Data Acquisition and Analysis of Test Beam for the ATLAS High-Granularity Timing Detector

Arthur Lafarge

On behalf of the ATLAS HGTD Group

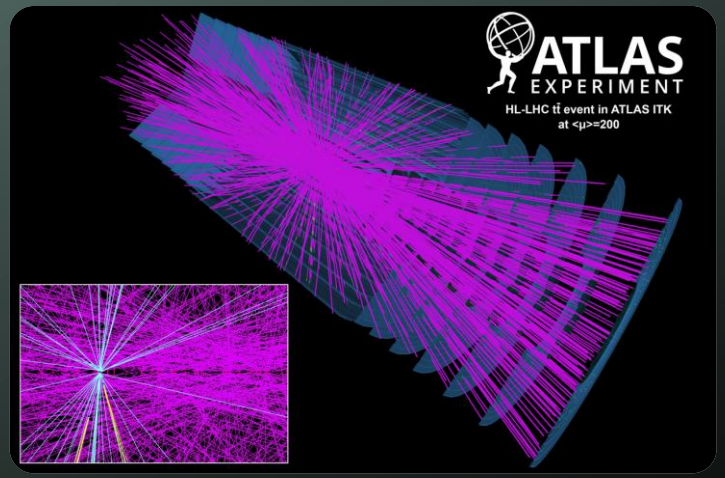
THE HIGH GRANULARITY TIMING DETECTOR

CONTEXT: HGTD & MODULE

The HL-LHC Program

- Up to 200 simultaneous collisions
- ~5 time the current pile-up

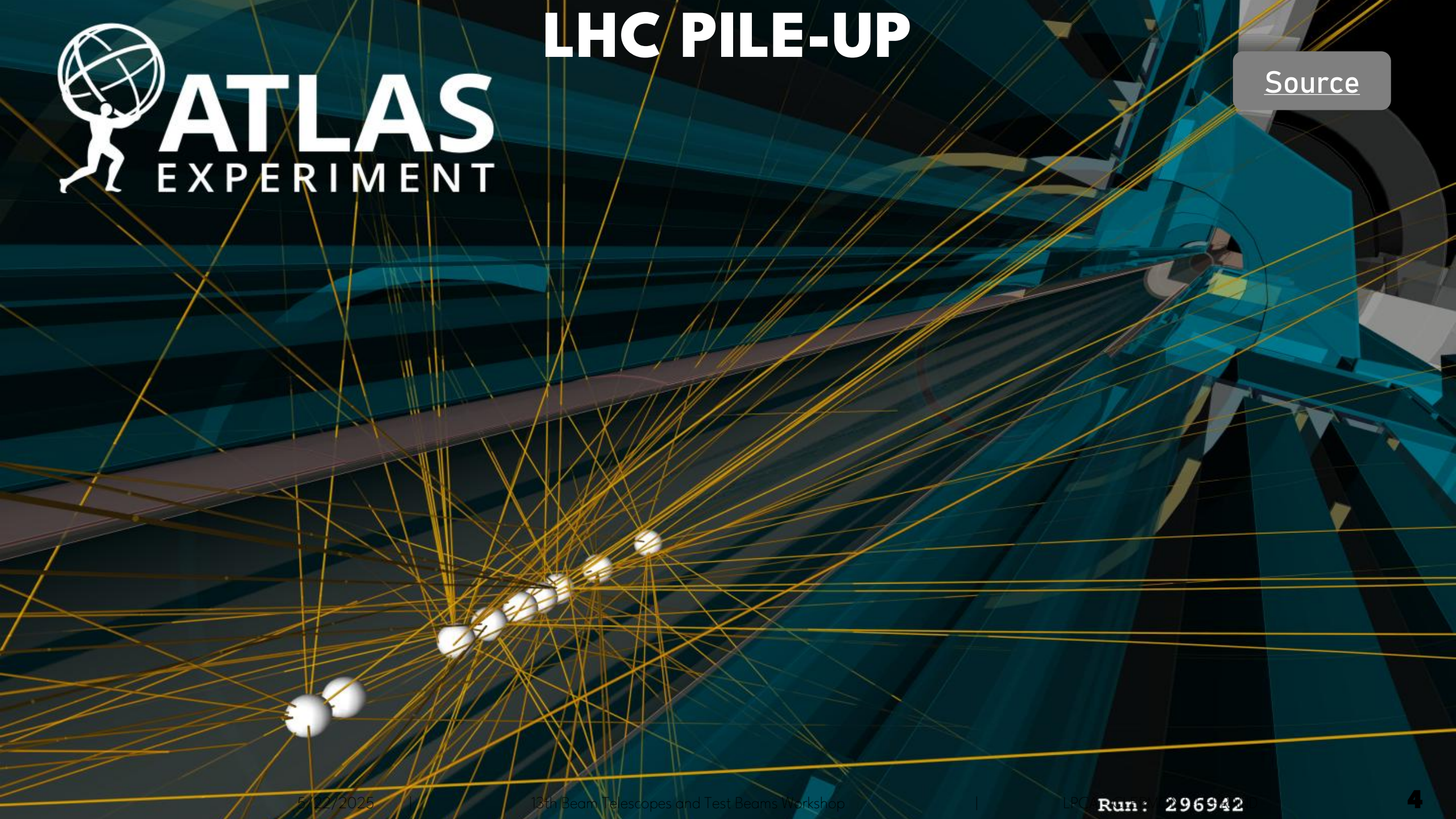
→ Multiplied by 6 the collected data



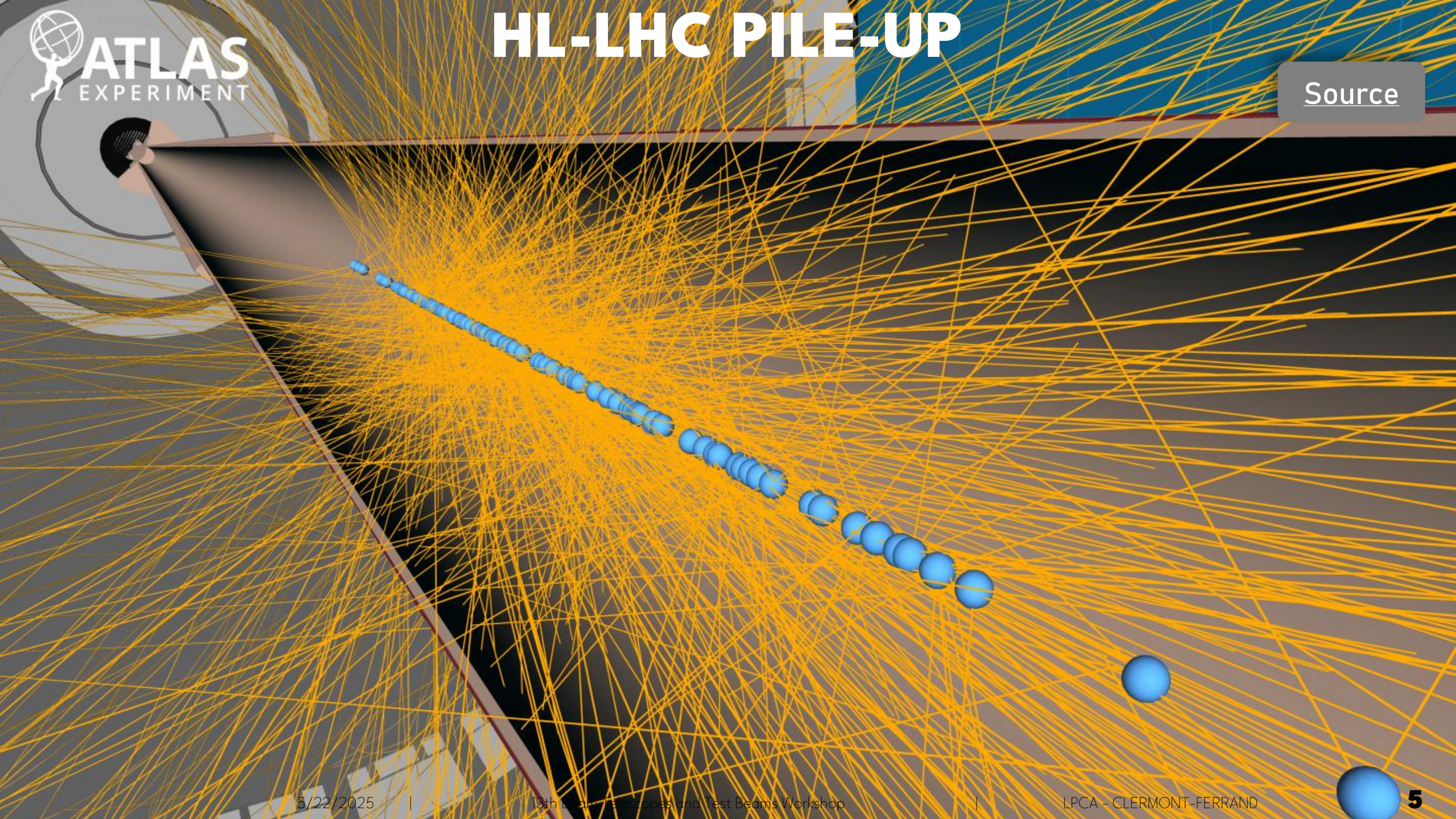
Necessity to add a timing dimension

LHC PILE-UP

Source



HL-LHC PILE-UP



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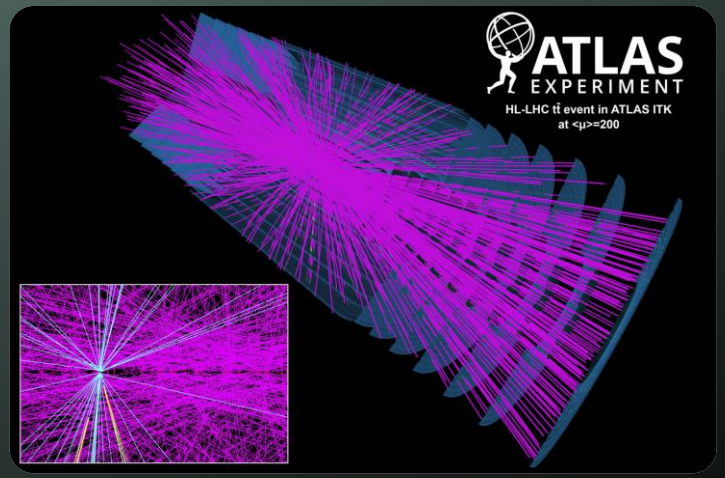
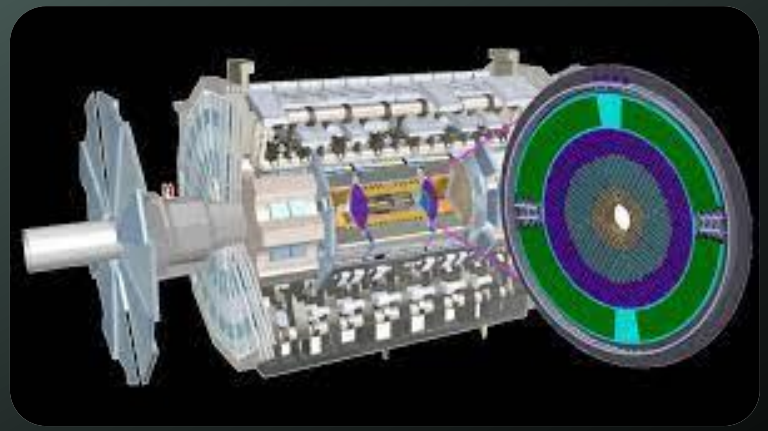


Necessity to add a timing dimension

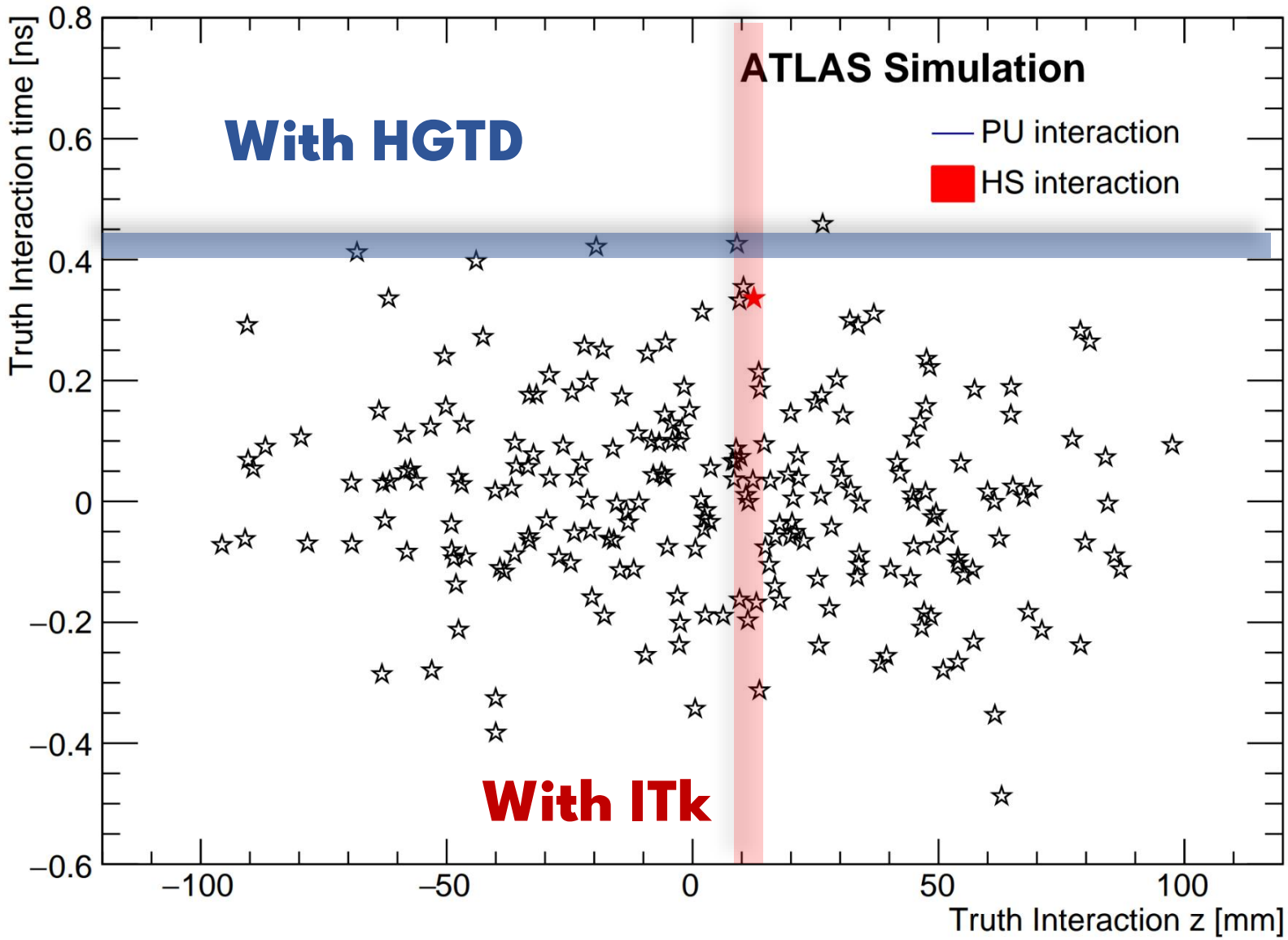
High Granularity Timing Detector

- New ATLAS sub-detector
- ~2030 (Run 4)
- 8032 modules (ASIC+sensor)
- $2.4 < |\eta| < 4$



Spatial constraint and high exposure to radiation

TRACK SEPARATION



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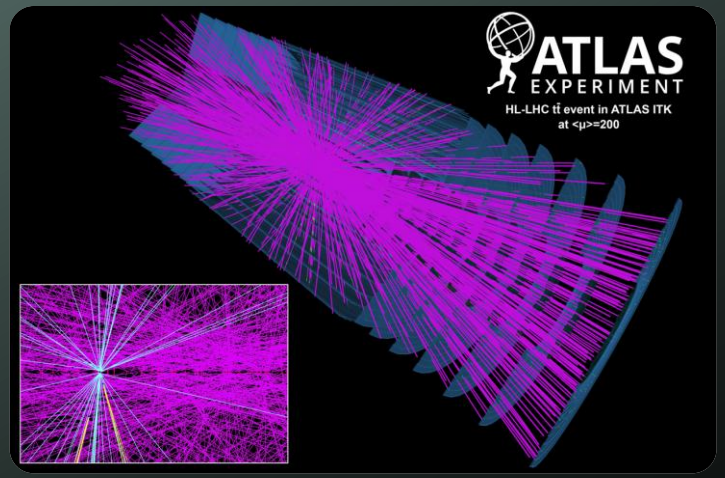
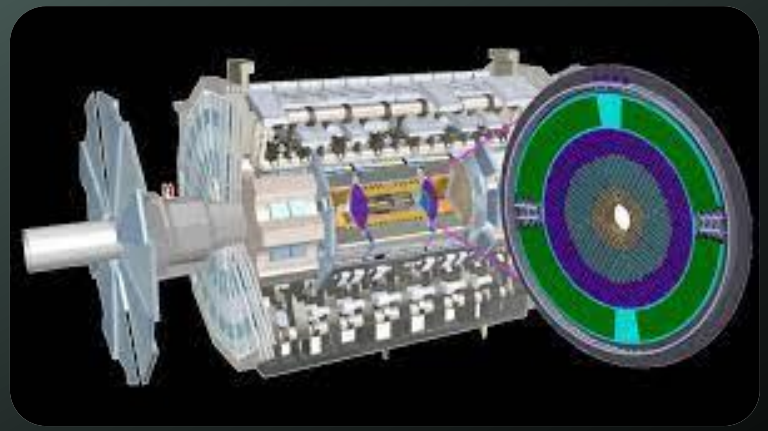


Necessity to add a timing dimension

High Granularity Timing Detector

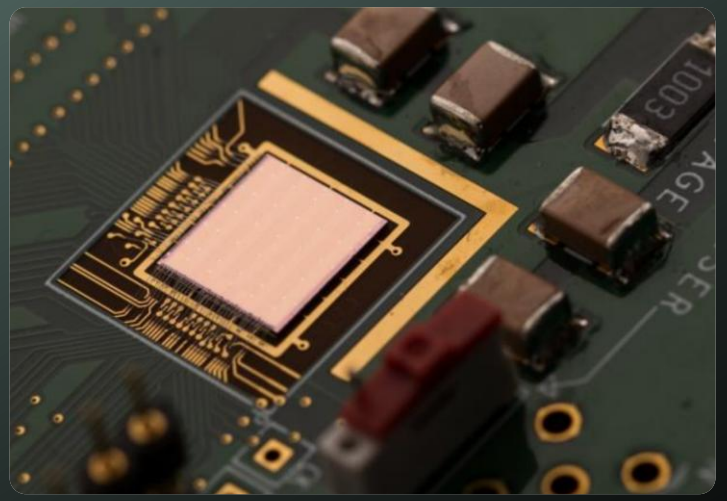
- New ATLAS sub-detector
- ~ 2030 (Run 4)
- 8 032 modules (2×ASIC+sensor)
- $2.4 < |\eta| < 4$



Spatial constraint and high exposure to radiation

Module

- ASIC + LGAD (sensor) $\times 2$
- 225 pixels
- $1.3 \times 1.3\ mm$



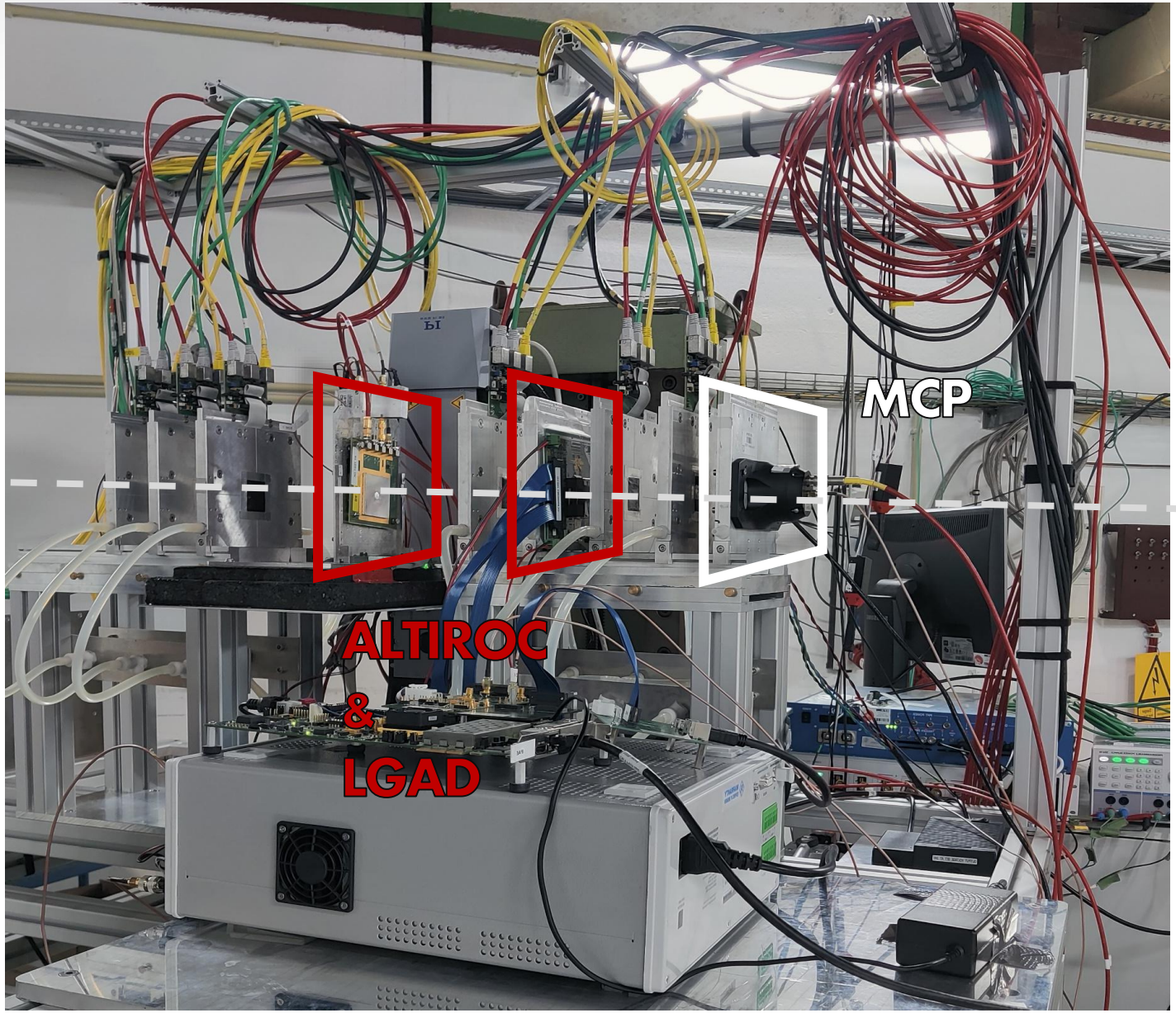
Precision <50 ps per hit

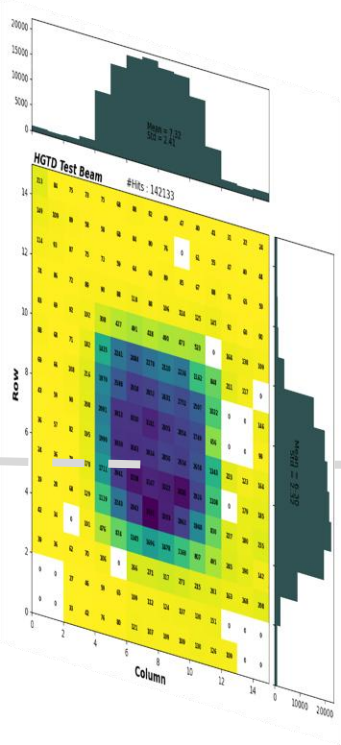
More details given in the talk of Theodoros Manoussos

MEASURING THE RESOLUTION

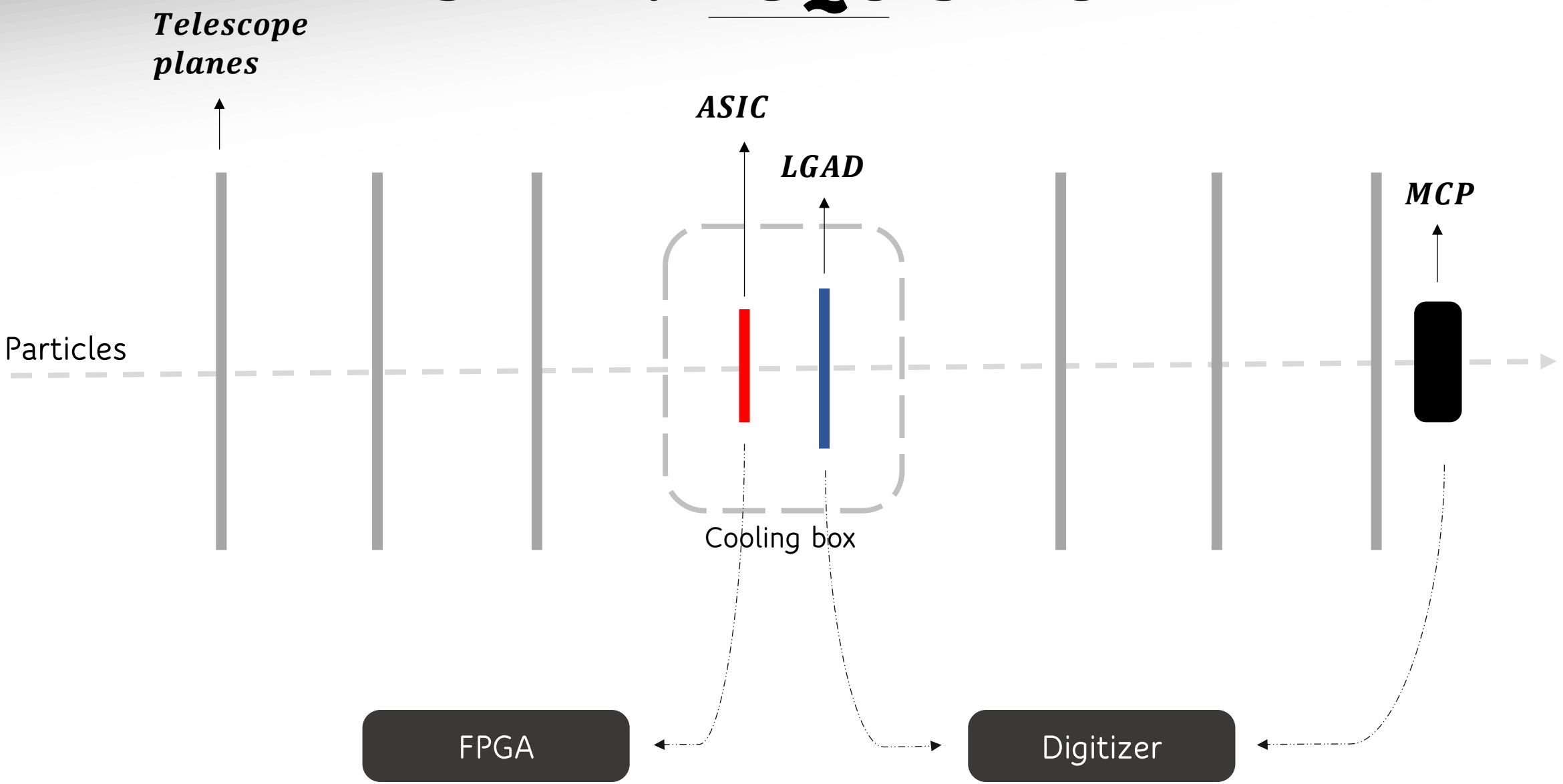
TESTBEAM SETUP

Beam





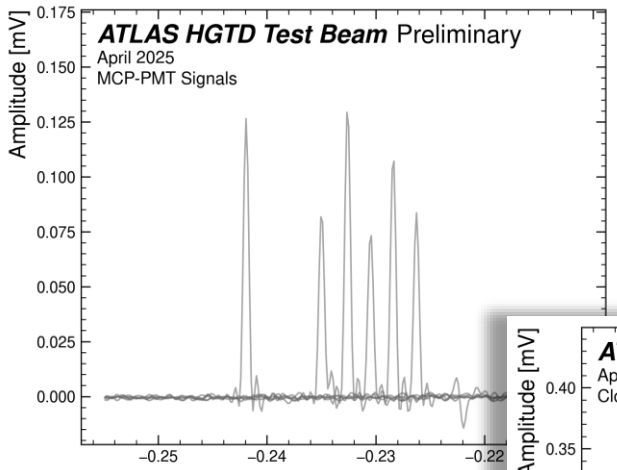
STEP I: ACQUISITION



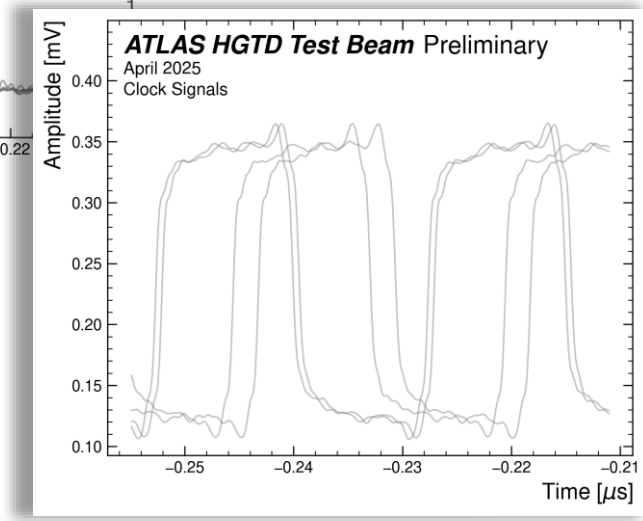
STEP II: EXTRACT TIMING

Digitizer Side

MCP-PMT



Clock

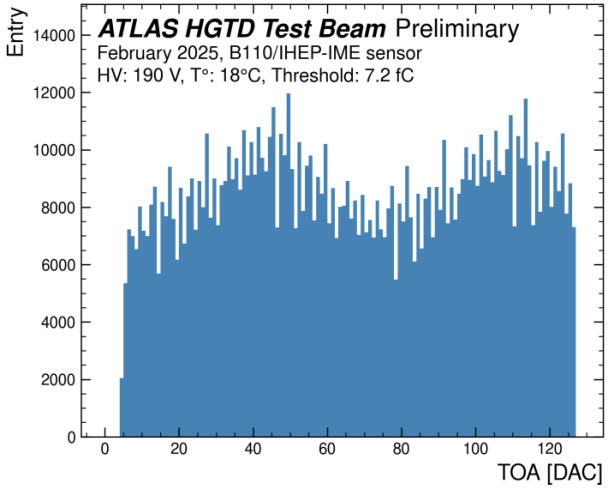


Constant Fraction Discriminator to determine the timing of the hits

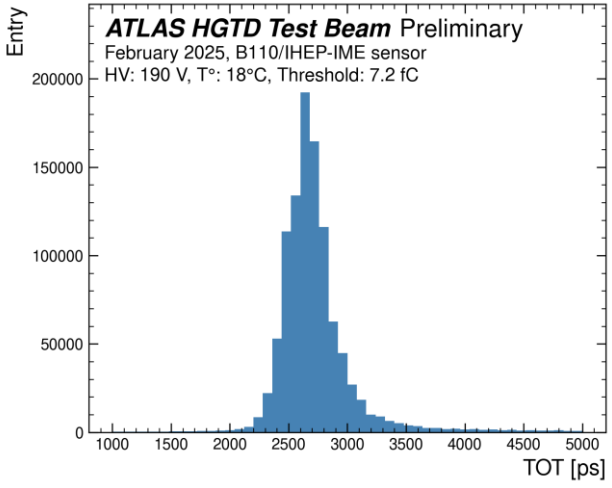
ALTIROC Side

- TOA & TOT IN DAC UNIT
  - TOA Range $\sim 2.5\ ns$
  - TOT Range $\sim 10\ ns$
- TOA Distribution should be flat…

TOA

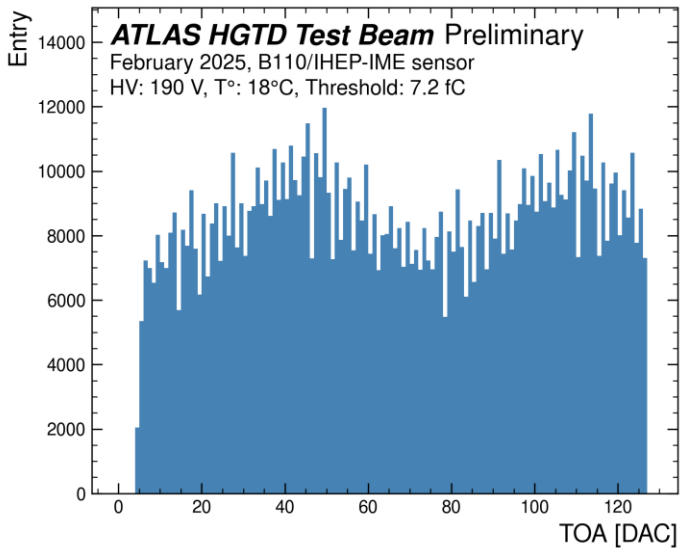


TOT



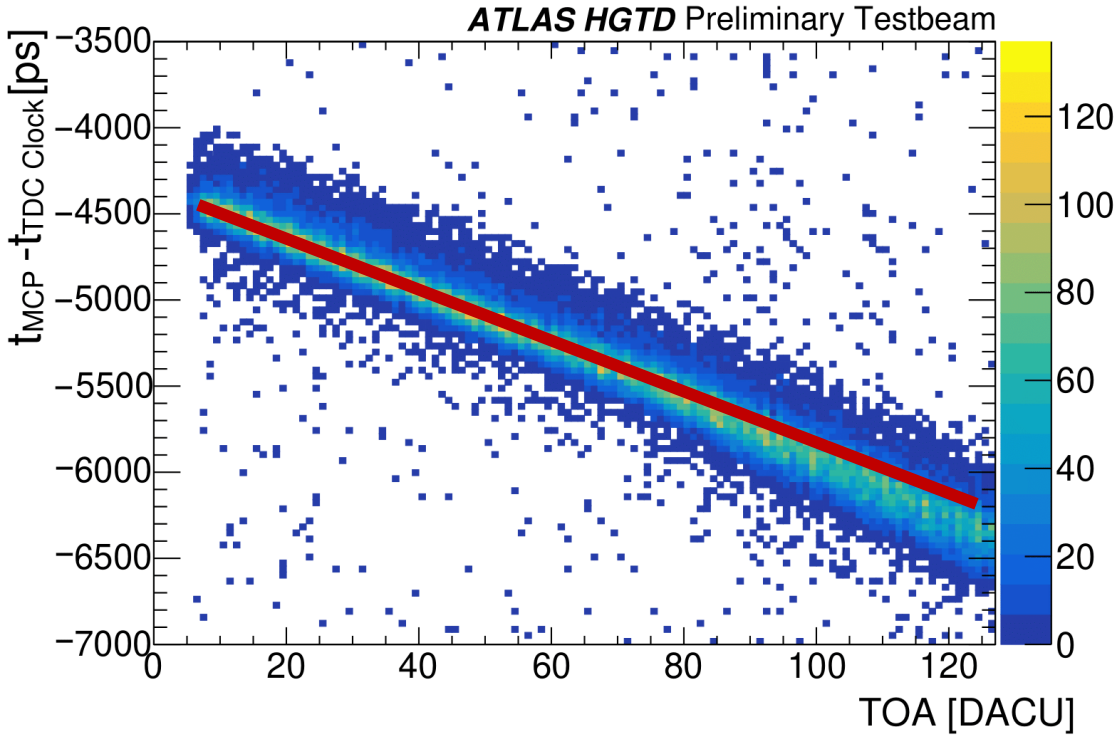
STEP III: CONVERT TOA IN ps

- **Determine the LSB: ASIC calibration**
  - **LSB (Least Significant Bit) = quantized step of Time-to-Digital (TDC) converter**
    - Nominal design: LSB $\sim 20\ ps$
    - In the reality : LSB is varying for each TOA bin
      → Differential Non Linearity (DNL)



In test bench the TOA distribution is almost flat → low DNL

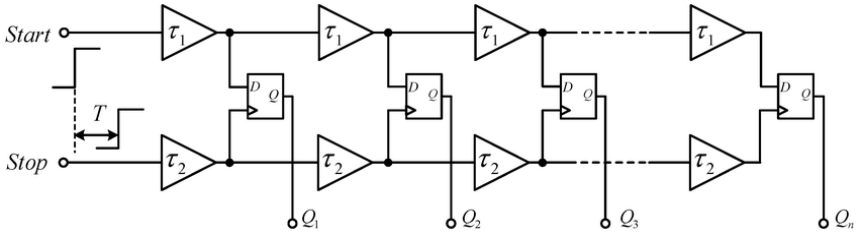
- **A different story for test beams**
  - Using data-drive method for LSB calibration
  - Non flatness caused by DNL



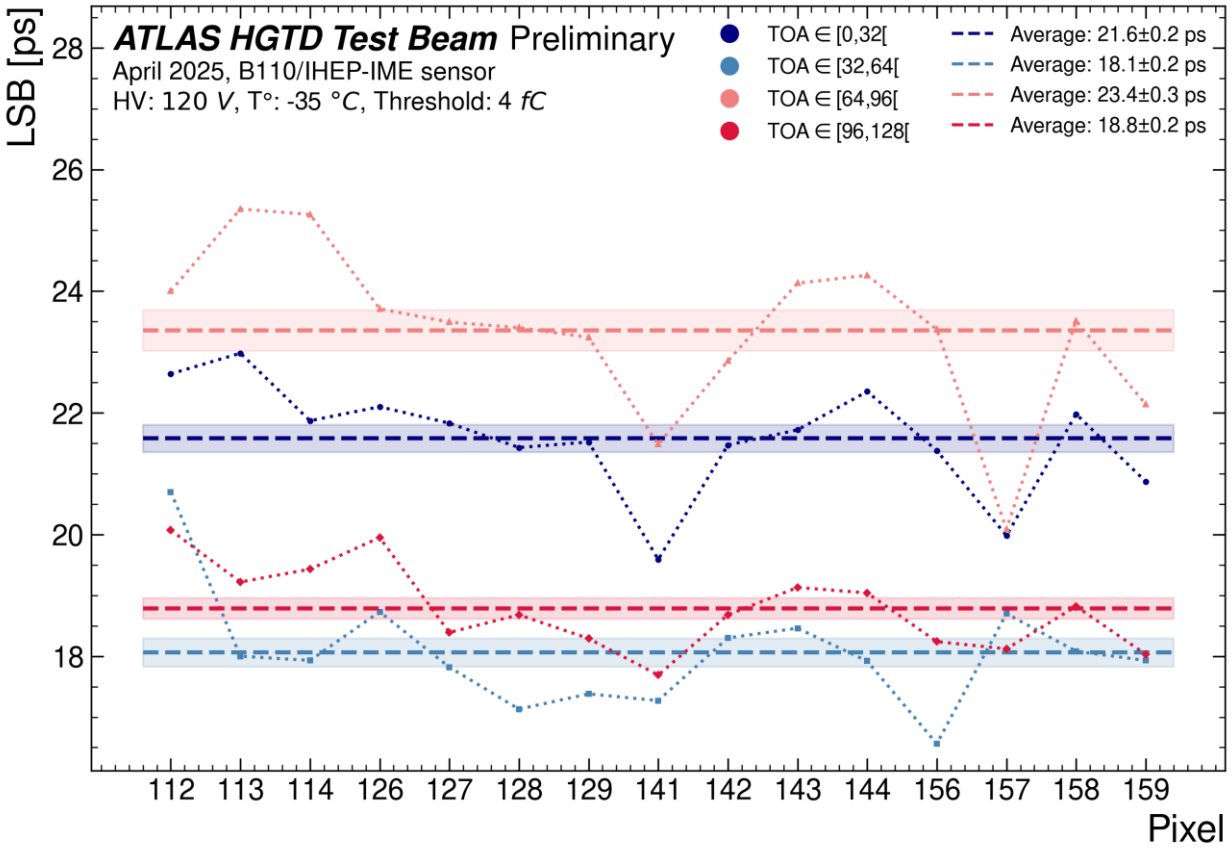
STEP III: DETERMINE THE LSBs

- **Compute 4 LSBs**
  - TOA TDC is divided in 4 cycles
    - 4×32 cells in delay line

0-31	32-63	64-95	96-127



source

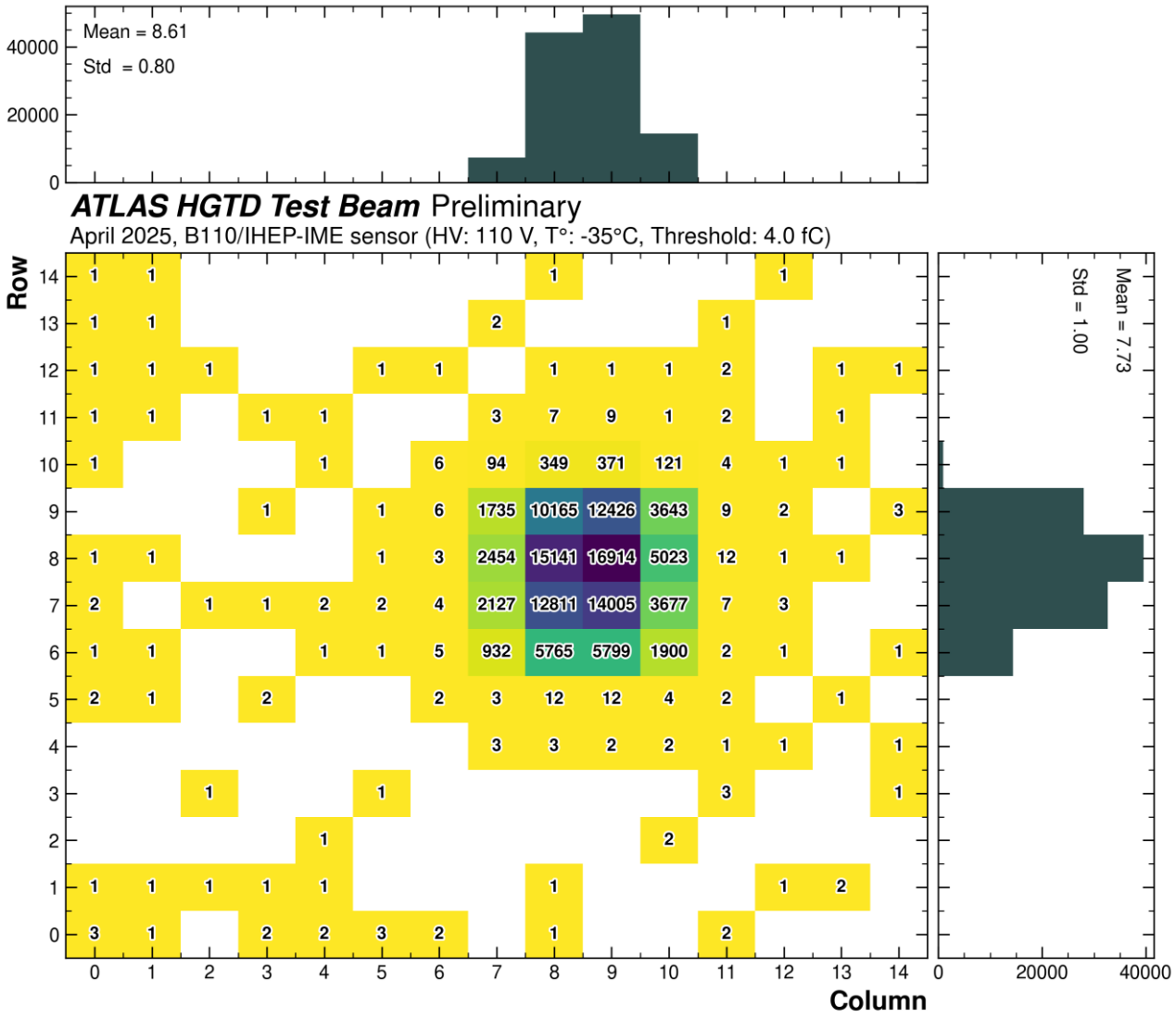


- **The LSBs tuning**
  - Dependence of external factors (Temperature, High/Low Voltages)

STEP IV: REMOVE NOISE

- **Small beam spot**
  - ~9 pixels (~5 mm^2)
- **Hits occurring in the full ASIC**
  - **Noise**
  - **Multi-particles scattering**
- **Degradation of the resolution**

Tracking to remove noise



STEP IV: REMOVE NOISE

- **Corryvreckan for tracking reconstruction and more**

1) DUT Alignment with MIMOSA planes

- DUT boarder through occupancy map

2) Tracking reconstruction

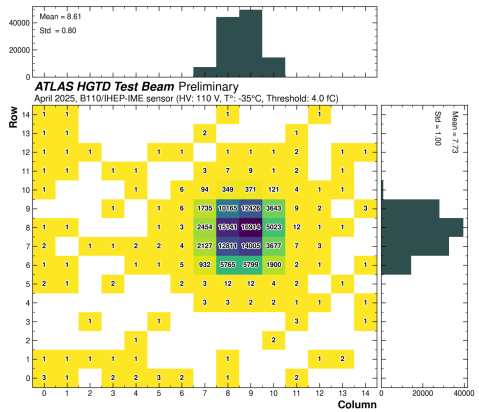
- Iterative χ^2 minimization
- $\geq$1 hit in 2 nearest planes
- $\geq$5 total hits

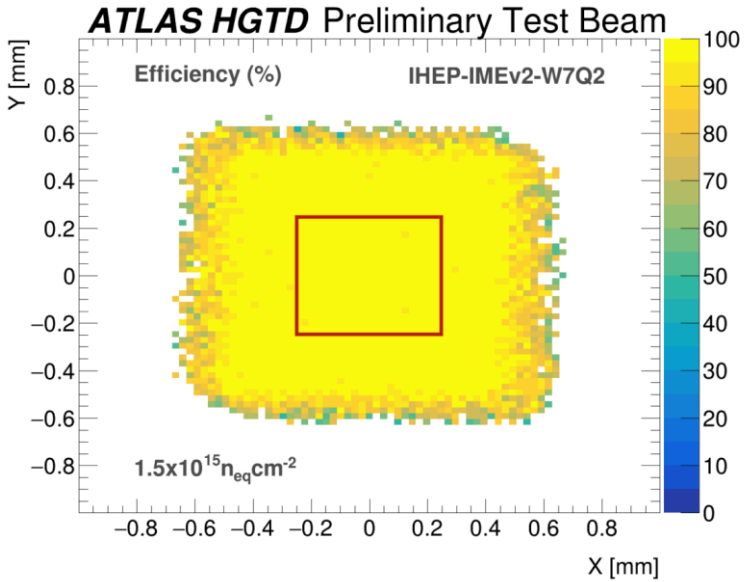
3) Synchronization between telescope and digitizer

4) Extrapolate track to ALTIROC

- Associate TOA to hit in MCP

This step was not performed in the following results





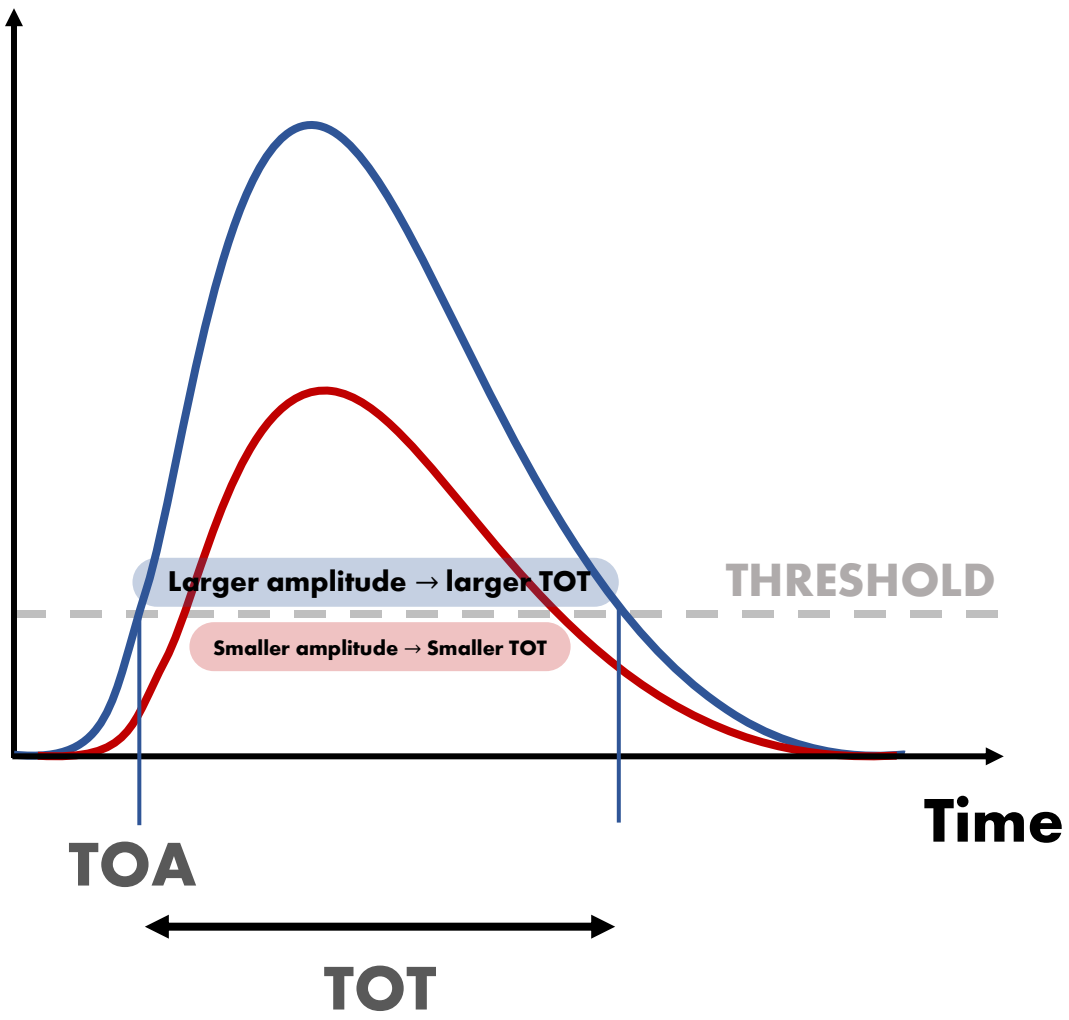
STEP V: TOA & TIME-WALK

Definitions

Time-Walk : variation in the timing of a signal's rising edge (TOA) as a function of its amplitude

TOA: Time Of Arrival

TOT: Time Over Threshold



STEP V: COMPUTE RESOLUTION

- **Definition**

$$\Delta t\,[\mathrm{ps}] = TOA\,[DAC] \times LSB\,[ps] - (t_{MCP}\,[ps] - t_{clock}[ps])$$

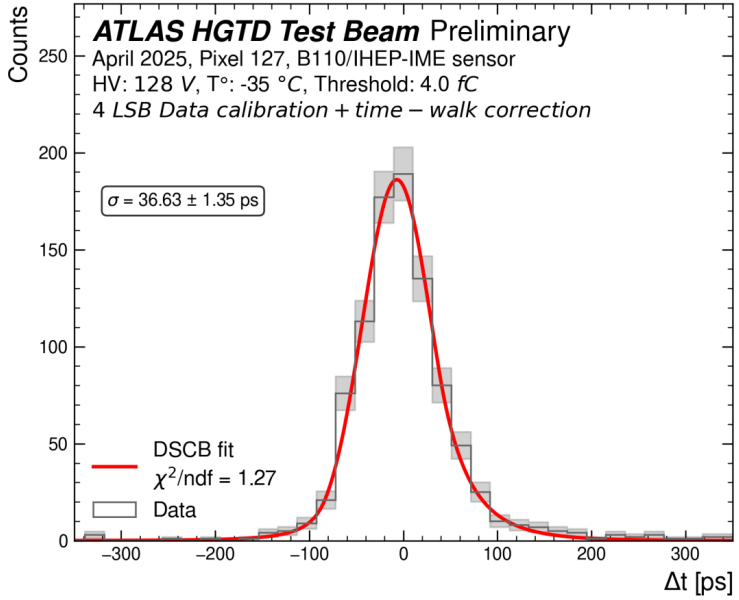
Time Measured by ALTIROC
→ In DAC unit

Resolution of TOA TDC
→ To convert in ps

t_{MCP} triggered w.r.t clock
→ Obtained from Digitizer

Reference
→ Obtained from Digitizer

- **DSCB fit on Δt**
  - σ taken as the resolution



DECORRELATING THE EFFECTS

CONTRIBUTIONS TO THE RESOLUTION

- **Theoretical resolution**
  - Time-Walk effect
    - Dependence of the time at which a signal crosses a given threshold depends on its amplitude
  - Jitter
    - Caused by the noise in the electronics
  - Landau
    - Stemming from fluctuations in energy loss as a charged particle passes through the sensor
  - Clock
    - Timing precision of the system clock that distributes timing signals to different parts
  - TDC
    - Arises from the finite resolution of the TDC used to digitize and Non-linearities in bins

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

< 25 ps

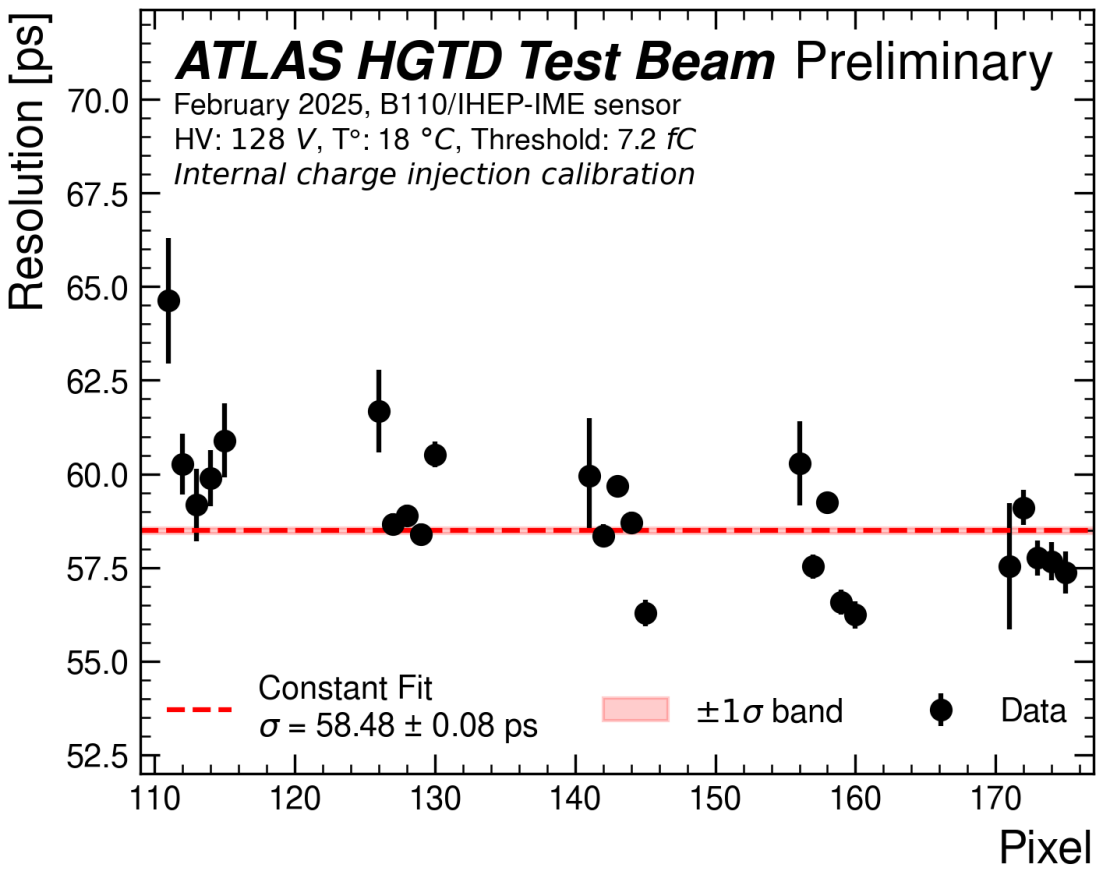
< 35 ps

< 10 ps

1 LSB CALIBRATION – SOFTWARE

- **Starting point**
  - Injection based calibration using delay scan
    - Moving the phase shifter

58.5±0.1 ps



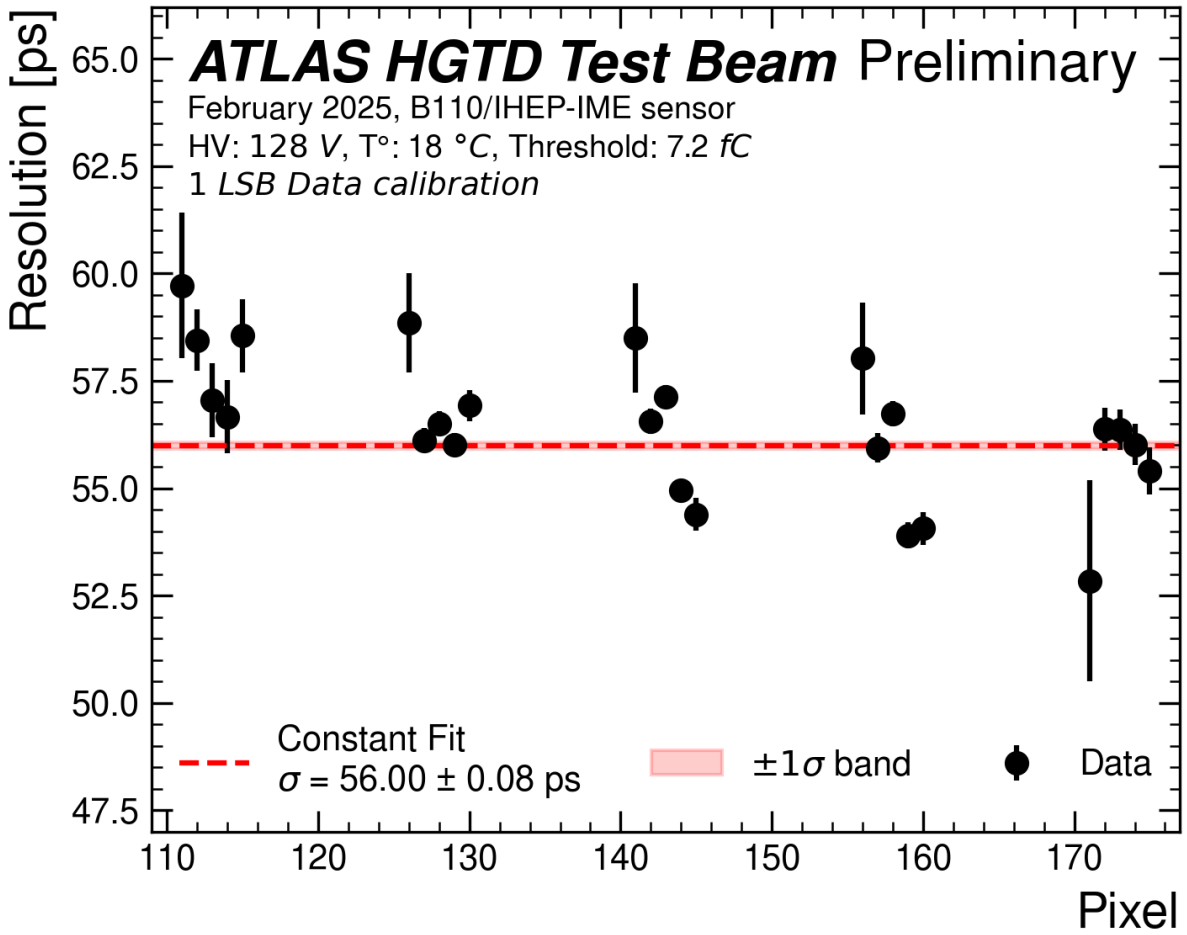
1 LSB CALIBRATION – DATA

- **Considering 1 LSB**
  - LSB is assumed to be constant across the full TOA range

  → Case where non DNL negligible

- **Data calibration**
  - Procedure
    - For each TOA range we are varying the LSB to find $\min\left(RMS(\Delta t)\right)$

56.0±0.1 ps



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- **Considering 1 LSB**
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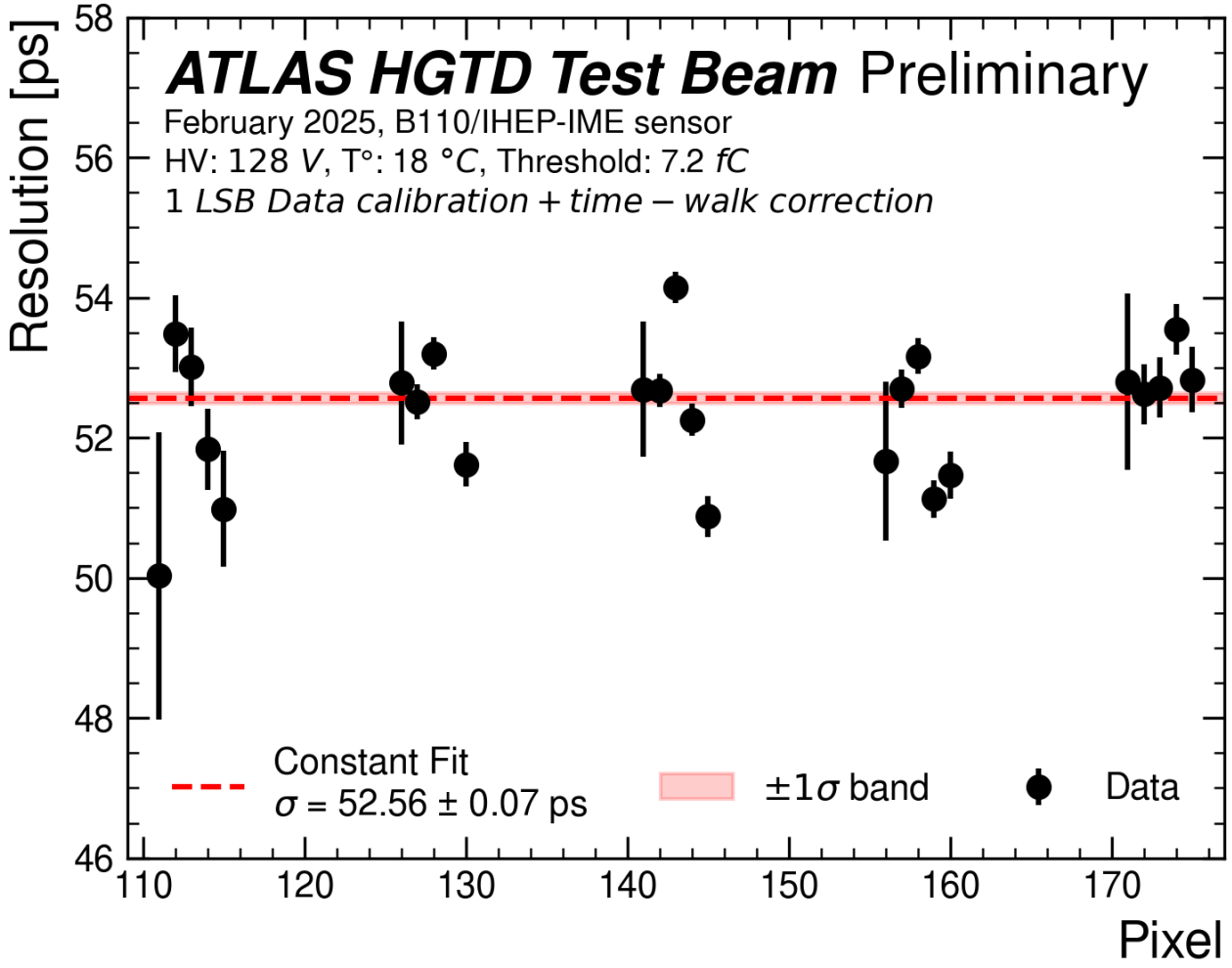
  → Case where non DNL negligible

- **Data calibration**
  - Procedure
    - For each TOA range we are varying the LSB to find $\min(RMS(\Delta t))$
- **And time-walk correction**
  - Resolution is uniform across pixels

52.6±0.1 ps



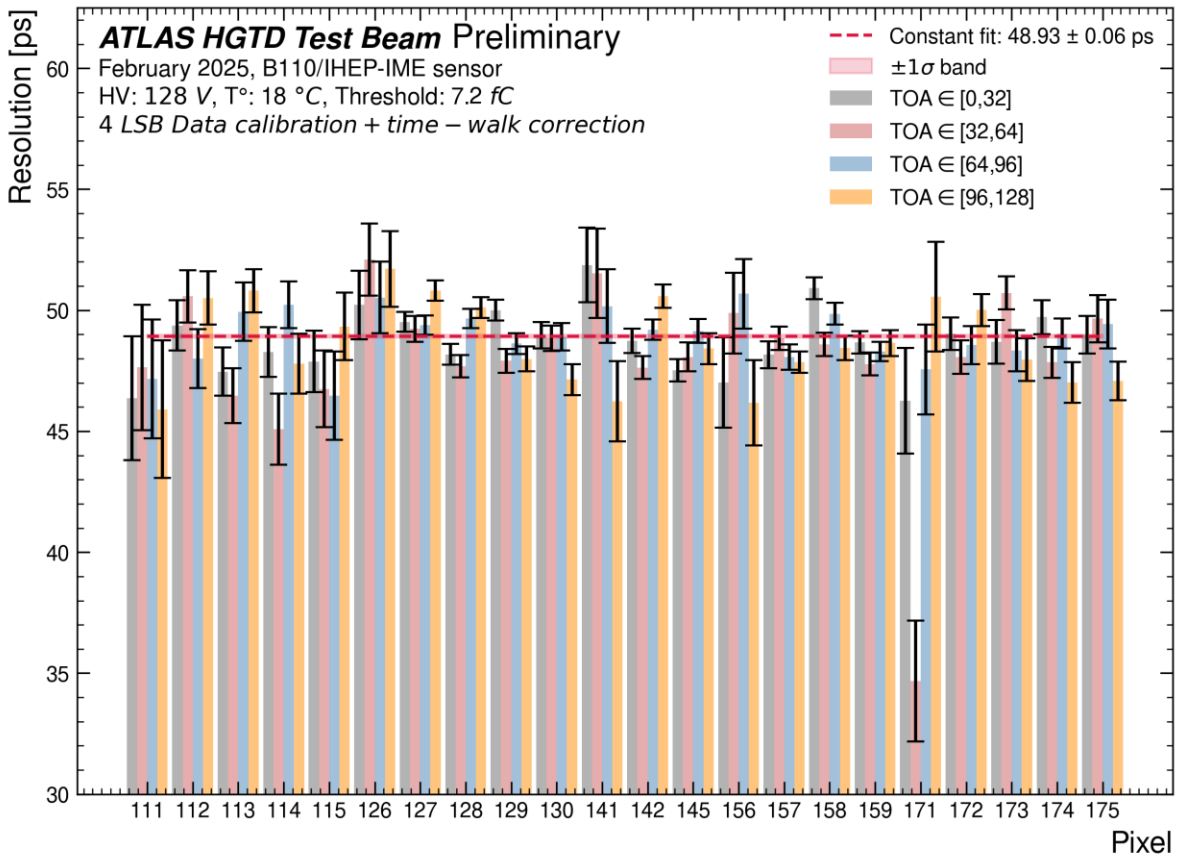
4 LSB CALIBRATION – DATA

- **Considering the DNL of TDC**
  - Architecture based on 32 TDC bins

  → 4 LSB are been determined per pixel

- **Consistent values across ranges/pixels**
  - No dependency to the position of the pixel

- **Different internal behavior in terms of LSB calibration**
  - Difference of ~7 ps between internal calibration for LSB and data-driven calibration



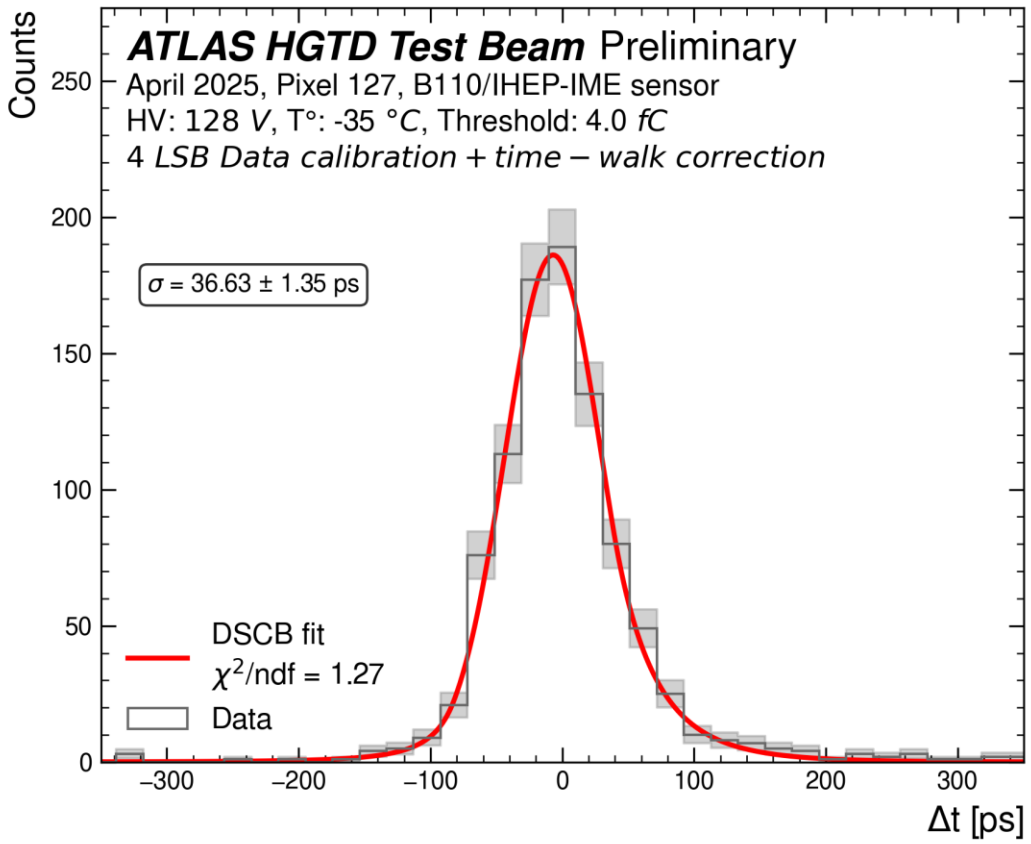
48.9±0.1 ps

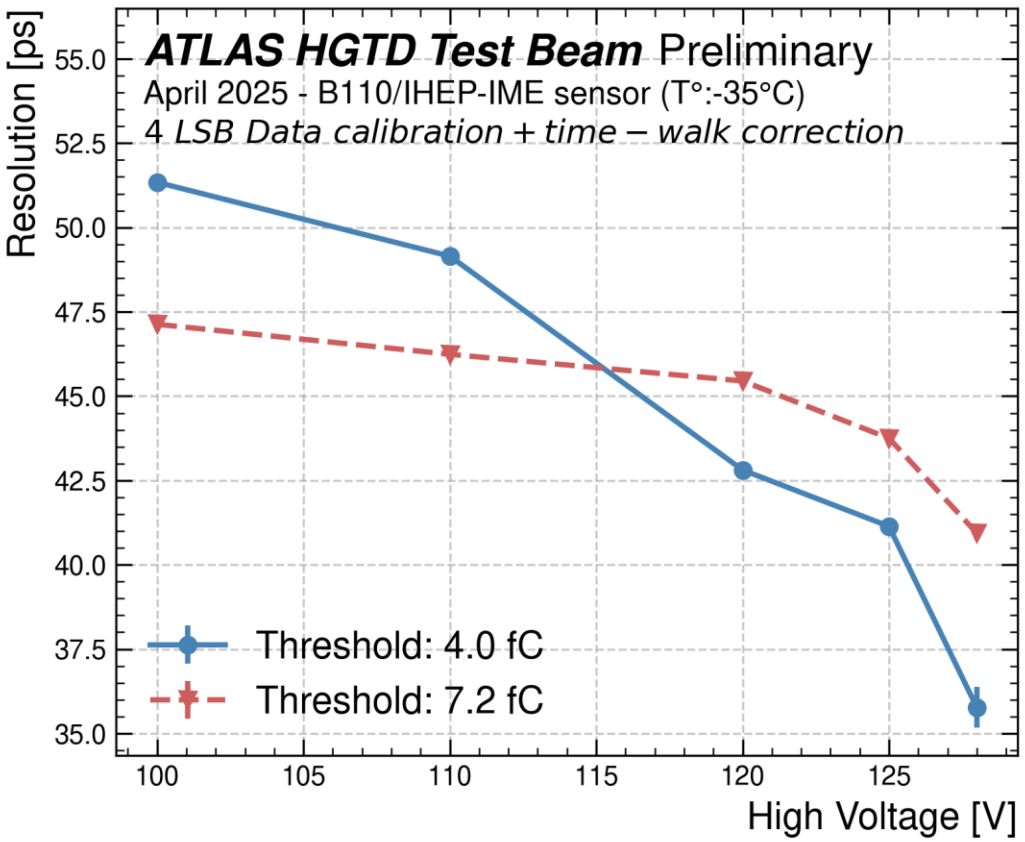
The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

RESOLUTION PERFORMANCE

HYBRIDS RESULTS

- **Sub 40 ps reached for hybrids (ASIC+sensor)**
  - For ~16 different pixels

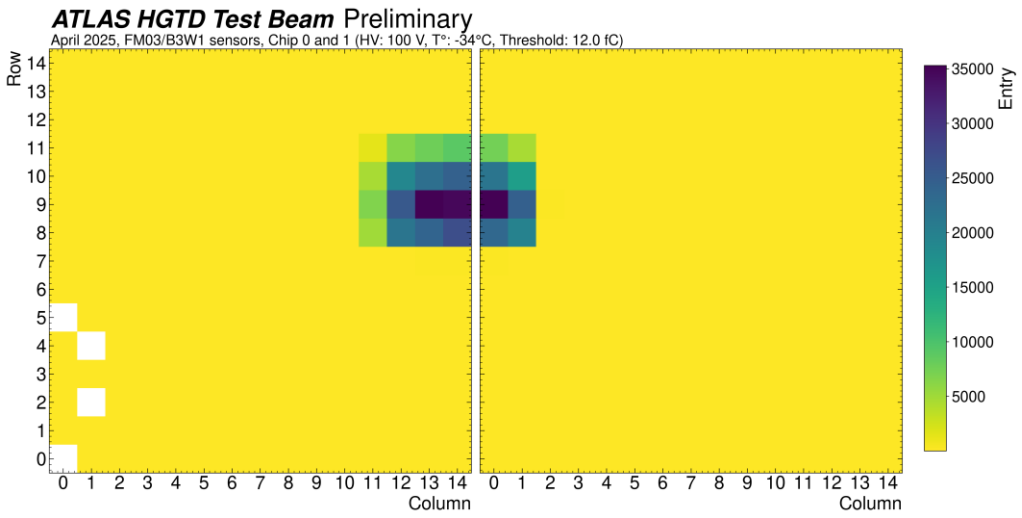




Excellent performance well below the 50 ps requirement

MODULES RESULTS

- **Good performance obtained with modules (1 module = 2 hybrids)**
  - Additional characterizations are ongoing

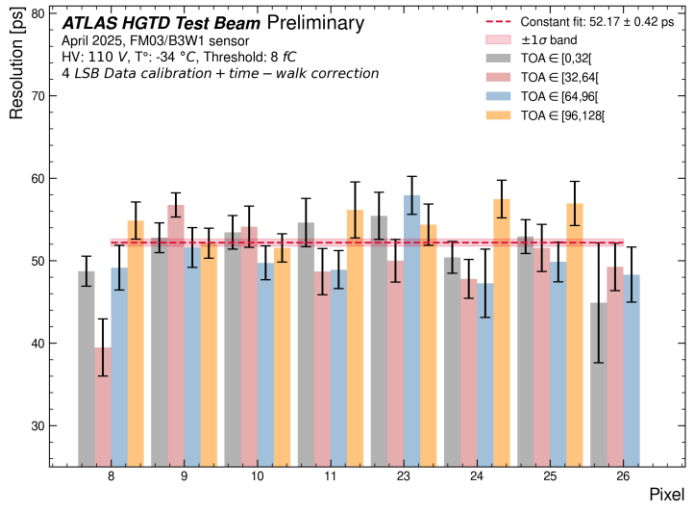


- **Sub 50 ps have been reached**
  - Bad clock jitter of about 20 ps

~4 ps to remove on those values

  - The expected 40 MHz clock is assumed to have negligible contribution

52.2±0.4 ps
4 ps to be substracted



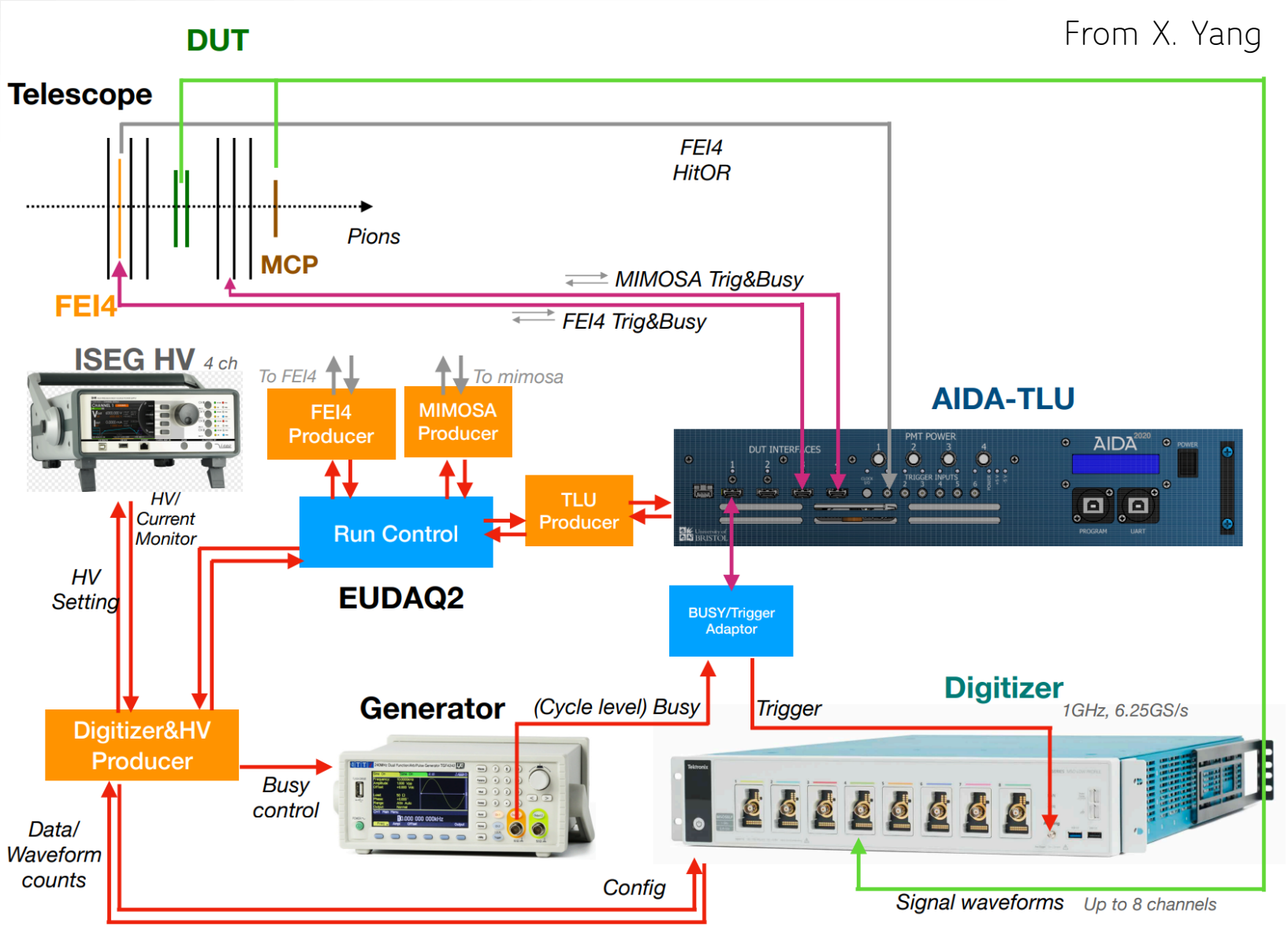
CONCLUSION

- **Sub 40 ps was reached for hybrids**
- **Sub 50 ps resolution obtained on modules**
- **Some effects are investigated to improve further the performance**
  - Differential non-linearity of TOA TDCs
- **Ongoing efforts**
  - Improving the data acquisition: Acquiring more and more data
  - 1st setup with 3 chips during last TB campaign
  - Complete readout with the nominal DAQ (Felix)

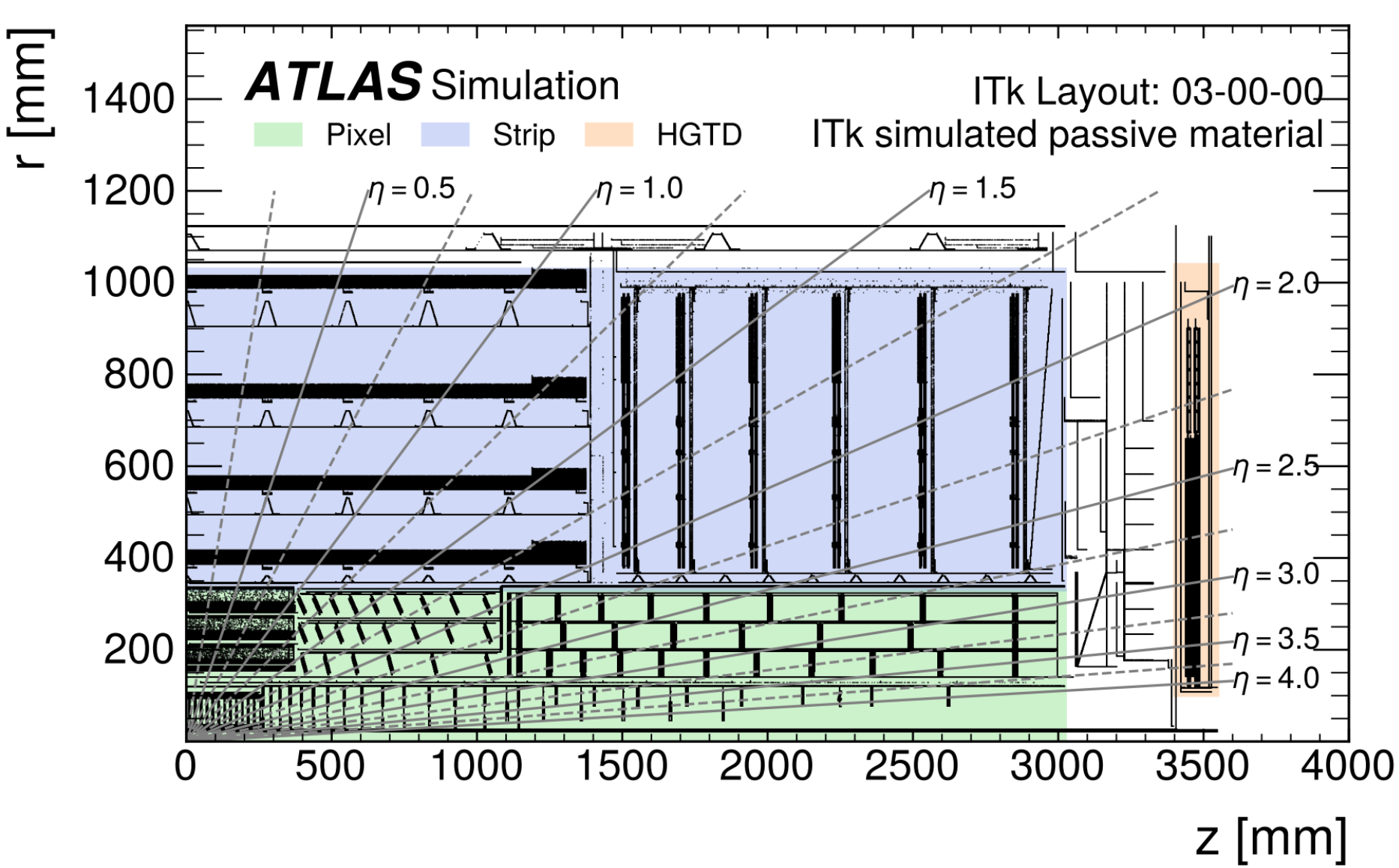
BACKUP

DAQ SETUP

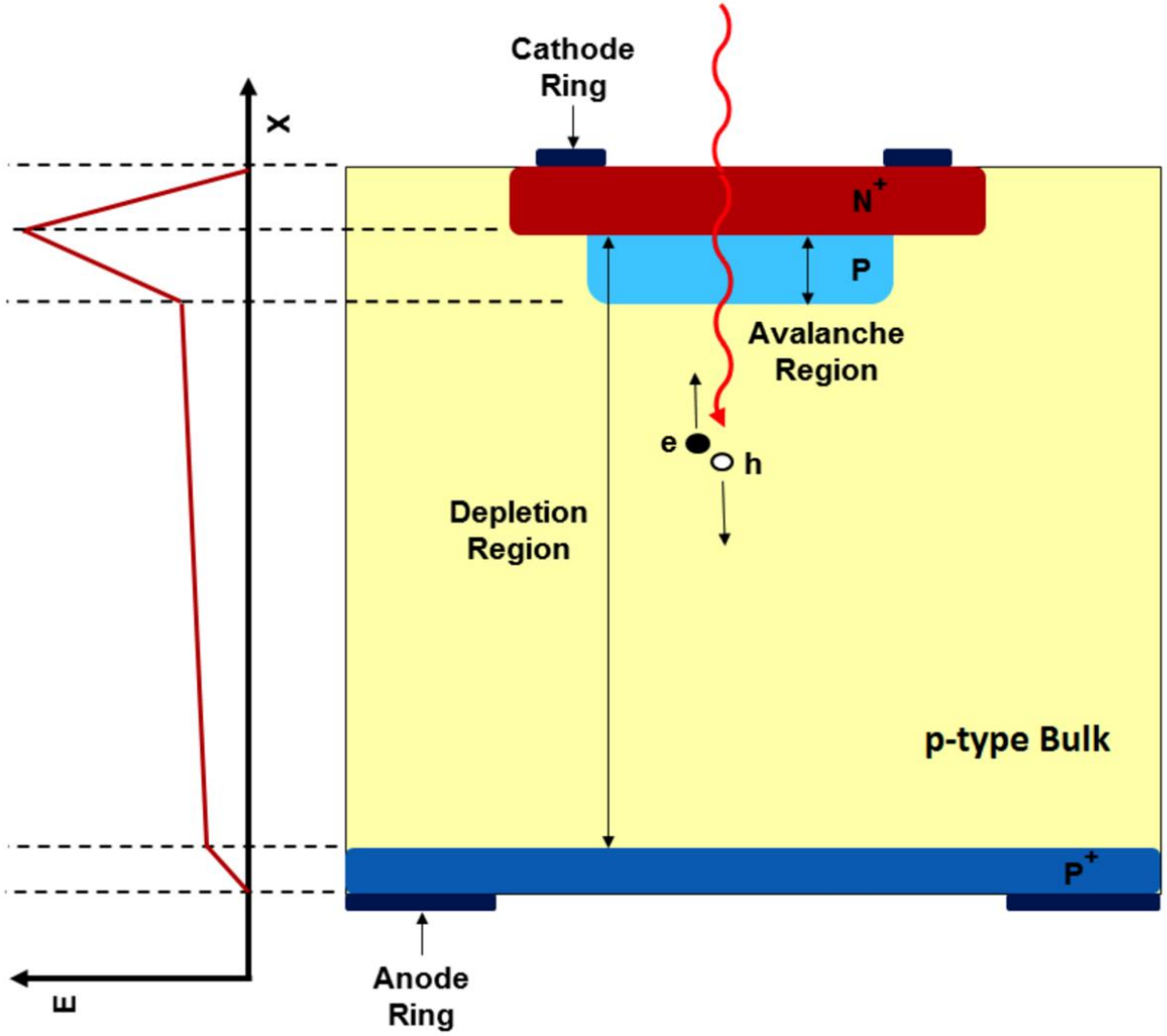
From X. Yang



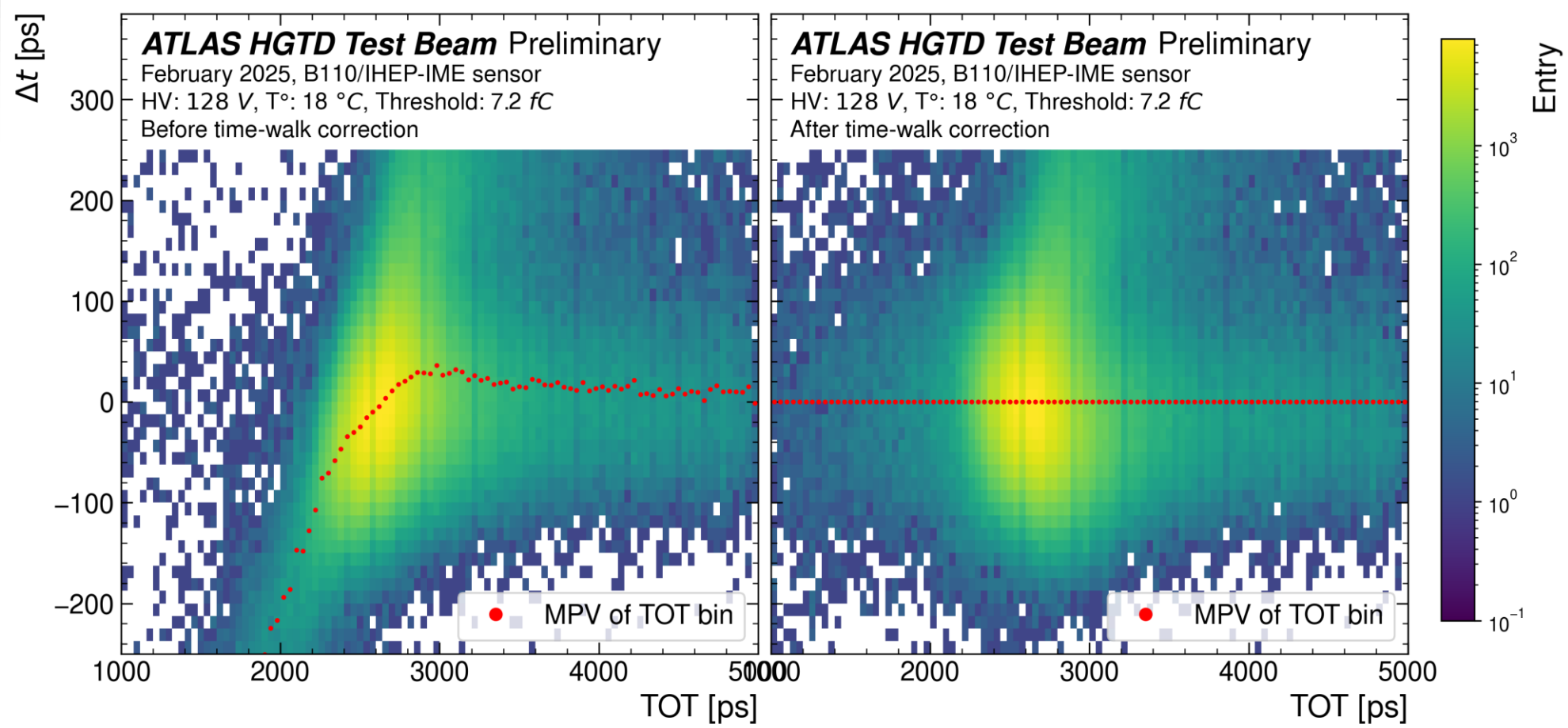
INNER DETECTORS POSITION



LGAD SENSOR


Cathode
Ring
x
N+
P
Avalanche
Region
e
h
Depletion
Region
p-type Bulk
P+
Anode
Ring
E

STEP V: TIME-WALK CORRECTION



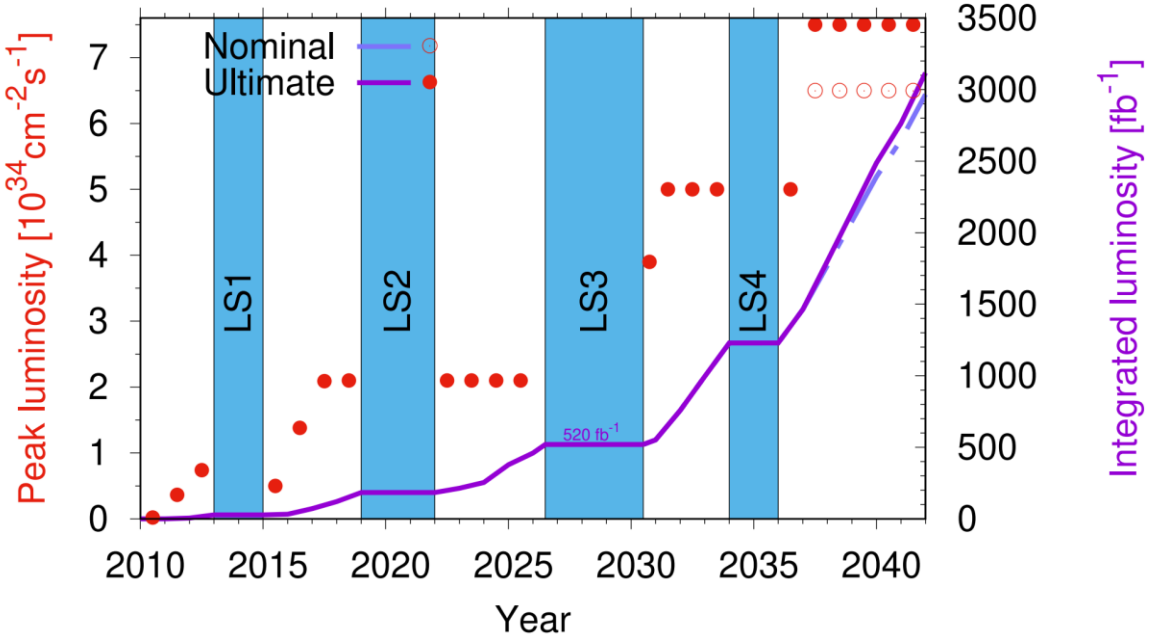
Affect the accuracy of TOA and must be corrected

THE HIGH LUMINOSITY ERA

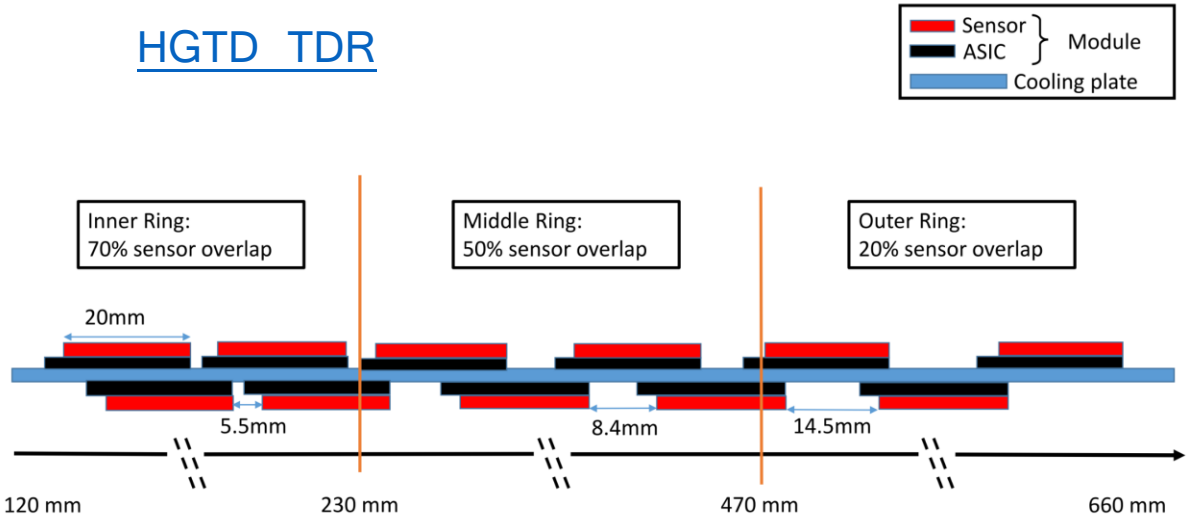
- **Increasing by 6 the amount of data**

ATL-UPGRADE-PUB-2025-001

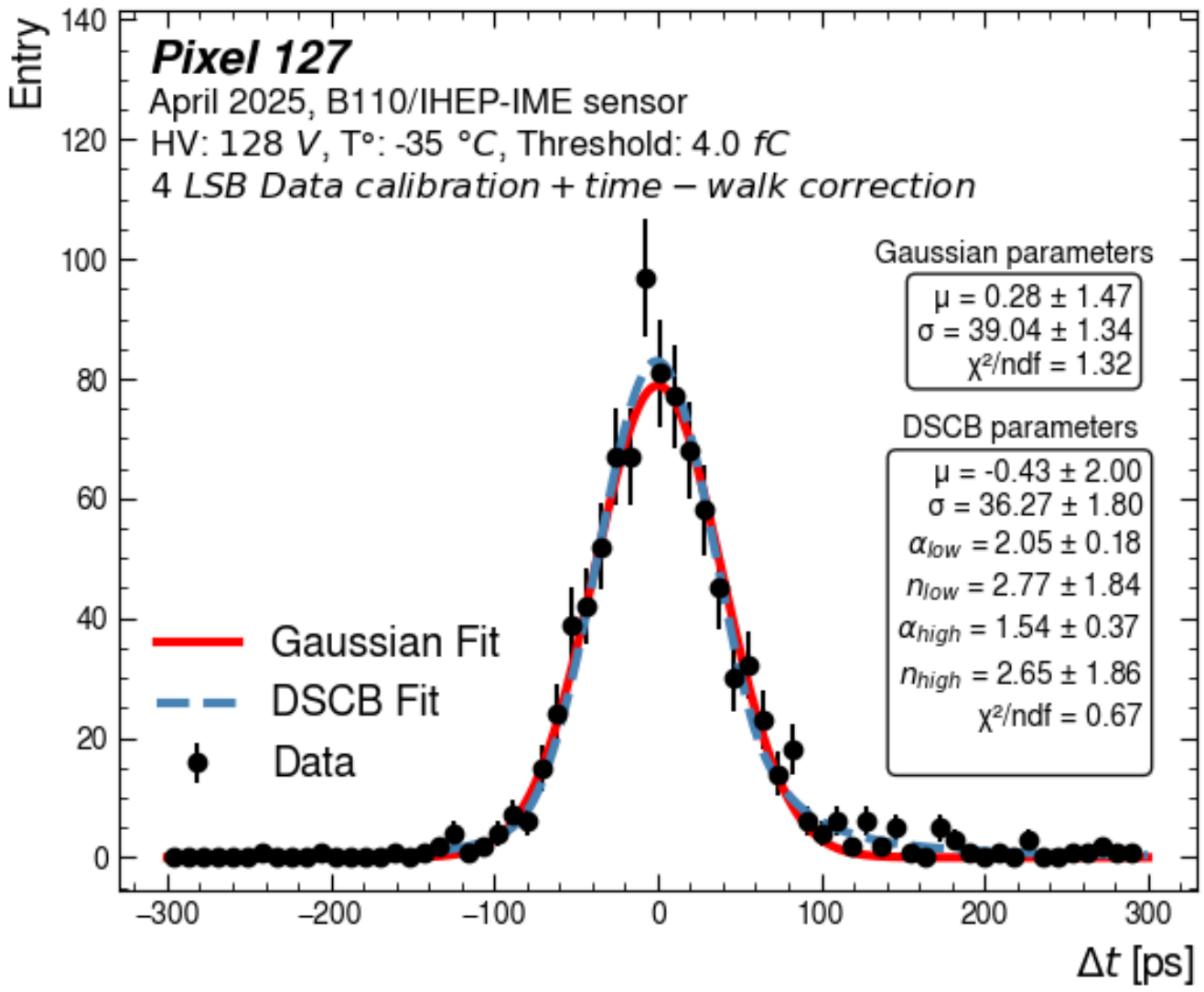
- **Increasing overall the pile-up**



HGTD TDR



DSCB *vs* GAUSSIAN FIT

- **Both are generally compatible**
  - Gaussian not model well the tails
    → better χ^2 with DSCB
  - Distribution should be symmetrized using tracking

- **Difference of $\mathcal{O}(1\,ps)$**