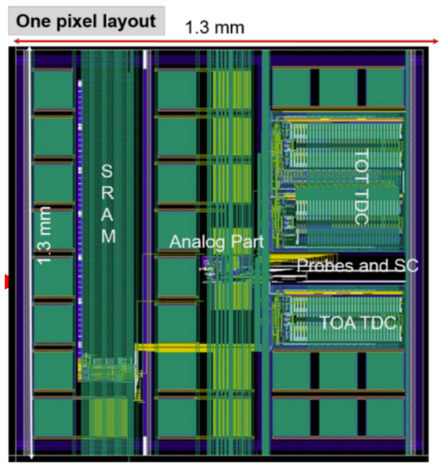


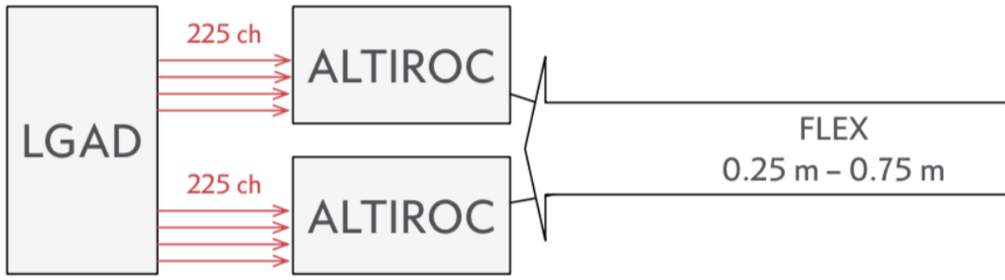
HGTD front-end and readout electronics

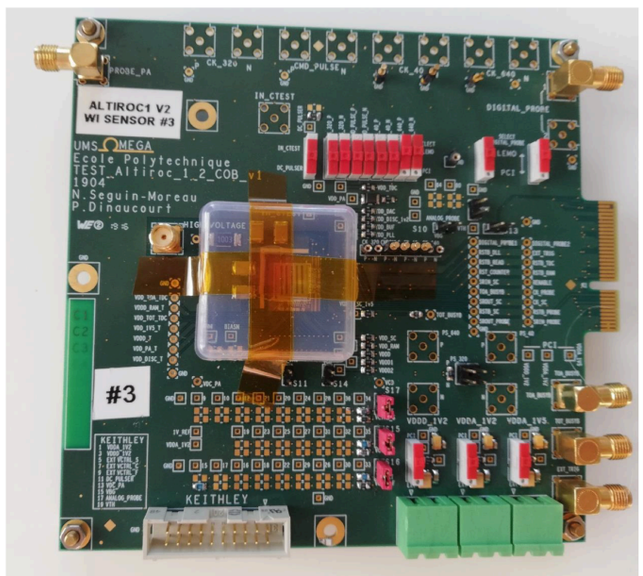


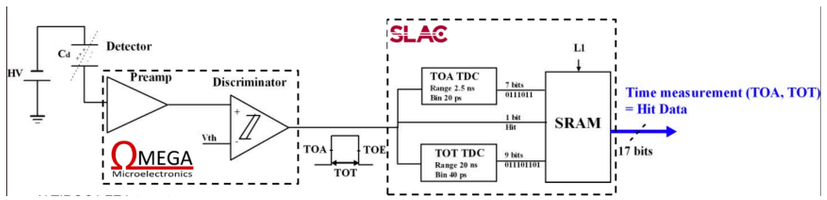


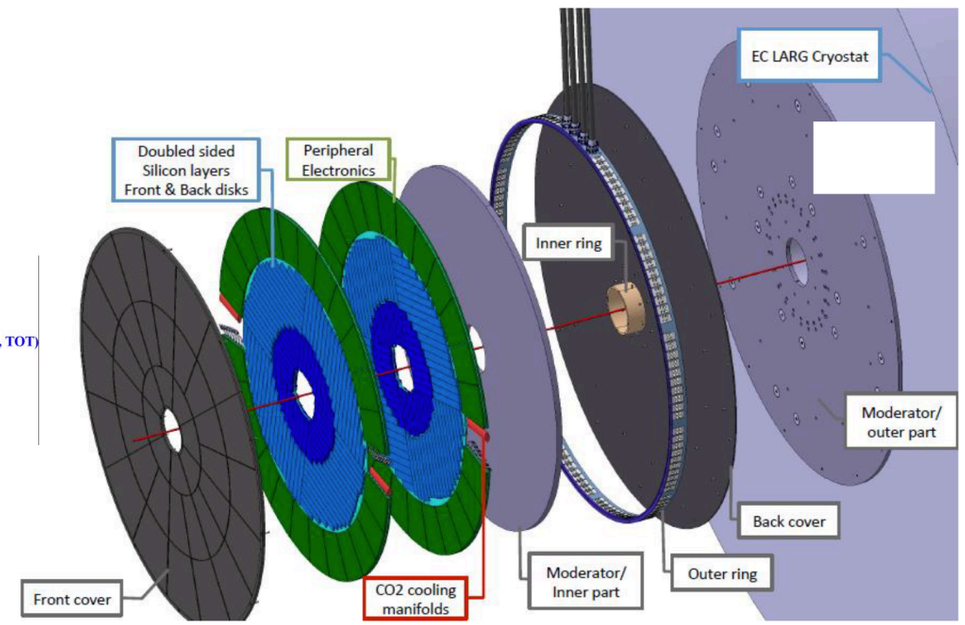




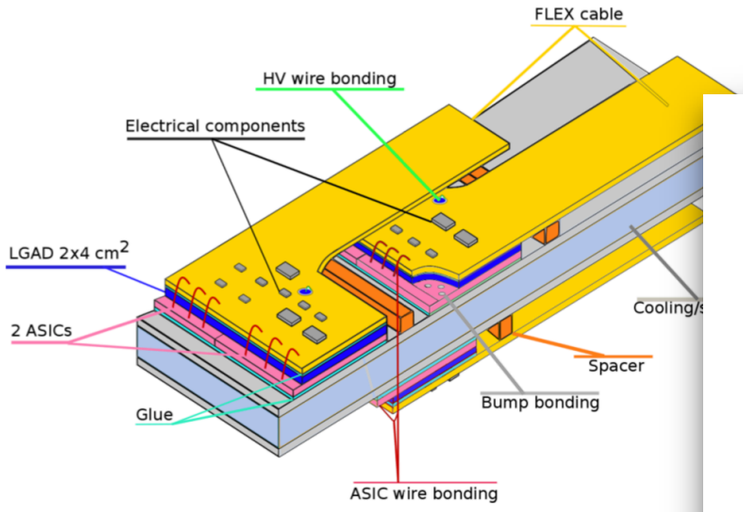


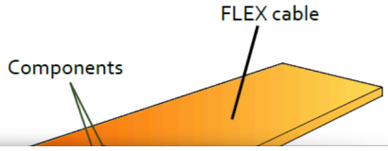


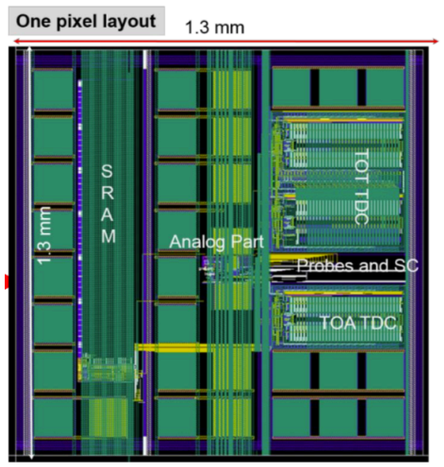


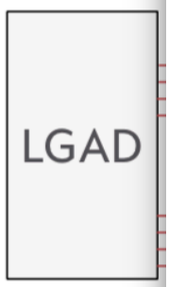


HGTD front-end and readout electronics









ALTIROC ASIC (CMOS TSMC 130 nm)

Single pixel read-out (225 channels/ASIC) measuring time of arrival (TOA), time over threshold (TOT)

ALTIROC0: single pixel analog readout (pre-amp + discr.) for 2x2 1x1 mm^2 sensors (0_V1 Dec '16, 0_V2 Dec '17)

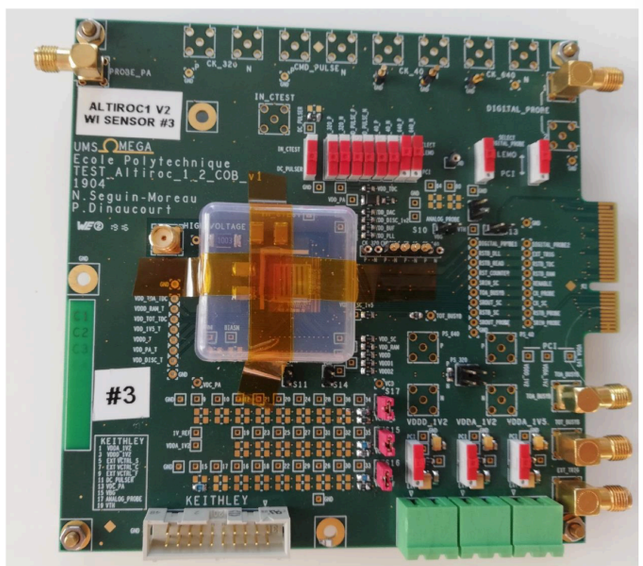
ALTIROC1: 5x5 complete channels (PA, discr., TDC, SRAM) readout bump bonded to sensors (1_V1 testing since end of 2018; 1_V2 with minor mod. testing since July '19)

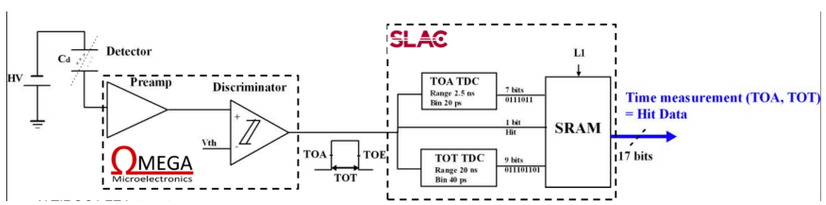
ALTIROC2: final 15x15 version (submission expected mid '20)

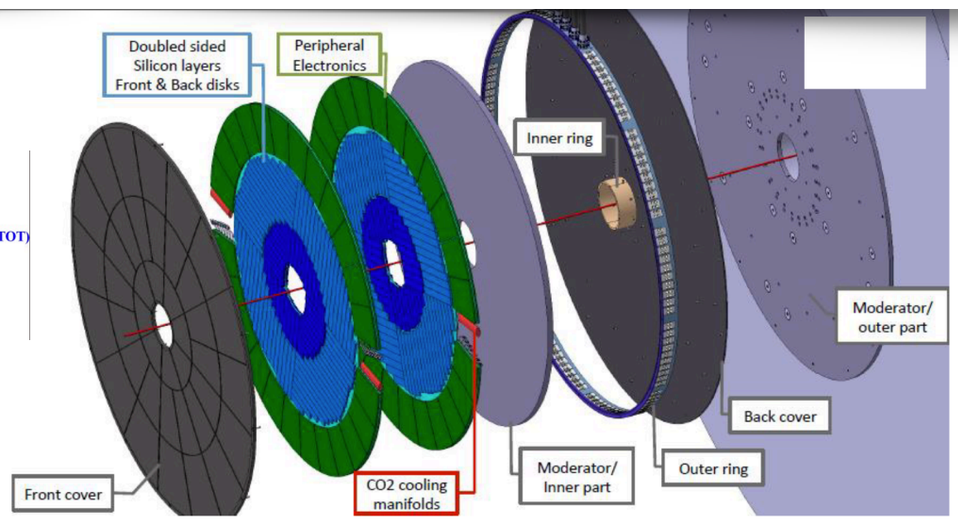
Reads out:

at 1 MHz, after L0 trigger: **detailed hit information**

at 40 MHz: **number of hits** for each ASIC at outer radii (real-time, per-crossing luminosity measurement with time-sideband subtraction)





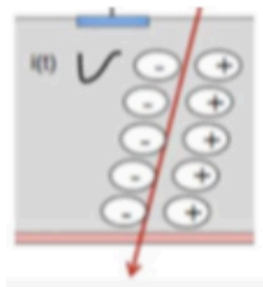


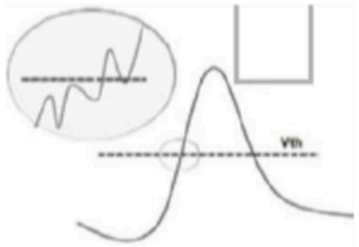
HGTD front-end and readout electronics

$$\sigma_{timing}^2 = \sigma_{Landau}^2 + \frac{\sigma_{elec}^2}{\sigma_{jitter}^2 + \sigma_{time\ walk}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2}$$

Goals

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





< 25 ps

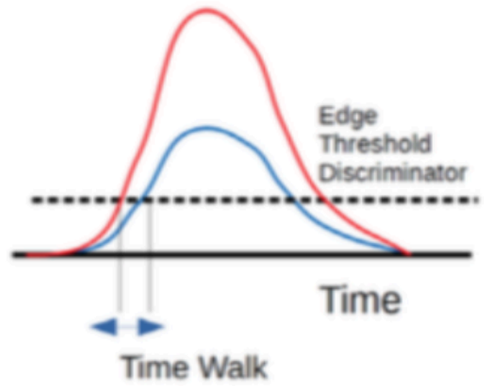
Jitter term

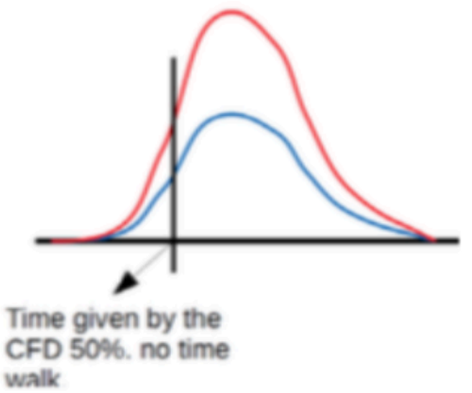
$$\sigma_{jitter} \approx \frac{t_{rise}}{S/N}$$

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





Maximum jitter (σ_{elec})	**25 ps at 10 fC at the start of the HL-LHC and 70 to 85 ps after 4000 fb-1 for 2.5 fC**
TDC contribution	**< 10 ps**
Time walk contribution	**< 10 ps**
TDC conversion time	**< 25 ns**

HGTD front-end and readout electronics

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

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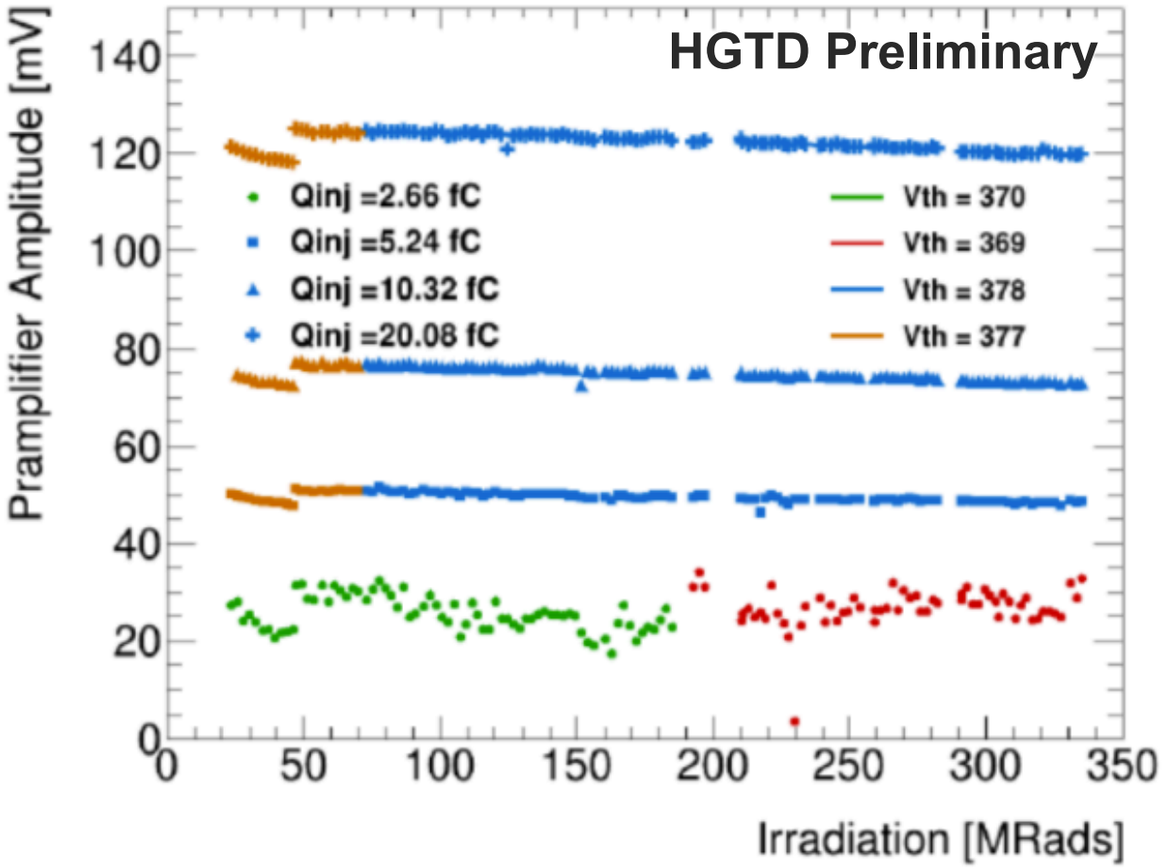
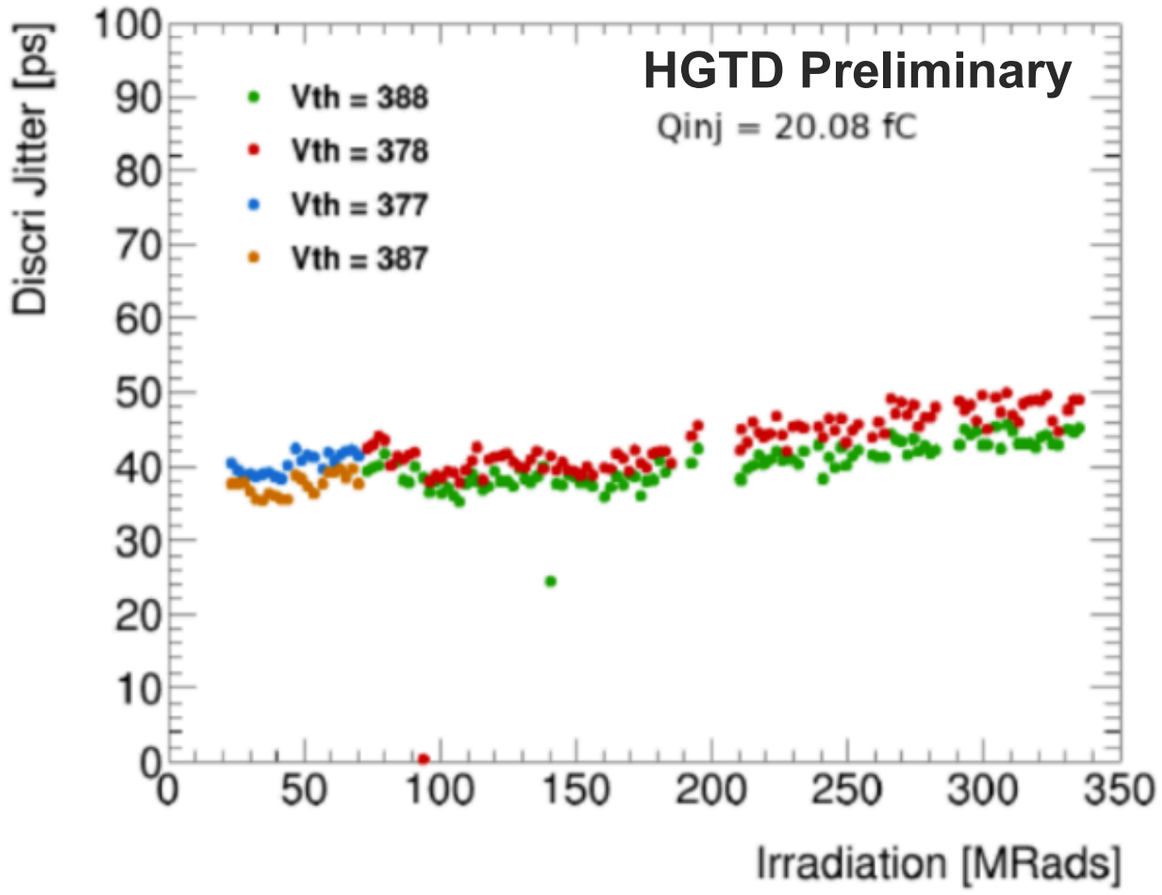
Landau term: < 25 ps, reduced for thin sensors (35-50 μm)

ALTIROC1-V1 (5×5) irradiated with x-rays to 340 MRad (June/July 2019)





Small degradation of preamp amplitude and discriminator output jitter; PLL still working after 340 MRad

Best achieved resolution for LGAD+ALTIROC after time-walk correction:
45 ps @ Qinj=5 fC after TID to be compared with 35 ps obtained before

HGTD front-end and readout electronics

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

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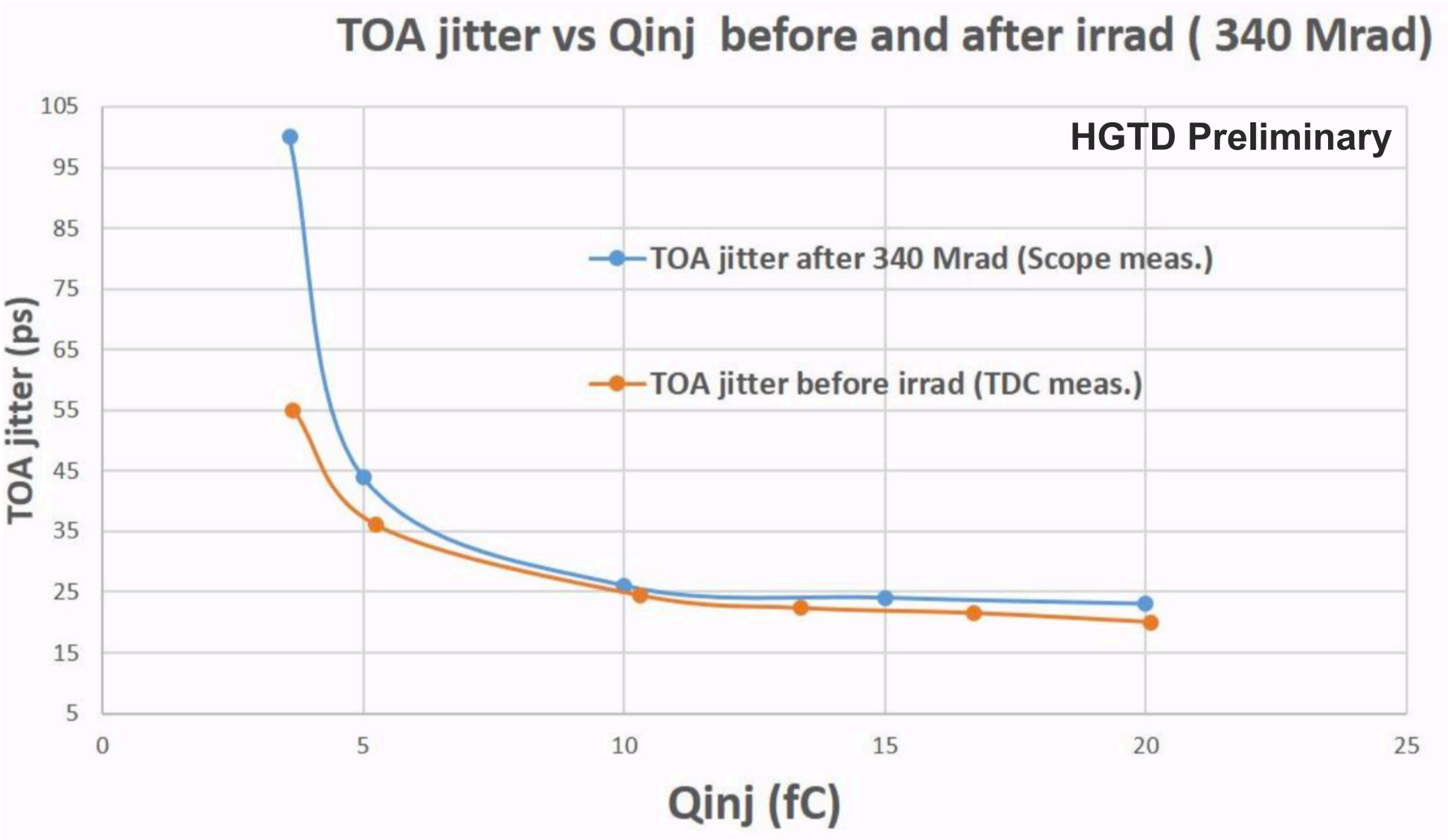

HGTD front-end and readout electronics

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Goals

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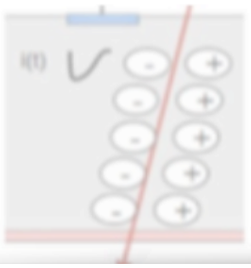
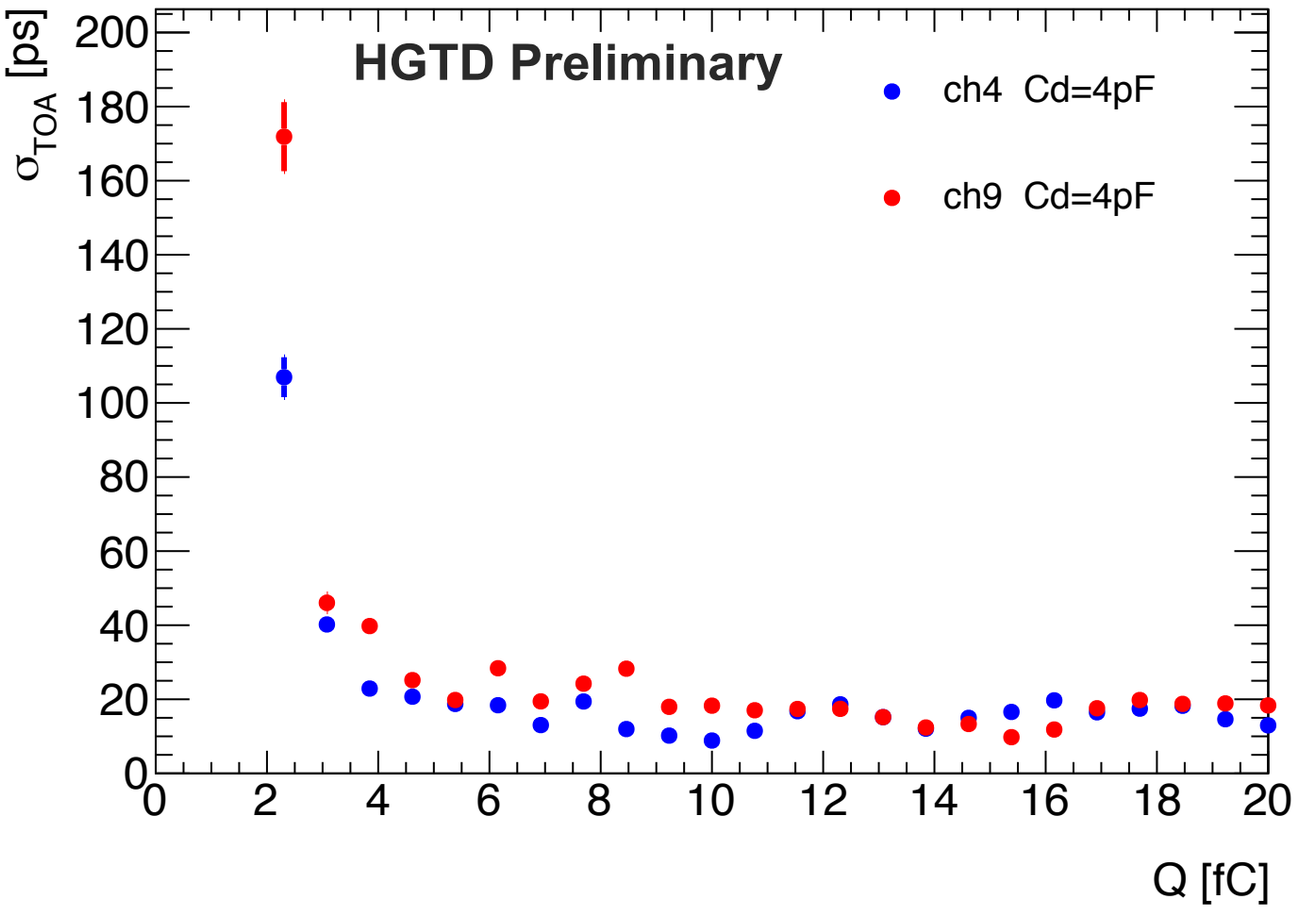
Jitter term

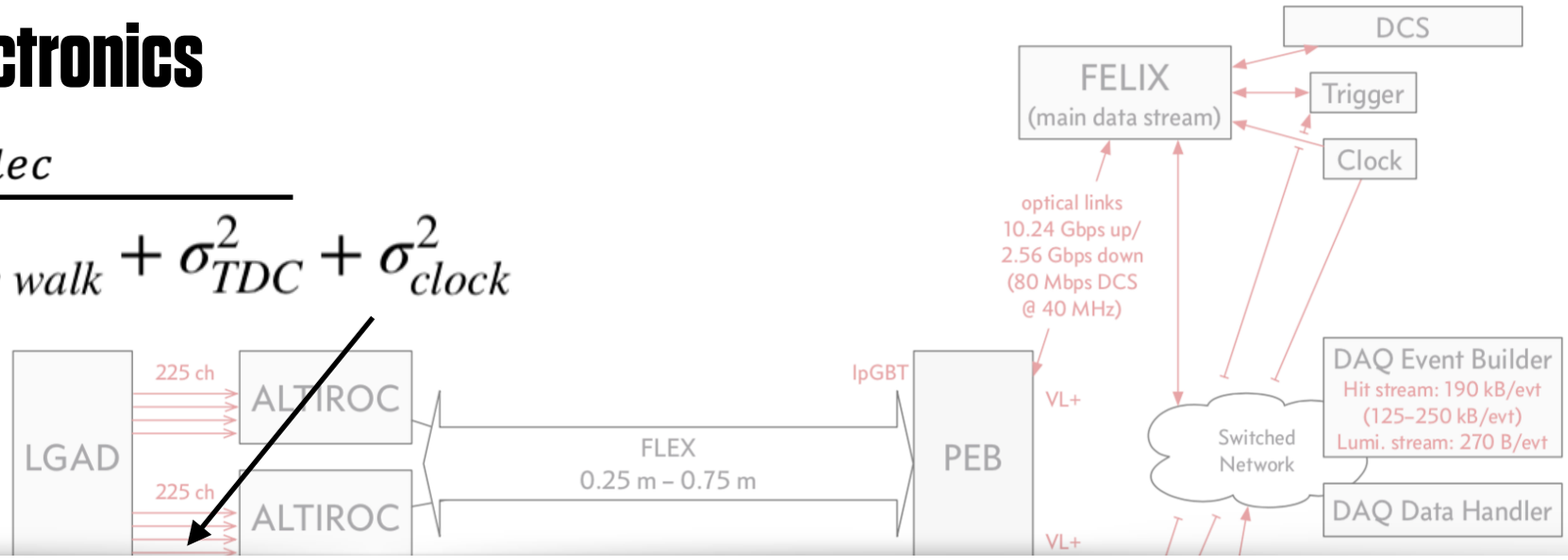


ALTIROC1 TDC performance to be more intensively tested in DESY testbeam next month

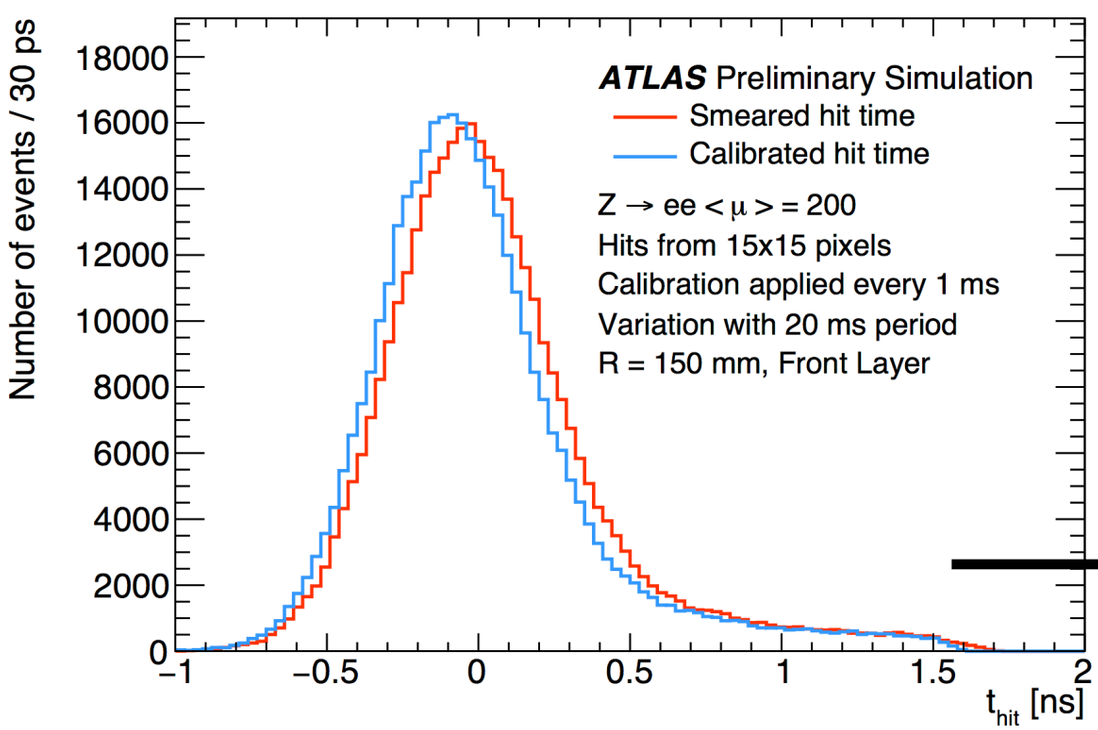


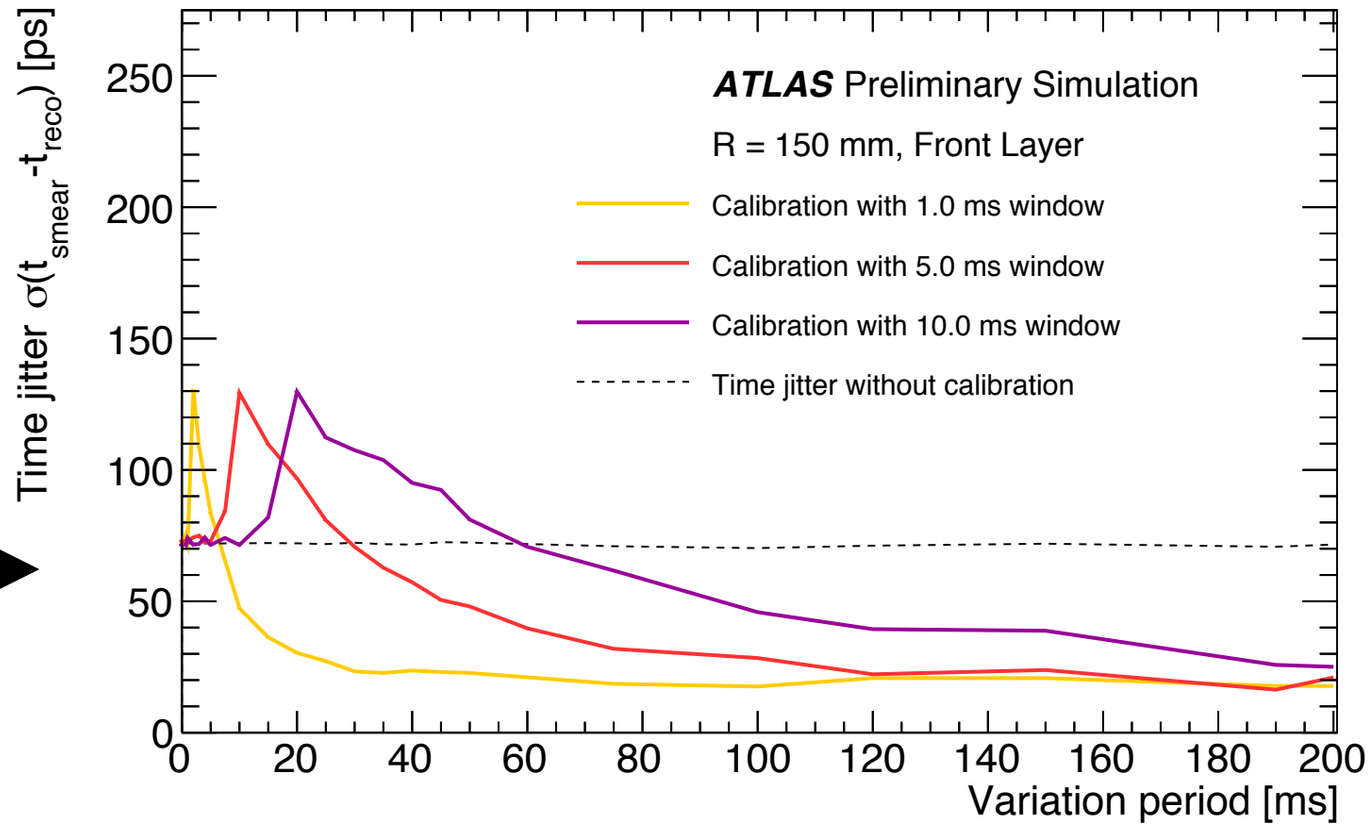
HGTD front-end and readout electrodes

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



Real-time continuous intercalibration of clock distribution path using mean hit time





Example: jitter from the ASIC, FELIX, flex cable, lpGBT, and ATLAS collision time drift, + sinusoid of arbitrary period

With correct choice of accumulation time (1–10 ms shown), calibration improves precision (relative to uncalibrated 70 ps horizontal line) for effects with periods greater than 10 ms

Physics: HGTD as luminometer

luminosity is potential *keystone measurement* for LHC precision programme — G. Salam, LHCP 2016

- Count hits in outer ring(s) at 40 MHz
- Time-averaged hit multiplicity has strong linear dependence on number of interactions
- Estimate of better than 10^{-3} stat uncertainty using 1 s integration time
- For control of systematics

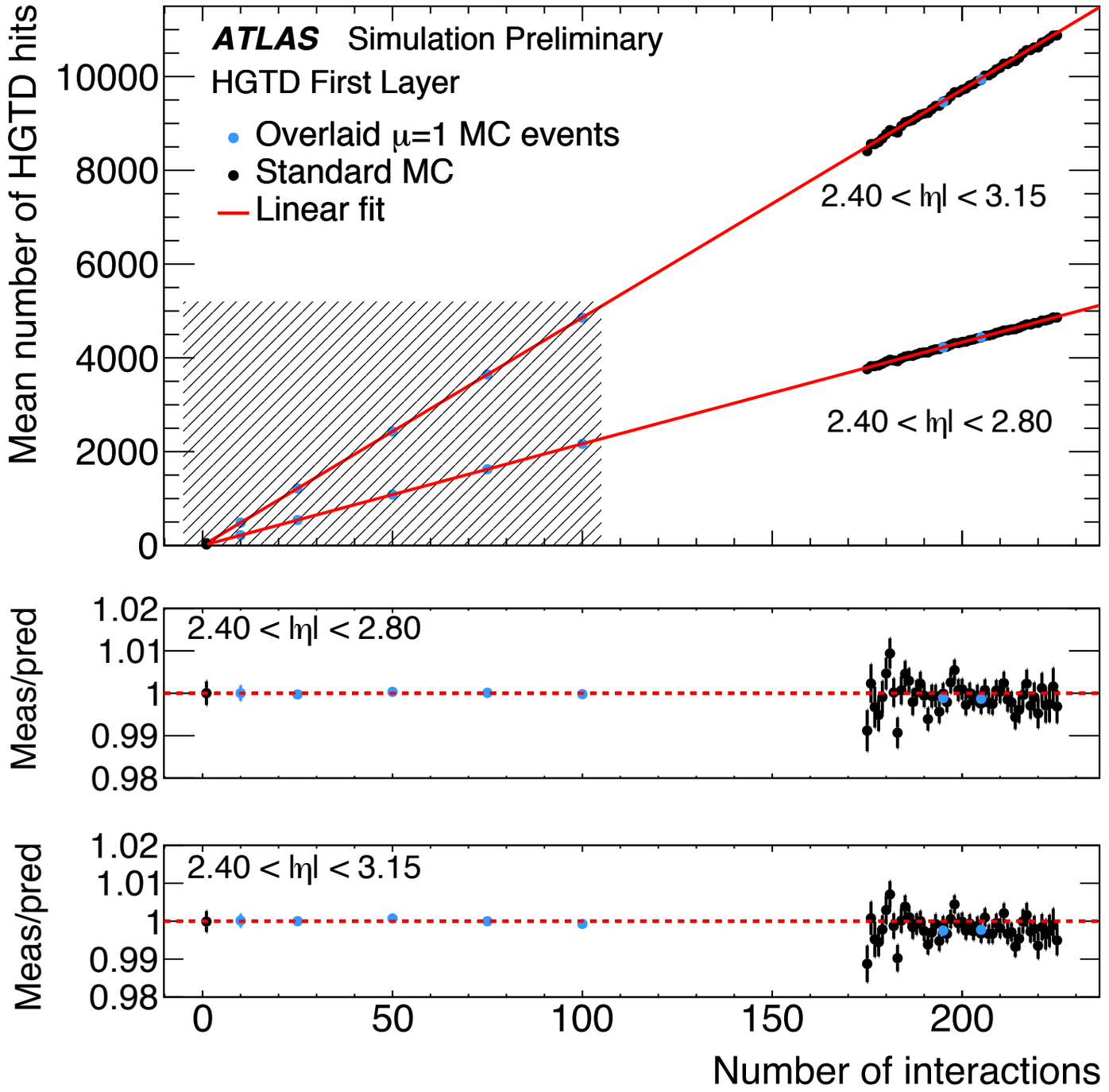
  Out-of-time sideband subtraction

  Ability to count per ASIC and BCID (geometric dependence)

- Online lumi measurement

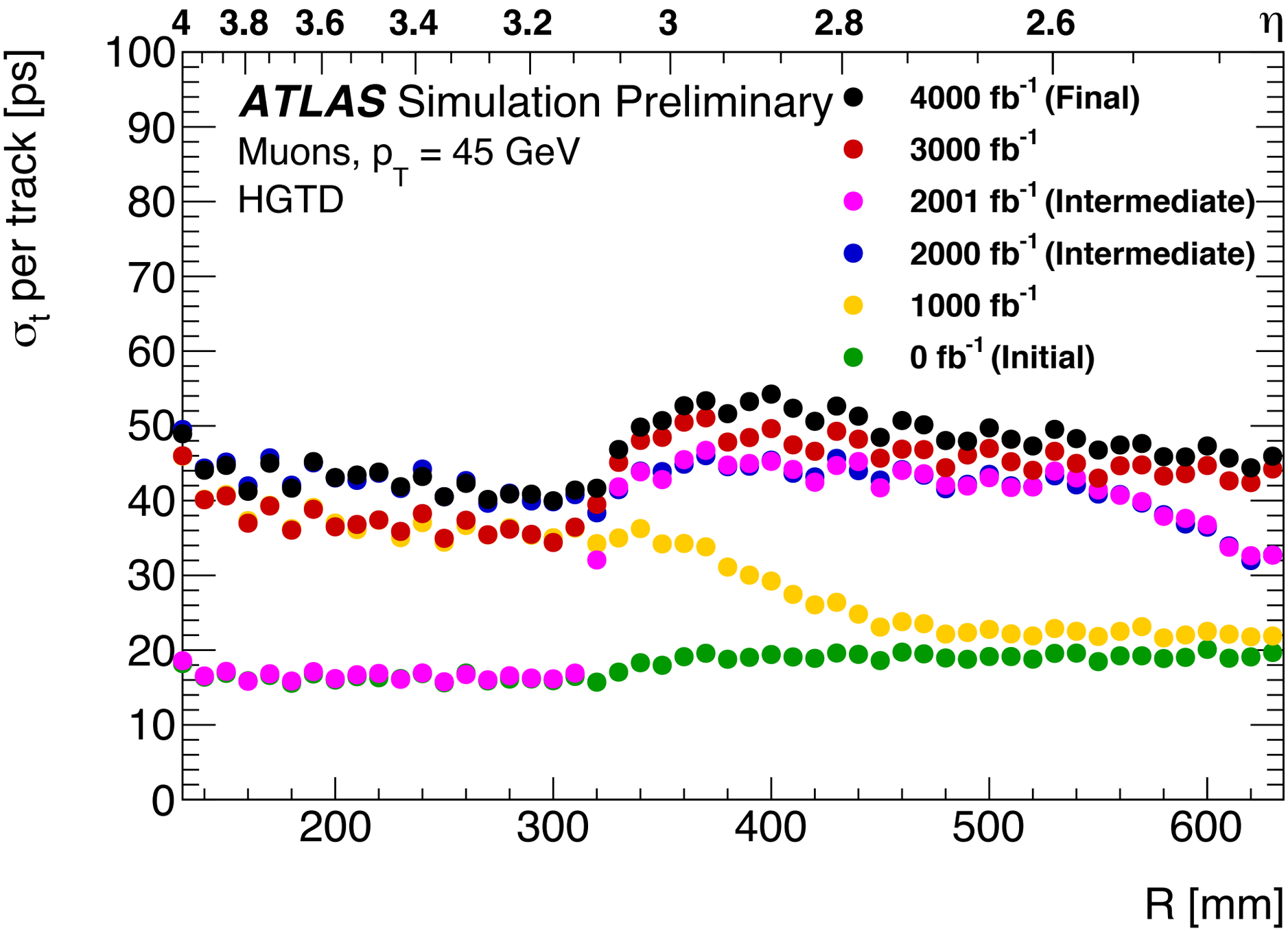
  Low latency: 100 ns (ASIC) + fiber length

  Possibility for real-time feedback to LHC lumi-leveling

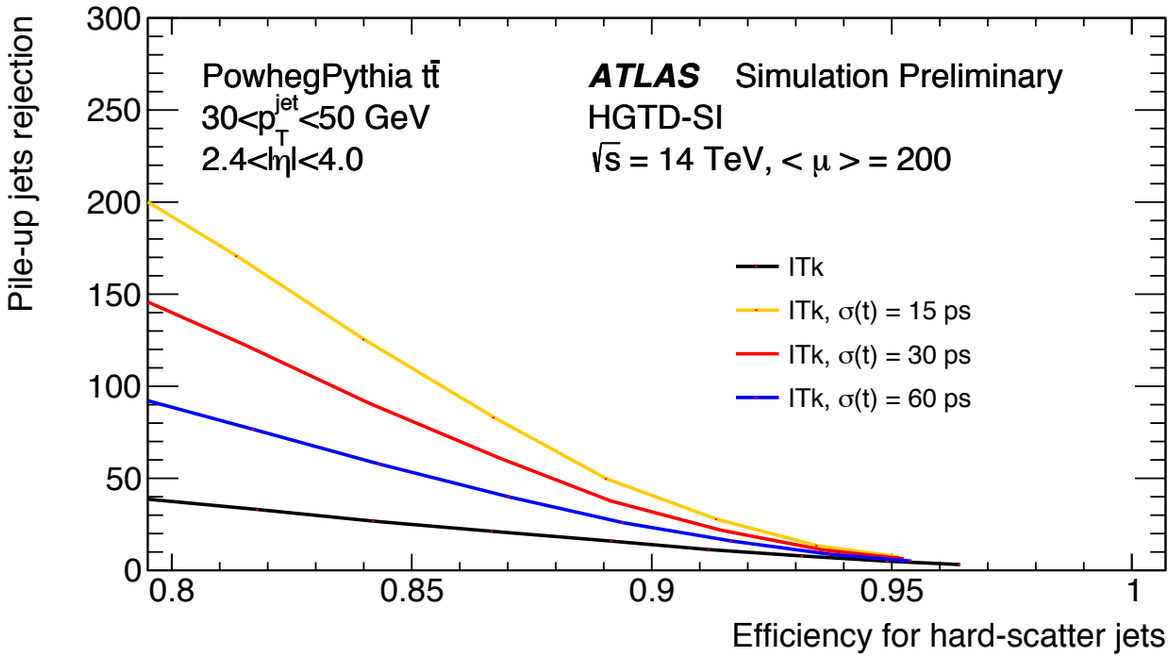


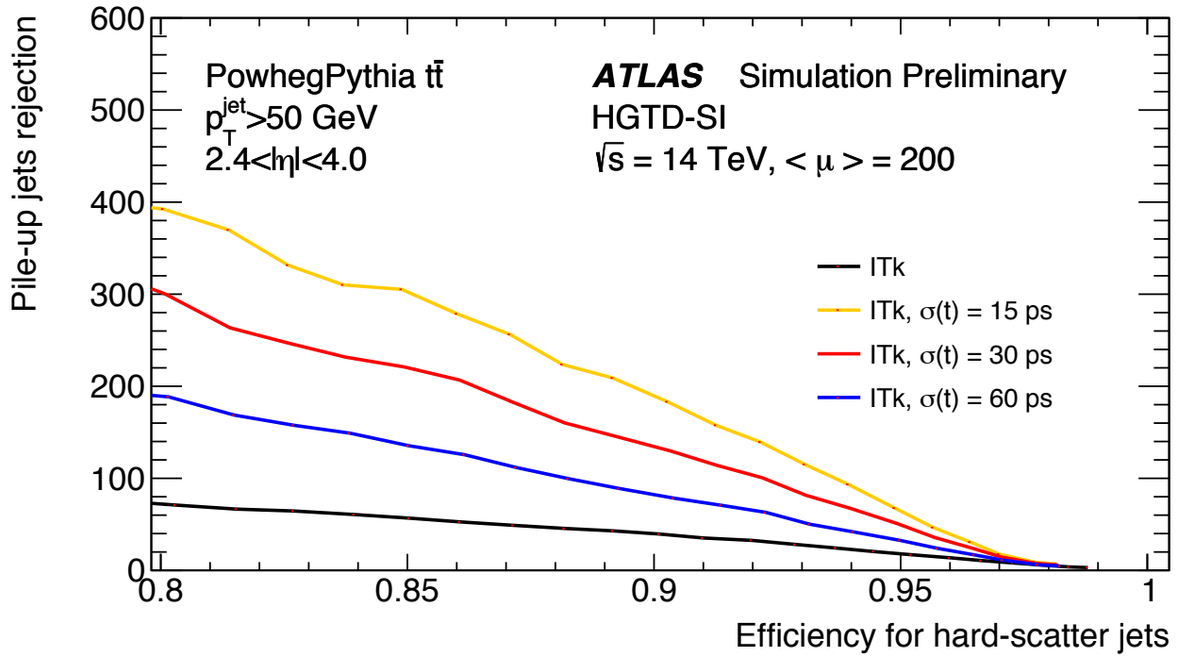
HGTD Performance: Track-level

Performance with 2-ring geometry



HGTD Object Performance Examples Forward Jets



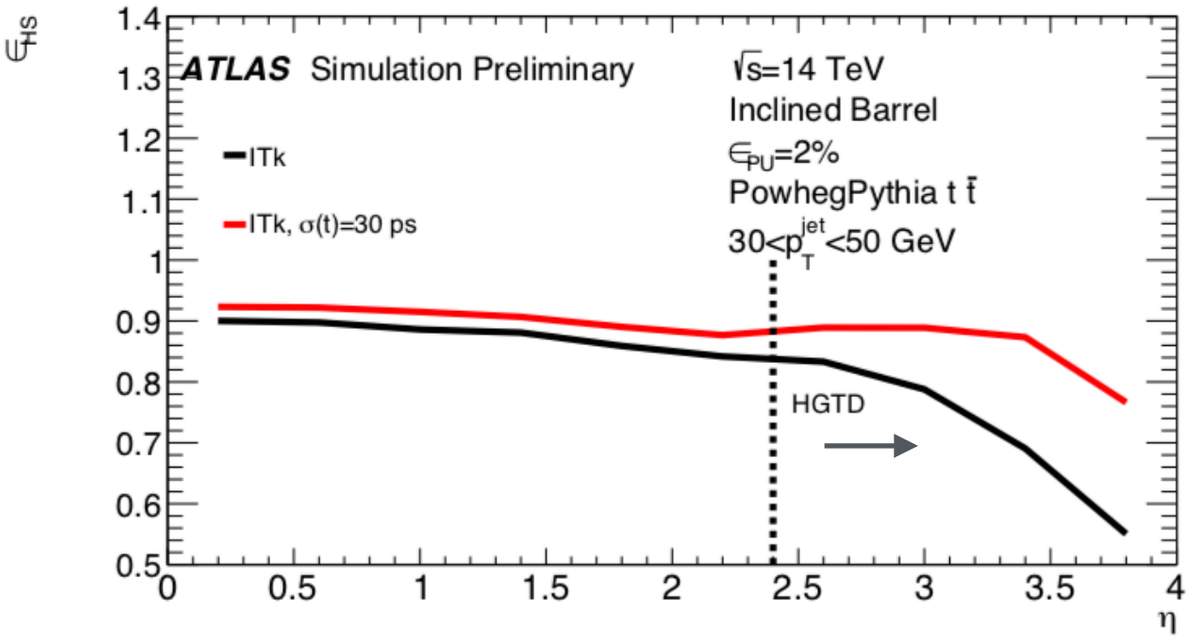


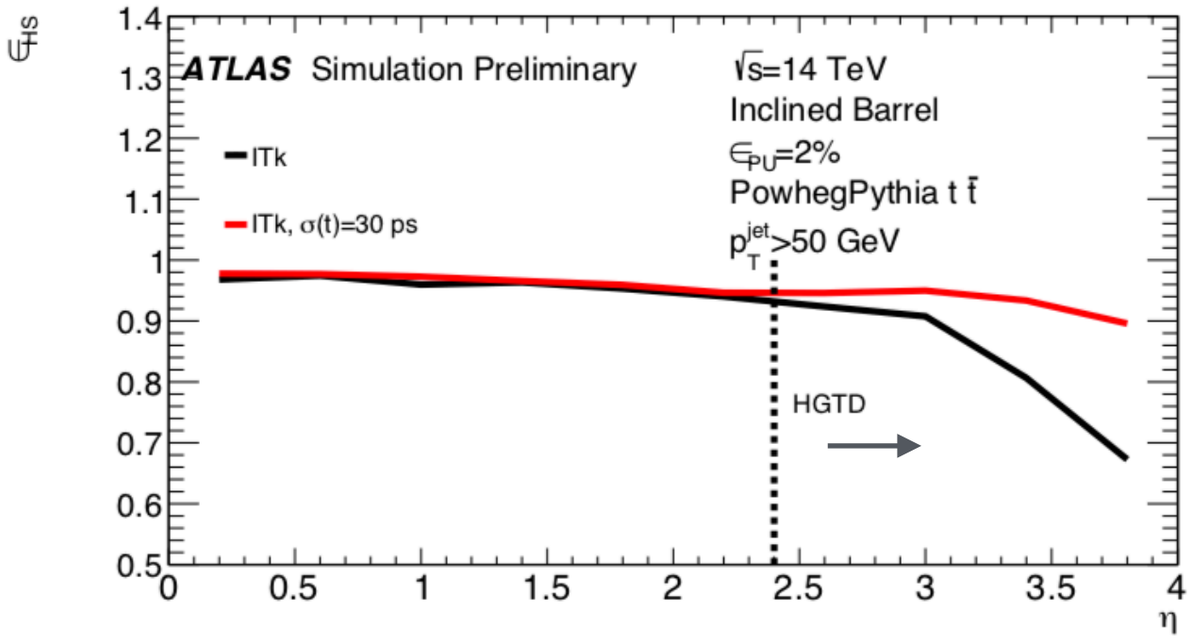
With HGTD:

improved PU jet rejection by ~3x for fixed HS efficiency

improvement in S/sqrt(B) equiv to ~3x lumi. increase

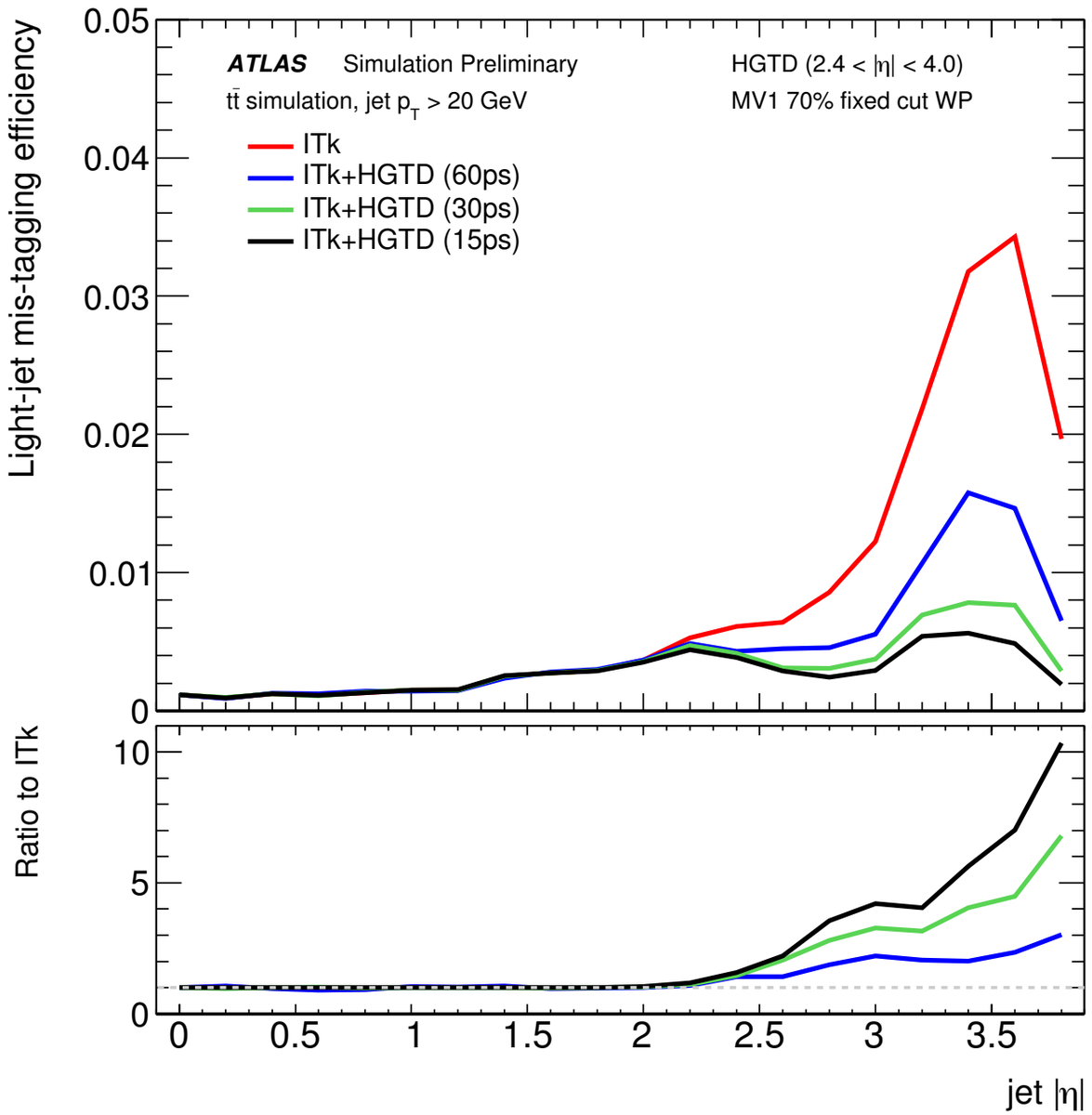
recover forward efficiency for fixed PU jet rejection





2% pile-up jet efficiency

HGTD Object Performance Example: Forward Jet B-Tagging



By removing pile-up tracks from b jet candidates, the performance of b-taggers is significantly improved

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, and can also provide luminosity measurement

- optimized sensor+FE design already achieves performance needed for HL-LHC
- further R&D through 2020 of sensors and electronics

HGTD Technical Proposal already approved by LHCC

Technical Design Report is planned for April 2020

Additional Slides