



Luminosity Measurement with the ATLAS High-Granularity Timing Detector (HGTD) at HL-LHC



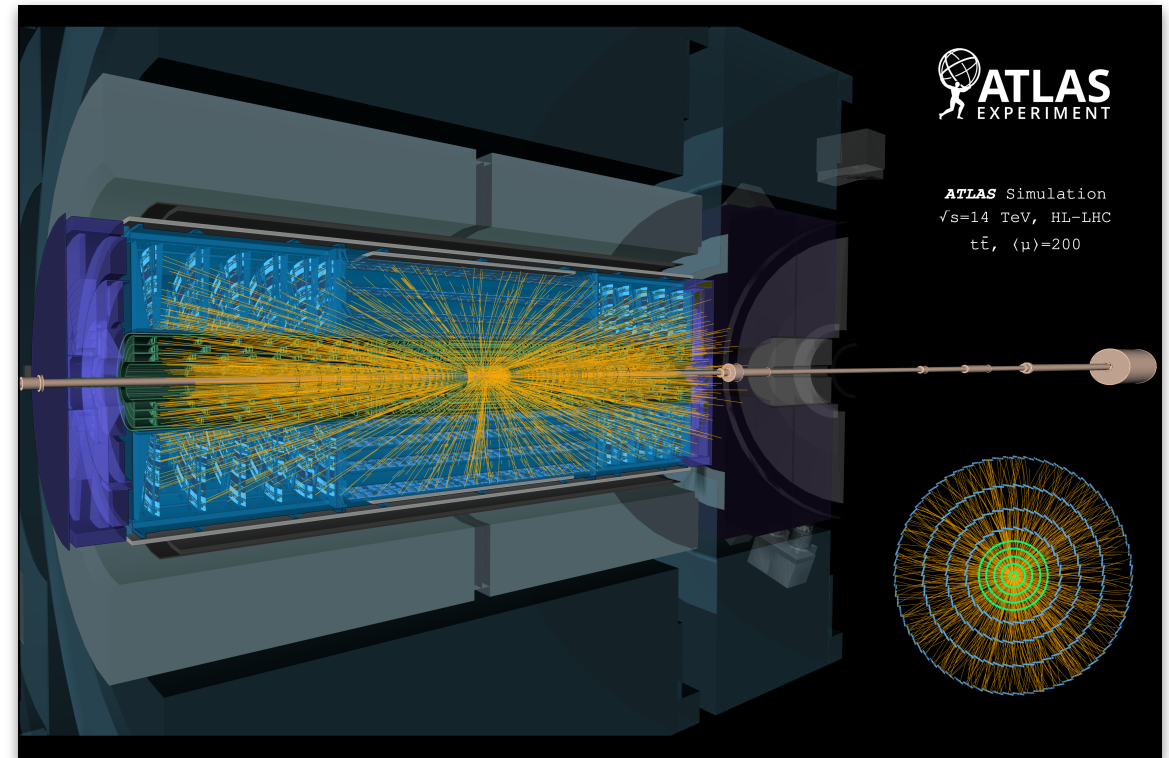
Magdalena Vande Voorde

September 17, 2026

Partikeldagarna, Lund

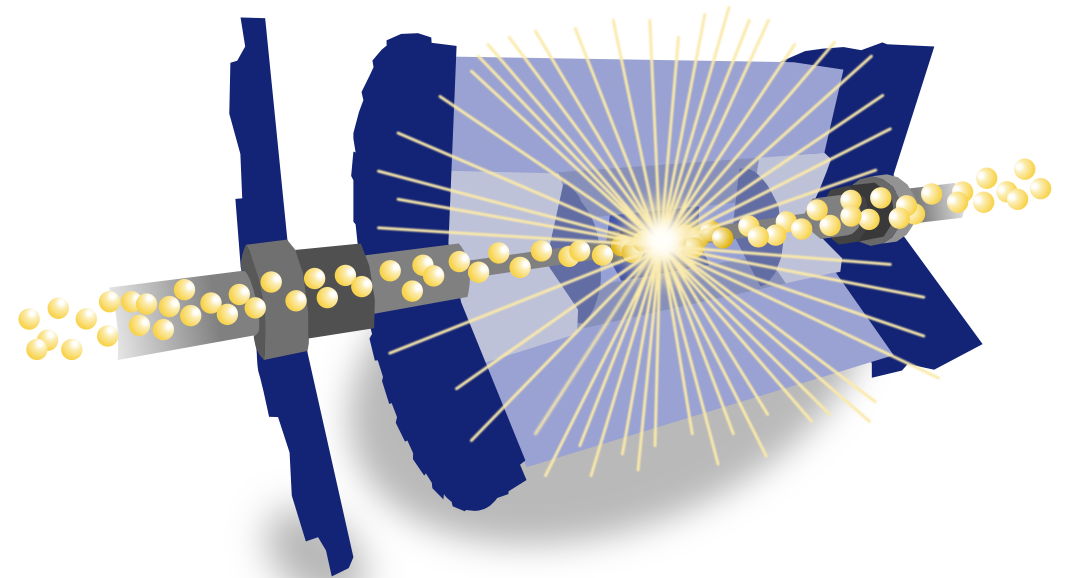
LHC enters the high luminosity era

- Run 3 of Large Hadron Collider (LHC) ended in June this year
 - High Luminosity (HL)-LHC will start in 2030
 - ATLAS enters the final phase of their phase-II upgrades
- HL-LHC will deliver an increase of instantaneous luminosity $\rightarrow \sim \text{x6}$ more integrated luminosity compared to current dataset from LHC
 - Great for high precision measurement
 - A luminosity precision of 1% assumed to reach physics goals of ATLAS
- But comes with challenges...
 - Higher pileup of up to 140-200 interactions per bunch crossing
 - Much higher detector activity $\rightarrow$ higher radiation damage
- How will we reach a $<1\%$ luminosity uncertainty in these challenging conditions?

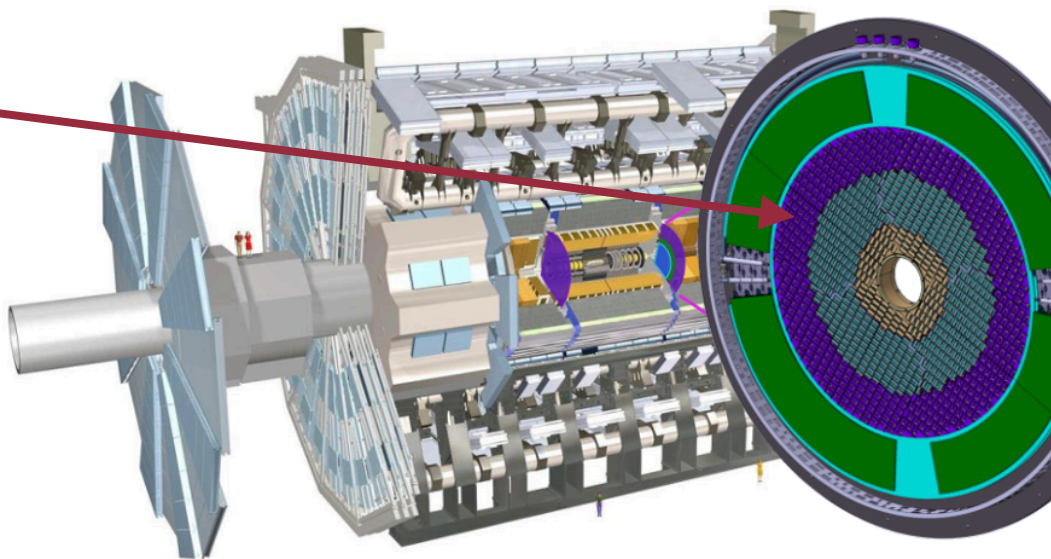


Luminosity at HL-LHC

- To measure luminosity in ATLAS we determine the number of inelastic pp collisions (=pileup)
 - Any data source (more or less) linear with pileup can be used to determine the luminosity
 - e.g hit or event counting in dedicated luminosity detectors, number of tracks, current drawn, etc.
 - Each method is calibrated in dedicated van der Meer scans at low pileup (~ 1) and the absolute luminosity is then extrapolated to physics conditions (LHC ~ 40 -50, HL-LHC ~ 140 -200)
- Luminosity measurement at the HL-LHC will follow the same principles but consider the challenges
 - Longer extrapolation from vdM to physics conditions
 - need precise calibration transfer to high pileup
 - More radiation
 - continuously assess and understand the stability of each method with time and radiation dose
 - Overall, need several robust and complementary luminosity detectors/methods to reach $<1\%$ luminosity uncertainty



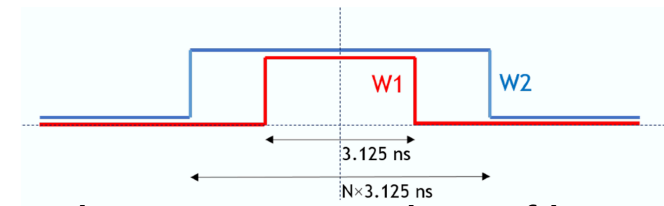
High Granularity Timing Detector (HGTD)

- HGTD has 2 double sided disks on each side, located about 3.5 meters from the interaction point
 - 2m diameter, 12 cm thick
 - Covers forward region $2.4 < |\eta| < 4.0$
 - $2.4 < |\eta| < 2.8$ for luminosity readout (blue ring)
 - Built of 15x15 Low Gain Avalanche Diodes (LGAD) sensors
 - Bump-bonded to an ASIC, ATLAS LGAD Timing Integrated ReadOut Chip (ALTIROC)
 - 2 hybrids (LGAD + ALTIROC) per module
 - In total 8054 modules (~ 3.6 M readout channels)
 - 4256 modules used for luminosity readout
- 
- The image shows a 3D perspective view of the ATLAS High Granularity Timing Detector (HGTD). It is a long, cylindrical structure composed of many modules. A red arrow points from the text '2.4 < |η| < 2.8 for luminosity readout (blue ring)' to a specific region on the right-hand disk. This region is highlighted in blue in the circular cross-section view. The cross-section shows a central hole, followed by a green ring, then a blue ring (the luminosity readout region), and an outer green ring. The main 3D view shows the detector's position relative to the interaction point, which is represented by a small red dot at the end of a long tube.
- HGTD will be able to separate collisions in time
 - Timing resolution of 30-50 ps per track (bunch spread ~ 180 ps)
 - With low occupancy (due to high granularity) and fast signals HGTD is also well-suited as a luminosity detector
 - Average number of hits expected to be proportional to the luminosity
 - Will be able to operate at full pileup range, with bunch-to-bunch luminosity measurement

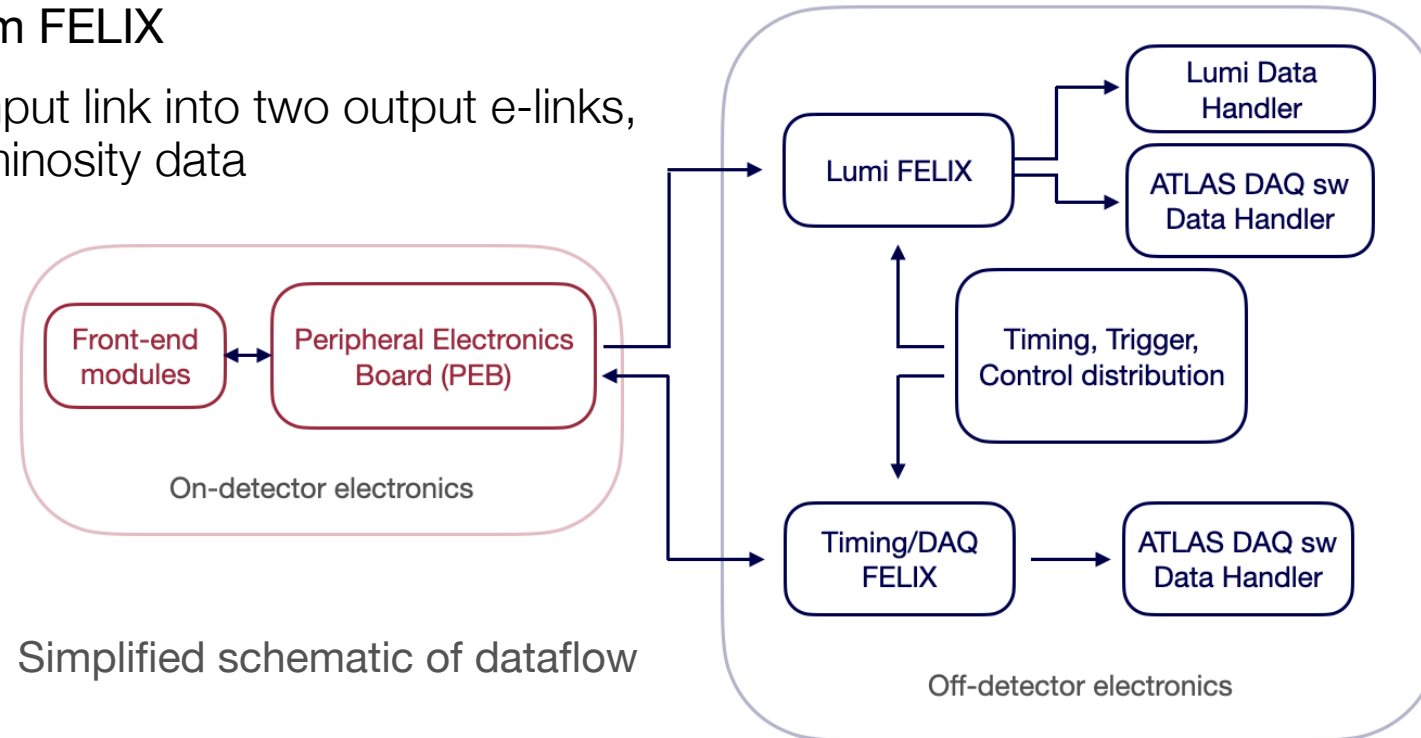
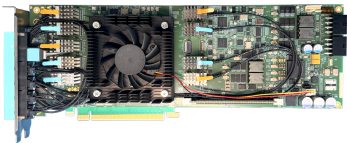
Readout architecture and luminosity data stream

- Raw lumi data is sent from ALTIROC for each bunch crossing slot
 - Occupancy (number of hits) in two time windows - a central time window for measurement (3.125 ns), a larger sideband window for background monitoring ($N \times 3.125$ ns)
- Processed lumi data from FELIX
 - Split each physical input link into two output e-links, with two different luminosity data

Central (W1) and sideband (W2) time windows



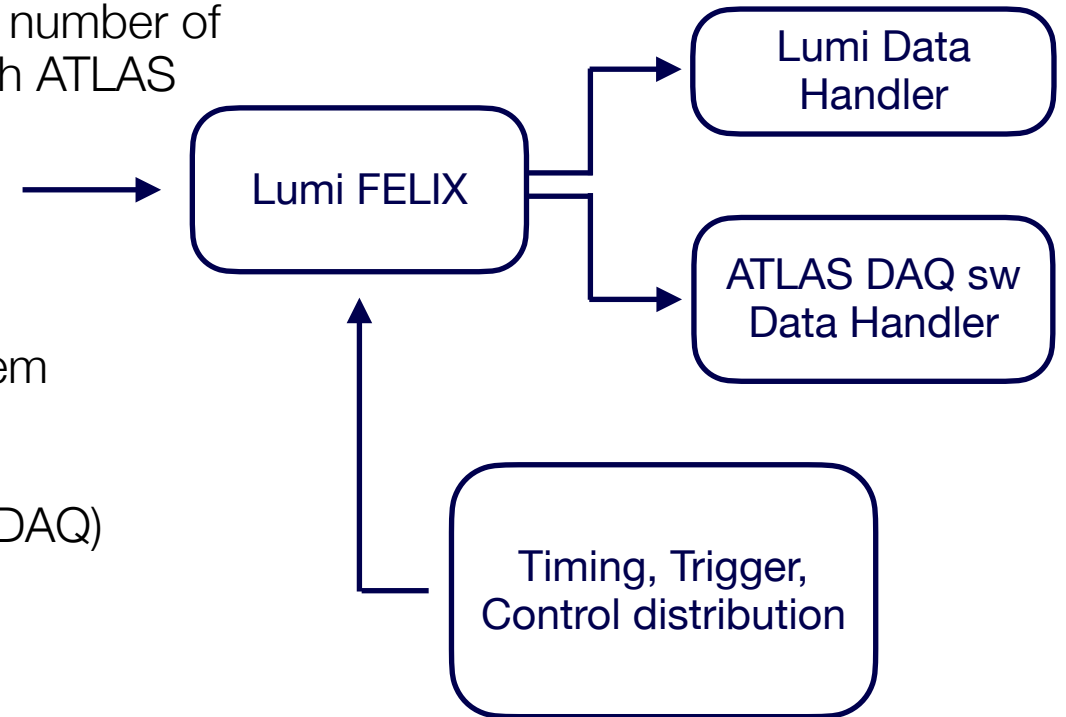
FELIX - ATLAS phase-II readout cards used by all sub-systems



Simplified schematic of dataflow

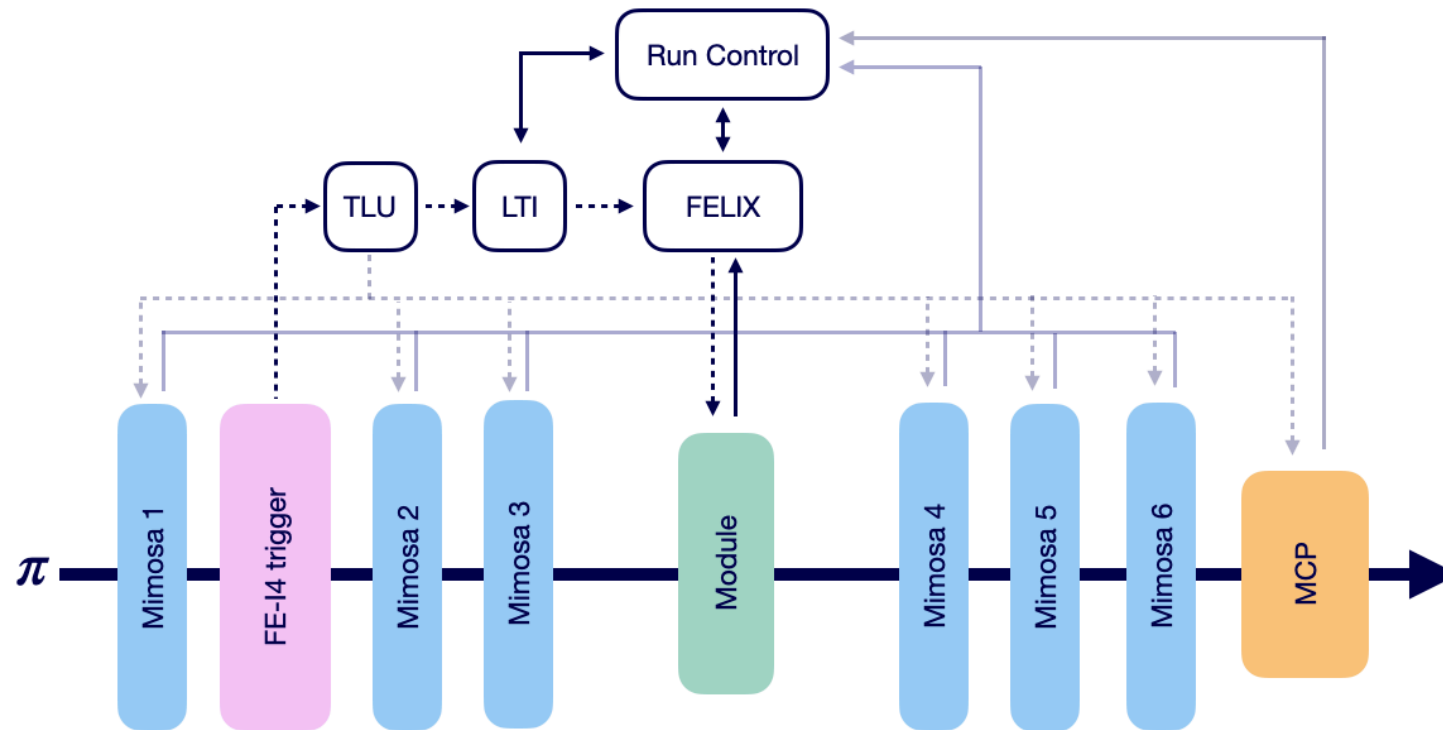
Readout architecture and luminosity data stream

- Aggregated data - for luminosity measurement:
 - Occupancy readings aggregated over #LHC turns, up to ~ 100 turns
 - Reduction from 40MHz to ~ 100 Hz
 - Further processed by dedicated sw that aggregates the number of hits within certain time block boundaries, and stored with ATLAS luminosity raw data
- Per-event data - for stability checks and debugging:
 - Occupancy readings for triggered events
 - Raw data buffered until triggers received from TTC system
 - Reduction from 40MHz to ~ 1 MHz
 - Further processed with central ATLAS data acquisition (DAQ) system, stored with the rest of ATLAS raw data



HGTD testbeam July 2026

- Several testbeams done to test hit efficiency and timing performance in sensors, hybrids, and modules
 - Done with dedicated testbeam DAQ and readout, November 2025 first try with FELIX based readout
- Testbeam at SPS in July first time with ATLAS phase-II equipment for trigger/clock distribution (LTI - Local Trigger Interface), chip calibration with FELIX, and full end-to-end luminosity readout!



Testbeam at SPS with

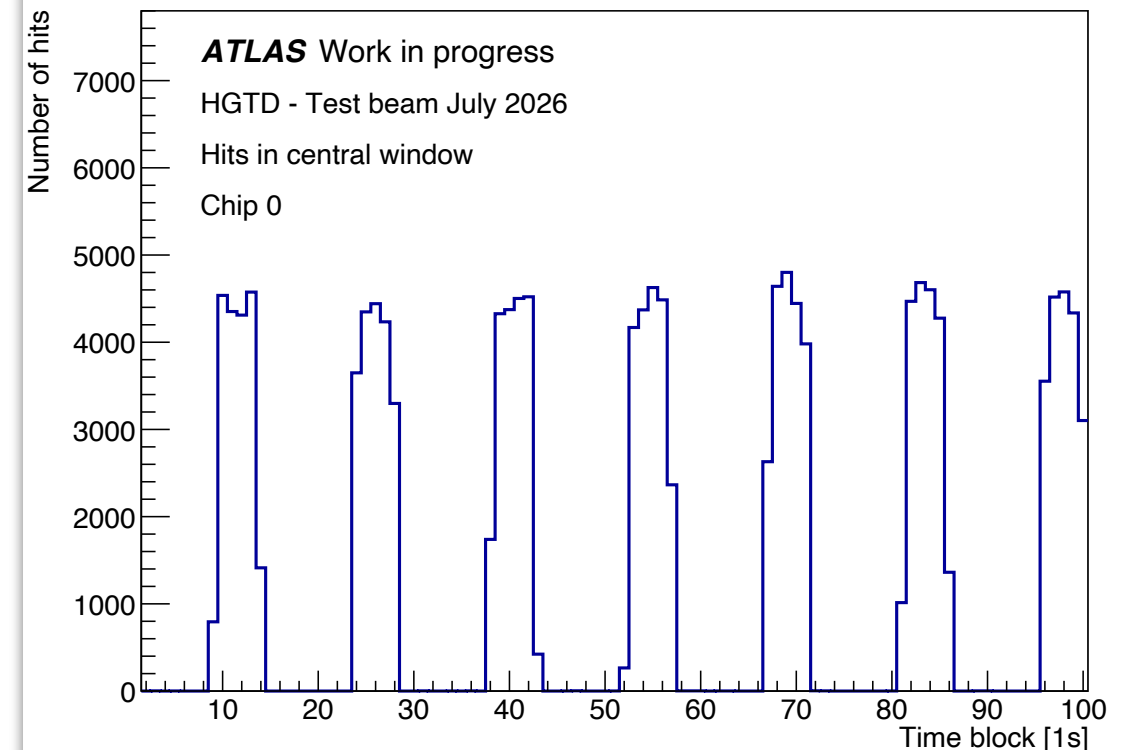
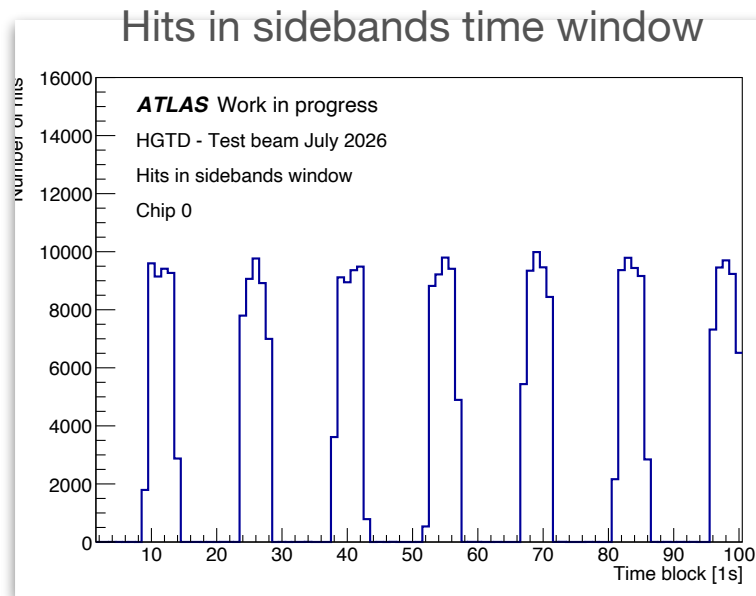
- 120 GeV pion beam
- 6 Mimosa planes for tracking readout
- Micro-channel plate (MCP) for granular timing reference
- FE-I4 reference plane for triggering
- Trigger Logic Unit (TLU) for trigger generation

Example results - aggregated luminosity data - chip 0

- Hits aggregated within (user defined) time blocks of 1s
- Hits both in the central time window and sidebands window
 - Sideband hits $\sim$ x2 central hits
- The spill pattern from SPS is clearly visible!
 - About 5 s spills every $\sim$ 14th second

Similar results for chip 1, see [backup](#)

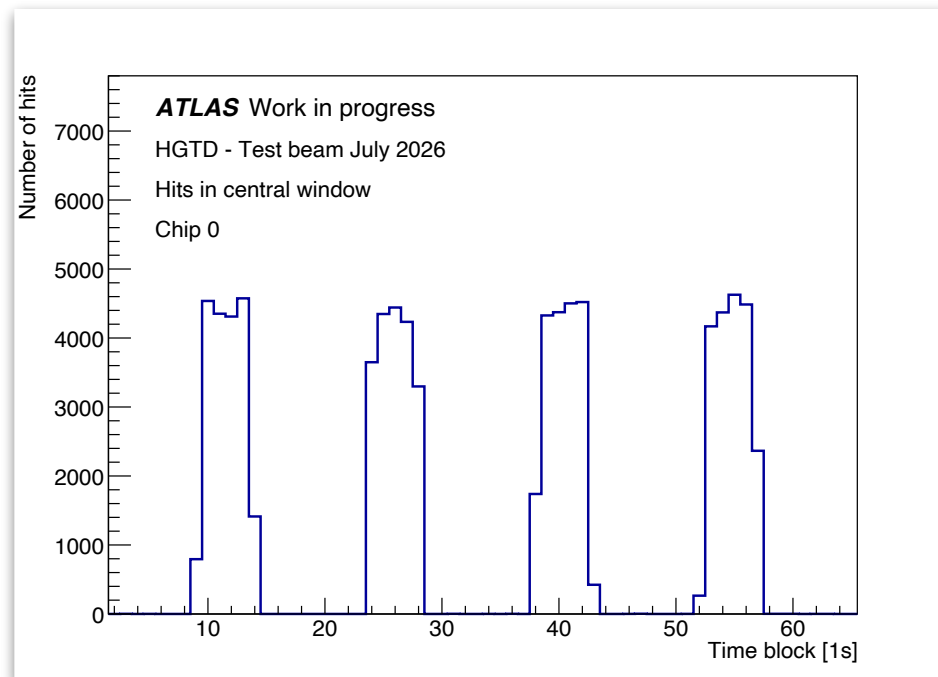
Hits in central time window



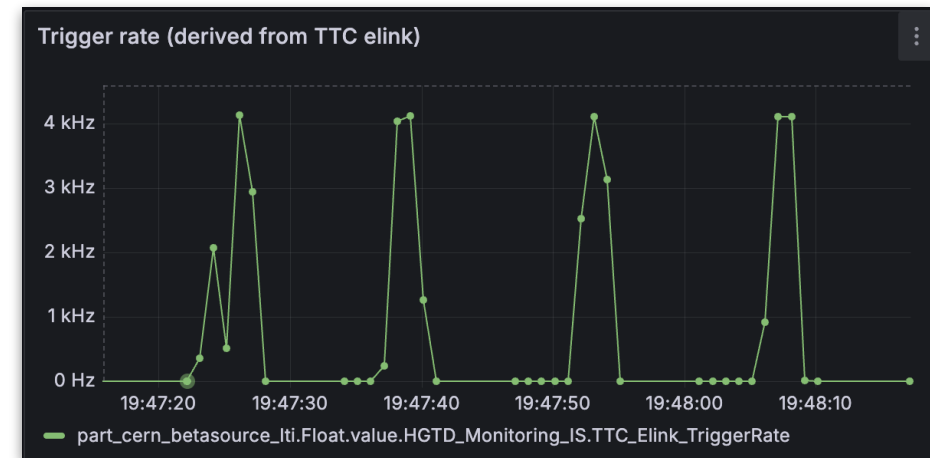
Example results - aggregated luminosity data

- Trigger rate available in our monitoring system
- Comparing start of run - we see spill pattern match between the trigger rate and the luminosity data
- Indicates luminosity readout works well and as expected!

Hits in central time window

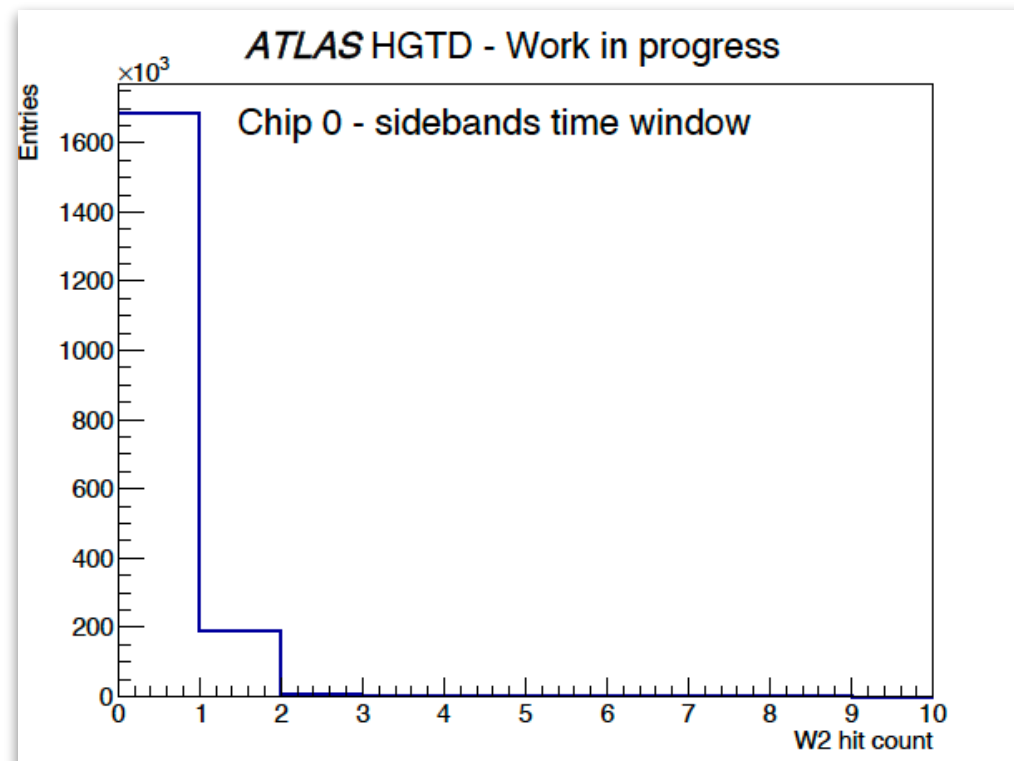
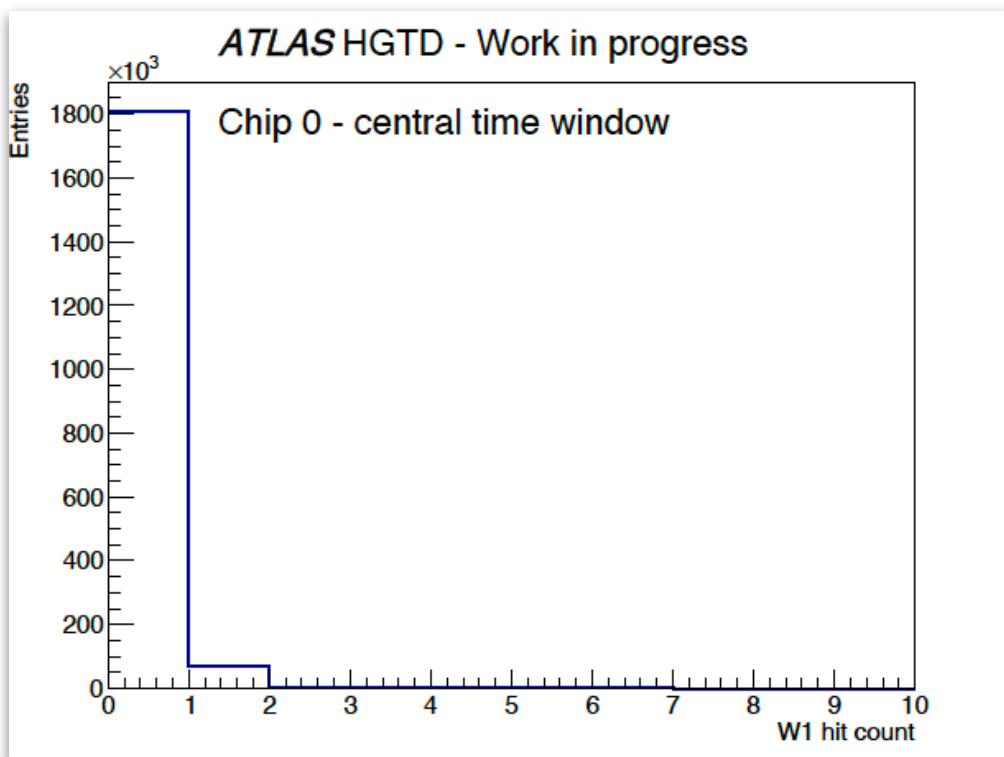


Trigger rate



Example results - per event lumi data

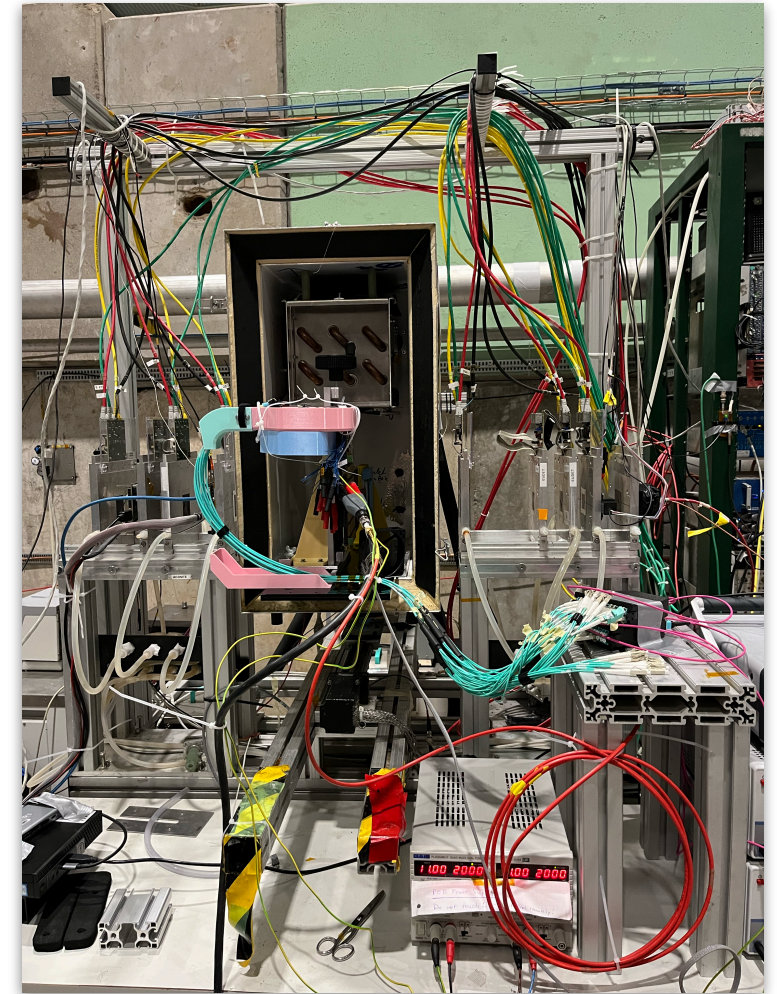
- Data also seen in the per event data stream!
- Work ongoing to properly compare the per event luminosity data with the timing data and the rest of the testbeam readout (Mimosa, MCP, FE-I4)



Conclusion and summary

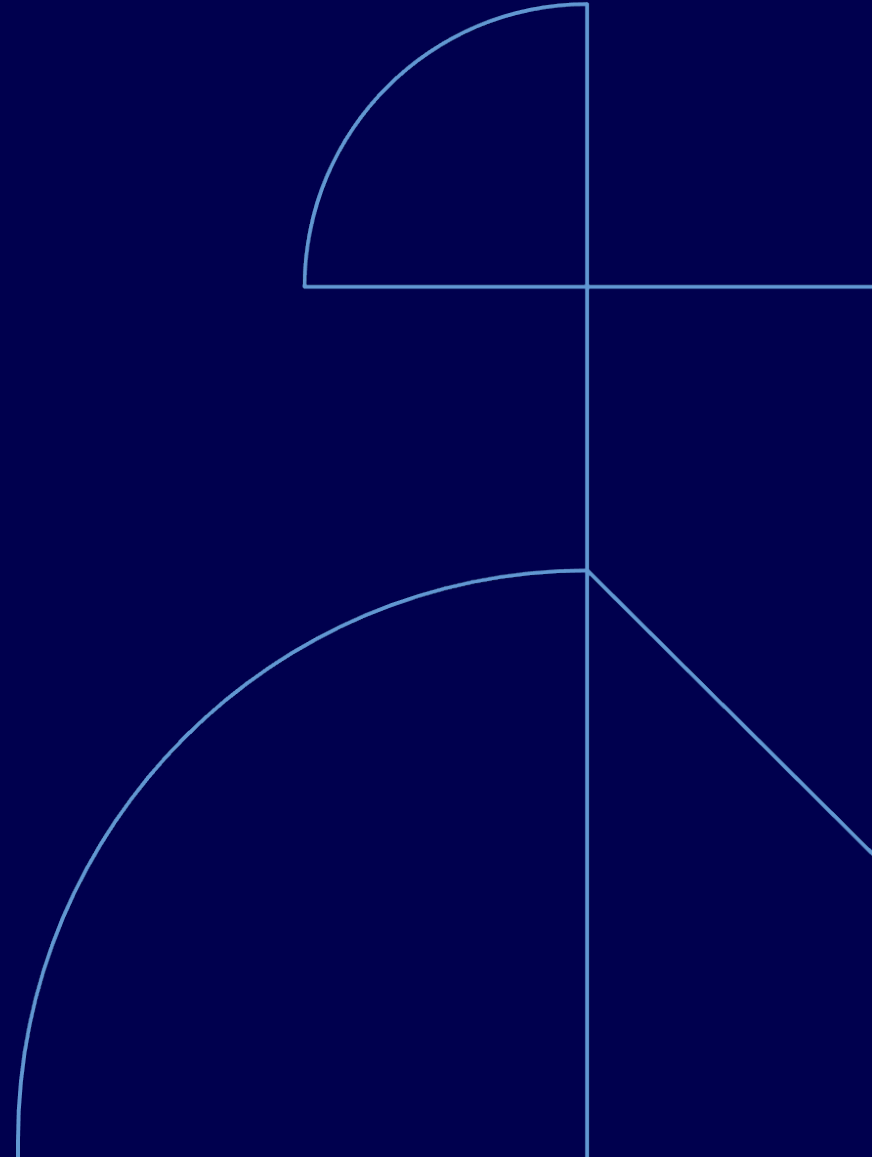
- ATLAS has a $<1\%$ luminosity precision goal set for HL-LHC
- HGTD is a timing and luminosity detector able to tackle this target
 - Several years of R&D, now in production phase of detector parts and modules
- Latest testbeam first test with luminosity readout
 - Recorded both aggregated and per event luminosity data, demonstrates readout path works end-to-end!
- Next steps
 - Further study of the testbeam data
 - Test scalability of system with larger setup (demonstrator setups at CERN with ~ 100 ASICs)

Thank you for your attention!



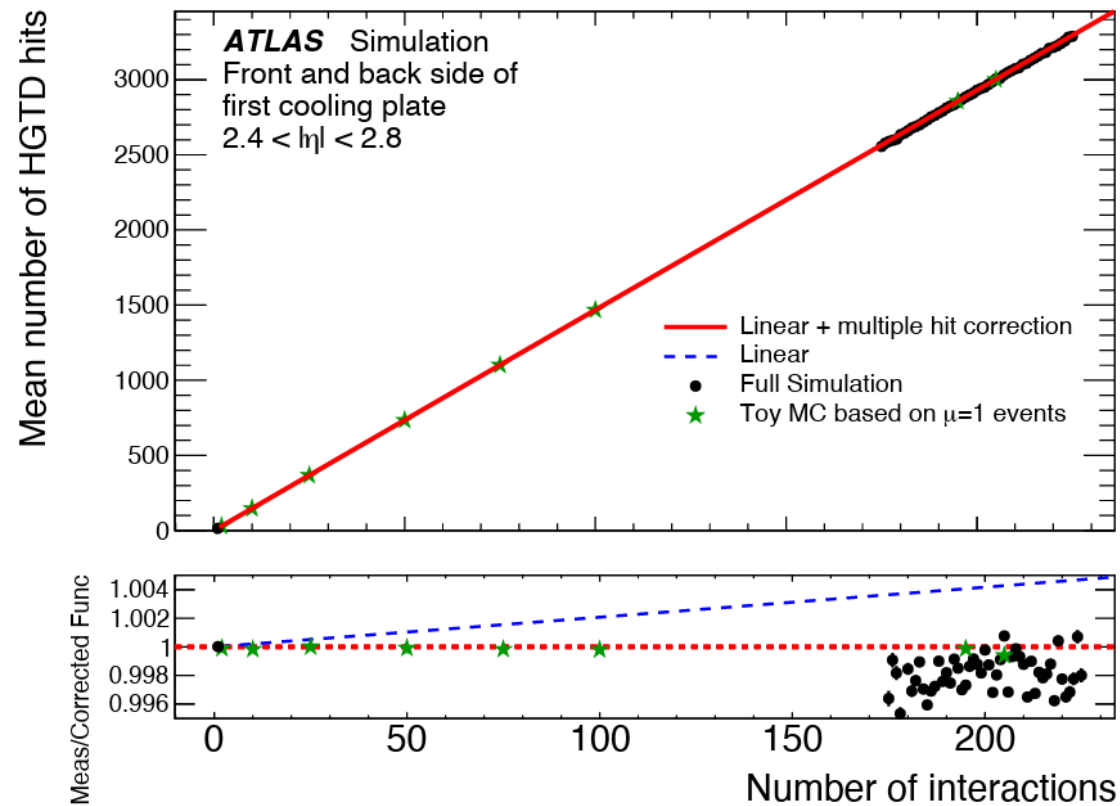


Backup



HGTD linearity with pileup

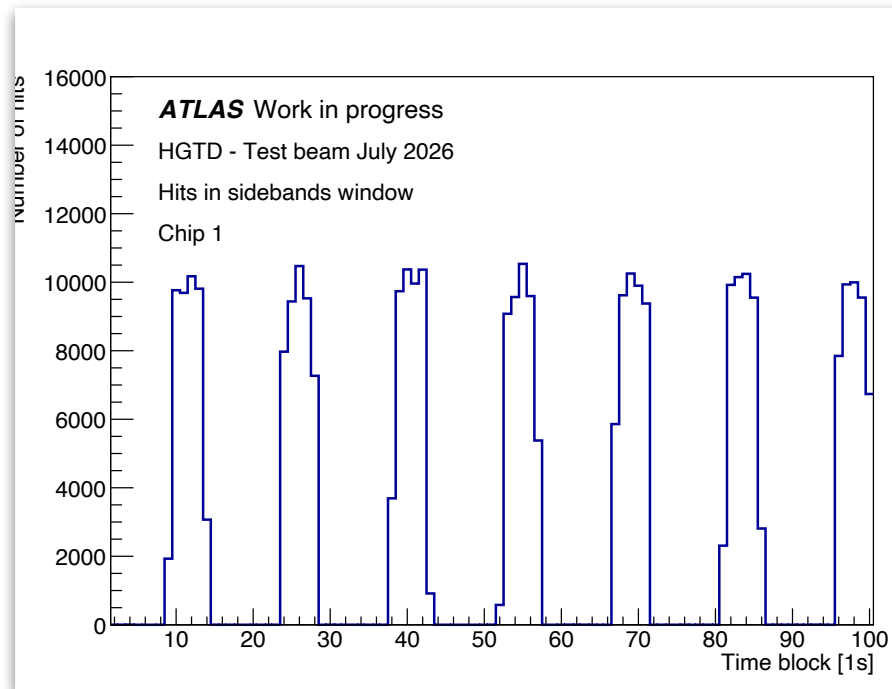
- From MC simulation
- In HGTD Technical Design Report
- Multiple hit correction = when 2 (or more) particles pass through the same sensor



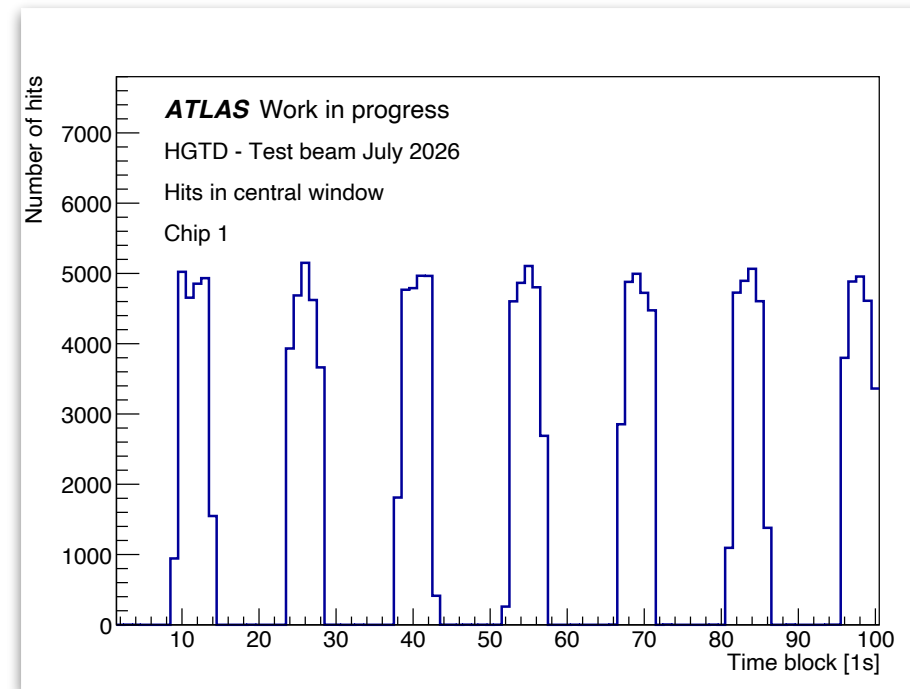
Example results - aggregated luminosity data - chip 1

- Similar results for second chip in the same module
 - Clear spill pattern
 - Sideband hits $\sim$ x2 central hits

Hits in sidebands time window

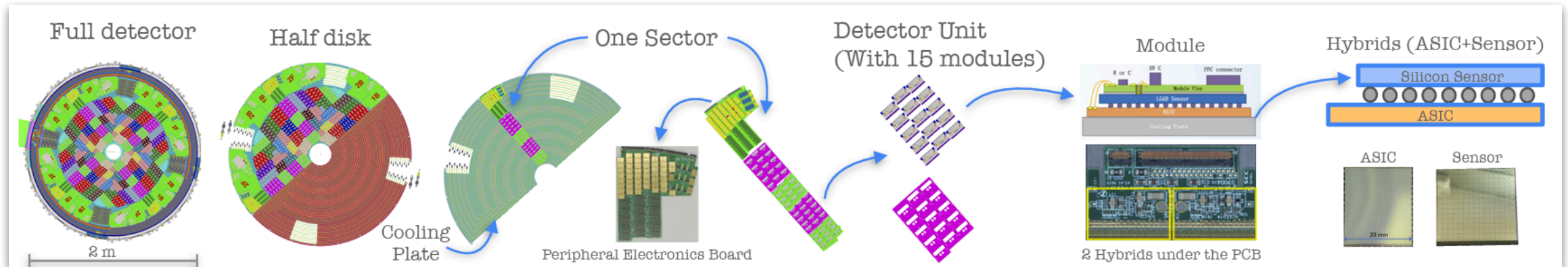


Hits in central time window



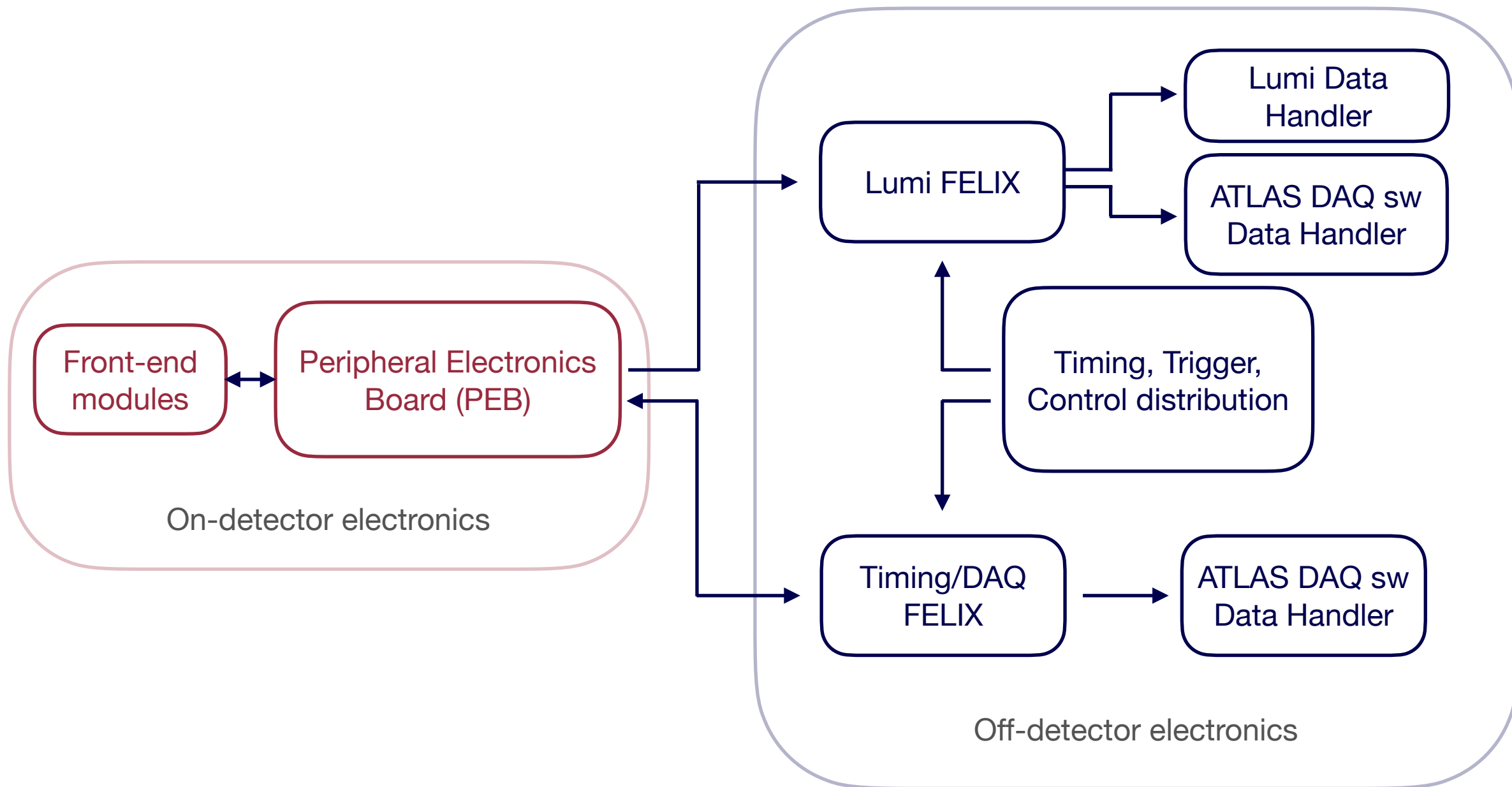
Production status

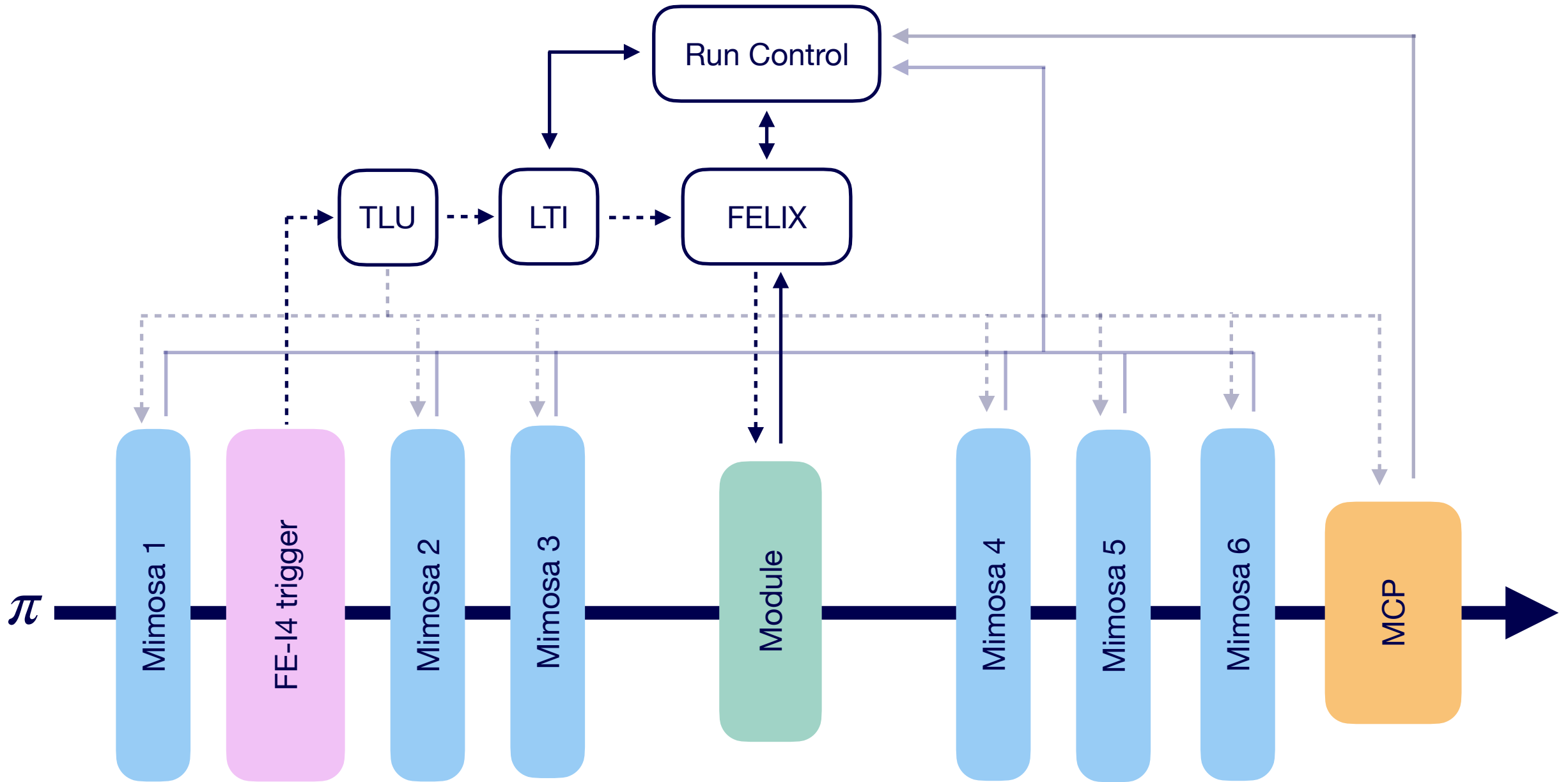
- ~ 60% of sensors fabricated
- Several sites performing quality tests to ensure sensors are working before hybridization
- Module assembly and detector unit construction ongoing at five sites
 - Every module is tested on powering, ASIC, communication, calibration and noise, several times before installation



From HGTD ICHEP talk by M. Leite

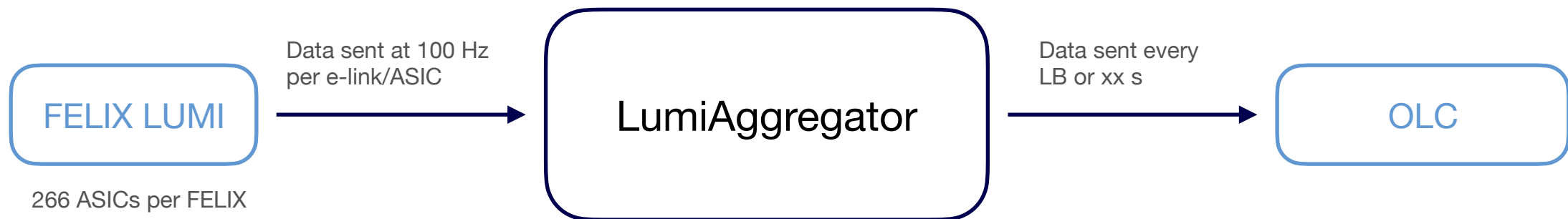
Dataflow schematic



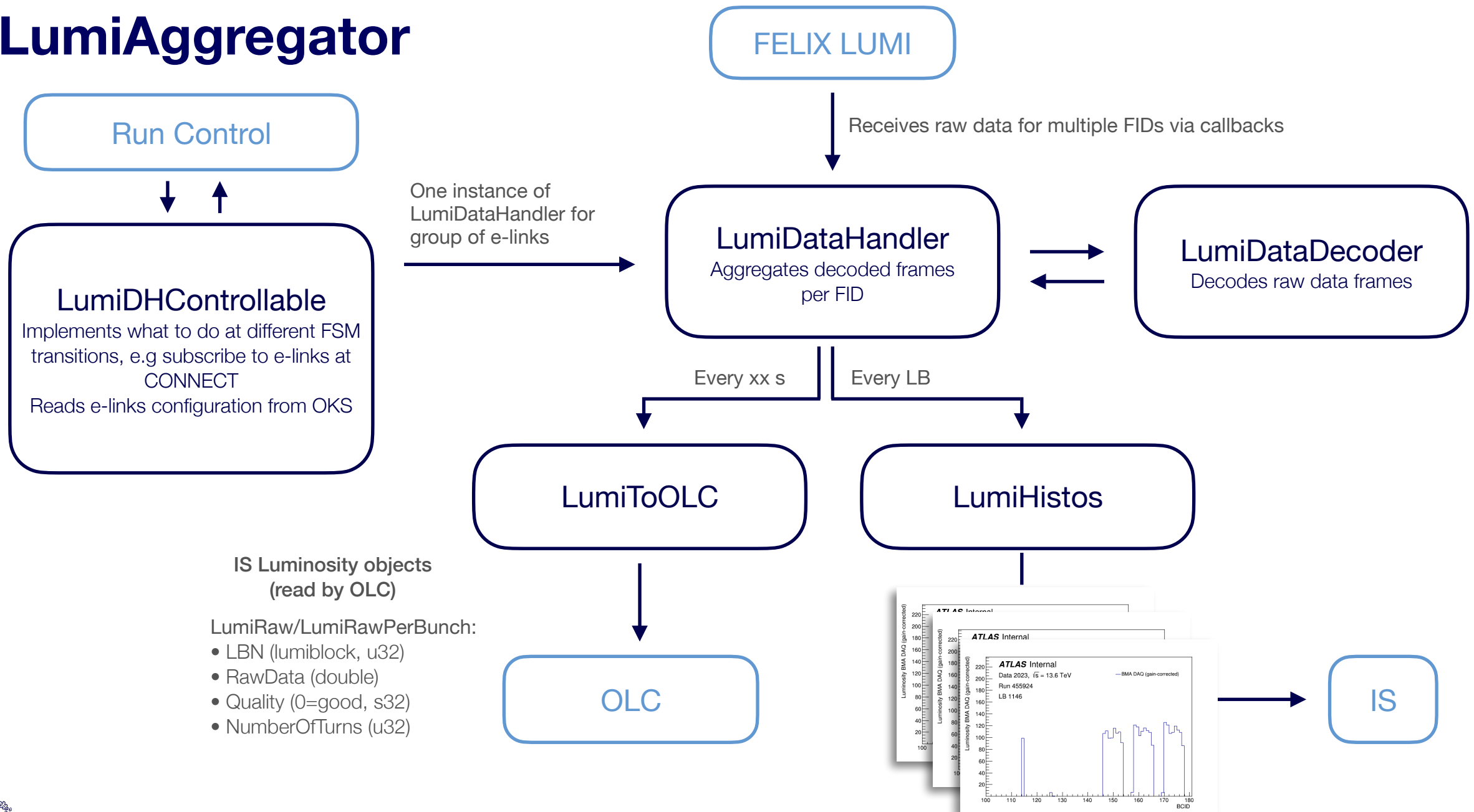


Goal of luminosity data handler (LumiAggregator)

- The LumiAggregator process the aggregated luminosity data from FELIX, it should
 - Subscribe to a configurable number of e-links publishing aggregated lumi data
 - Further aggregates the occupancy levels per BCID up to luminosity block (LB) boundaries (time blocks)
 - Record average occupancy values per channel and per BCID
 - Allow for data quality monitoring
- LumiAggregator will run on the lumi FELIX hosts, in parallel to the PerEvent SWROD (common ATLAS DAQ Data Handler)
- Will not be connected to regular dataflow, but publish occupancy values to the Online Luminosity Calculator (OLC)
- Will run either as part of the ATLAS partition or standalone (to provide luminosity information when ATLAS is not running)
- Aggregated -> Dataframes of 14.3 kB sent at 100Hz for each e-link $(266 \text{ (Altirocs per FELIX cards)} * 2 \text{ (FELIX cards per server)} * 14.3 \text{ kB (per frame)} * 100 \text{ Hz} = 760.76 \text{ MBps} = \mathbf{6.086 \text{ Gbps}}$ from one host)
- Per-event -> Dataframes of 48 bits sent at 1MHz for each e-link $(266 \text{ (Altirocs per FELIX cards)} * 2 \text{ (FELIX cards per server)} * 48 \text{ bits (per frame)} * 1 \text{ MHz} = 3.192 \text{ GBps} = \mathbf{25.54 \text{ Gbps}}$ from one host)

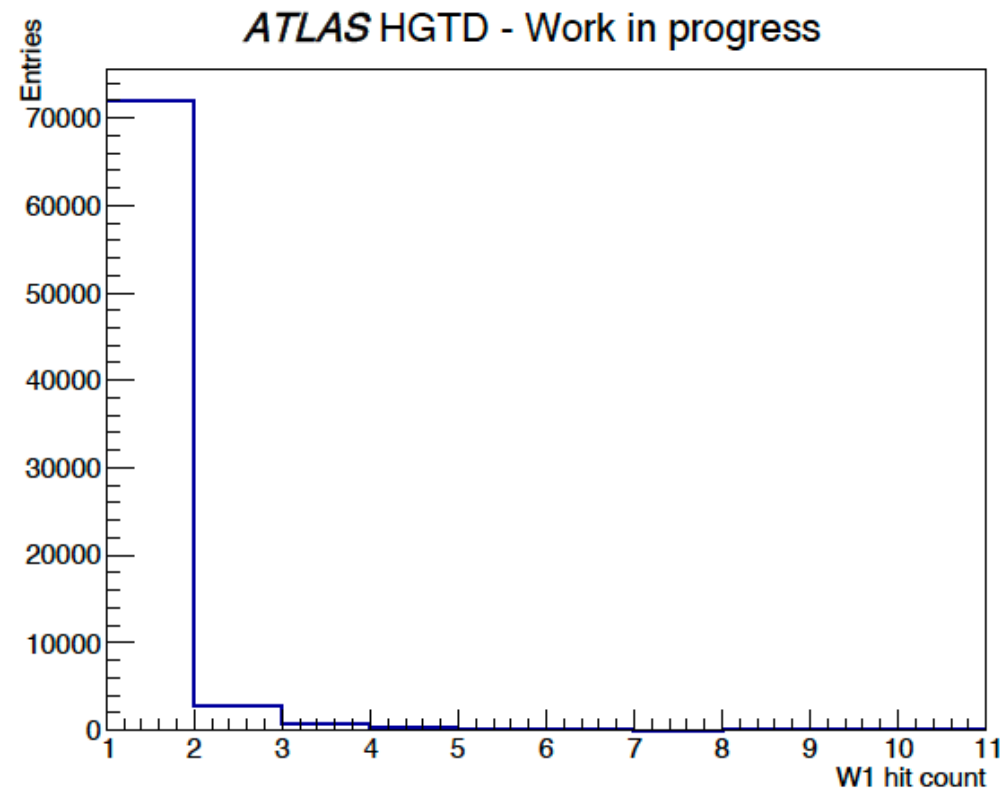


LumiAggregator



Zoom in per event data

- Hit count 1-11



Luminosity at LHC

- The luminosity is essentially a measure of the number of inelastic proton-proton collisions produced by the LHC at a given interaction point
- Luminosity measured from the inelastic pp collision rate

$$\bullet \quad \frac{dN_{inelastic}}{dt} = \mathcal{L}(t) \cdot \sigma_{inelastic} = \mu f_{rev}$$

$$\rightarrow \mathcal{L}_b = \frac{\mu f_{rev}}{\sigma_{inel}}$$

- Pileup μ cannot be measured directly, due to the limited coverage of the ATLAS detectors
- Instead we measure μ_{vis}

$$\bullet \quad \mathcal{L}_b = \frac{\mu f_{rev}}{\sigma_{inel}} = \frac{\epsilon \mu f_{rev}}{\epsilon \sigma_{inel}} = \frac{\mu_{vis} f_{rev}}{\sigma_{vis}}$$

- Luminosity can be determined using any method that measures μ_{vis} and σ_{vis}
 - Instantaneous luminosity $\mathcal{L}(t)$ [cm⁻²s⁻¹] $\propto$ the number of pp collisions per second
 - Integrated luminosity $L_{int} = \int \mathcal{L}(t) dt$ [cm⁻²] = [fb⁻¹] $\propto$ the number of pp collisions in a data sample

✨ luminosity parameters ✨

- $\mathcal{L}_b$ - instantaneous luminosity per bunch crossing
- μ - number of inelastic pp collisions per bunch crossing, also referred to as pileup
- $\sigma_{inelastic}$ - total inelastic pp cross section, around 80 mb
- f_{rev} - revolution frequency set to 11245 Hz
- ϵ - acceptance x efficiency of the detector
- μ_{vis} - number of visible (detected) collisions per bunch crossing
- σ_{vis} - visible cross section

Monitoring luminosity - relative measurement

- Every luminosity detector monitors the luminosity in each run by measuring the visible interaction rate μ_{vis}
- There are different algorithms to determine μ_{vis}
 - Event counting
 - Determine the fraction of bunch crossings when a specified detector registers an "event" satisfying a given selection requirement (e.g having at least 1 hit in one side of the detector)
 - Then get μ_{vis} from Poisson probability for a bunch crossing to contain at least one event
 - Hit counting
 - Similar to event counting but counts the total number of hits per detector channel per

$$\text{bunch crossing} - P_{Hit}(\mu_{vis}) = \frac{N_{Event}}{N_{Ch} N_{BC}}$$

- Particle-counting/flux
 - Relies on observables that are directly proportional to the rate of particles interacting in the detector
 - E.g the measured detector current in specific calorimeter regions which is directly proportional to the total particle flux, used both by Tile and LAr
- Track counting
 - The average number of charged particle tracks is directly proportional to the luminosity
 - > determine luminosity from mean number of reconstructed tracks in randomly-triggered bunch crossings

Poisson probability

$$P(\mu) = \frac{e^{-\mu}}{N_{int}!} \mu^{-N_{int}}$$

$$P_{event}(\mu_{vis}) = \frac{N_{Event}}{N_{BC}} = 1 - e^{-\mu_{vis}}$$



$$\mu_{vis} = -\ln\left(1 - \frac{N_{Event}}{N_{BC}}\right)$$



Absolute luminosity calibration

- To use the measured interaction rate μ_{vis} as an absolute luminosity monitor, each luminometer and algorithm must be calibrated by determining its visible cross-section σ_{vis}
 - σ_{vis} is computed by measuring μ_{vis} and comparing it to the absolute luminosity determined from beam parameters (computed at the same time) in special van der Meer (vdM) runs
- Assuming that the particle density profile of the beams can be factored into independent horizontal (x) and vertical (y) components the luminosity can be fully determined from beam parameters as:

$$\bullet \quad \mathcal{L}_b = \frac{n_1 n_2 f_{rev}}{2\pi \Sigma_y \Sigma_x} \quad \text{with } n_1/n_2 - \text{the number of protons per bunch in beam 1/2}$$

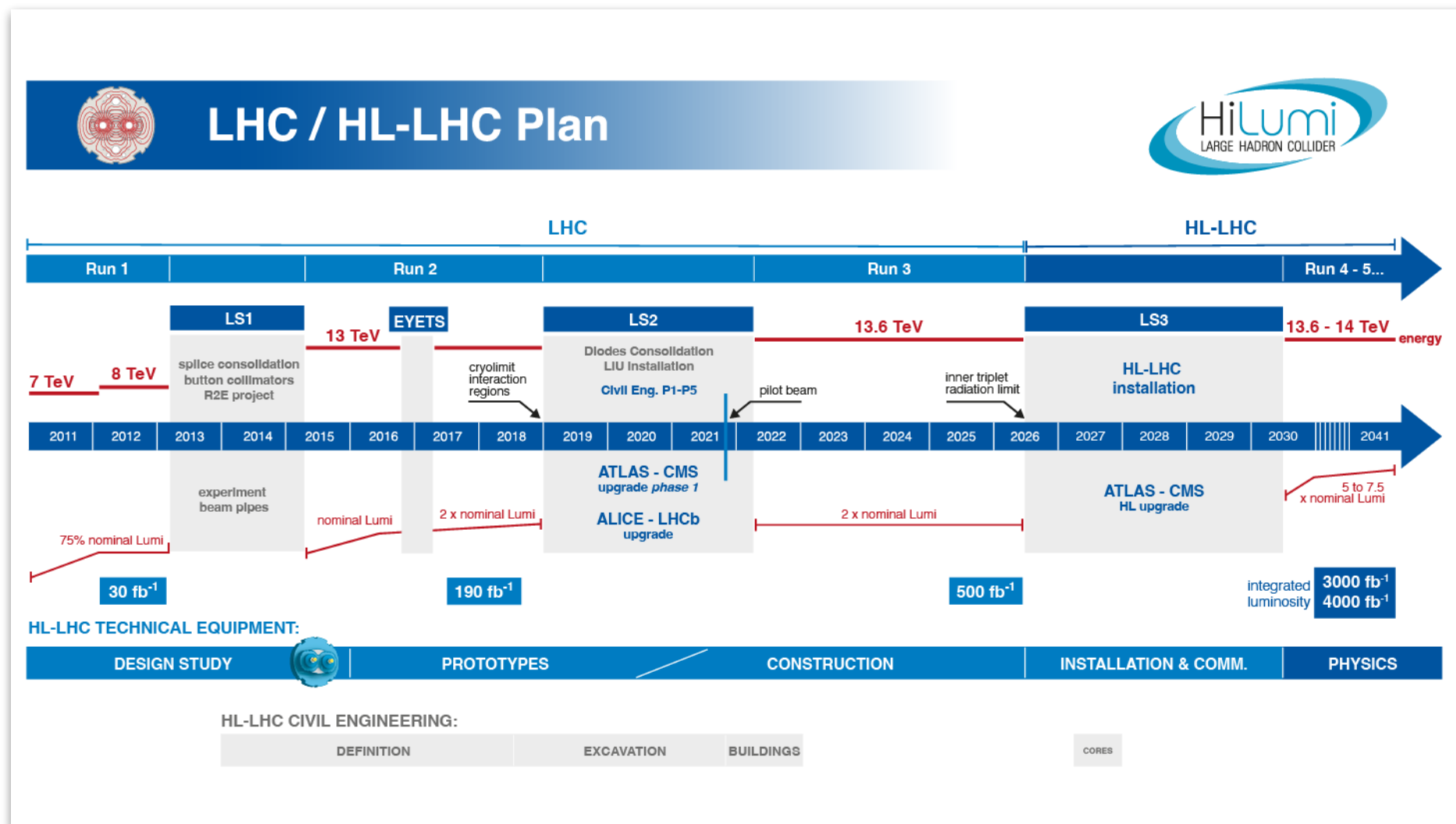
$$\text{and } \Sigma_i = \sqrt{\sigma_{i1}^2 + \sigma_{i2}^2} - \text{convolved beam sizes}$$

- In the vdM method $\Sigma_{x/y}$ are computed from beam-separation scans at low μ
 - For detectors/algorithms that are not sensitive enough to be independently calibrated in vdM scans, are usually anchored to LUCID (or track counting) by normalising the measurement (in some dedicated data) to the calibrated LUCID value
 - Tracks are anchored to LUCID in vdM, while calorimeters (EMEC, FCal, TILE) are anchored to the corrected tracks in 10 runs around the vdM



LHC/HL-LHC schedule

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HL-LHC physics

- ATLAS and CMS HL-LHC prediction for couplings in Higgs sector
- From [Snowmass report](#)

