# HGTD T0 Calibration Status and Plans

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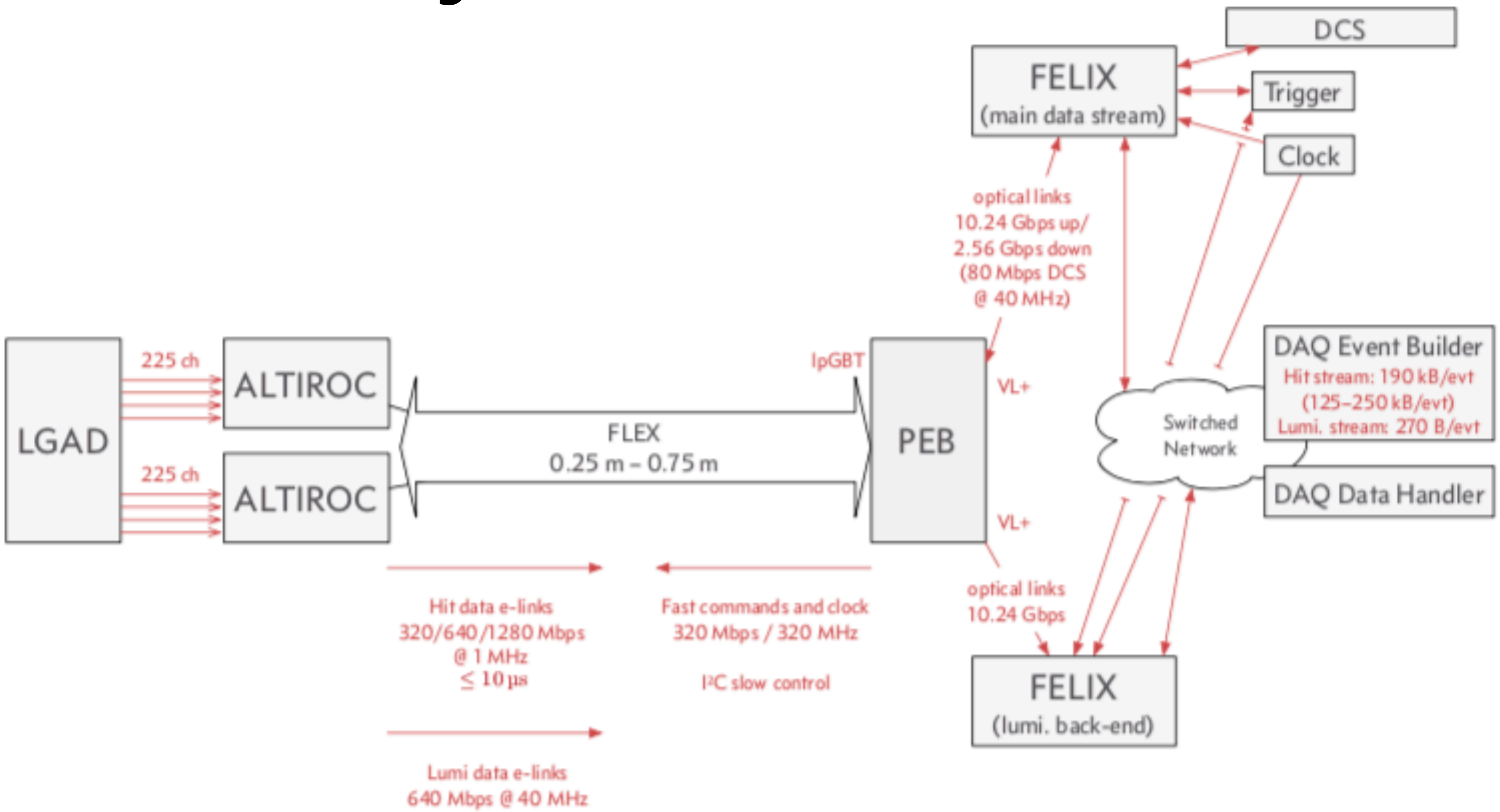
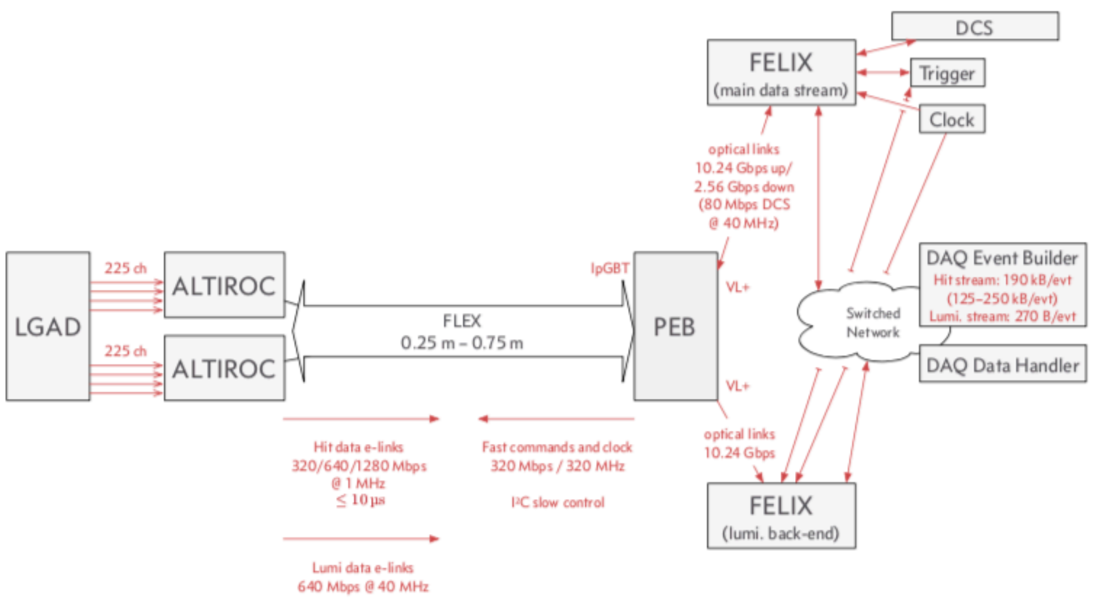
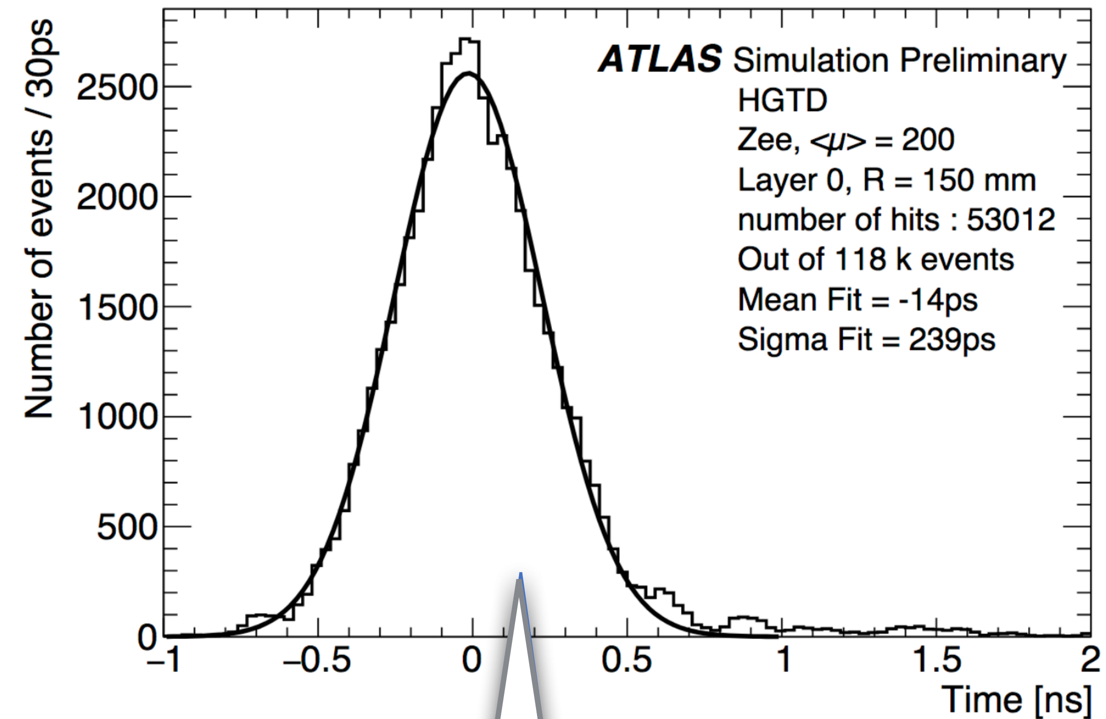
# Why t0 calibration?




- Calibrating and synchronise a precise timing detector is a difficult problem.
- Any temporal variation in the time clock distribution may compromise the ultimate resolution of the detector
  - The sensors themselves will have a resolution of ~40 ps per hit
  - The contributions to the time resolution from the on-detector electronics (UX15) and from the clock distribution (USA15) must be made much smaller than this.
  - *Goal to have clock dispersion for HGTD less than 10 ps across a wide range of frequencies and over the detector acceptance*

# Why t0 calibration?

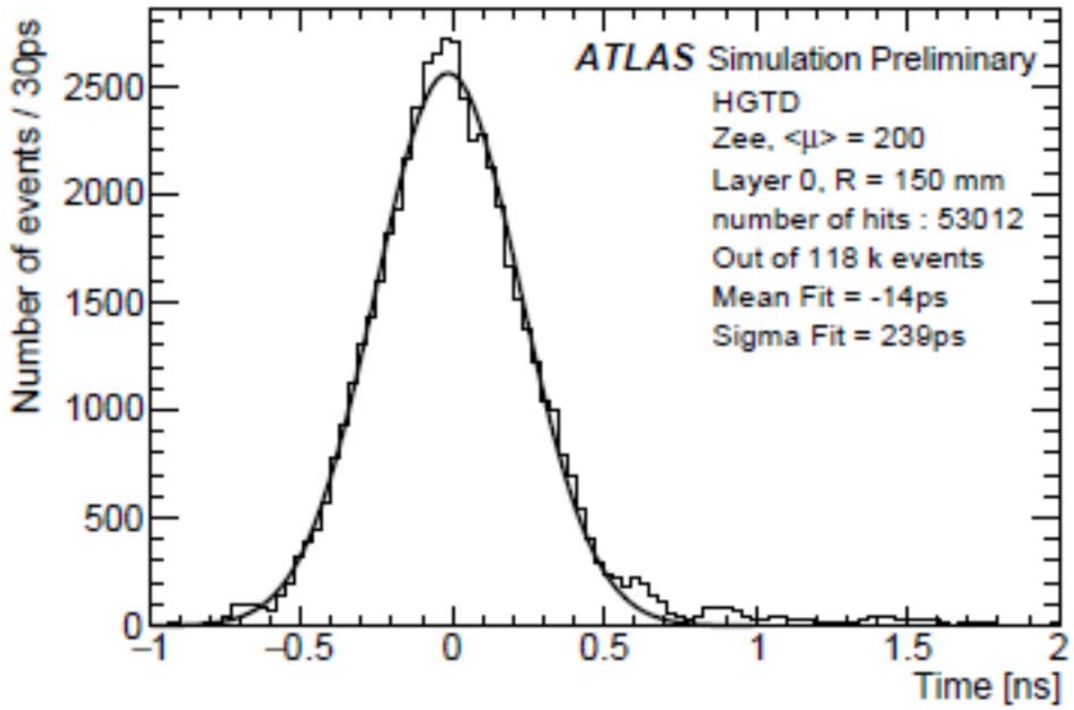



*Hit time: Gaussian core derived from the time dispersion of the LHC collision convolved with the combined hit time resolution of the sensor and electronics*

- Contribution to the timing resolution
  - **Static variations:** ToF, propagation times to distribute the clock to each ASIC ( ie. flex cables lengths )
  - **Dynamic variations:** the variation of the clock with time eg noise in the flex cables, and low-frequency day/night temperature changes.
- *These effects must be monitored and calibrated to minimise static and dynamic contributions to the timing measurements*

# T0 calibration with data




Inclusive hit time distribution in a pixel : rms 240 ps

→ Can measured T0 of pixel to better than 5 ps with 10000 hits

Taken into account occupancy, it corresponds to $10^5$ events at inner radius and $10^6$ events at higher radius

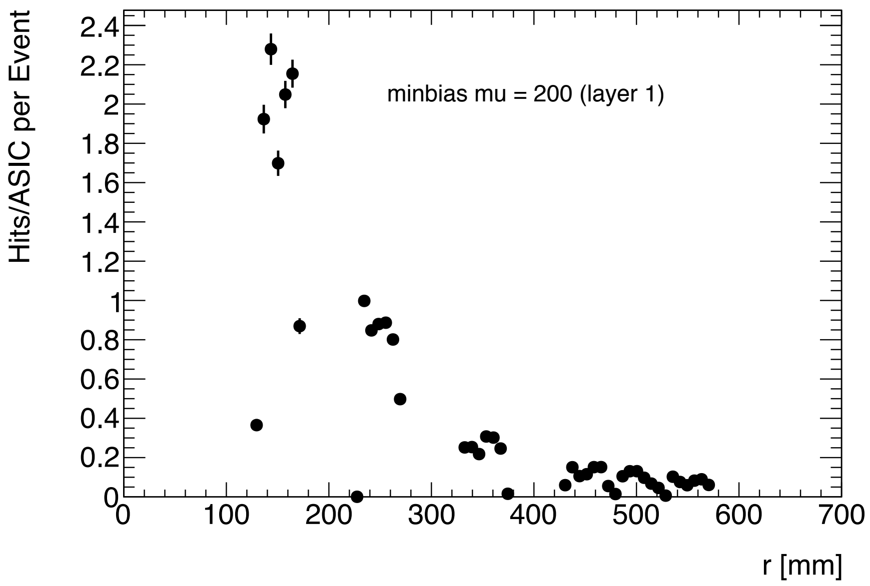
Assuming trigger rate of 10 kHz
→ Will take 10s at inner and 100 s at higher radius

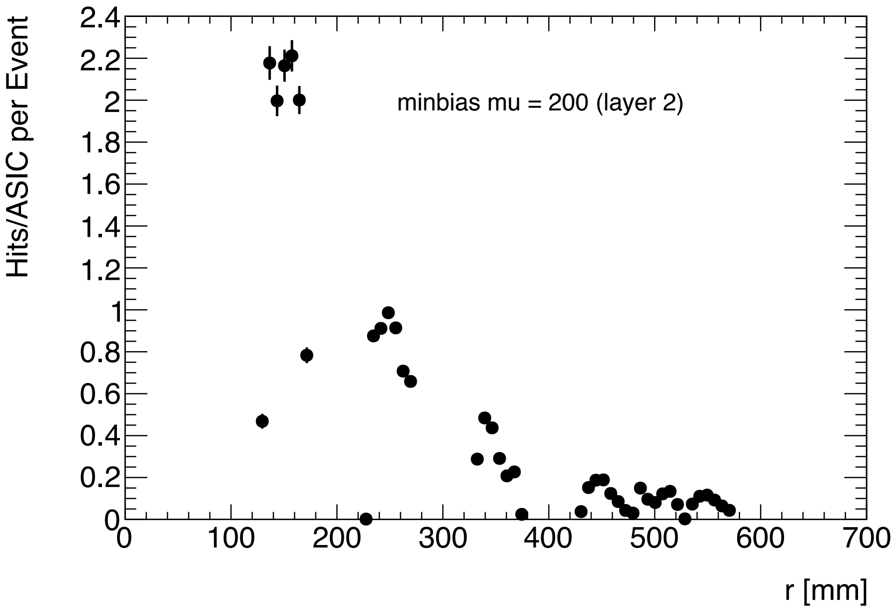
→ As static contribution in ASIC can average t0 over ASIC (225 channels) → every 50 ms if needed

**Any variation larger than 20 kHz not corrected with data calibration**

# Details of the analysis

- MC samples: Zee samples with <μ> = 200
- Standard HGTD simulation from LArHit (more details here)
- Assuming event readout rate of 1MHz
- The different time dispersion components are emulated with a random gaussian smearing
- Radius and pad size define using pixel position



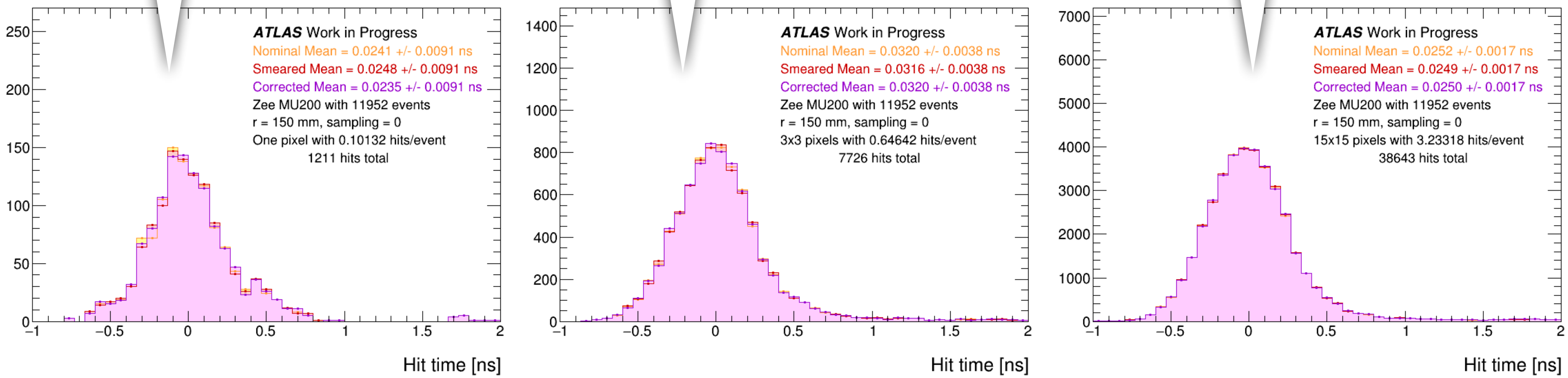

actual calibration works with hit distribution information (t,x,y,z) from LArHit simulation and the different jitter components (define next slide) are emulated with smearing radius and pad size define by hands no additional information about the events structure (eg Bunch-crossing)

# statistic/precision

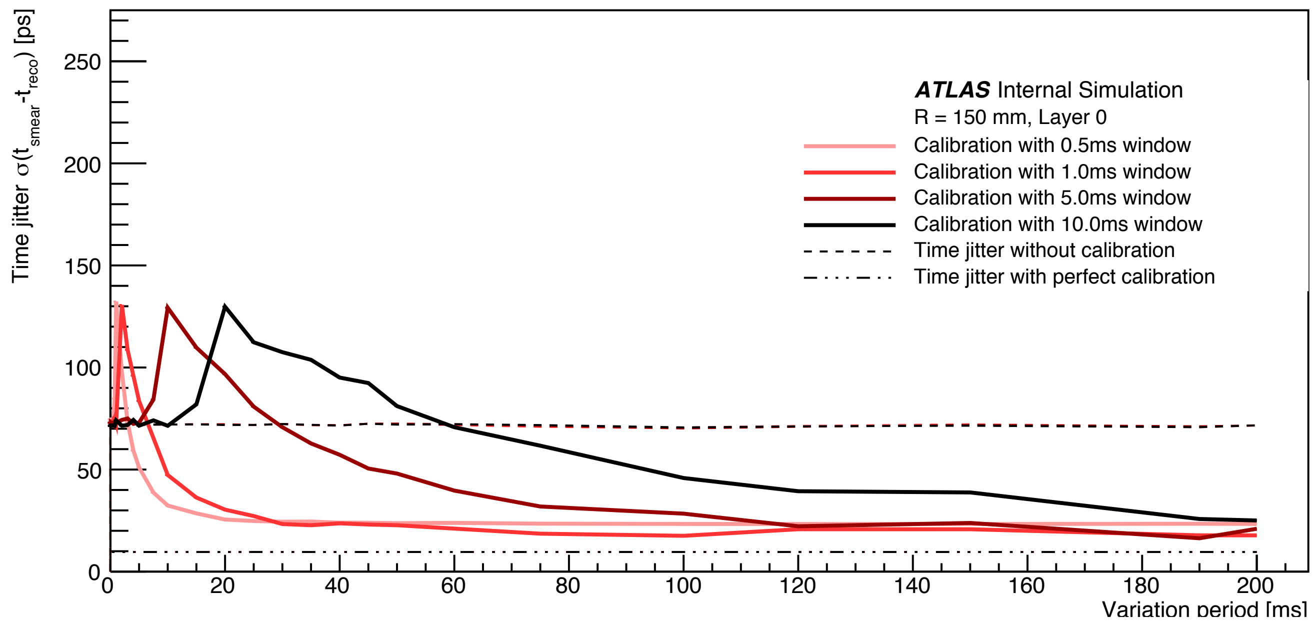
1 pixel with ~1200 hits and ~10ps precision

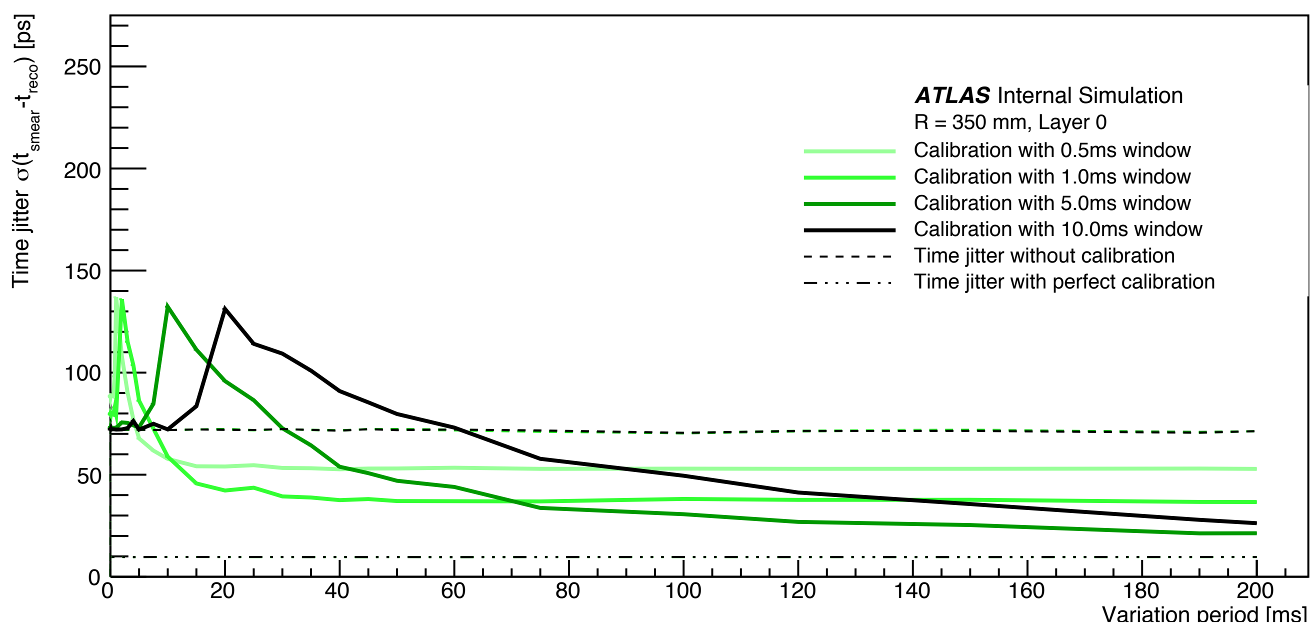
3x3 grid of pixels with ~8000 hits and ~3ps precision

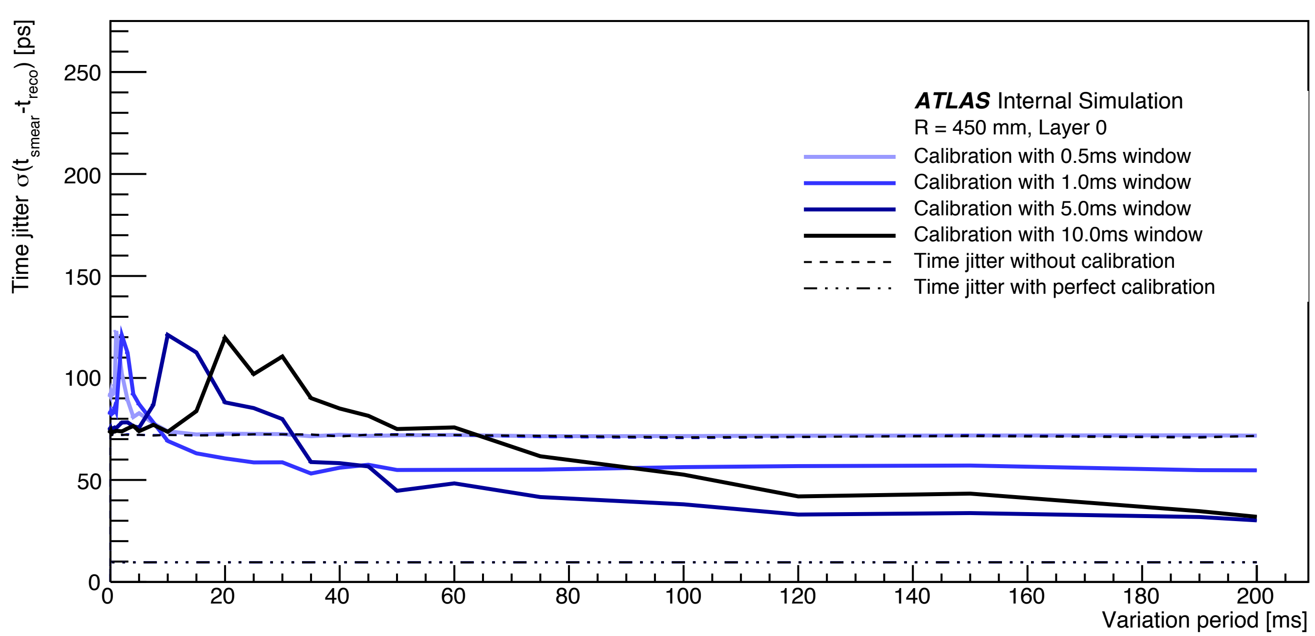
15x15 grid of pixels with ~40k hits and ~1ps precision




- Can also count hits from neighboring sensors
- Read by same ASIC => subject to the same time jitter and offsets




# ASIC $t_0$ precision for different clock variations

Hit time resolution ($t_{smear} - t_{reco}$) after the calibration procedure as a function of the variation period, and for several different choices of calibration window time, shown for $r$ = 150 mm, $r$ = 350 mm, and $r$ = 450 mm.

**NB. difference between the 3 plots the statistic collected in the pad considered**

**Smaller calibration** window can reduce $t_0$ jitter when shorter-term variations affect the hit time.
**Longer calibration** windows, which can collect more statistics and therefore more precisely determine $t_0$, result in a better hit time calibration.

*In general, more accurate calibrations can be calculated to correct for longer-term variations, and should result in smaller total clock jitter.*

# How to improve/TODOs

- In the current studies the expected jitter from the readout electronics and LHC bunch crossing time drift is emulated.
  - After calibration a hit time resolution of approximately 10 ps can be reached.
  - If add unknown sources of jitter the calibration procedure can reduce the total jitter to 20 ps for the time variations studied.
- This calibration procedure uses **conservative** values of clock jitter contributions. **Conservative** estimates for the expected ALTIROC and FLEX timing jitter were used.

- *How to improve ?*
  - ***A. improving input clock variation smearing***
    - the current terms for smearing need to be updated with dedicated studies on clock jitter in the ASIC & Flex
    - extending the number of sensors used to collect data, ie can hits collected by the whole detector be used to calculate a quick t0 correction? Can this be combined with a calibration calculated at a per-sensor or per-ASIC level?
    - applying a ~realistic trigger selection and seeing how the event rate (and available statistics) changes
  - ***B. improving simulation and get more information***
    - *Moving to SiHits simulation to have more information about bunch-crossing, pileup truth, pT track*
    - try to simulate bunch by bunch drift on T0

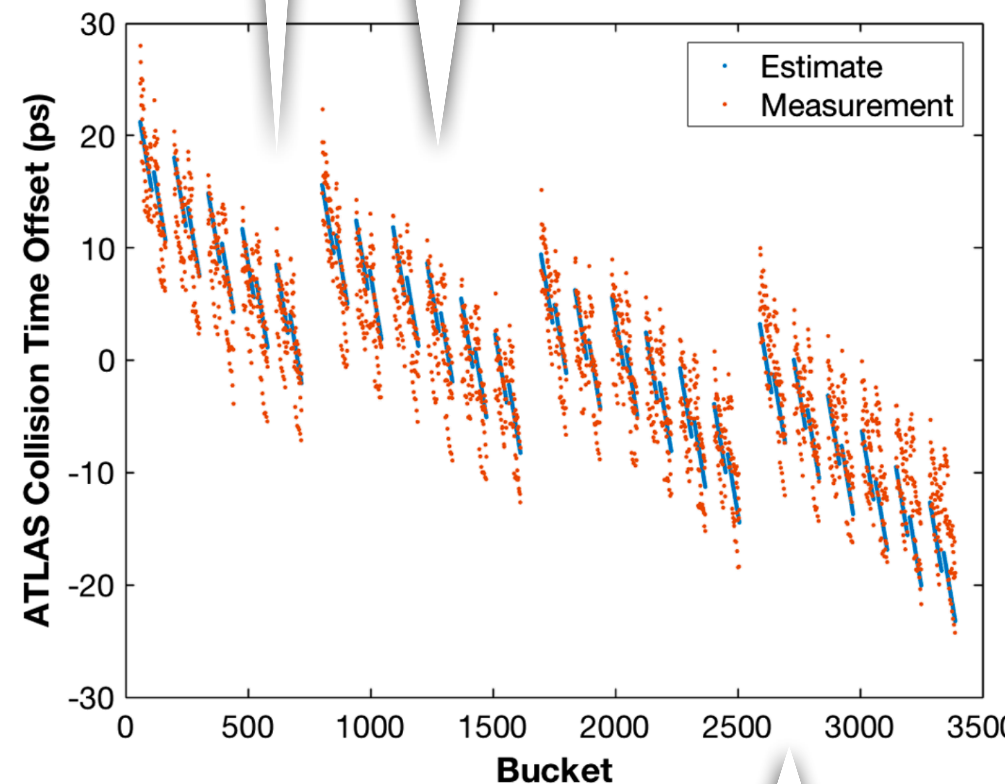
backup

# Timing Variation

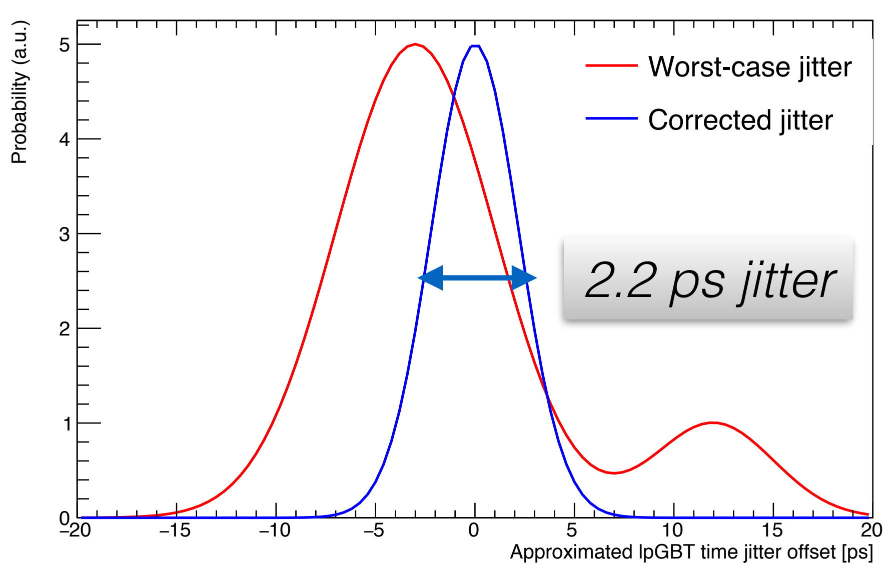
- **LHC per-bunch variation**: using ATLAS collision time offset from paper 5 ps jitter
- **Felix jitter**: taking 5.2 ps jitter from timing performance study
- Three separate random Gaussian 5 ps jitter to model **lpGBT, FLEX,** and **ASIC**
    - Temporary numbers to be updated when timing performance studies are available
- Static radially-dependent ToF variation of 0-70 ps
    - No significant impact on these per-sensor hit distributions

Taking measurement as offset for full smear

measurement - estimate as offset for calibrated hit time




Collision point time shift for the ATLAS detector



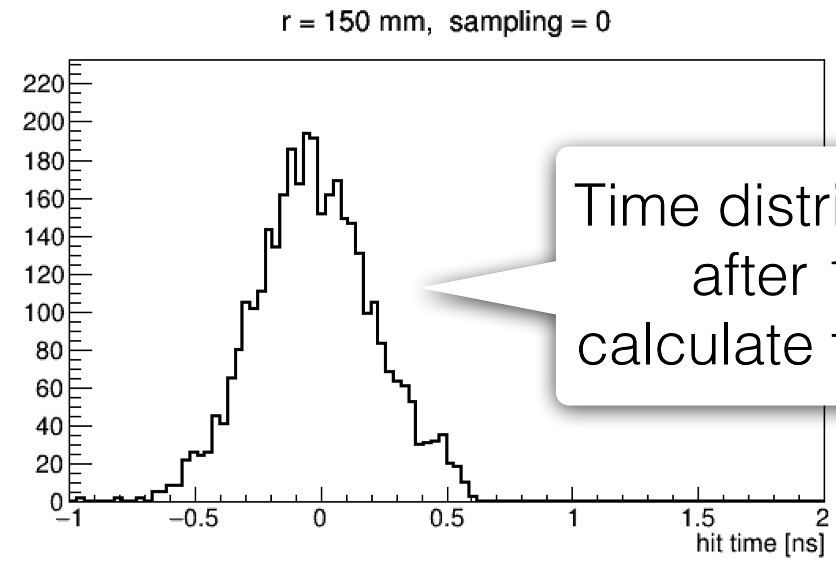
# Timing Variation

- **Can’t calibrate away event-by event random fluctuations**
  - (But are included in study anyway)
- Performance of calibration procedure will depend on how many longer-term variations (heat cycles or other effects) affect the time measurement , but these are largely unknown…
  - Instead parameterize these long-term variations and study how large / fast they could be and still meet our targets
  - Sinusoidally varying 100ps time offset with with a variable period

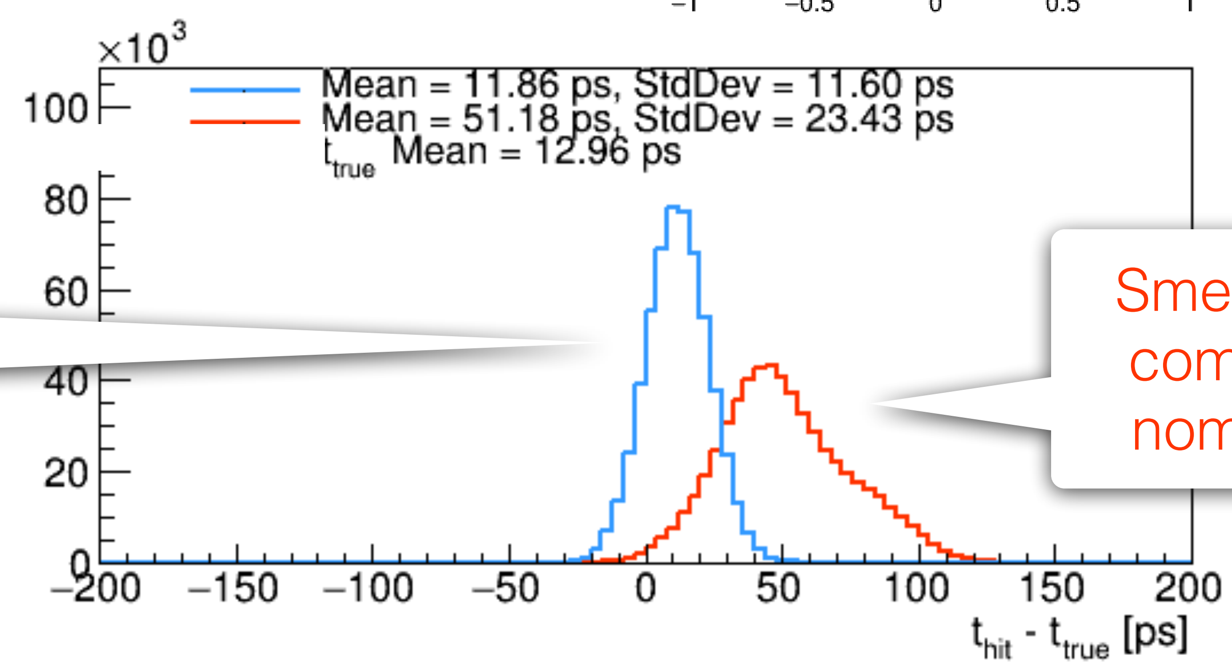
# Calibration procedure

t0 correction from a **15x15 grid of neighbouring sensor** —> corresponding to **1 ASIC** => subject to the same time jitter and offsets

- Derive t0 correction on a subset of MC events
- Apply to independent dataset and evaluate performance
- Measure the resolution




Time distribution of hits after 10ms => calculate t0 from mean



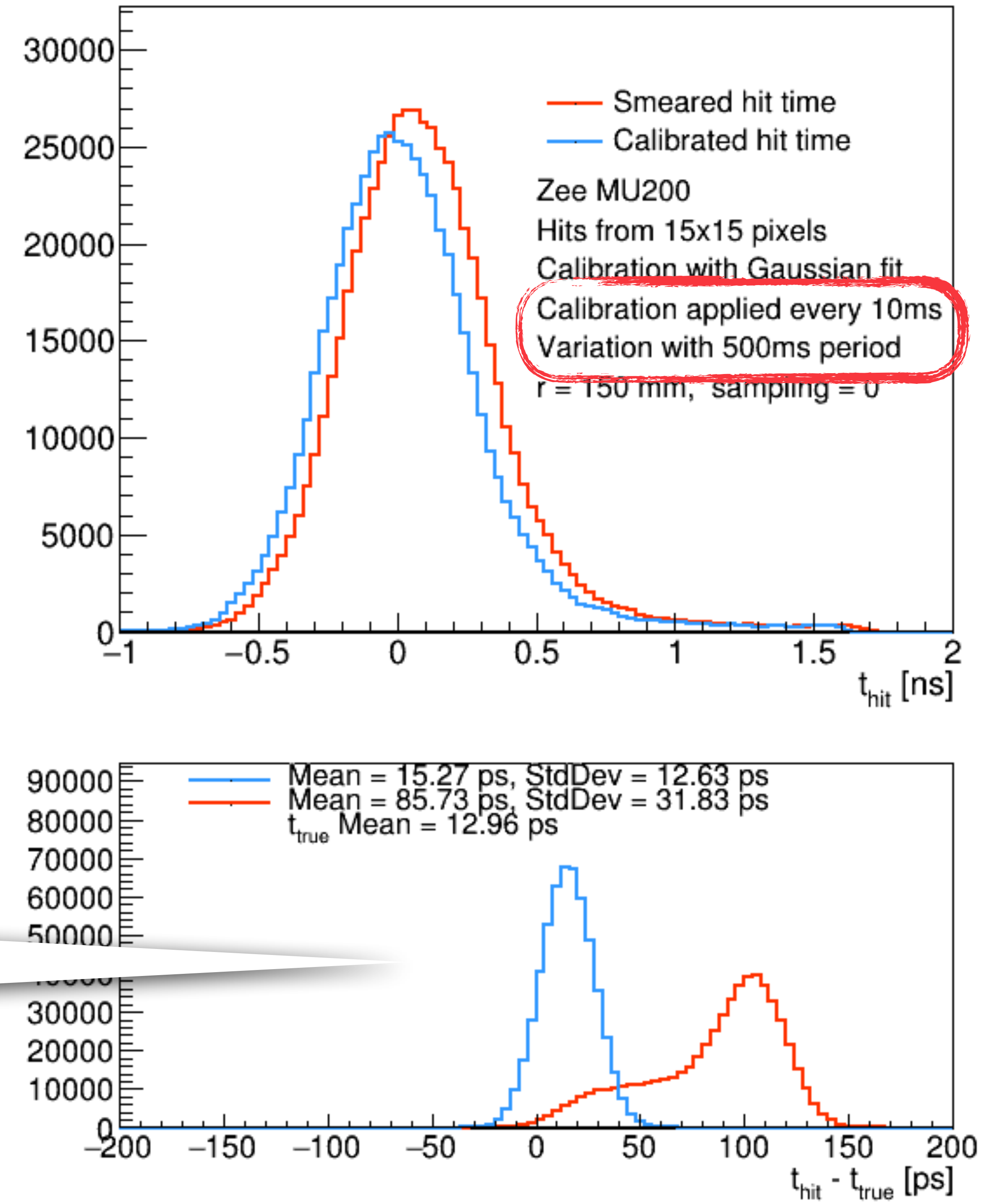

Calibrated time: apply LHC drift correction and t0 calibration

Smeared time compared to nominal time

the lengths of the time interval strongly affects the performance of the calibration

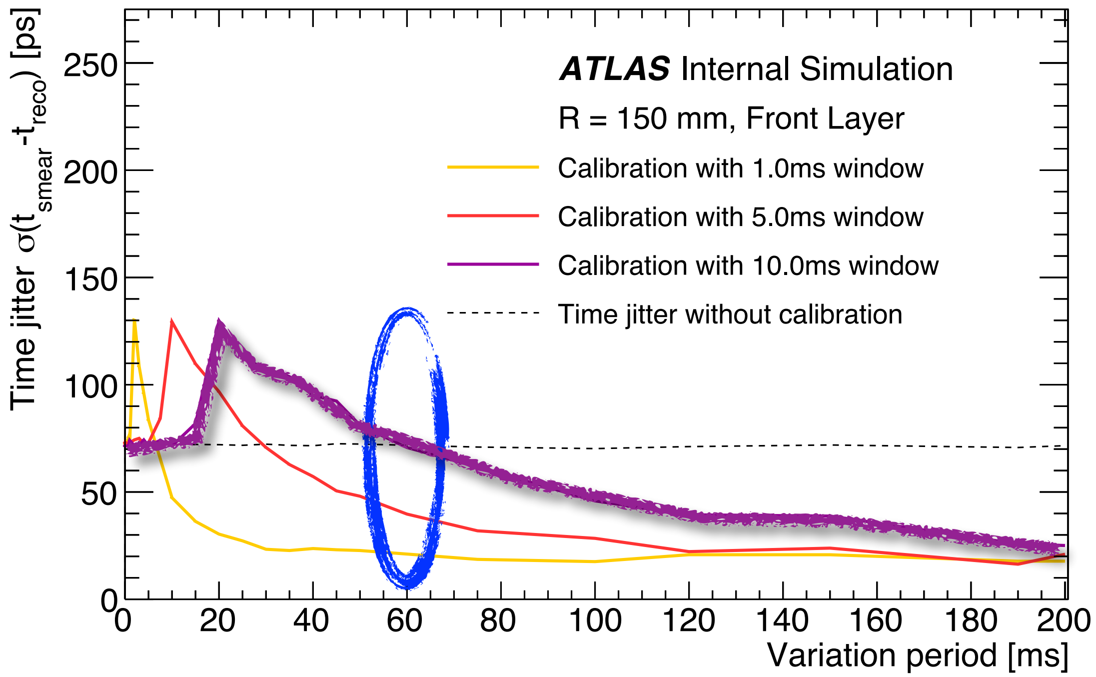
# Calibration procedure II

Calibration performance depends on timescale of effects being calibrated away….

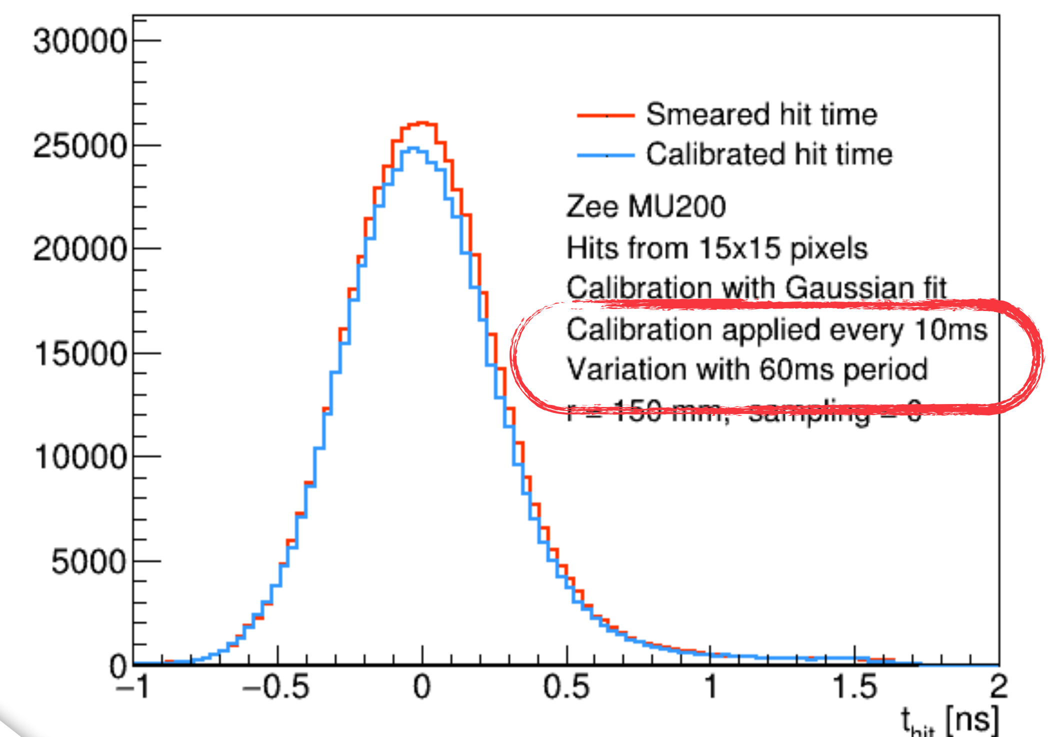



calibration timescale << variation timescale
calibration works 👍

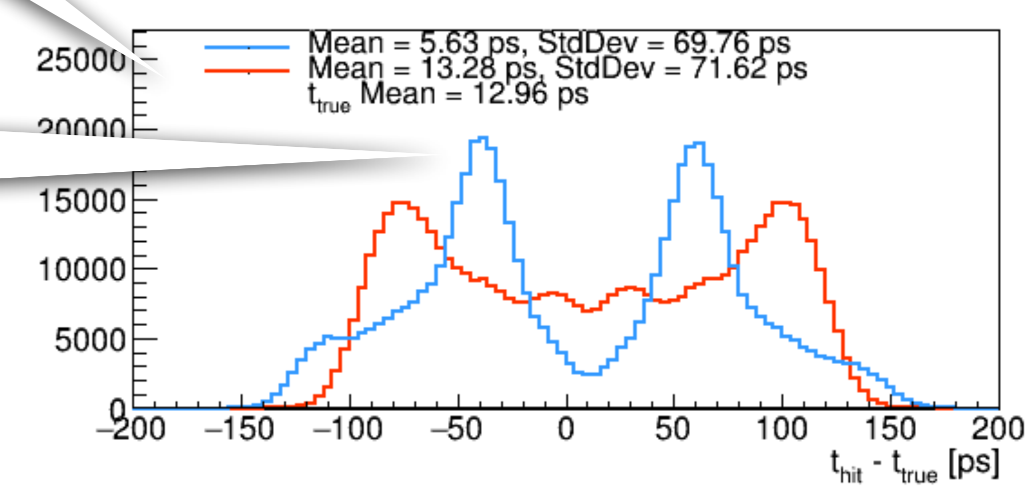
# Calibration procedure III




calibration performances as function of the integration time and the variation period

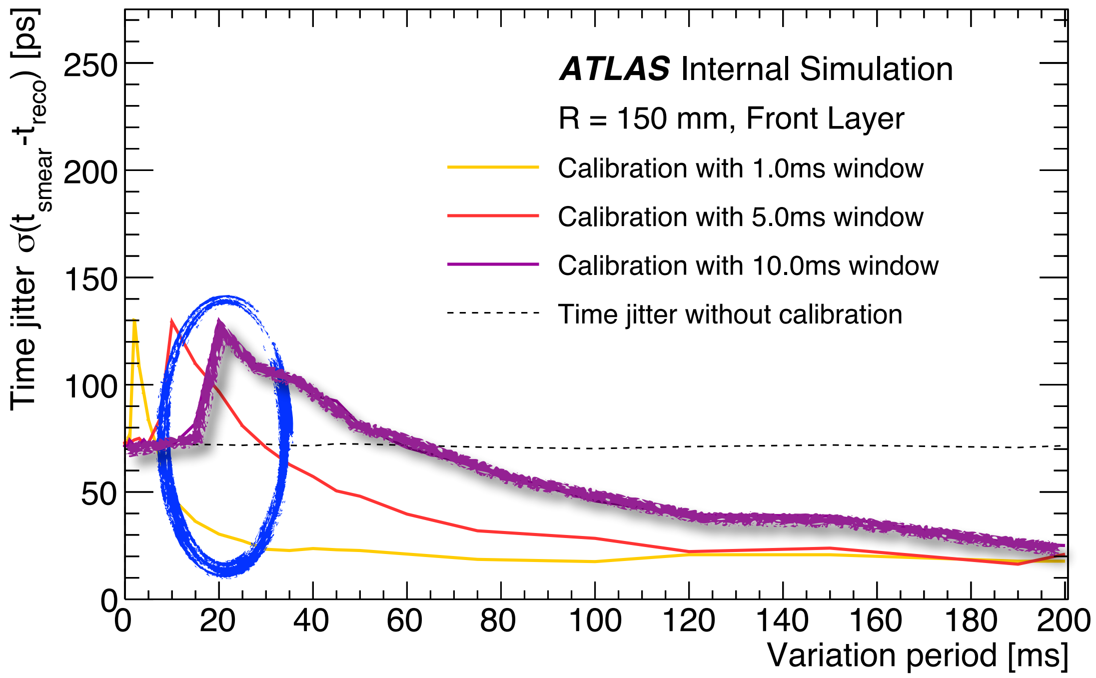


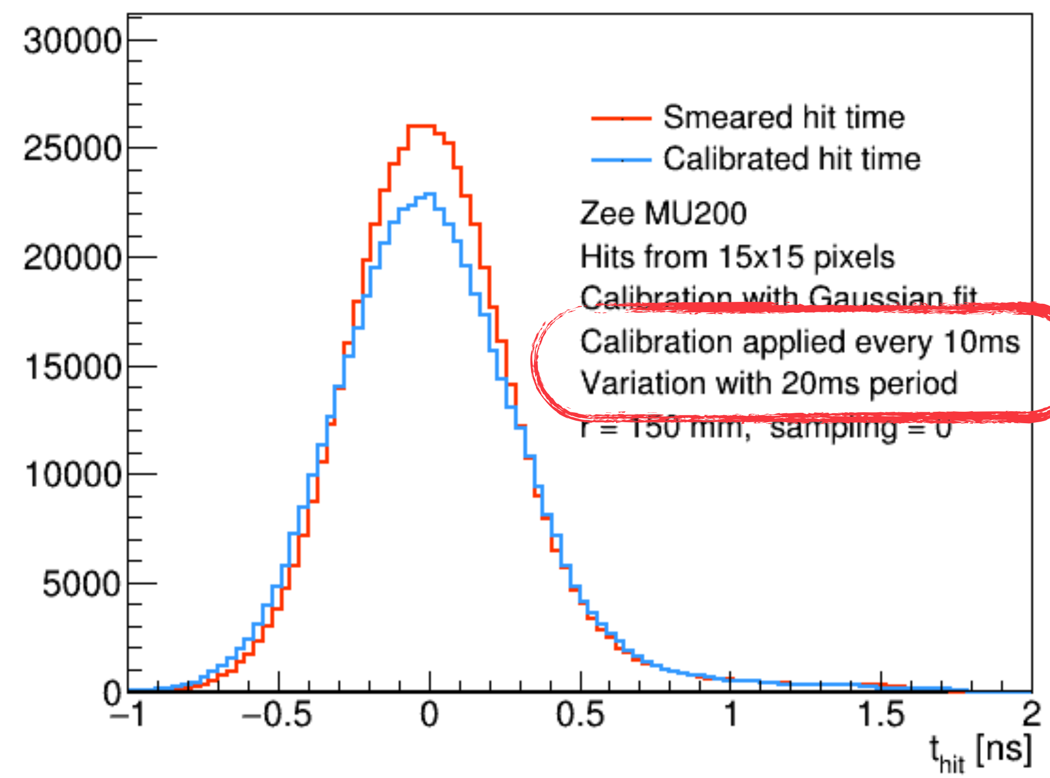

as variation timescale gets smaller, calibration provides worse resolution

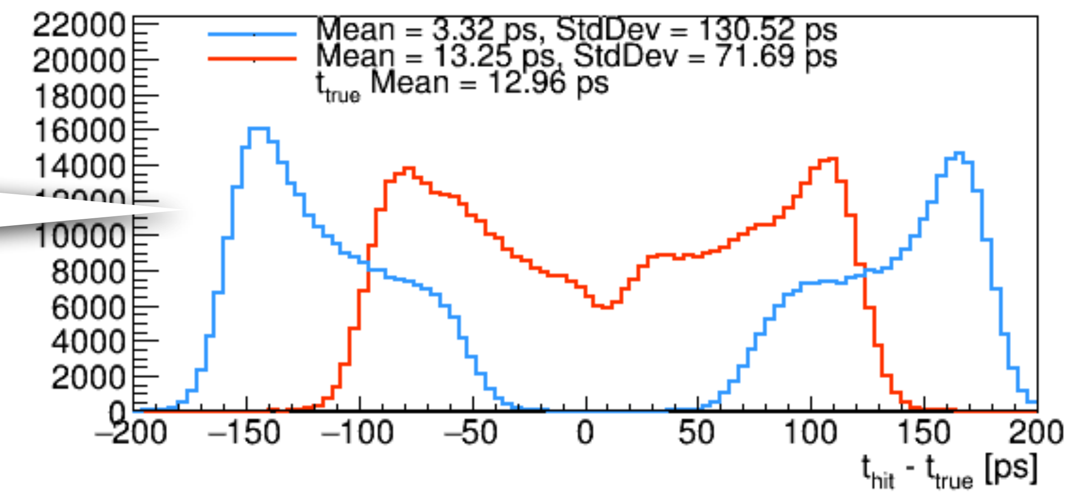



peaks for calibration resolution at **time difference** between hit **data collected for calibration** and **data to which calibration is applied**
Median difference of ~ 35ps

# Detailed procedure IV

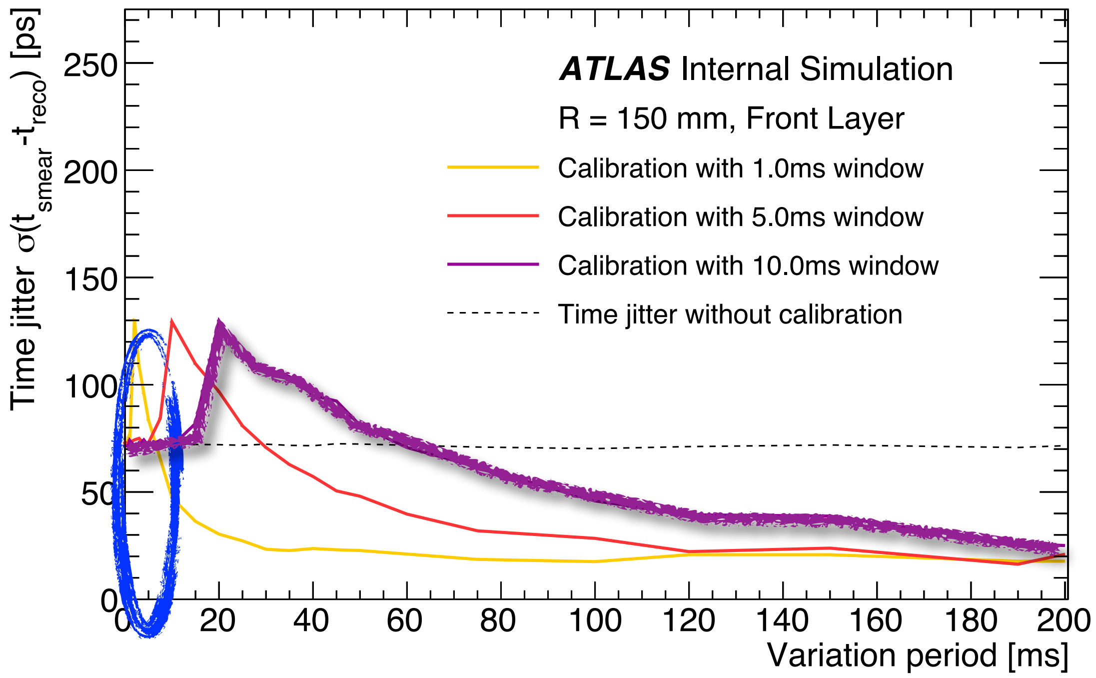


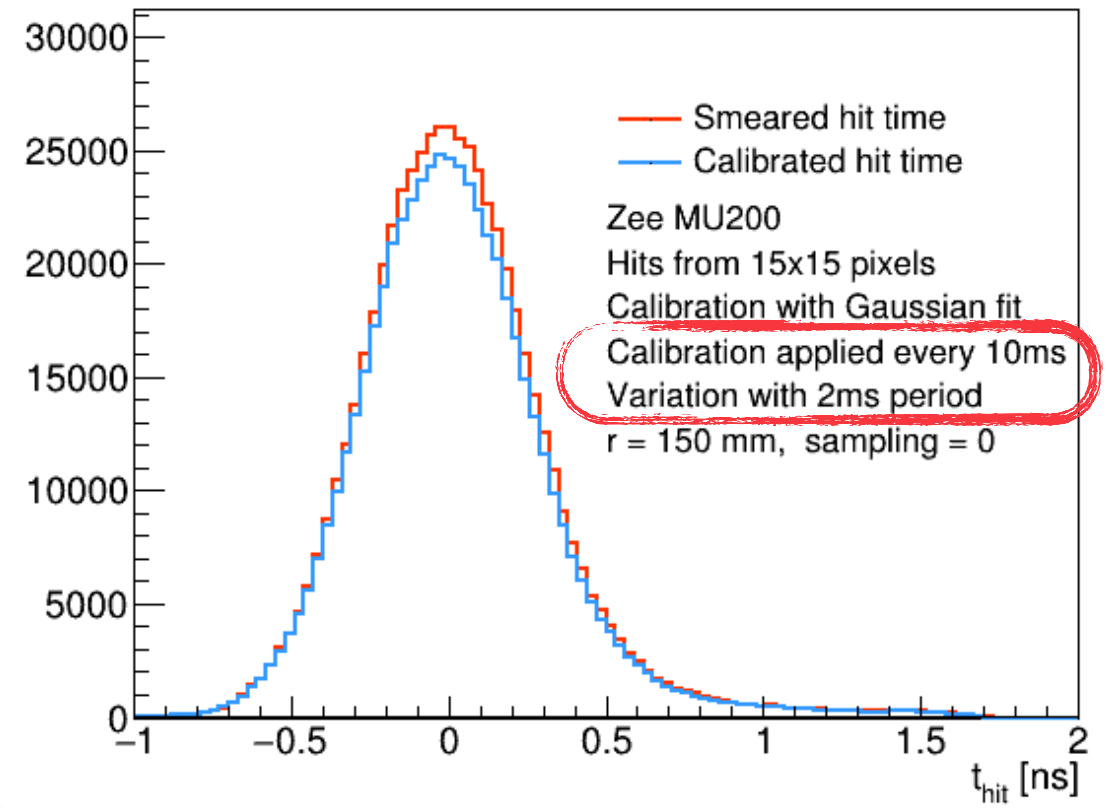



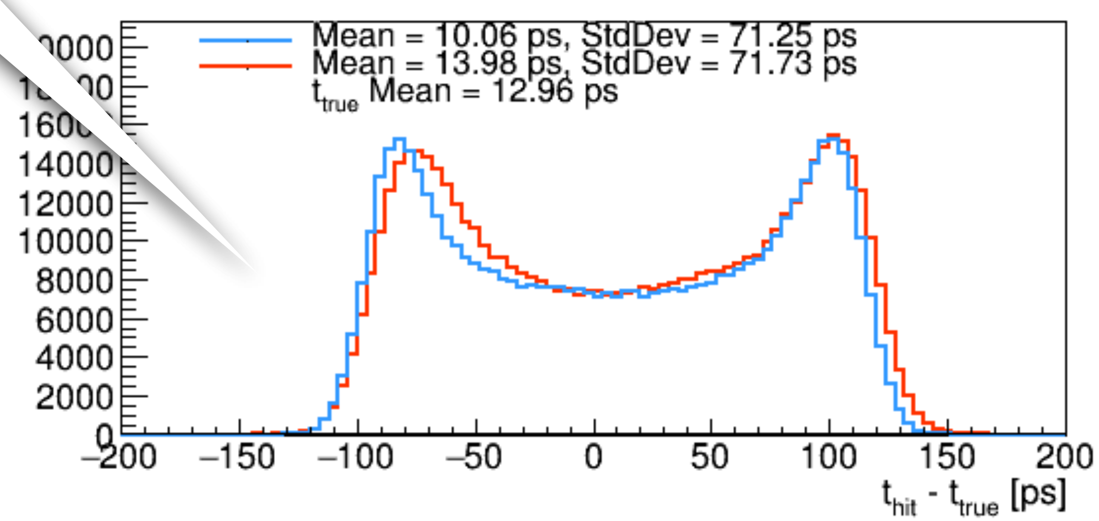

calibration timescale = 2*variation timescale maximally incorrect

# Detailed procedure V




calibration timescale > variation timescale
No significant improvement




Calibration timescale needs to be much shorter than variation => lower limit on timescale of variations that can be calibrated away

# ASIC $t_0$ precision for different clock variations

***The optimal calibration window size is a function of both the period of the variation to be corrected and the hit rate of the channel. More hits collected in a longer time period result in a better calibration, but the calibration window size needs to be small compared to the scale of the variation.***

**Smaller calibration** window can reduce $t_0$ jitter when shorter-term variations affect the hit time.

**Longer calibration** windows, which can collect more statistics and therefore more precisely determine $t_0$, result in a better hit time calibration.

In general, more accurate calibrations can be calculated to correct for longer-term variations, and should result in smaller total clock jitter.

# PLOTs for approval

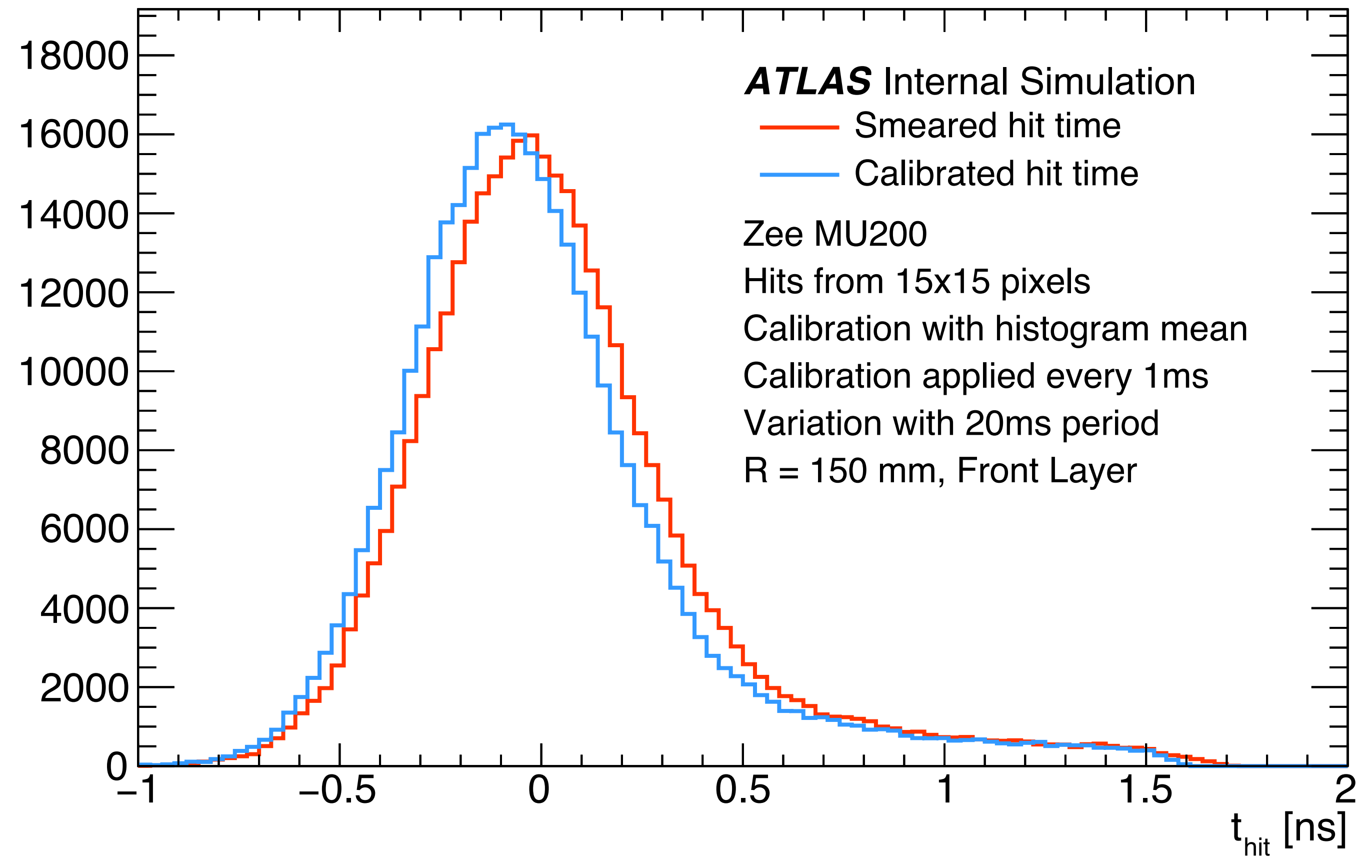



**Figure 1**: HGTD Hit time distribution before (red) and after (blue) the T0 calibration procedure. The calibration constant is calculated every 1ms from the mean of the smeared hit times of a grid of 15 by 15 sensors corresponding to one ASIC. The nominal hit time distribution is obtained from a Geant 4 simulation of the ATLAS Detector which includes the time resolution of the sensor and the time dispersion of the LHC collision. Non-Gaussian tails arise from late particles, backscatter, and other effects. Additional hit time smearing is applied to model the effects of clock jitter and time dispersion arising in the ASIC, flex cable, lpGBT, and FELIX. The expected systematic LHC RF variation time is added as an additional effect. Finally, a sinusoidally varying 100 ps offset of variable period is added to model sources of time jitter that might arise from heat cycles or other effects.

# PLOTs for approval

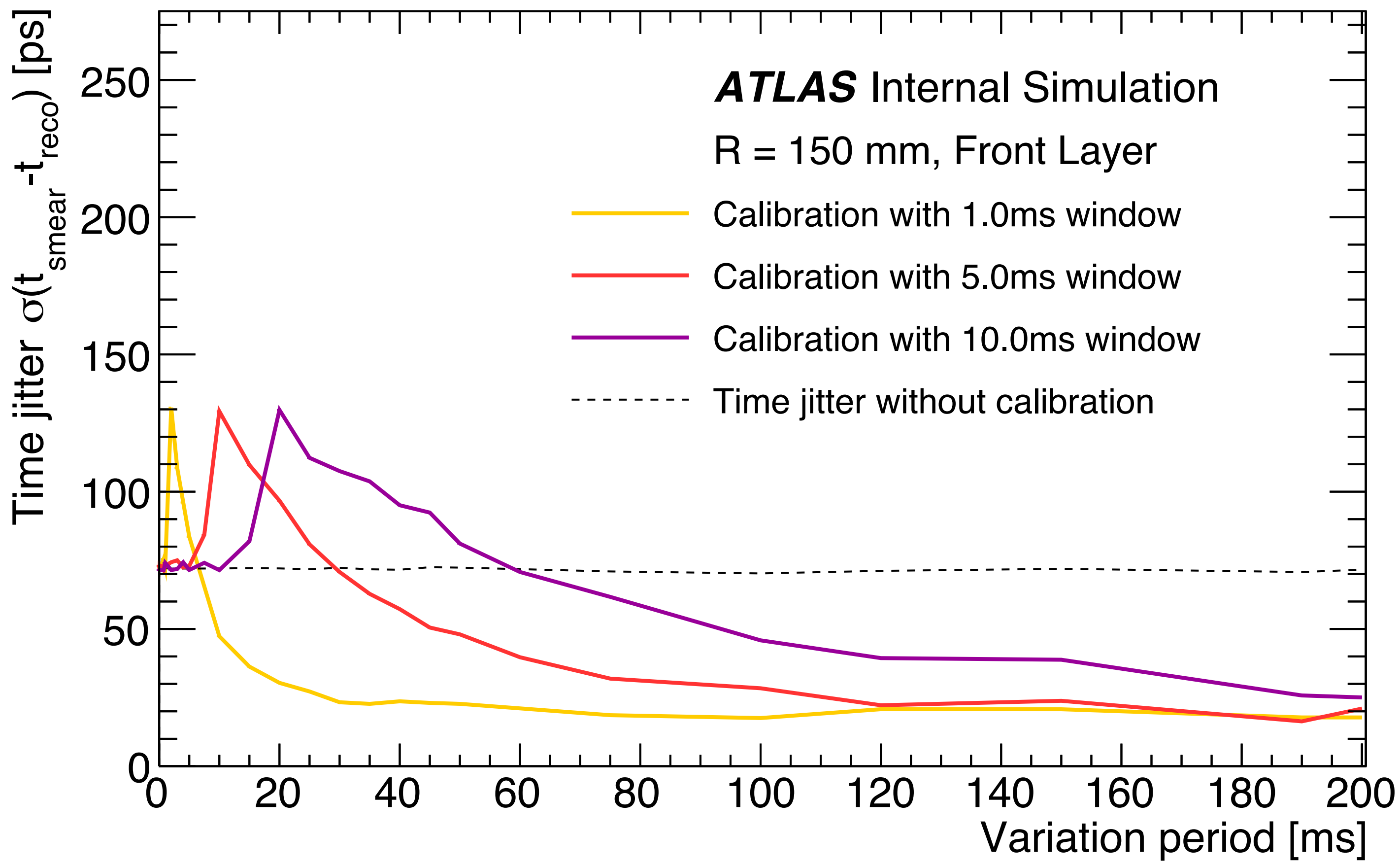



**Figure 2**: Hit time resolution $t_{smear}-t_{reco}$ after the calibration procedure as a function of the variation period, and for several different choices of calibration window time, shown for R=150 mm. $t_{reco}$ is the hit time taken from simulation and includes inherent hit time resolution effects from the sensor and electronics and the collision time spread. The $t_{smear}$ term adds additional sources of time jitter from the ASIC, FELIX, flex cable, lpGBT, and ATLAS collision time drift, with an additional sinusoidally varying 100 ps offset of variable period. If no calibration is applied the time jitter is approximately 70ps and is shown as the dashed line. For a variation period of greater than 10 ms, and with the right choice of calibration window size, the calibration procedure will always improve the $t_0$ precision.

# PLOTs for approval

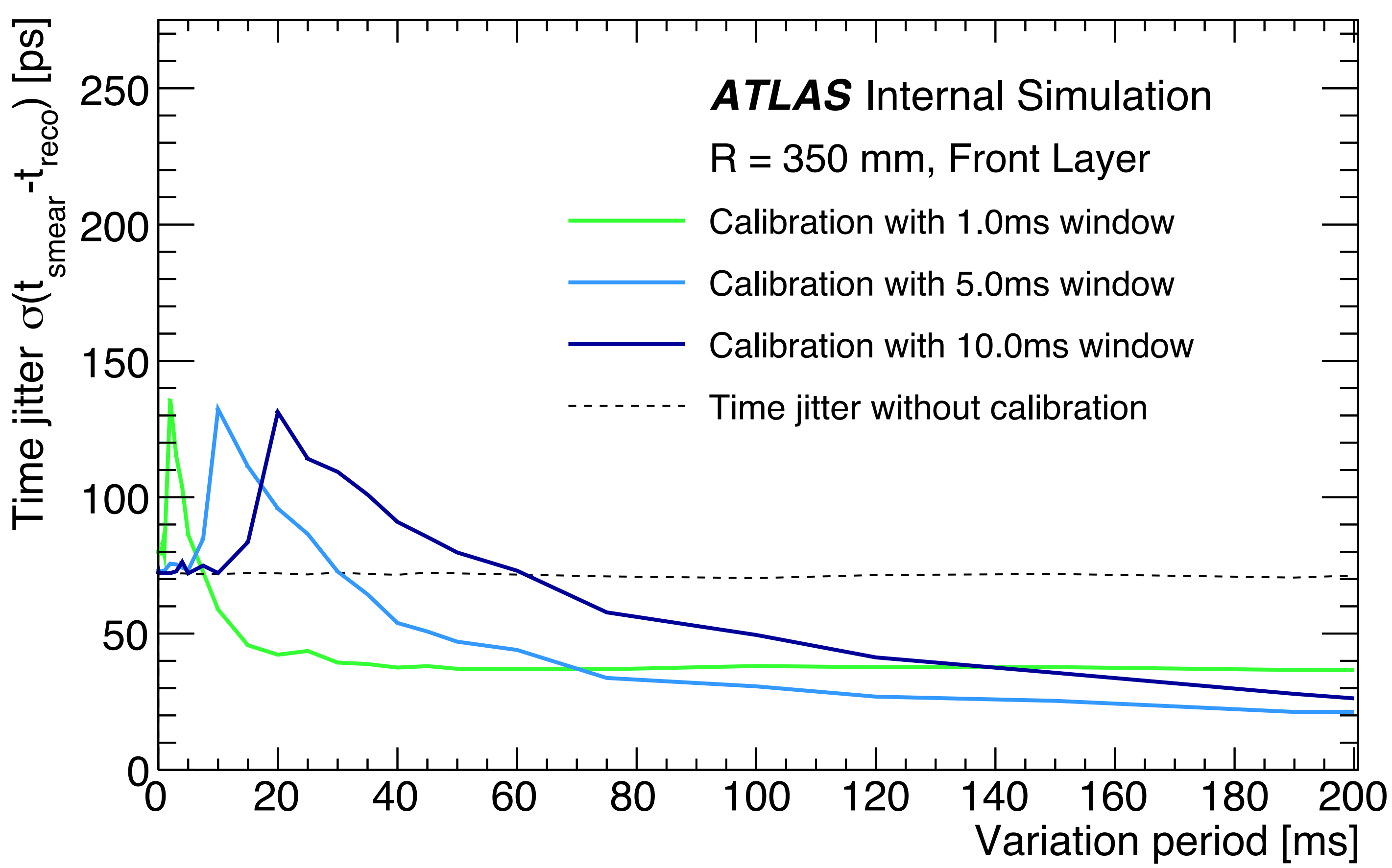
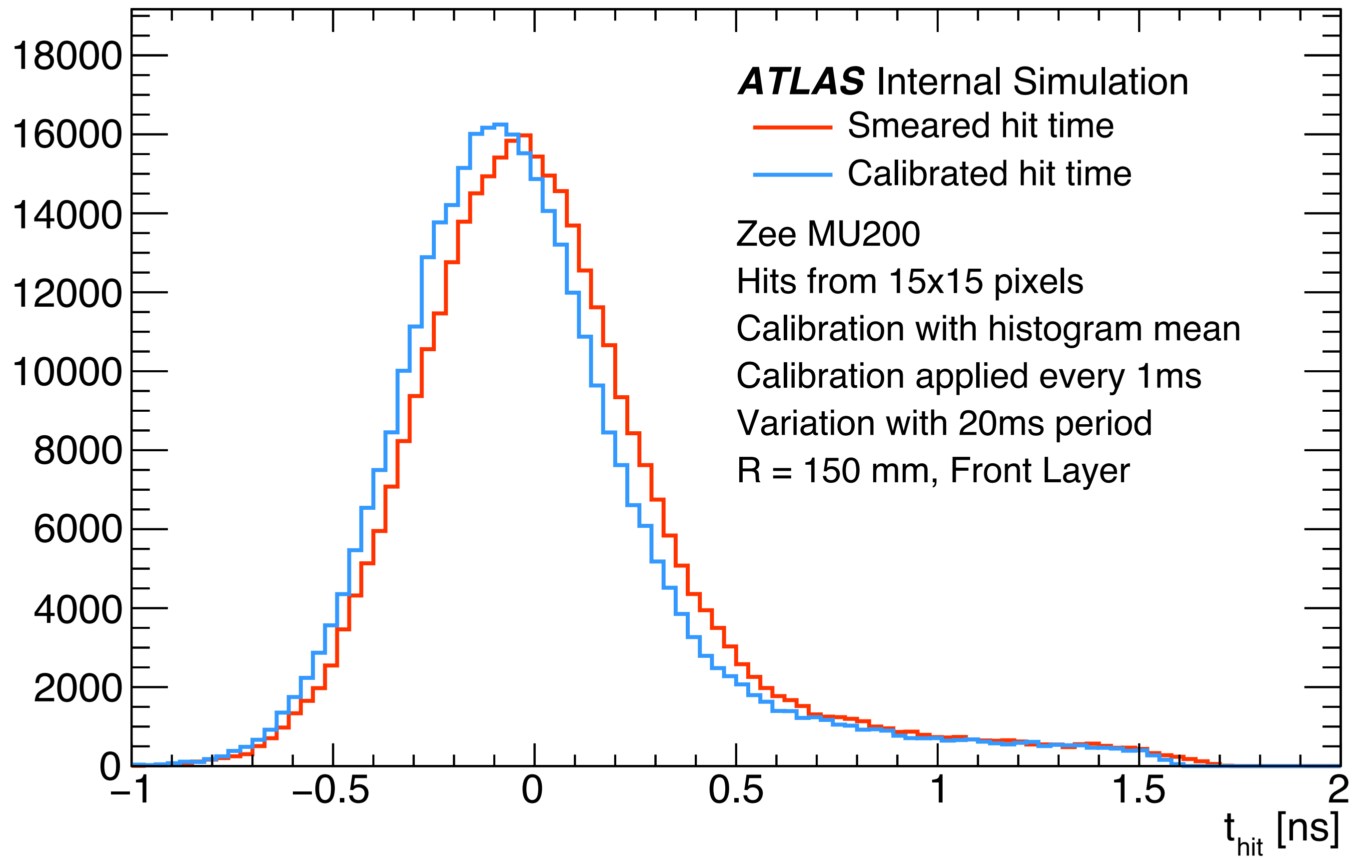



**Figure 3** : Hit time resolution $t_{smear} - t_{reco}$ after the calibration procedure as a function of the variation period, and for several different choices of calibration window time, shown for R=350 mm. $t_{reco}$ is the hit time taken from simulation and includes inherent hit time resolution effects from the sensor and electronics and the collision time spread. The $t_{smear}$ term adds additional sources of time jitter from the ASIC, FELIX, flex cable, lpGBT, and ATLAS collision time drift, with an additional sinusoidally varying 100 ps offset of variable period. If no calibration is applied the time jitter is approximately 70ps and is shown as the dashed line. For a variation period of greater than 10 ms, and with the right choice of calibration window size, the calibration procedure will always improve the $t_0$ precision.

# Mean shifts




- The mean of the distribution encodes information on the relationships between:
  - the global LHC clock on arrival to ATLAS
  - the mean LHC collision time for a given bunch
  - the reference clock phase at a given TDC.
- This mean shifts from zero through the cumulative effects of time-of-flight, clock propagation delays, and dynamic shifts of the clock phase during data-taking.
- Assuming that the relationship between the clock at the TDC and the LHC clock is stable within a given time interval, data collected during the interval can be used to sample the hits time distribution and estimate its mean, t0. This mean can then be used to correct the cumulative time offset of each channel individually.

# Time resolution

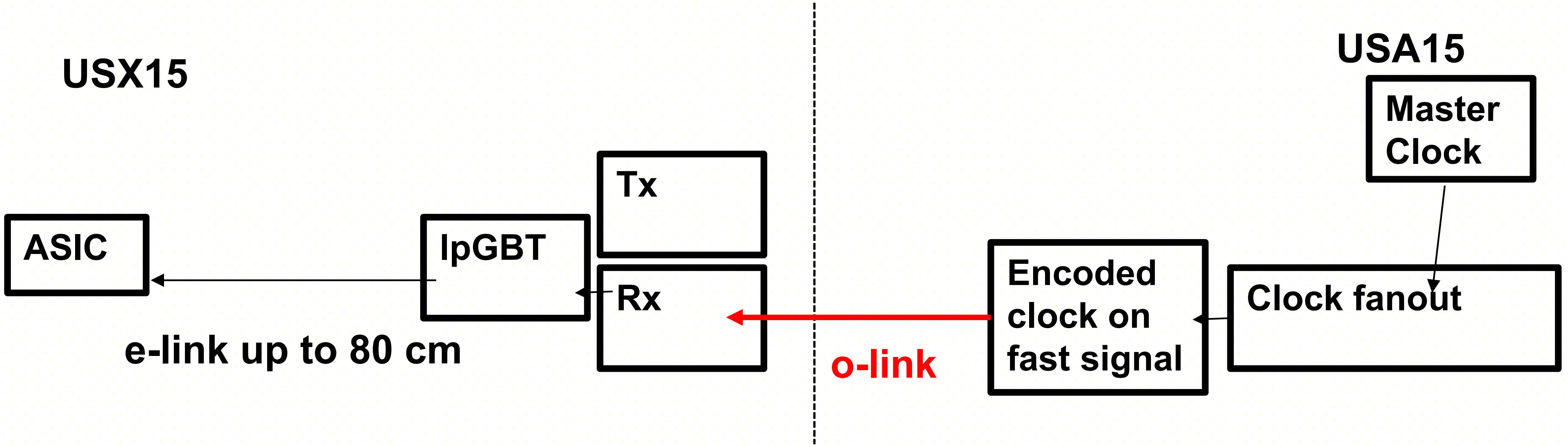
$$\sigma^2_{\text{total}} = \sigma^2_{\text{L}} + \sigma^2_{\text{elec}} + \sigma^2_{\text{clock}}$$

1) Sensor : 20-25 ps non irradiated, 40-50 ps after irradiation

2) Electronics jitter : < 25 ps
   TDC 20 ps lsb → < 5 ps
   Time walk after TOT correction < 10 ps

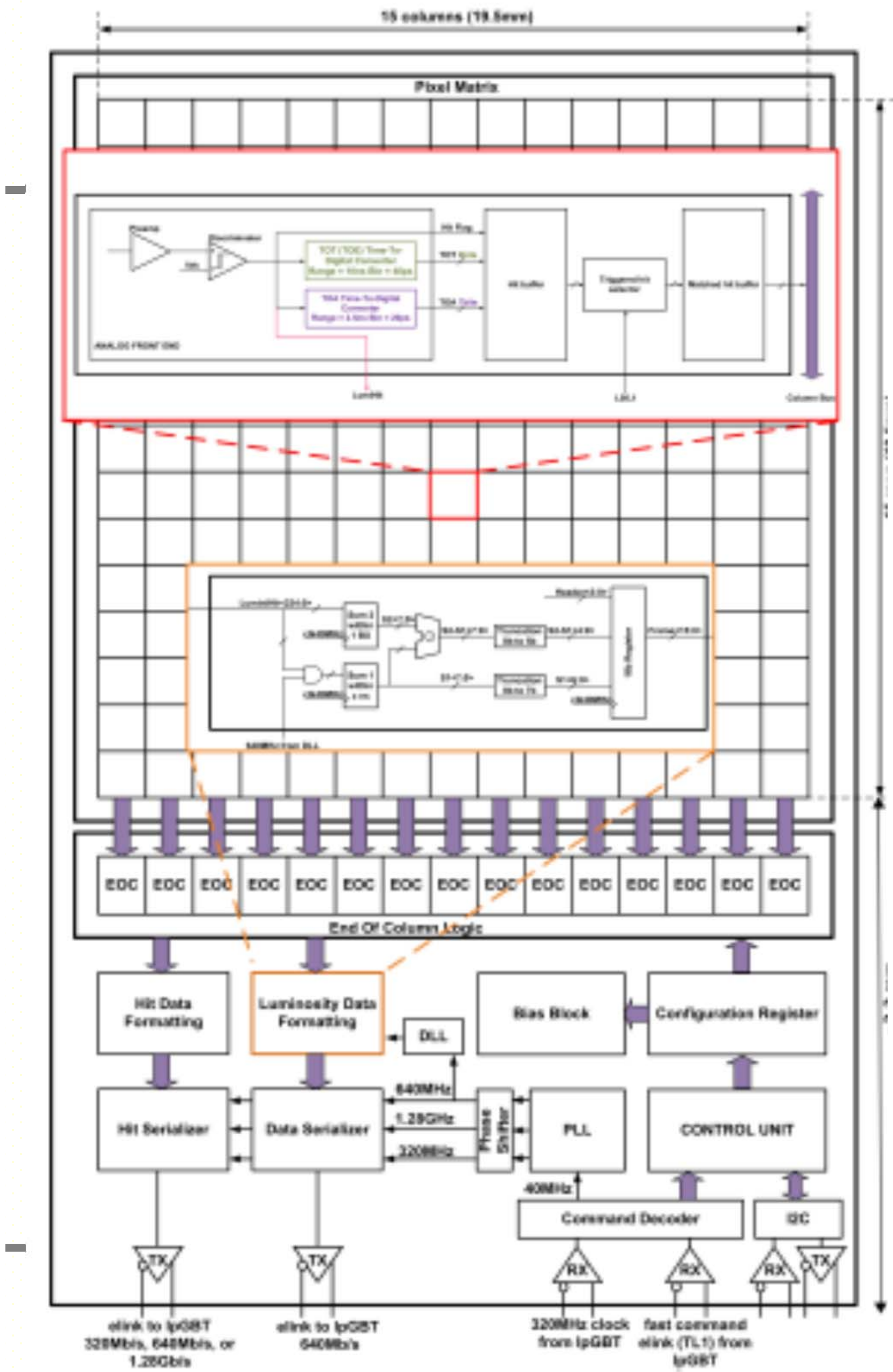
3) Clock and calibration :
   - local jitter < 10 ps
   - channel to channel intercalibration < 10 ps

# Clock distribution to ASIC




Any jitter or long term stability on the 40 MHz clock will induce a time resolution degradation
All clocks inside ASIC ALTIROC built from the 40 MHz encoded in the fast command of the lpGBT
lpGBT clock jitter : < 5 ps ?

https://indico.cern.ch/event/717613/contributions/2948657/attachments/1637743/2613754/HGTD-Clock.pdf




# ALTIROC and CLOCK

Input 40 MHz decoded from lpGBT

PLL to build 320 and 640 MHz clocks

Phase shifter common to 40/320/640 MHz (similar to phase shifter in 65 nm for lpGBT), accuracy ~100 ps
40 MHz phase adjusted as TDC active only over +1.25 ns around BC
Luminosity window (3.125 ns) centered on BC
Another PLL after phase shifter is jitter too large

Clock distribution to each channel as synchronous as possible

Internal pulser

# T0 calibration

Static contribution :
- Clock distribution in ASIC (similar in each ASIC)
- Different path length of the flex (e-link) as a function of ASIC position
  → can be measured with internal pulser, should stable with time
- Average Time of Flight of particles as a function of radius
  → can be computed, and measured with data.
  (partially compensated by flex length)

Dynamic contribution :
- Any dependence of the clock from USA15 to peripheral electronics (@-30 °c)
  - Very fast variation, seen as jitter on individual channel : cleaner ?
  - Phase variation (→T0) :
    Long/medium term (as day/night variation of 200 ps in ATLAS.)
    → use data to correct/monitor
  - Send back to USA15 the 40 MHz to compare with master clock ?