LUCID, the ATLAS luminosity detector in LHC Run-3 and its upgrade for HL-LHC

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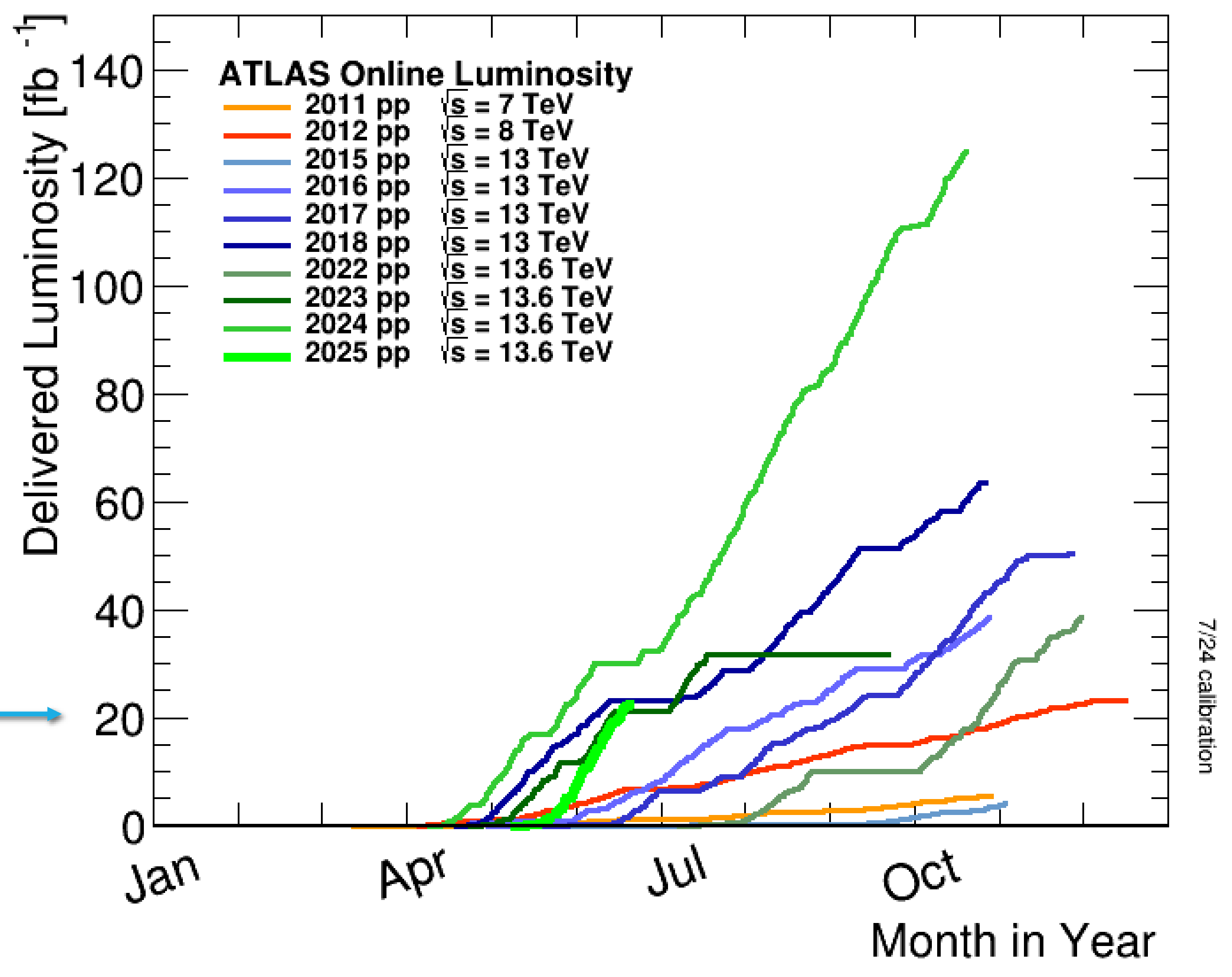
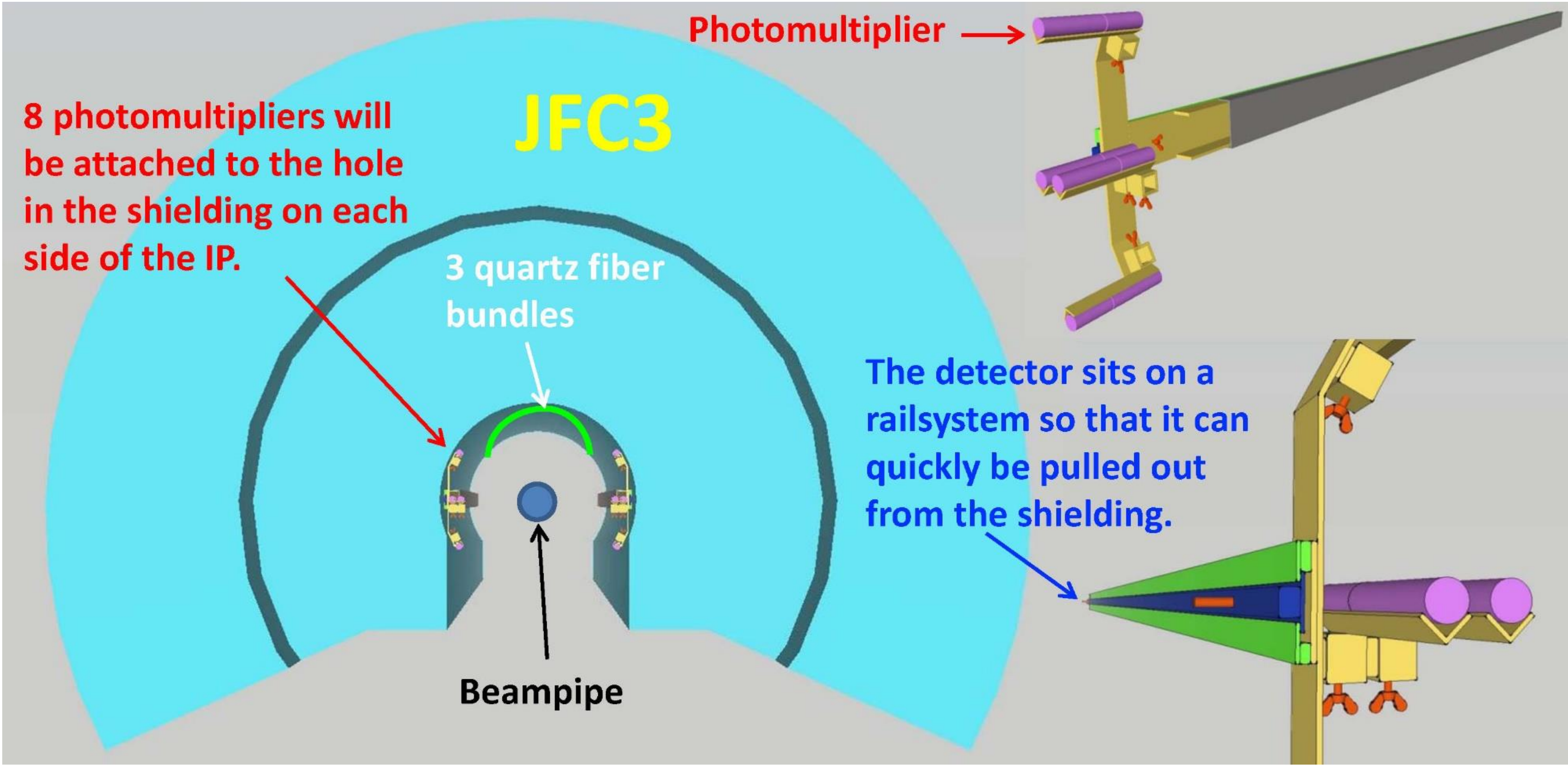
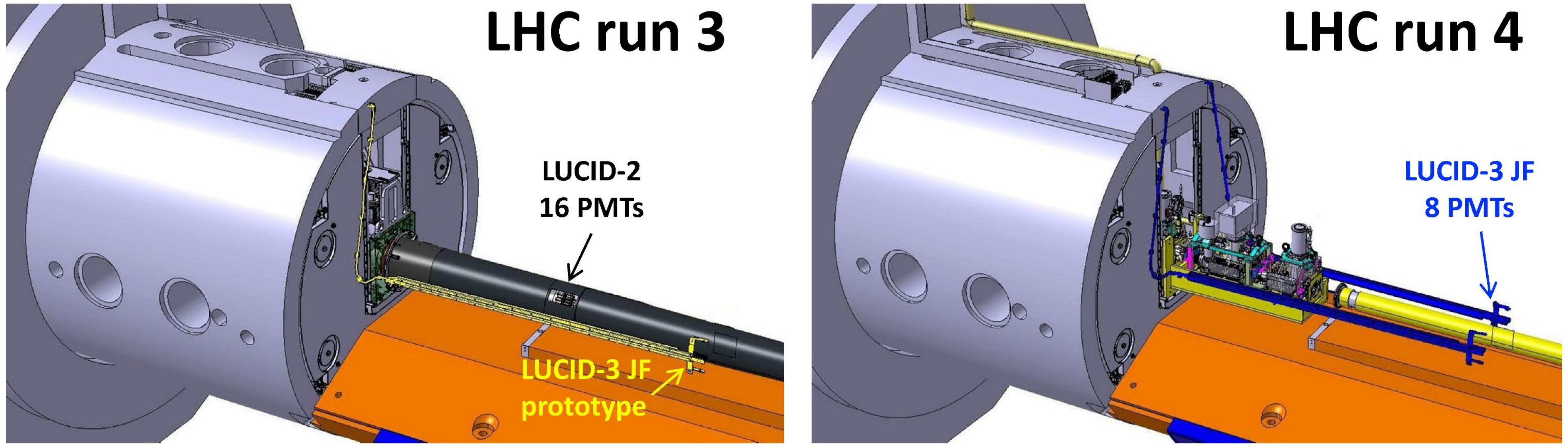
Introduction

- Luminosity: an essential parameter in accelerators
- LUCID 2 provides precise and reliable measurements in Run2 and Run3
  - Run 2: 0.8% uncertainty after final analysis
  - Preliminary 2022 + 2023 -> 2% uncertainty
- For HL-LHC a major upgrade is planned
- In Run 3, several prototype technologies were installed
- Analysis of their performance will be shown in this presentation







Why Luminosity?

$$L = \frac{f_{LHC} \sum_{i=1}^{n_b} N_{1i} N_{2i}}{4\pi\sigma_x\sigma_y}$$

LHC revolution frequency

Protons/ bunch

Beam width

$$L = \frac{R_{in}}{\sigma_{in}}$$

Interaction rate

Cross-section

Data to LHC – Online, continuous (2s blocks)

Data to ATLAS – Online, over a LB

- To adjust ATLAS trigger system to current LHC beam conditions
- Provided per-BCID

Offline measurement

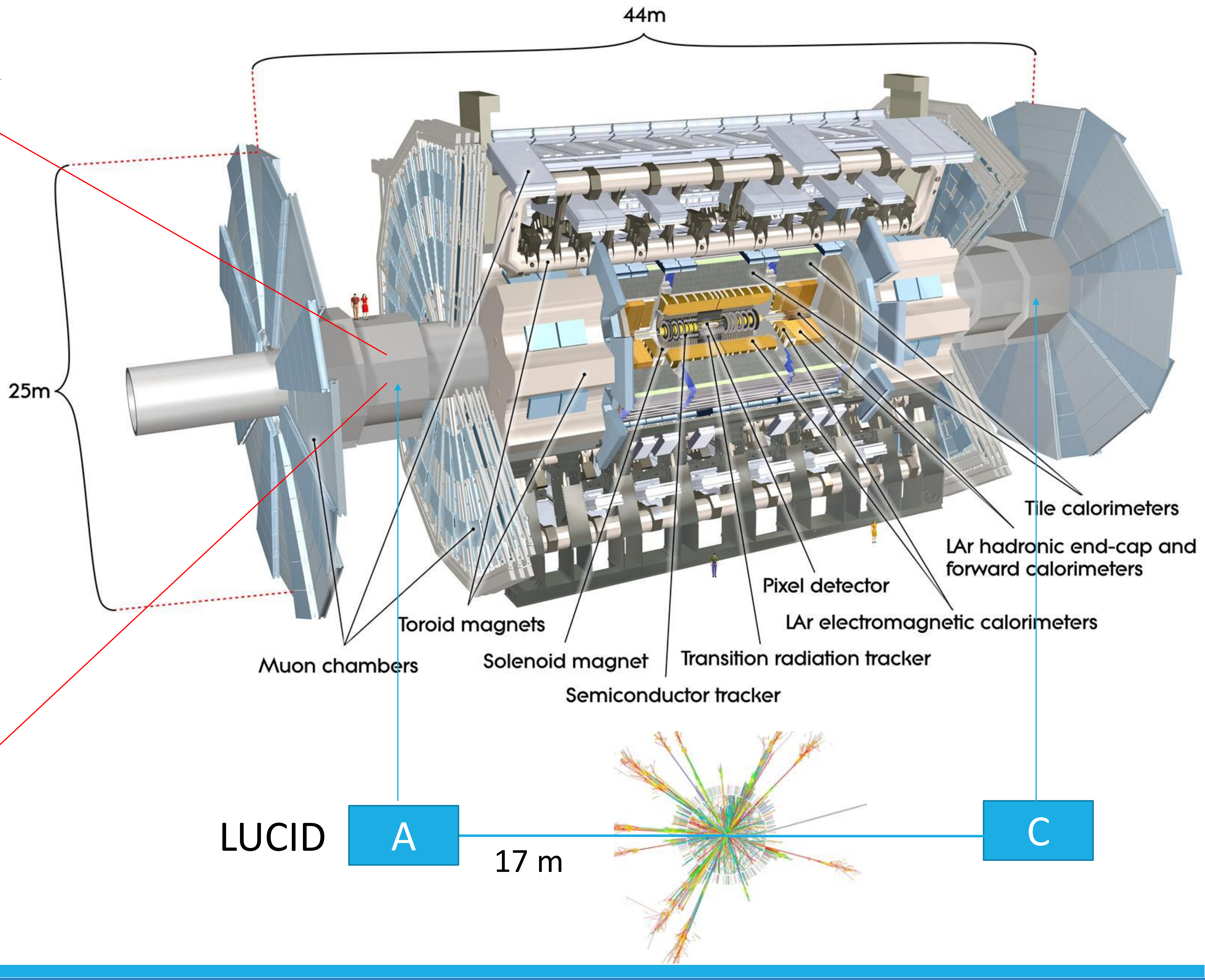
- Necessary for any cross-section measurement
- The more precise, the better

Some definitions:

- Bunch Crossing (BC) – when a proton packet collides. Identified by an ID number (BCID)
- Luminosity Block (LB) – a time span in which instantaneous luminosity has negligible variations ~60 s
- Pile up, μ = average number of interactions per BC

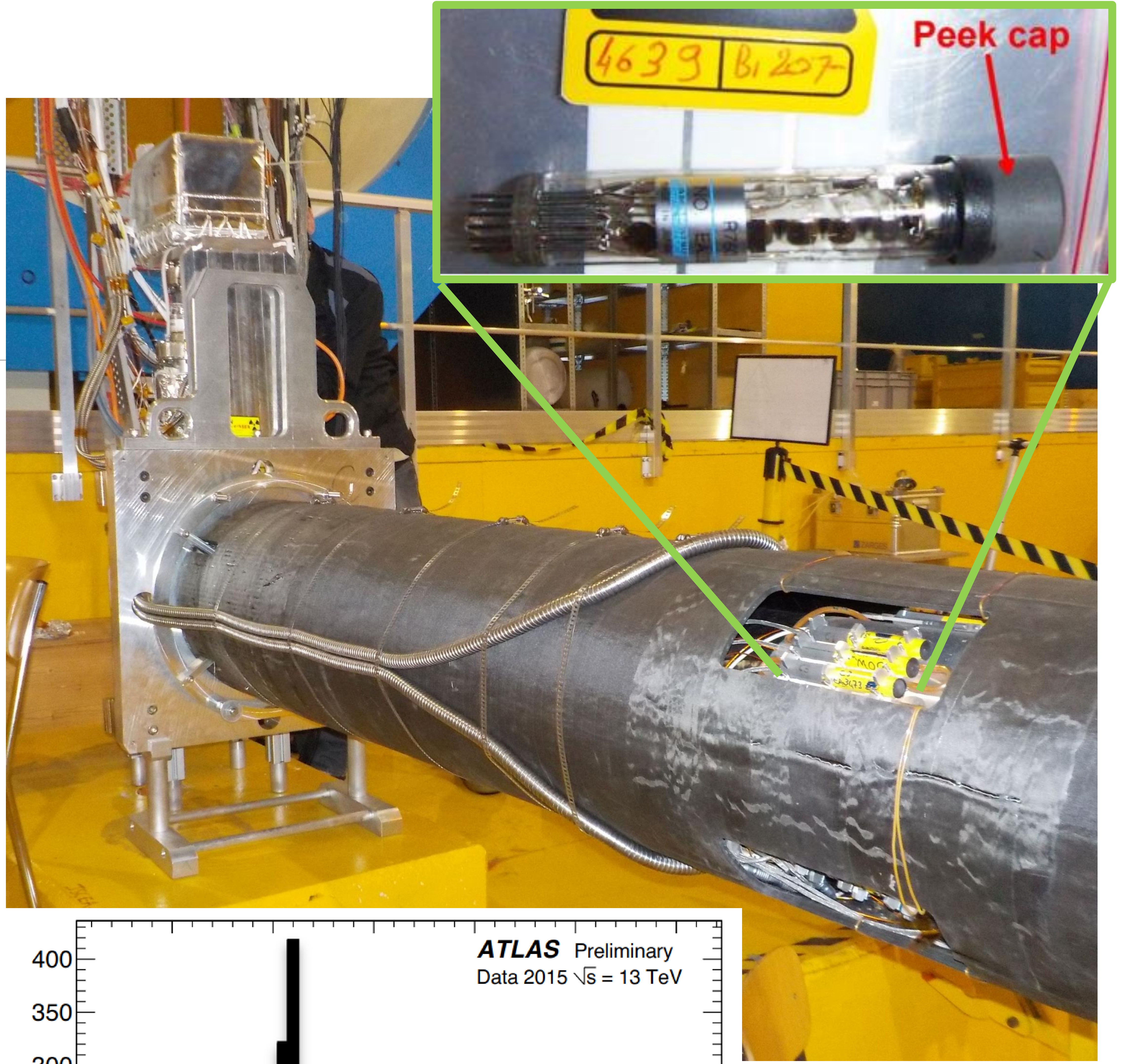
LUCID in ATLAS

LUCID A

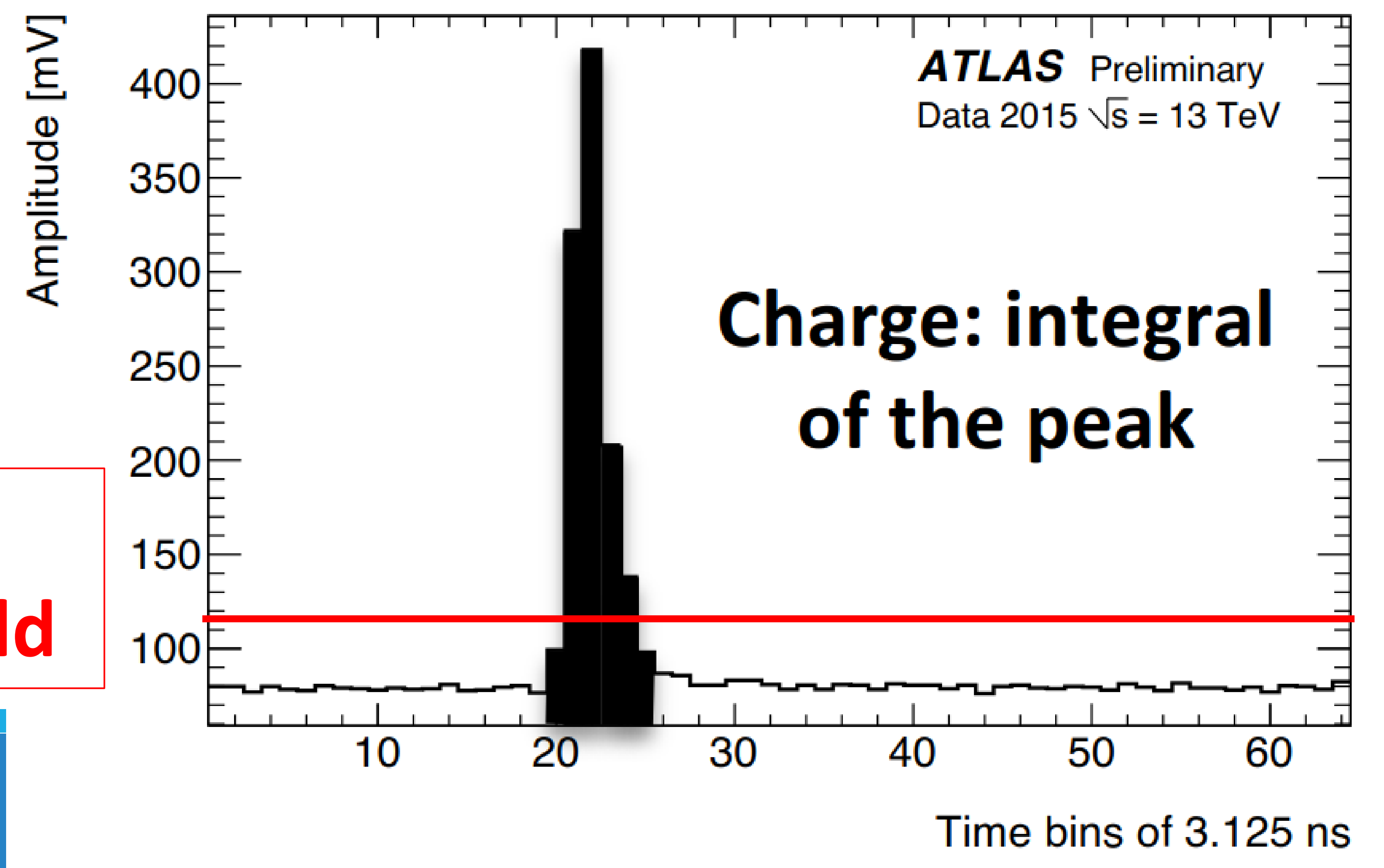


LUCID 2 in Run 3

- Main detector: Hamamatsu R 760 arranged in groups of 4 photomultipliers (PMTs) per side
  - Bi2 – the main luminosity group until 2024
  - Bi3 – the main group in 2025
  - Spares – to replace malfunctioning PMTs
- Innovative calibration system based on ^{207}Bi source deposited on the PMT window
  - Gain equalized by adjusting the PMT HV to keep the Bi peak at a constant amplitude
  - In 2025: continuous calibration during interfills thanks to full automation of the procedure
- Dedicated electronics handling digitization, discrimination and integration

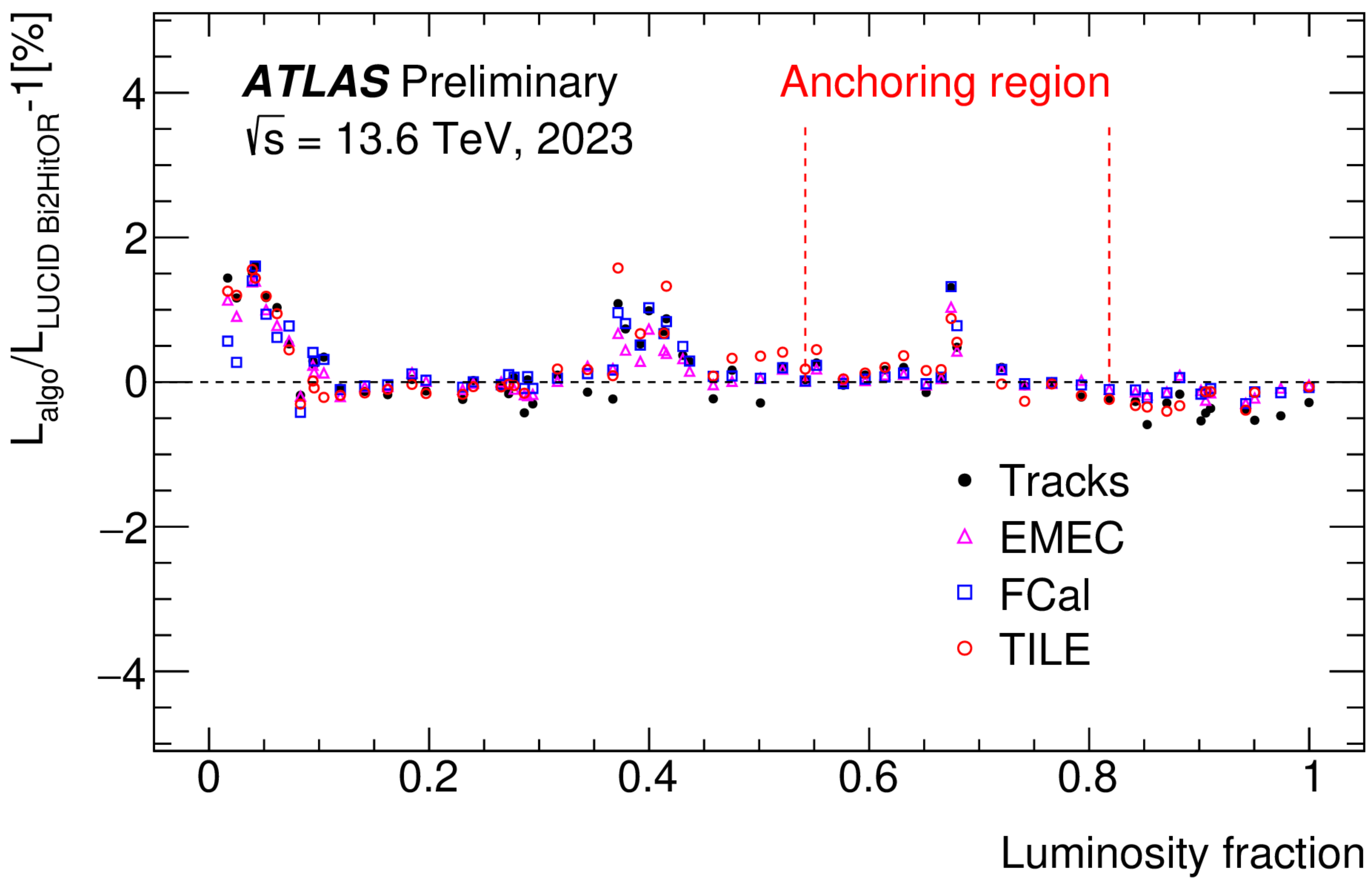


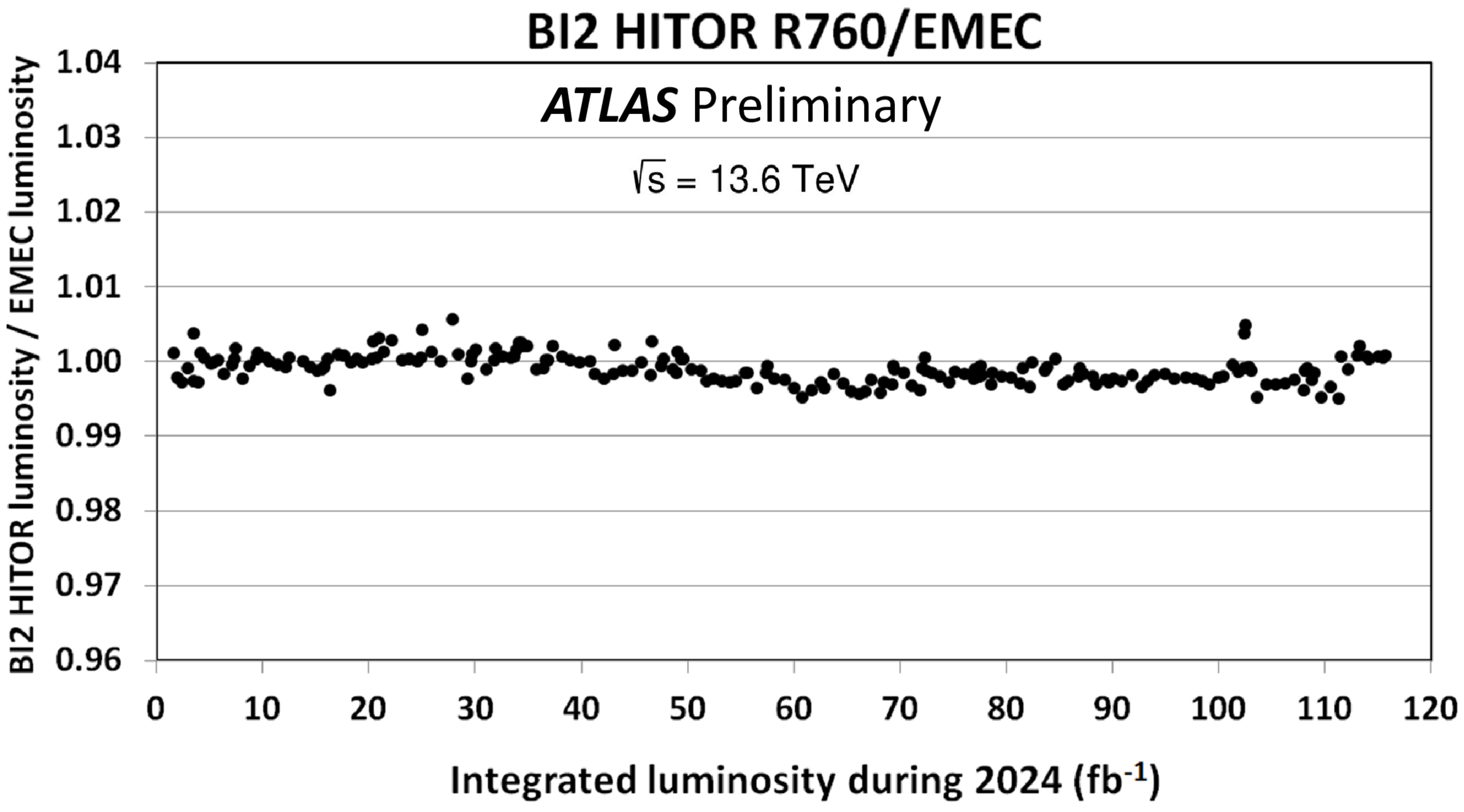
Hit: amplitude above threshold



LUCID luminosity measurement

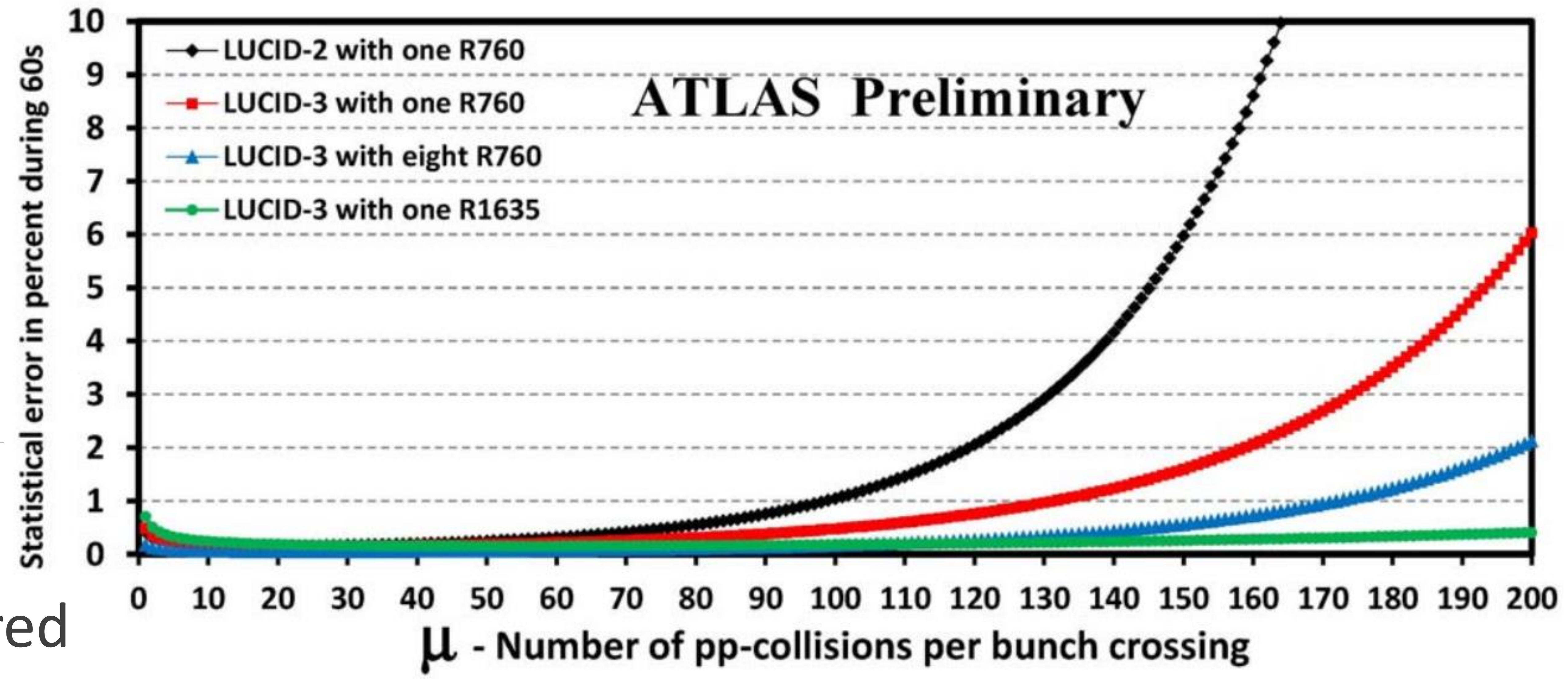
- LUCID measures luminosity by counting the number of PMTs that have a signal above threshold in each BC
- No trigger or dead-time-> Delivered LHC luminosity
- Luminosity is measured as a function of the BCID at 40 MHz in the full luminosity range (0.001< μ <100)
- Systematics, saturation, migration and temporary effects need to be studied and monitored
- In 2023 and 2024 LUCID delivered very stable luminosity (<1% variations) when compared with other measurements



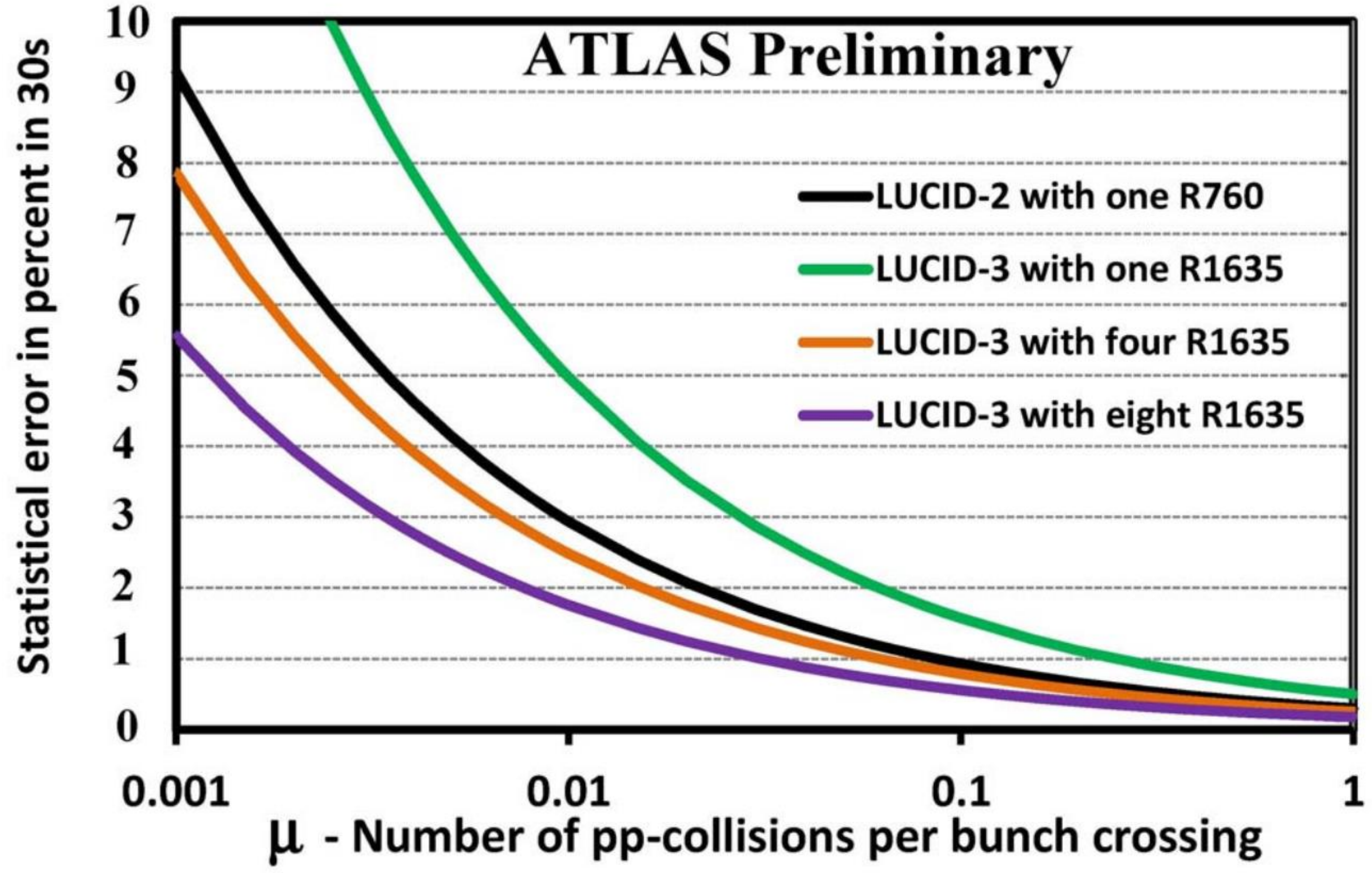


Tracks = count the numebr of tracks in dedicated sectors of the ATLAS Inner Tracker detector
EMEC = currents in special EM Calorimeter towers
Tile = currents in specific Had Calorimeter towers
FCal = currents in special Forward Calorimeter towers

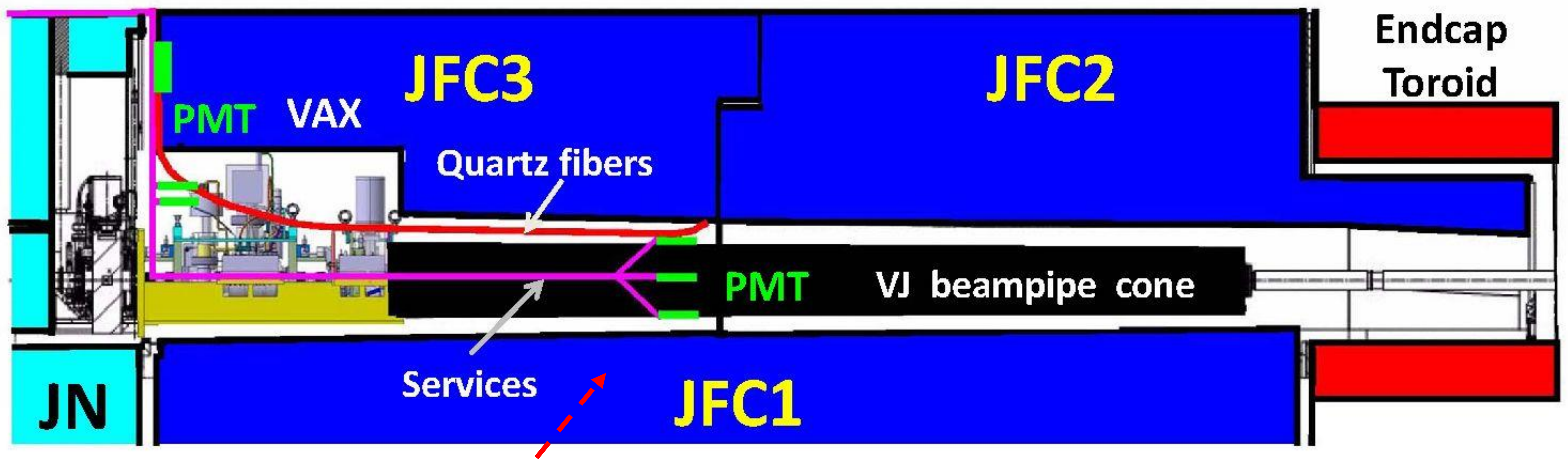
HL-LHC upgrade



- HL-LHC targets L=4000 fb-1 and μ =200
- For precision measurements, dL/L<1% is required
- Necessary to reduce the flux and acceptance of the detector
  - But maintain sensitivity in the low- μ calibration runs
- Combining the signals of multiple PMTs becomes not just a stability and redundancy measure, but a necessity
- New layouts will place PMTs in lower-flux areas
- New, smaller PMTs (Hamamatsu R1635) can reduce the acceptance
- Alternative technologies are also in development

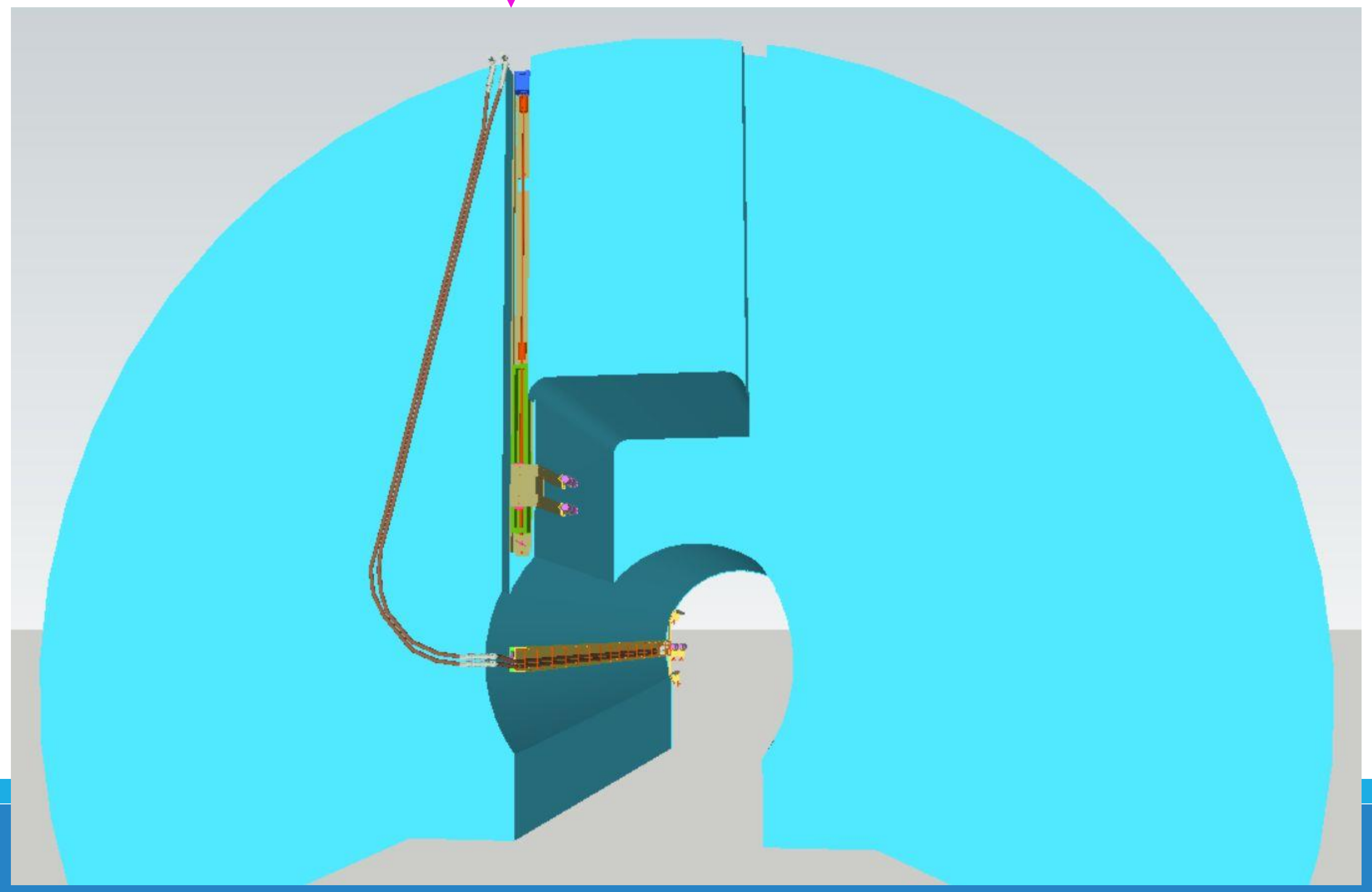


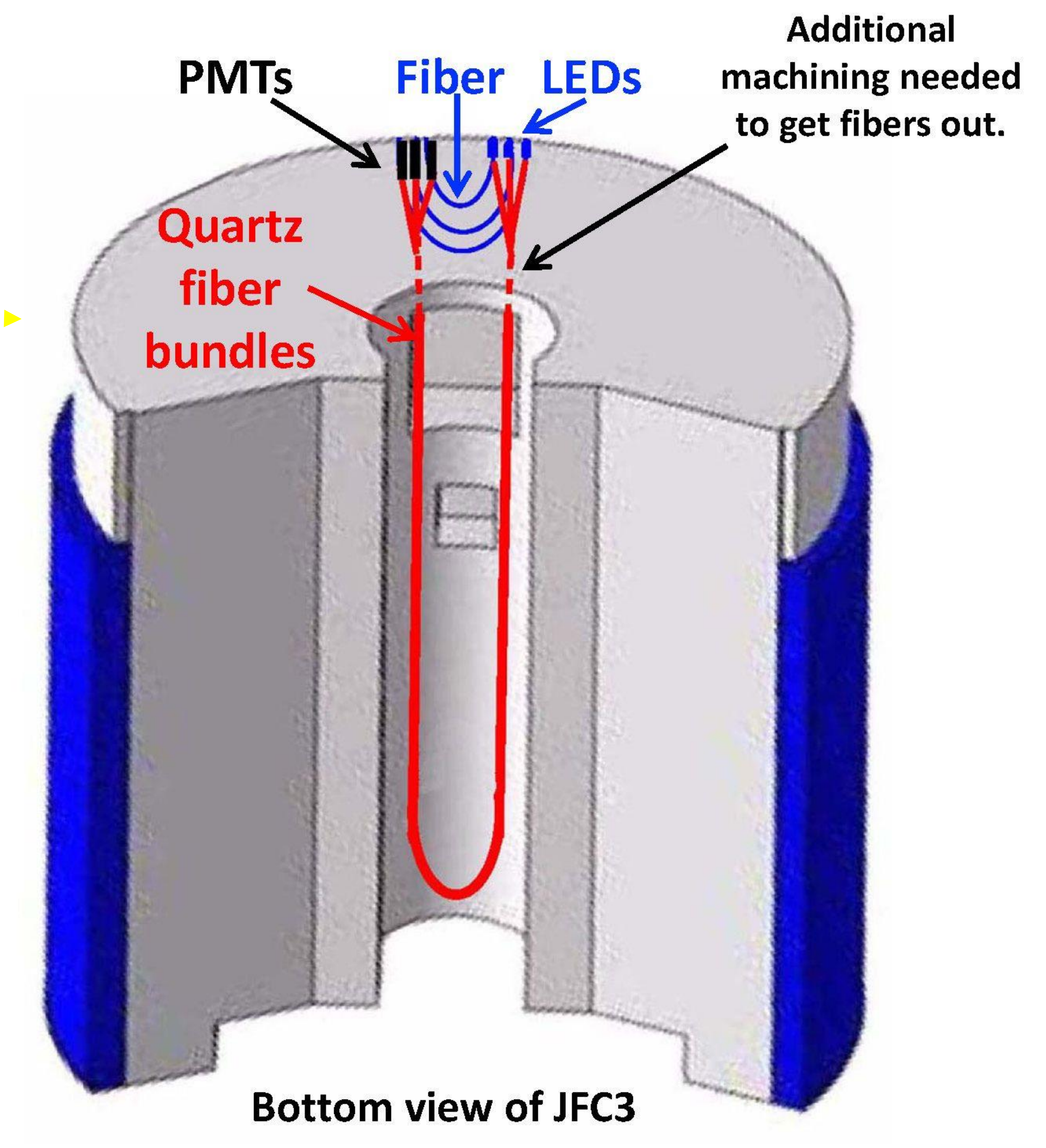
Zero starvation or saturation:
at high rate the statistical resolotion depends from the number of events where there is no signal



HL-LHC upgrade II

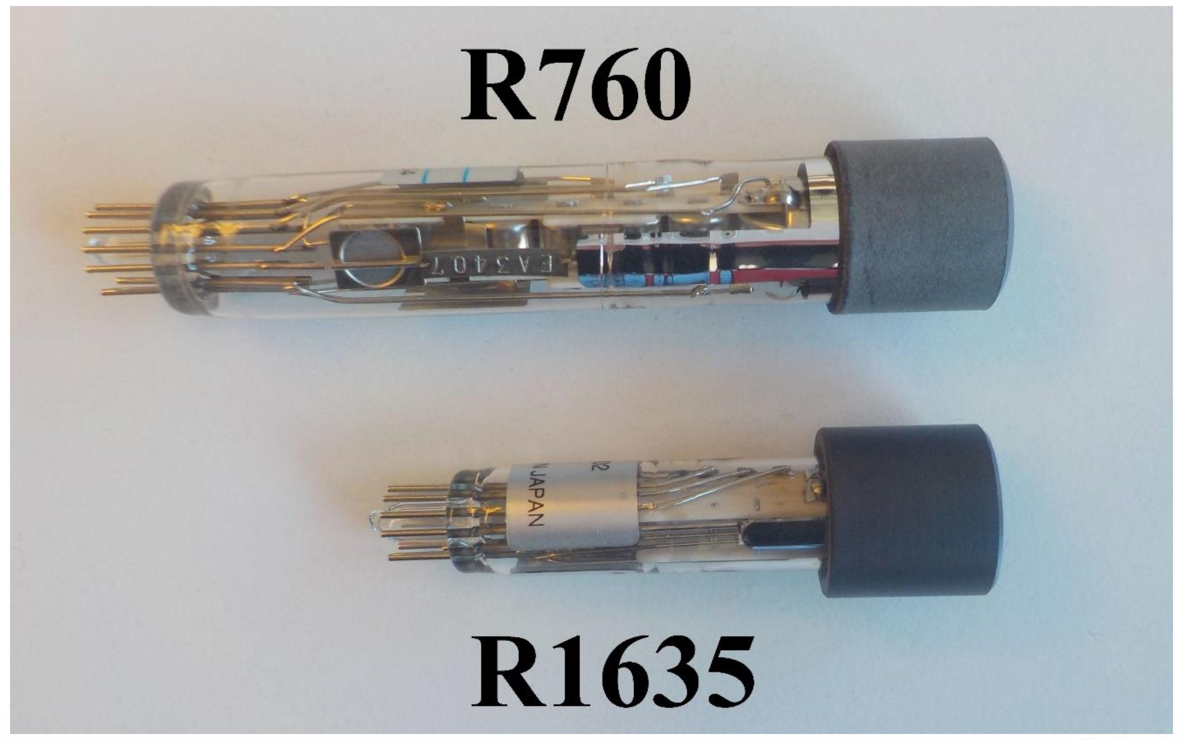
- The PMTs attached to the railing system will provide the main luminosity measurement in the whole L range, from VdM scans to μ =140 in LHC Run 4
- PMTs hidden behind the shielding provide a stable and almost linear measurement at μ values up to 200 with low uncertainty
- The fiber detector, considered as a possible upgrade, can produce a linear, risk-free luminosity measurement thanks to the protection it offers to its PMTs

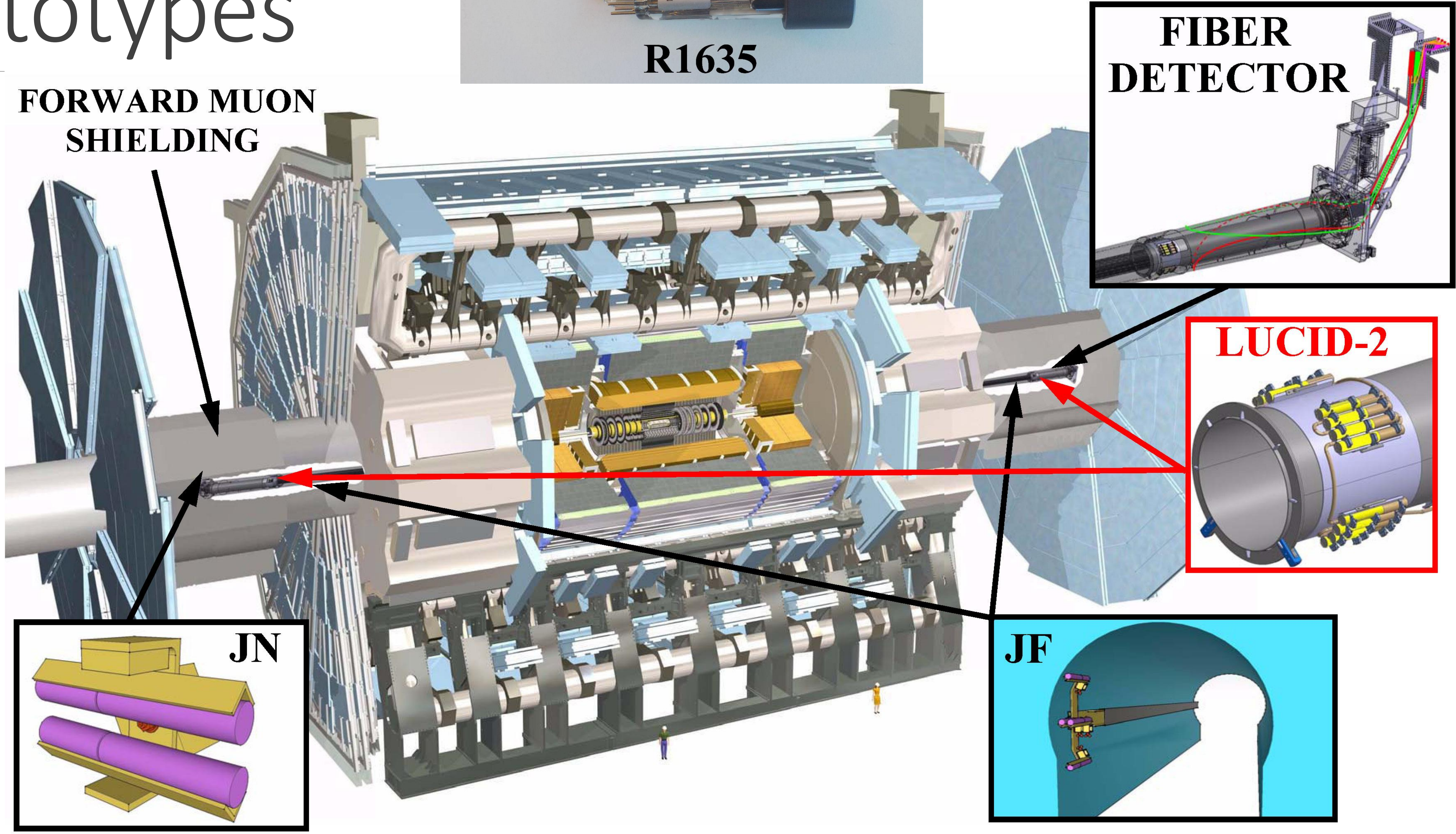




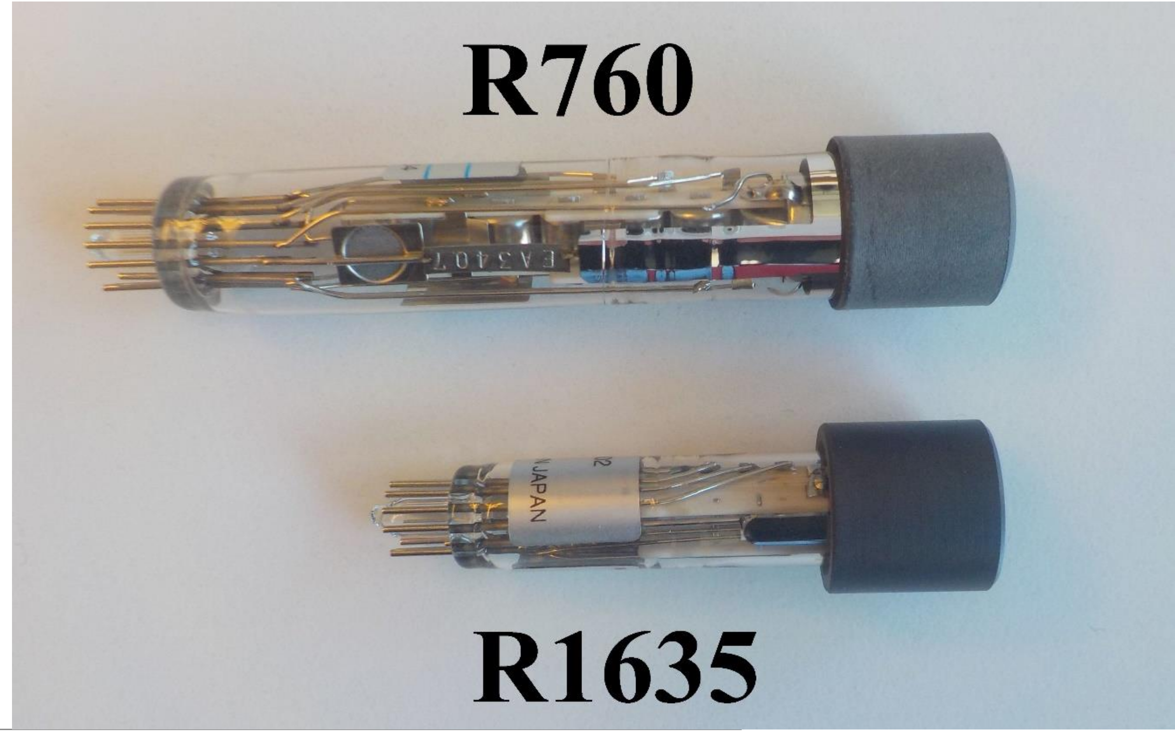
Run 3 prototypes

- R1635 PMTs 8mm window vs R760 10mm window
- Old and new PMTs attached to the JF shielding
- R760 behind the shielding (JN)
- The fiber detector

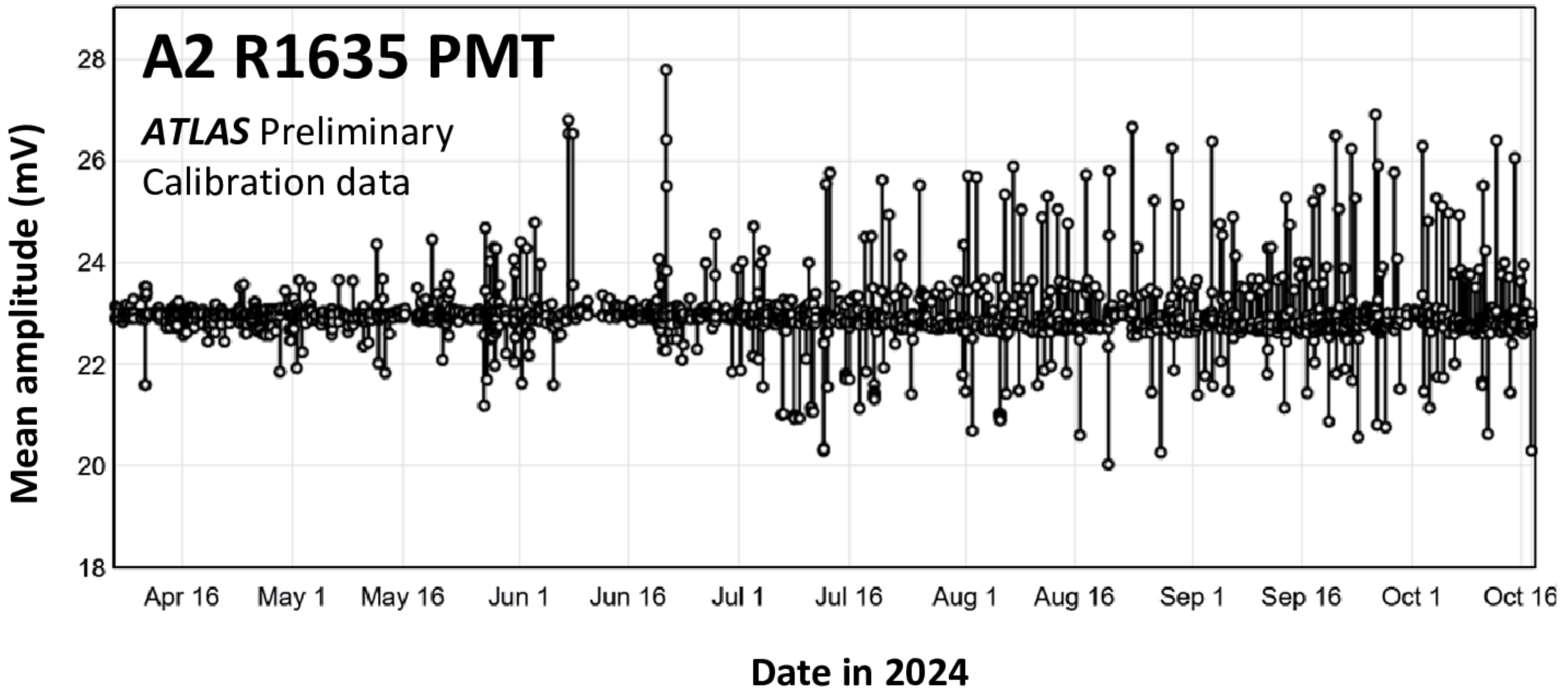


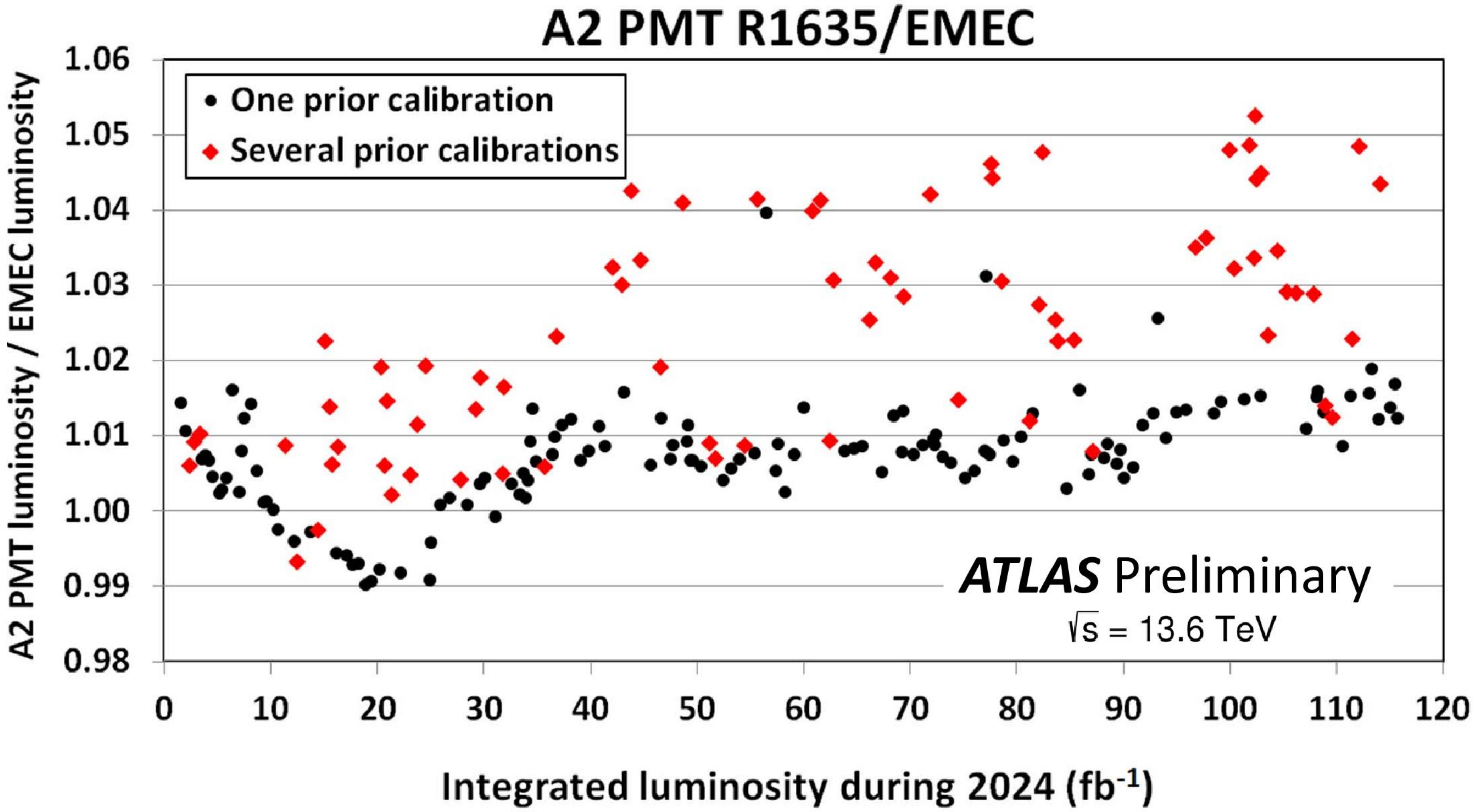


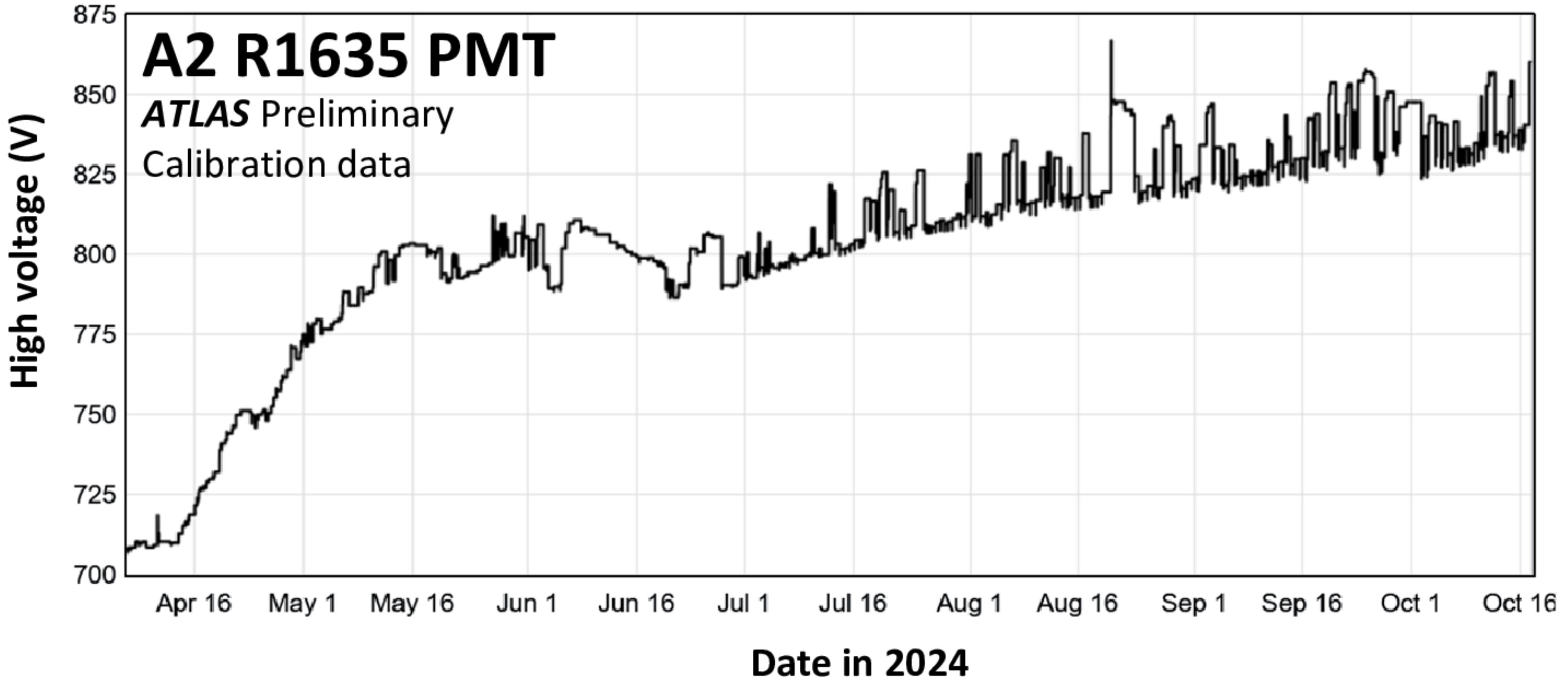
Prototype performance: R1635 PMTs



- R1635, modified with a fused silica window, installed around the beam-pipe
- Acceptance was reduced as expected (30%)
- Stability was not good over the year -> investigation
  - The effect seemed calibration-dependent

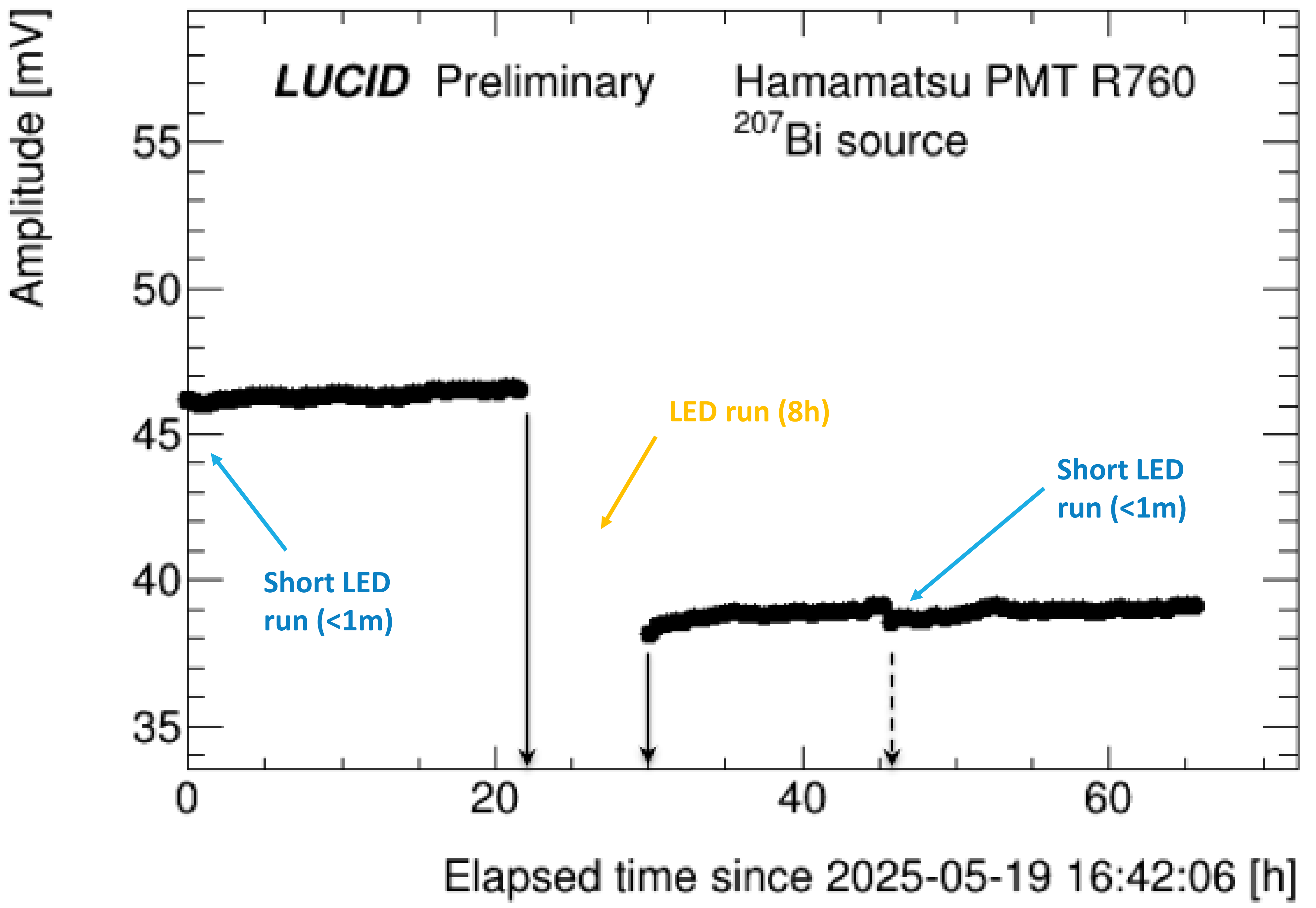


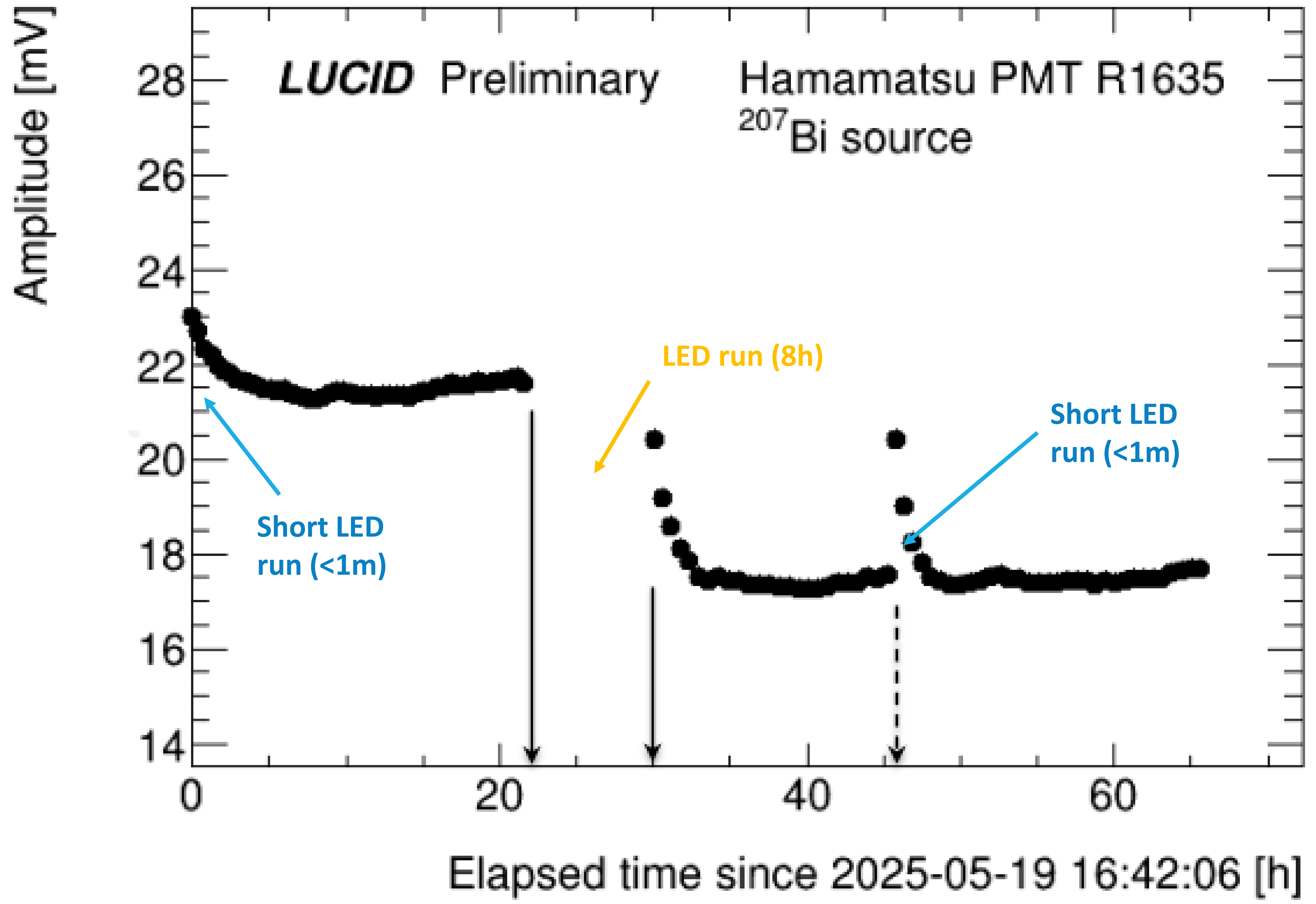




R1635 investigation

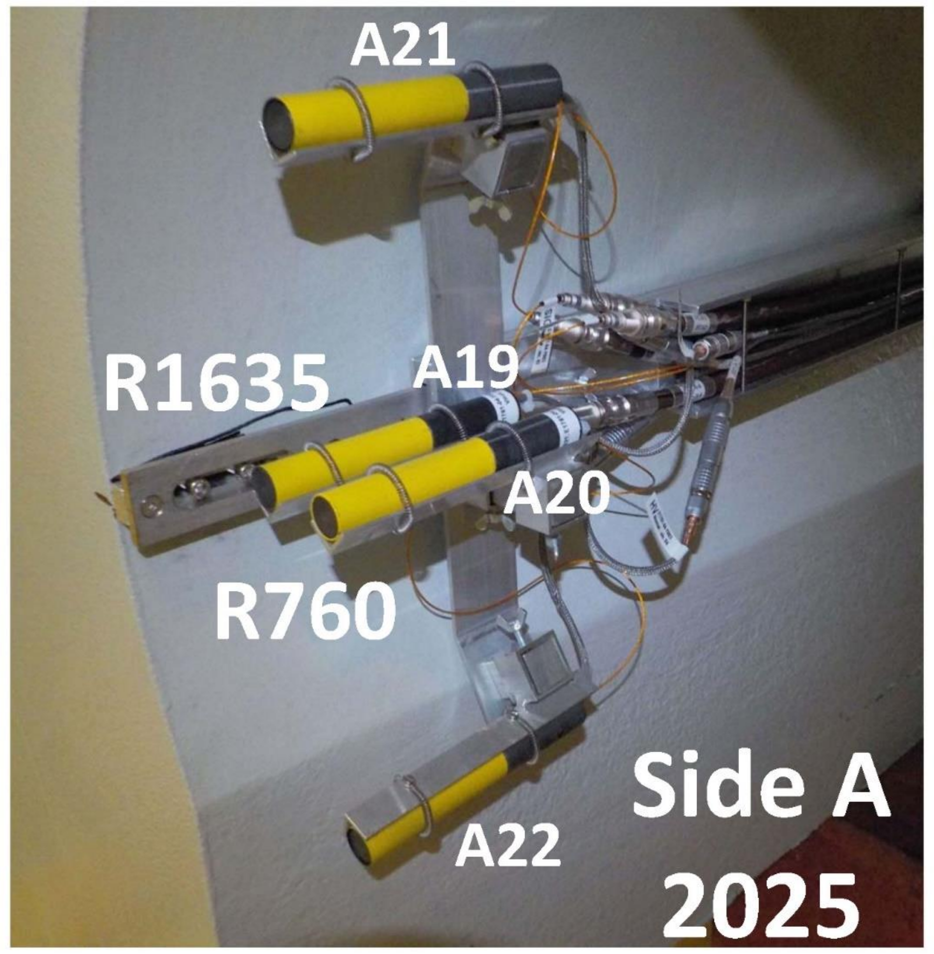
- Investigating the R1635 instability
  - LED light simulates long runs (but no activation)
  - Bi source to reproduce calibrations
- R760s behave as expected: a gain loss followed by a slow recovery
- R1635s see the calibration signal going down for hours
- High currents leave residual extra signals
  - This means that calibrations have a hard time finding the right value
  - Now testing continuous calibrations
  - Working with Hamamatsu to understand the source of the issue

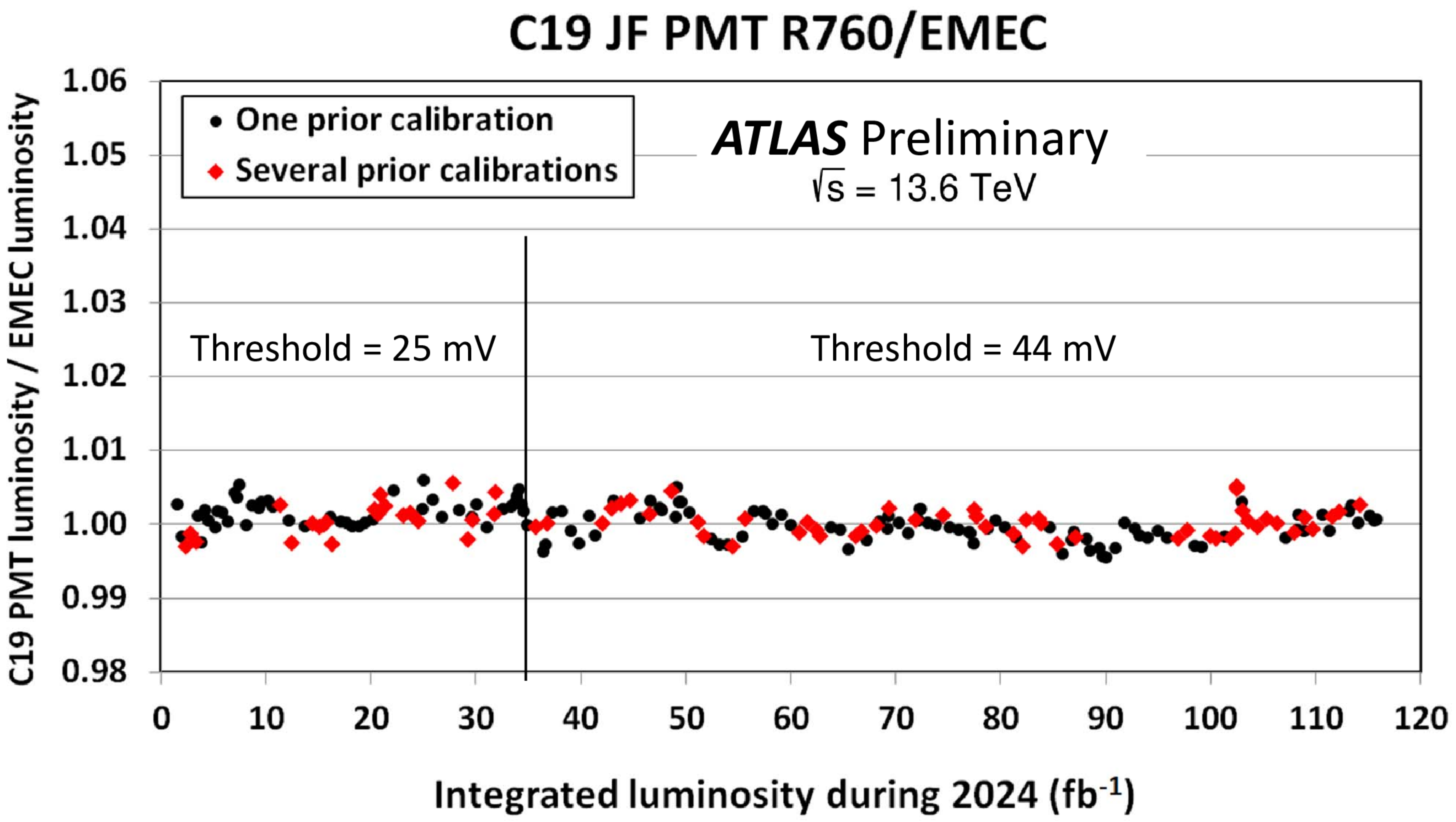




Prototype performance: JF - R760 on rails

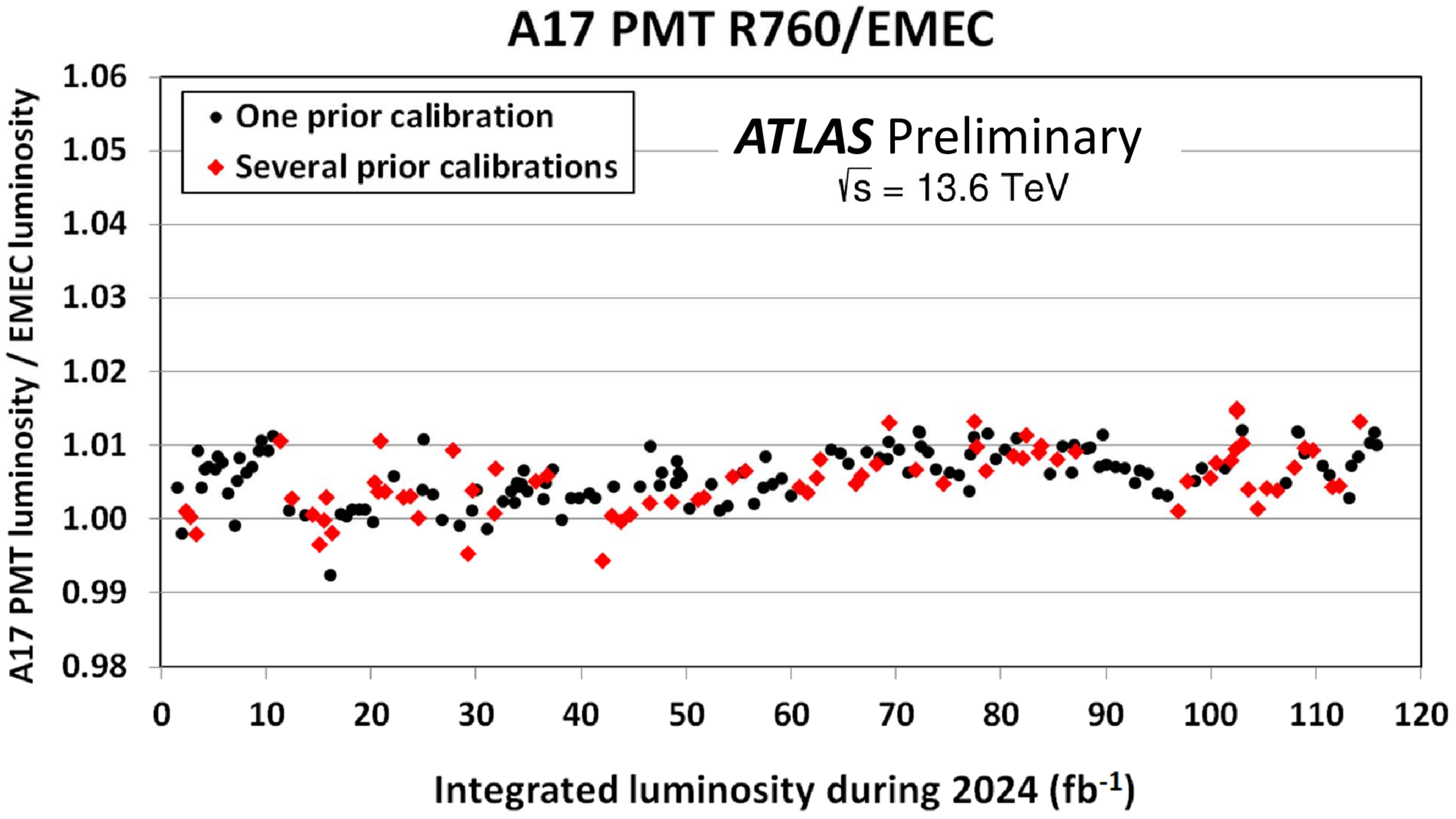
- R760 PMTs (and R1635), installed on railings attached to the JFC-shielding:
  - Further from the beam-pipe -> lower flow
  - Easy replacement every year
- The prototype layout showed the expected reduction in rate:
  - 8 or 16 R760s in Hit Counting will provide luminosity at $\mu = 140$, the LHC Run 4 target, but might saturate at $\mu = 200$
  - Tests are being made to increase the threshold that defines a hit in order to reduce saturation

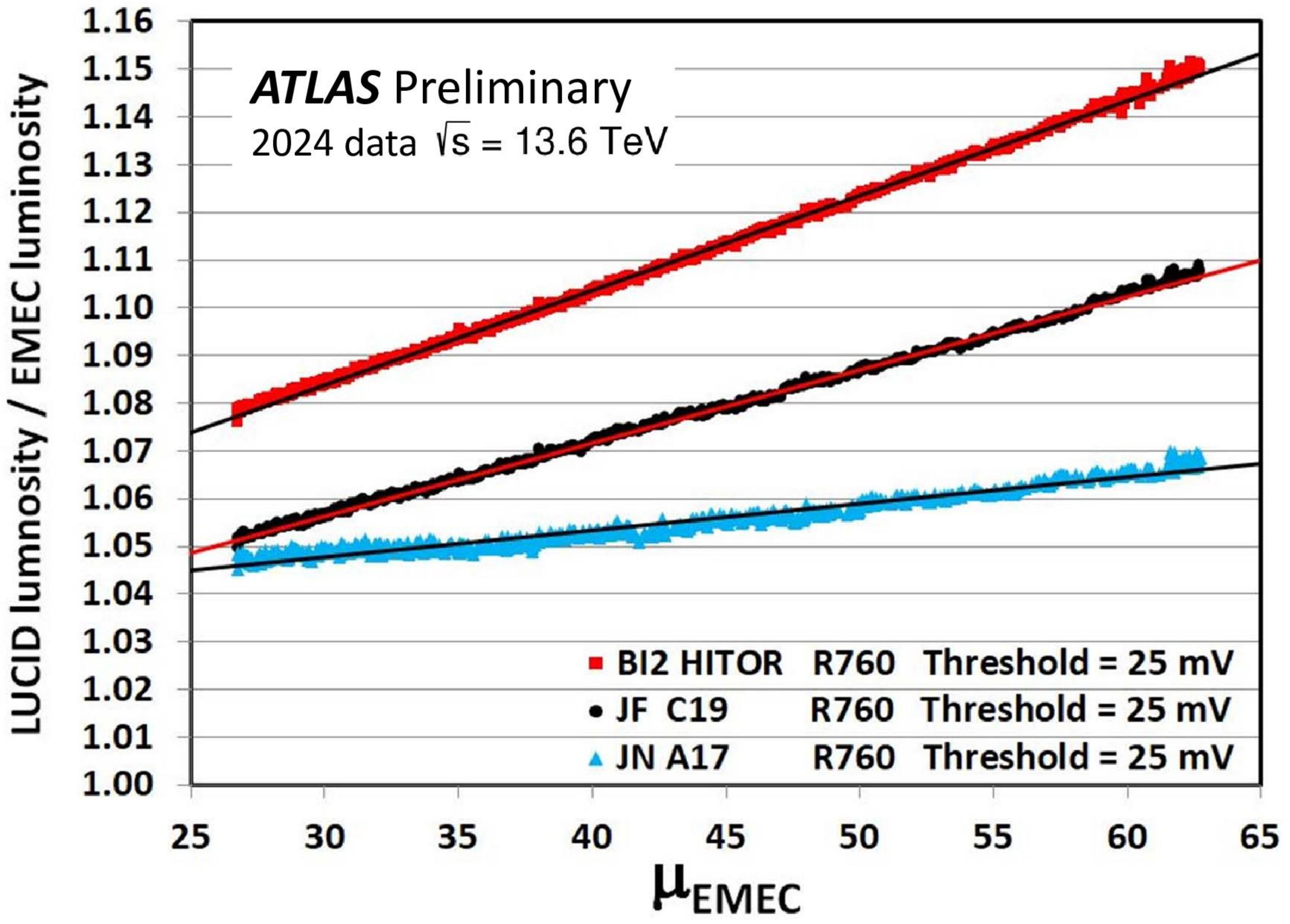




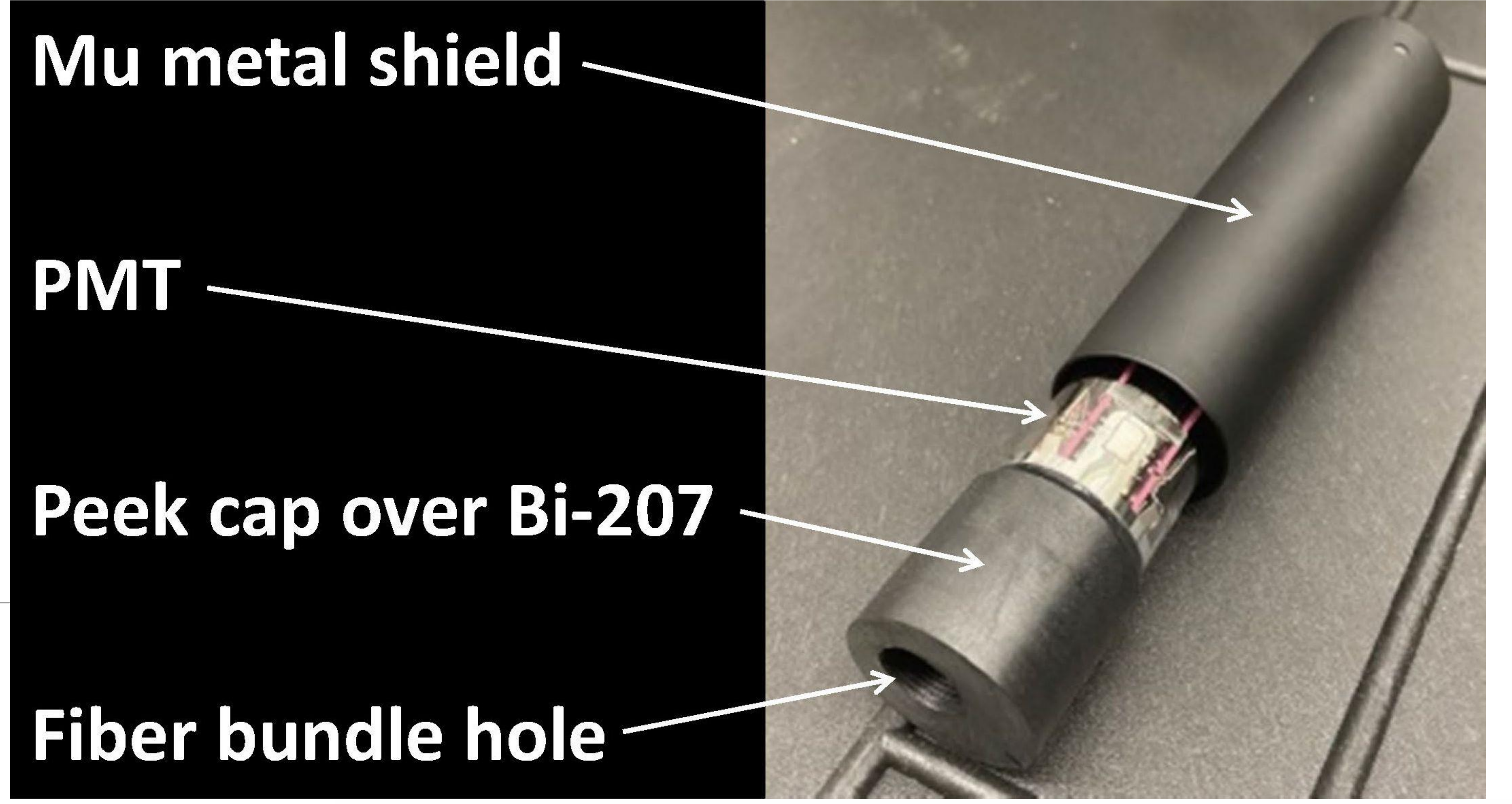
Prototype performance: the JN detector

- The JN detector is almost as stable as the JF detector, smaller μ -dependence
- Complementry detector that needs cross-calibration because it is not sensitive in VdM scans
- Investigating using a step-motor to optimize the position

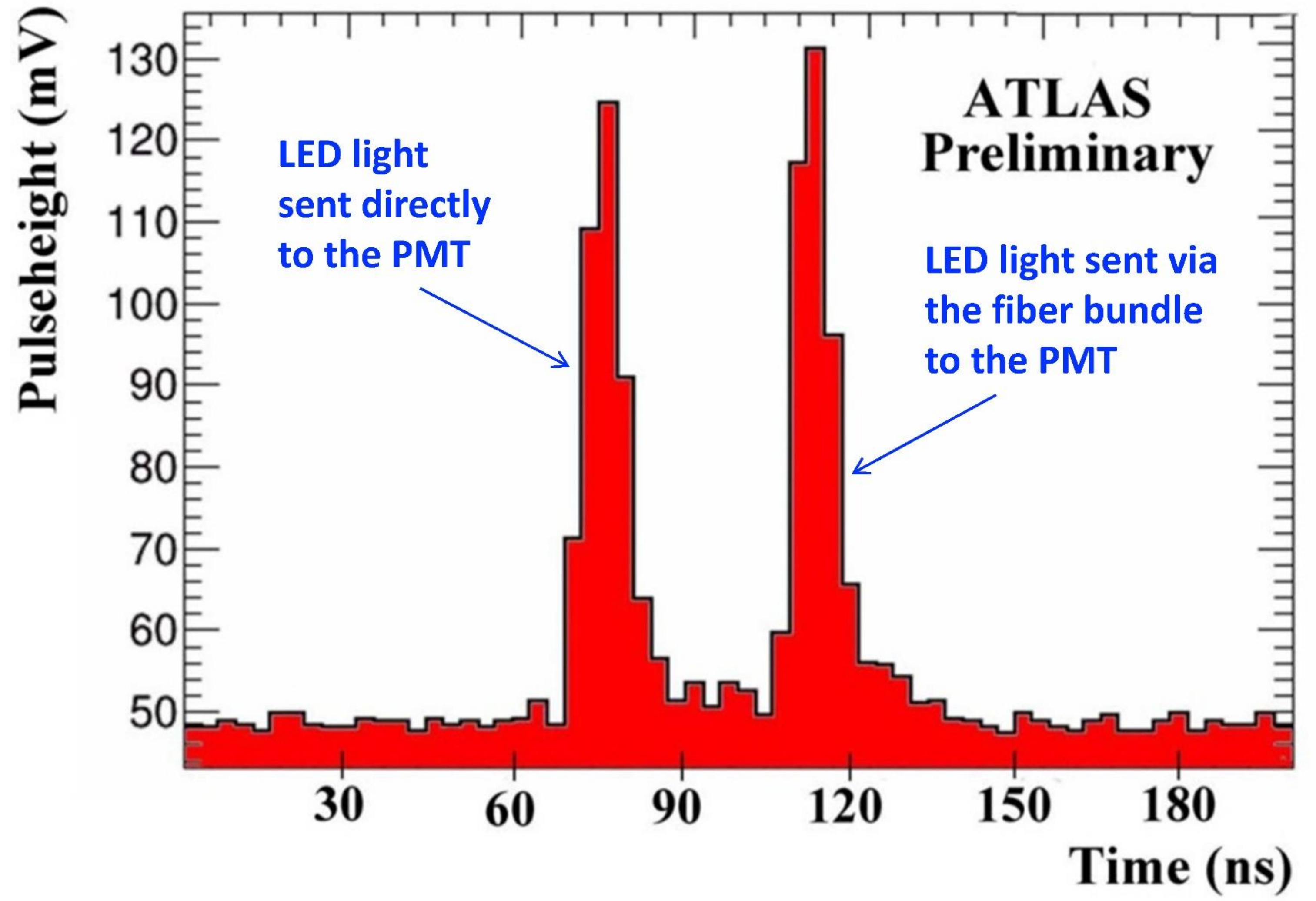


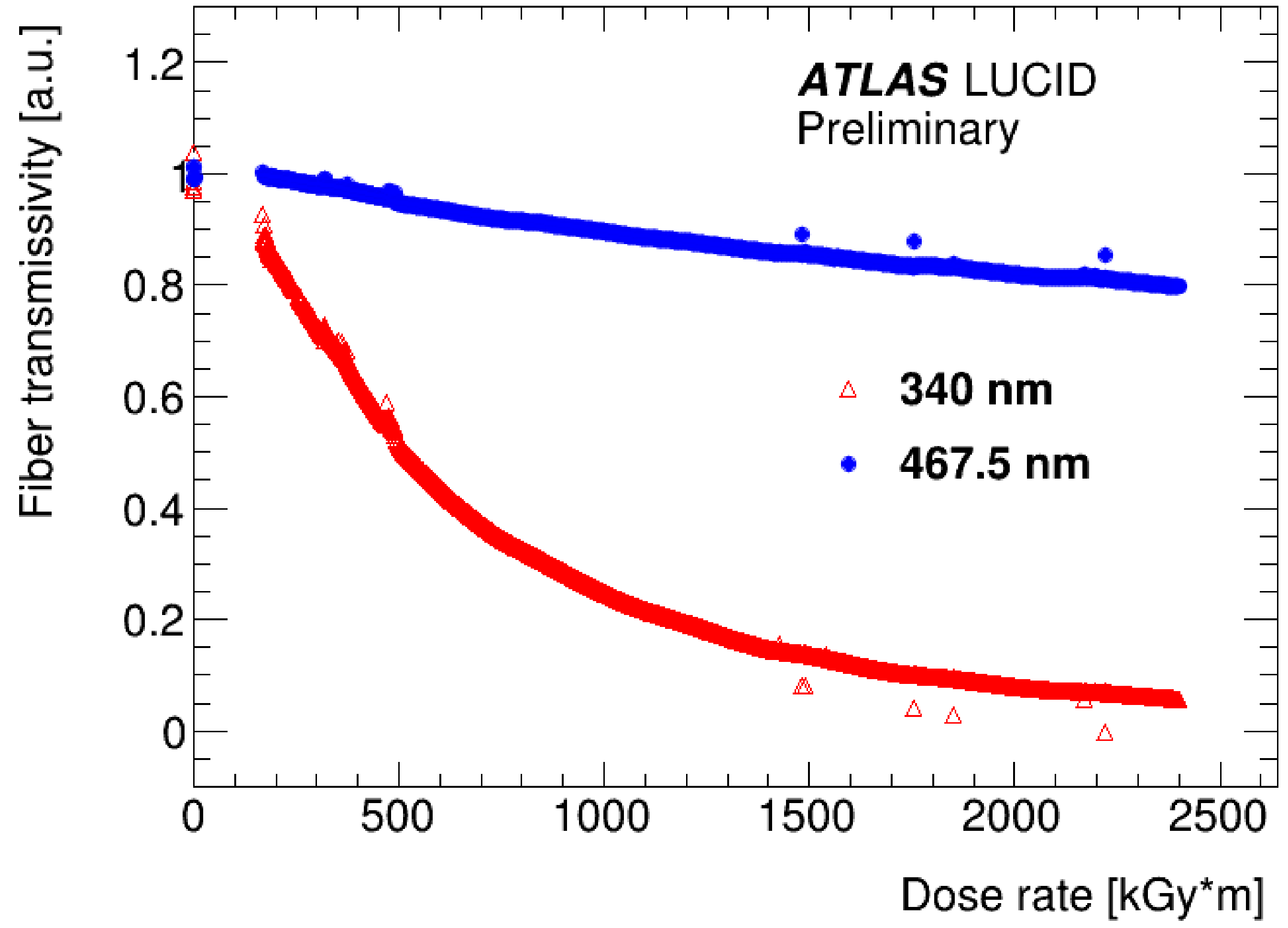


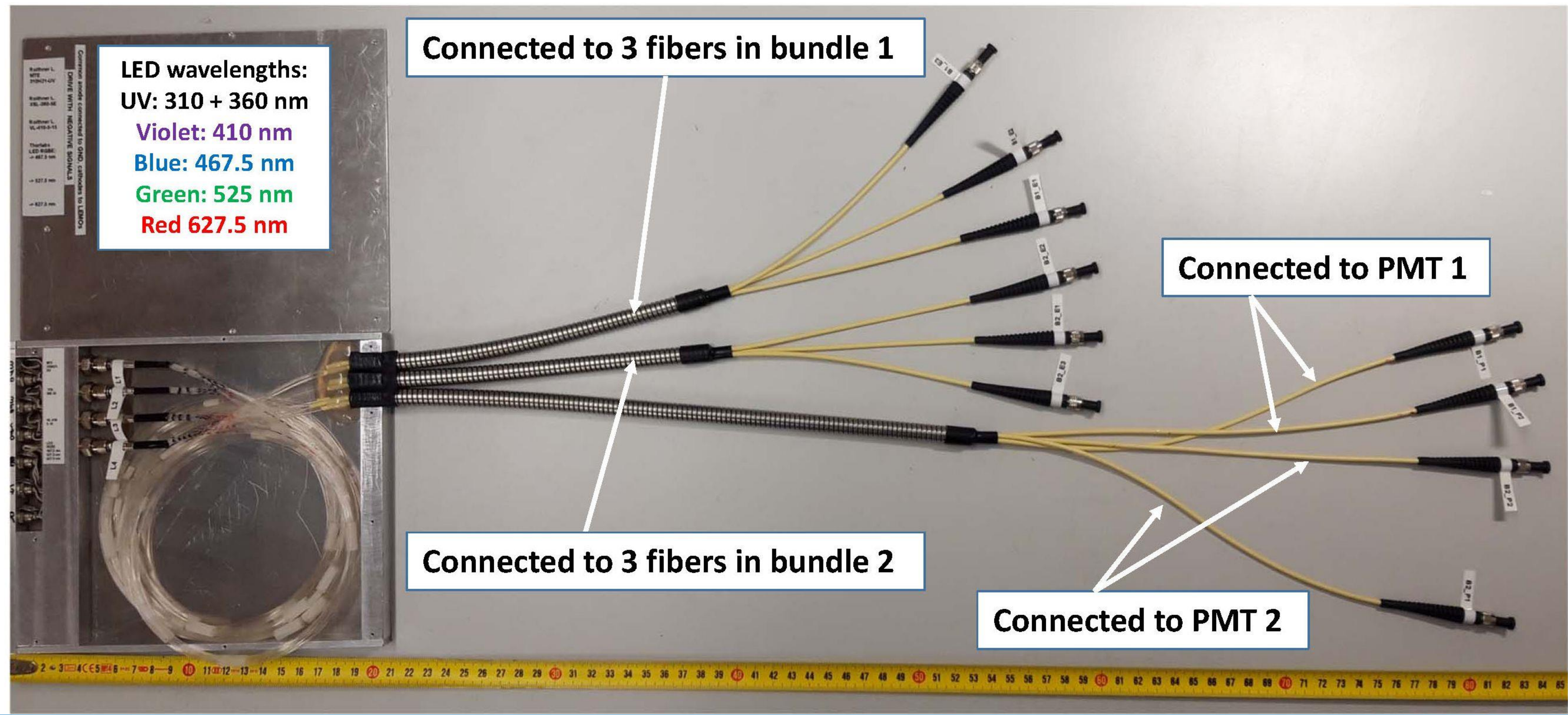
Fiber characterization and calibration



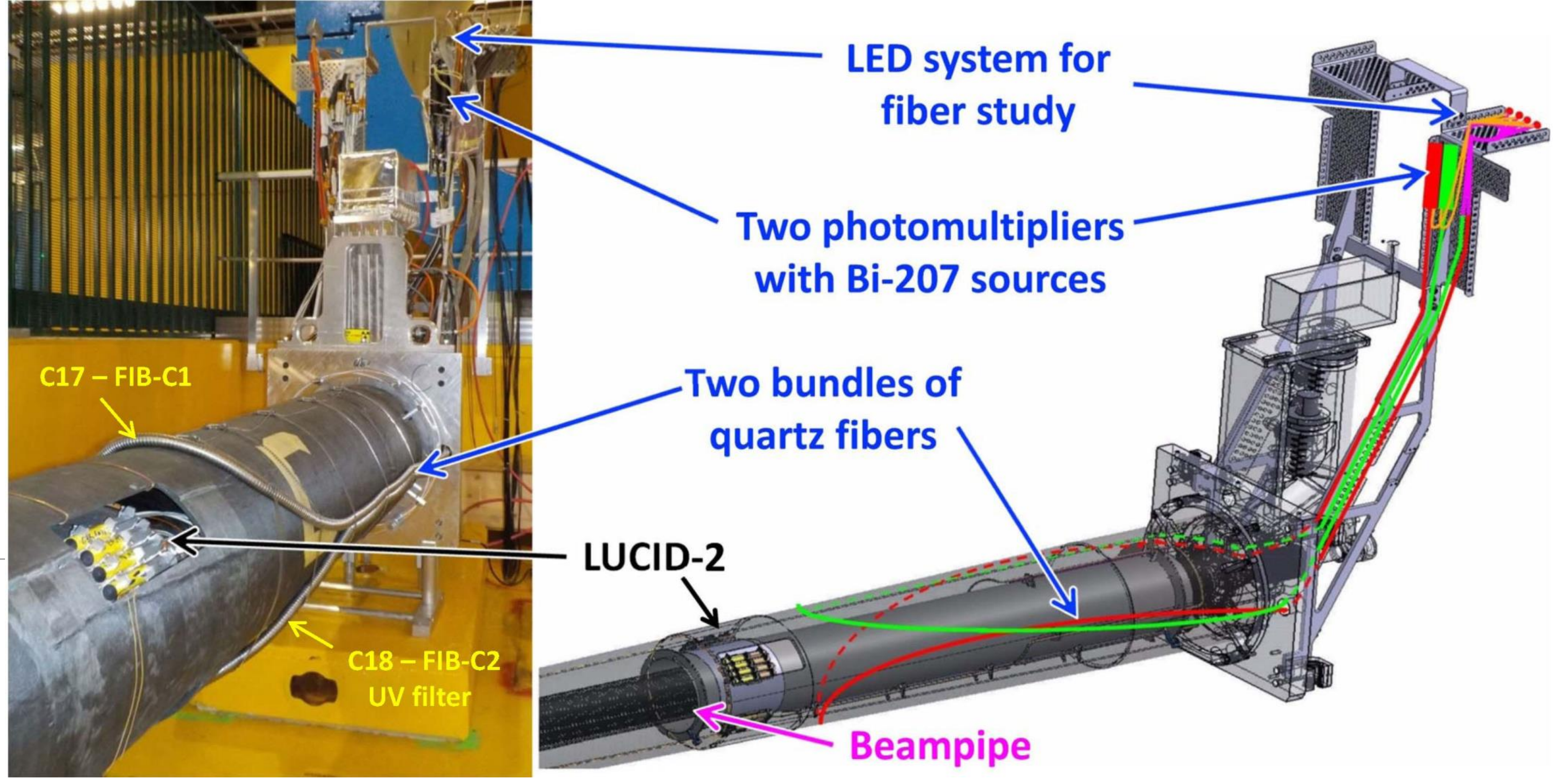
- The fiber degradation is monitored independently from the PMT gain
  - 6 wavelenght LED light is sent directly to the PMT or to the looping fiber
  - The peak ratio is monitored as fiber degradation
- Smilar setups were used in testbeams and irradiation campaigns to study the fiber transmission loss
- Introduction in Fiber A18 of a Cleartran UV filter to reduce relative degradation





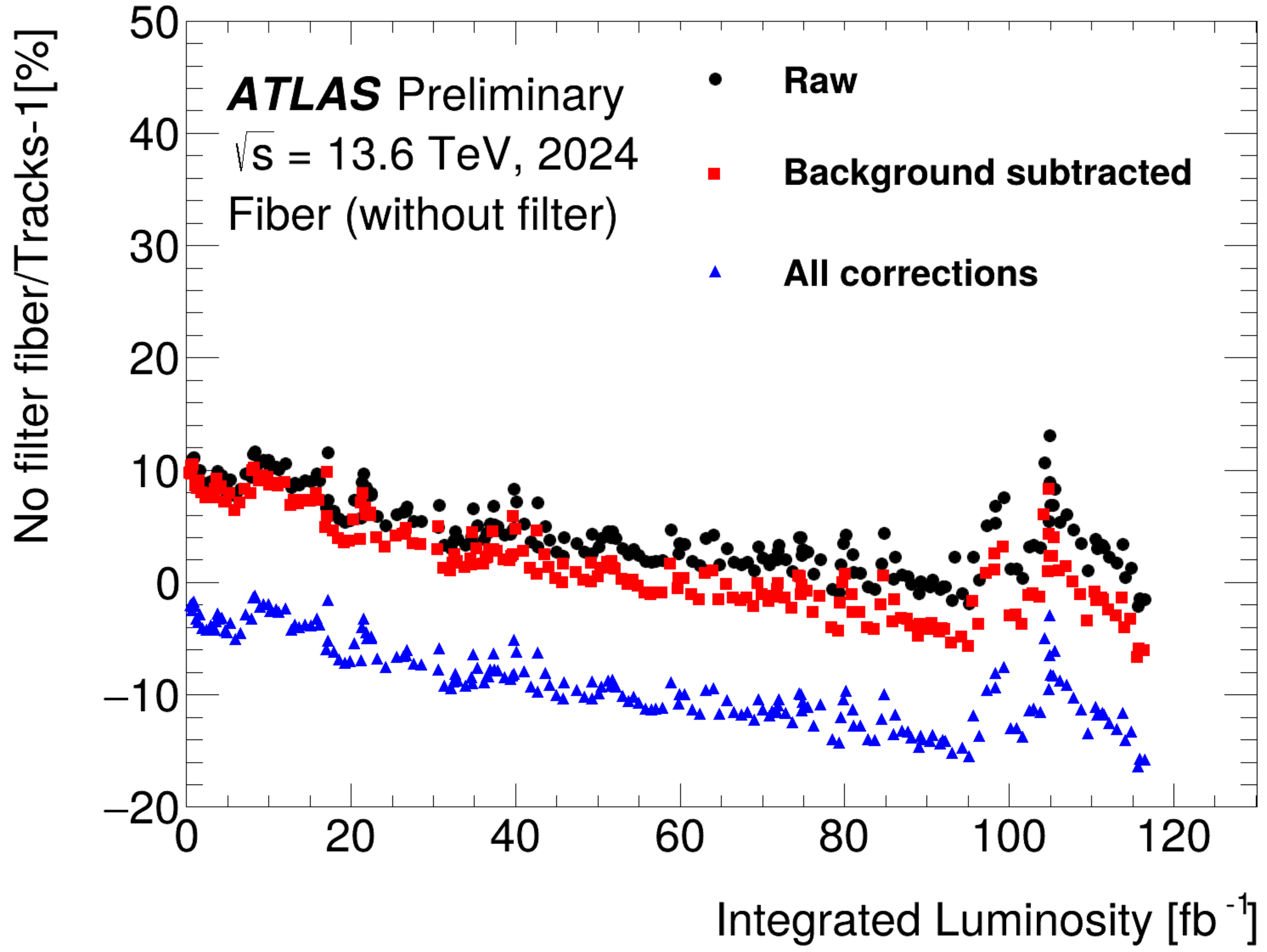


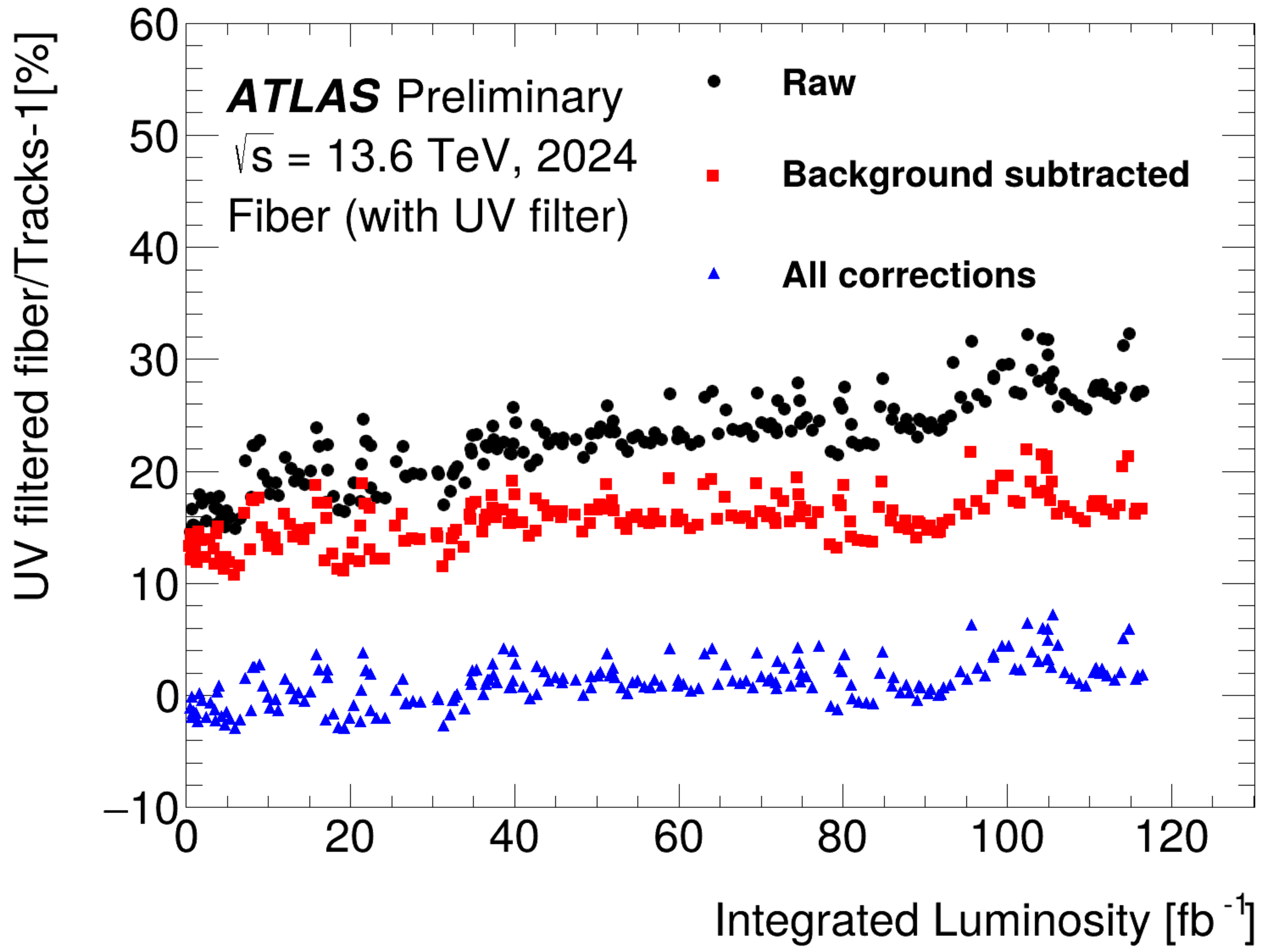
The fiber detector: stability and performance



- Main advantage: large PMTs in shielded area suffer small losses and no failures
- Drawbacks: long signal, large migration-> to be used in charge counting and corrected
- Charge counting: linear with μ, but sensitive to Gain changes

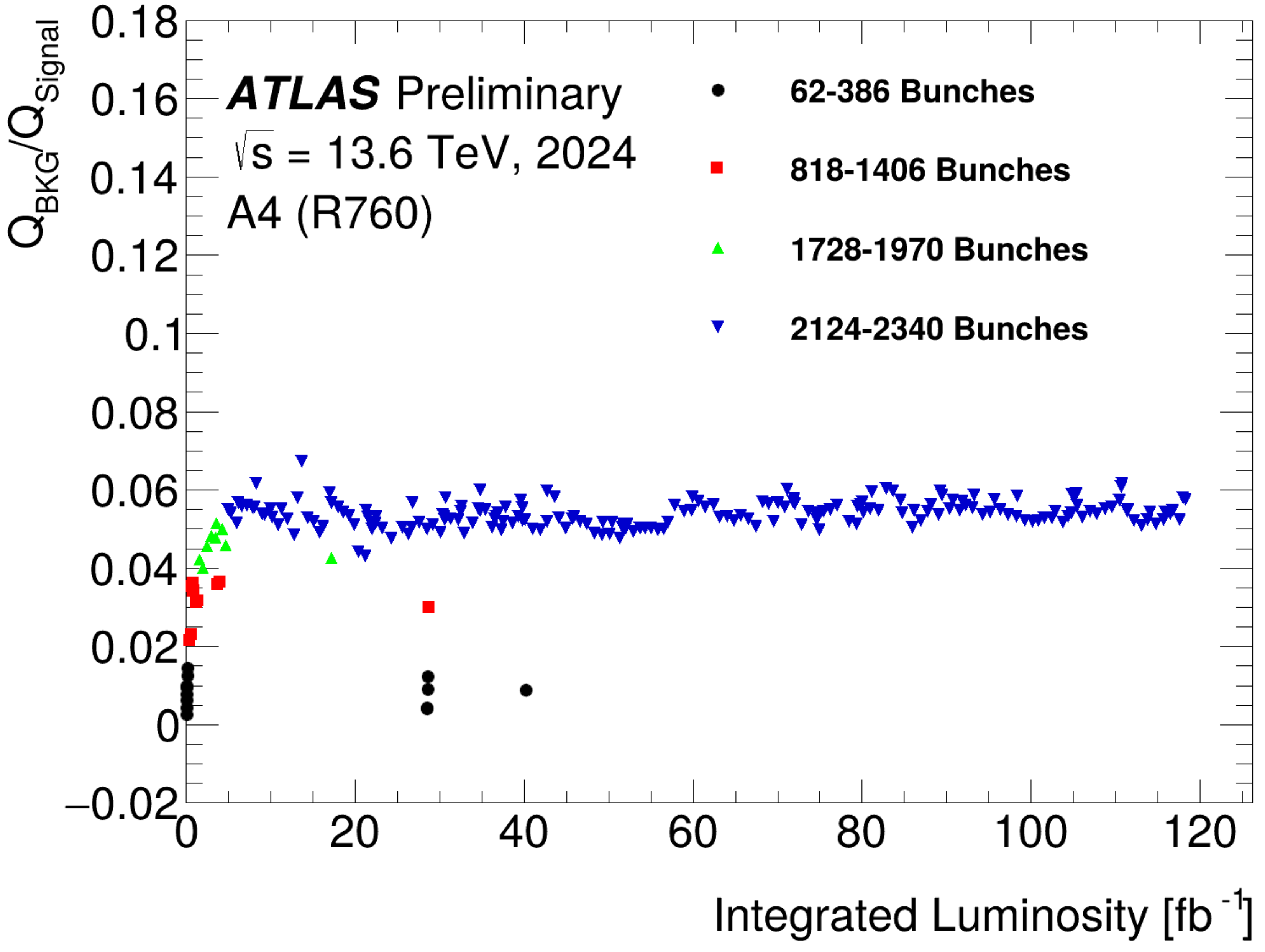
Fluctuations at about 5%
Unfiltered fiber 10% decrease
Backround correction and charge leak correction -> stable filtered fiber

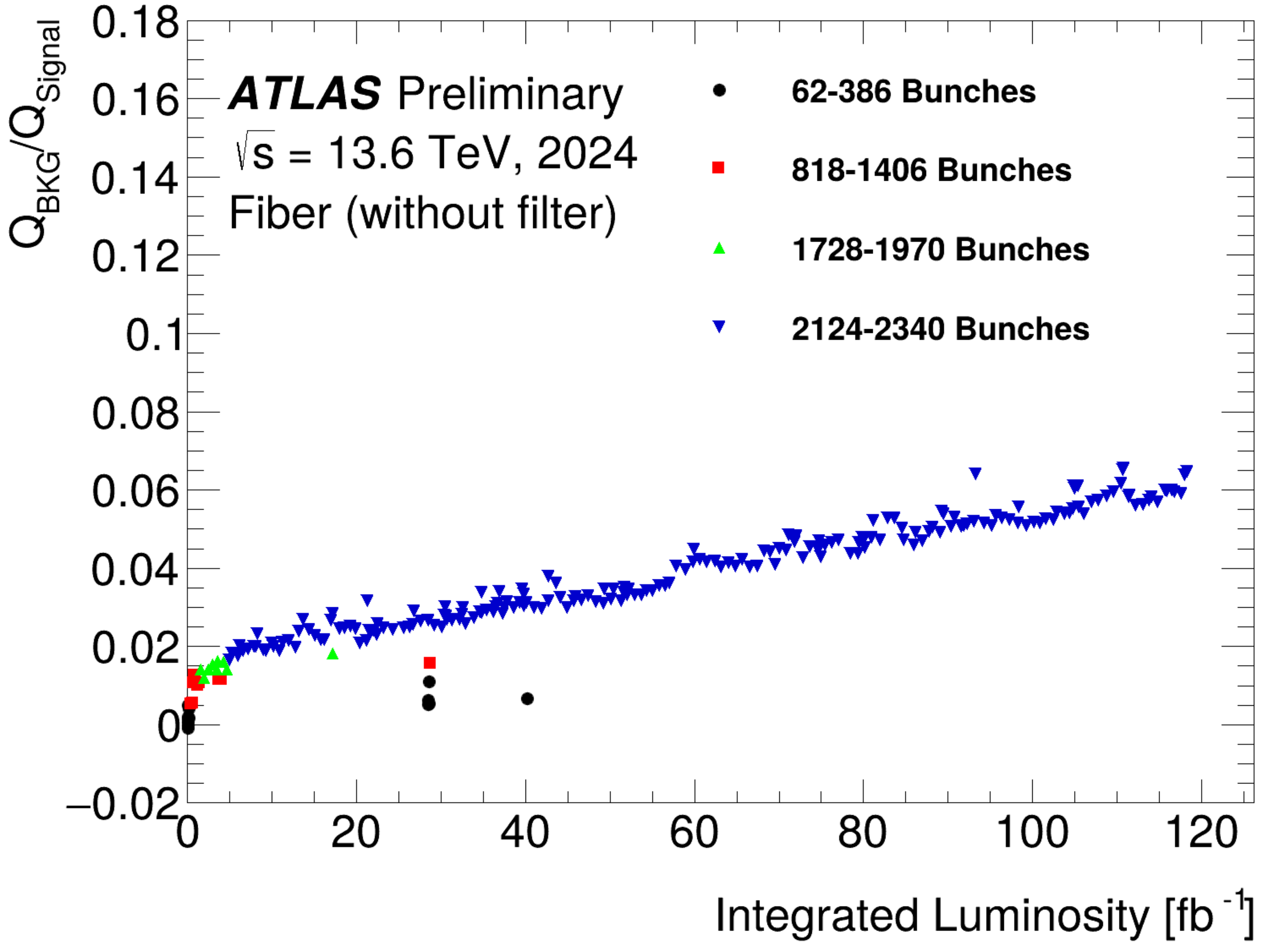


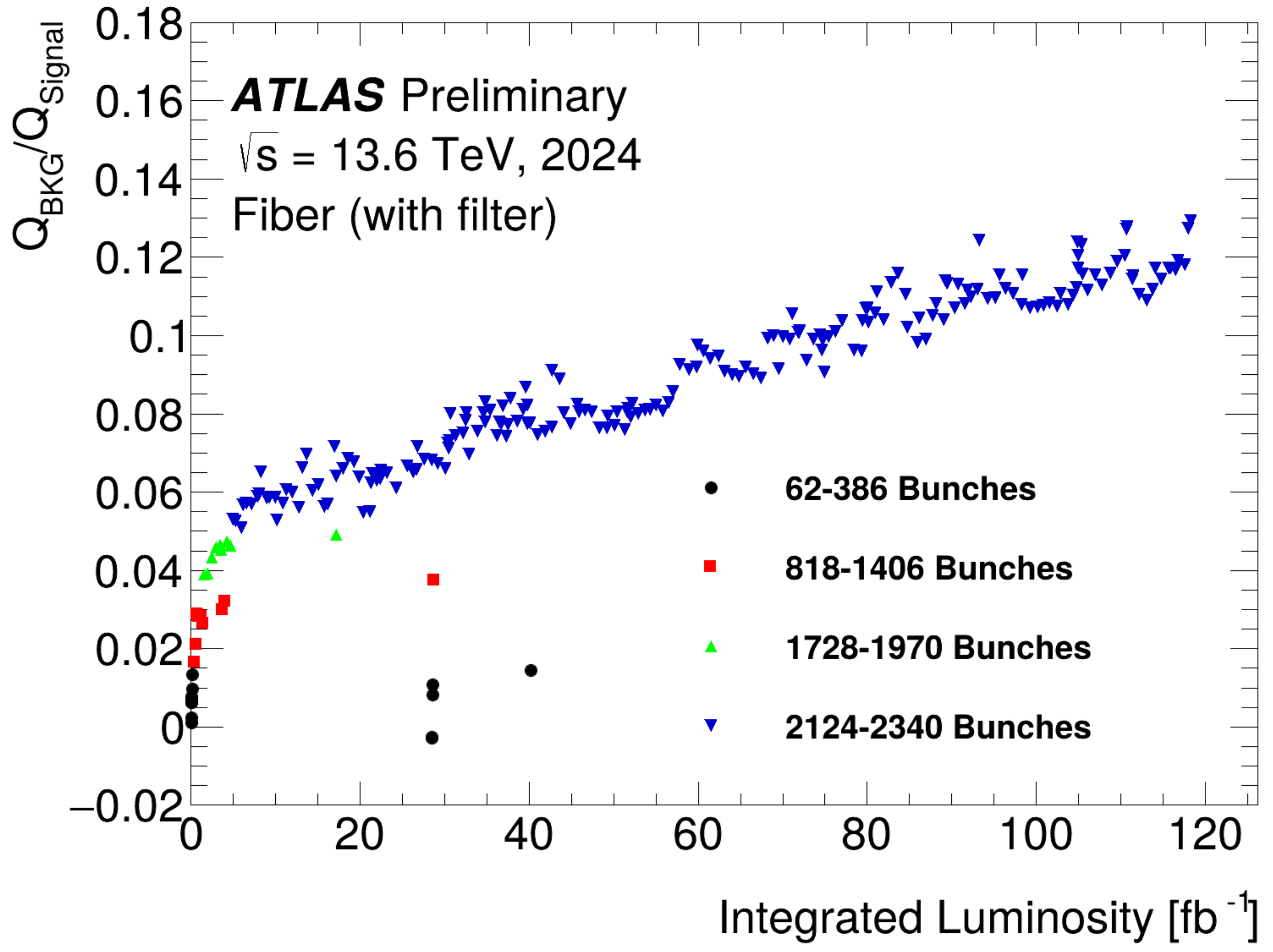


Fiber performance studies

- The drift up investigation shows an effect dependent from time and number of bunches
- Increase linked to defects in doped fused silica created by irradiation
  - Can it be a different process from Cherenkov light? Scintillation?

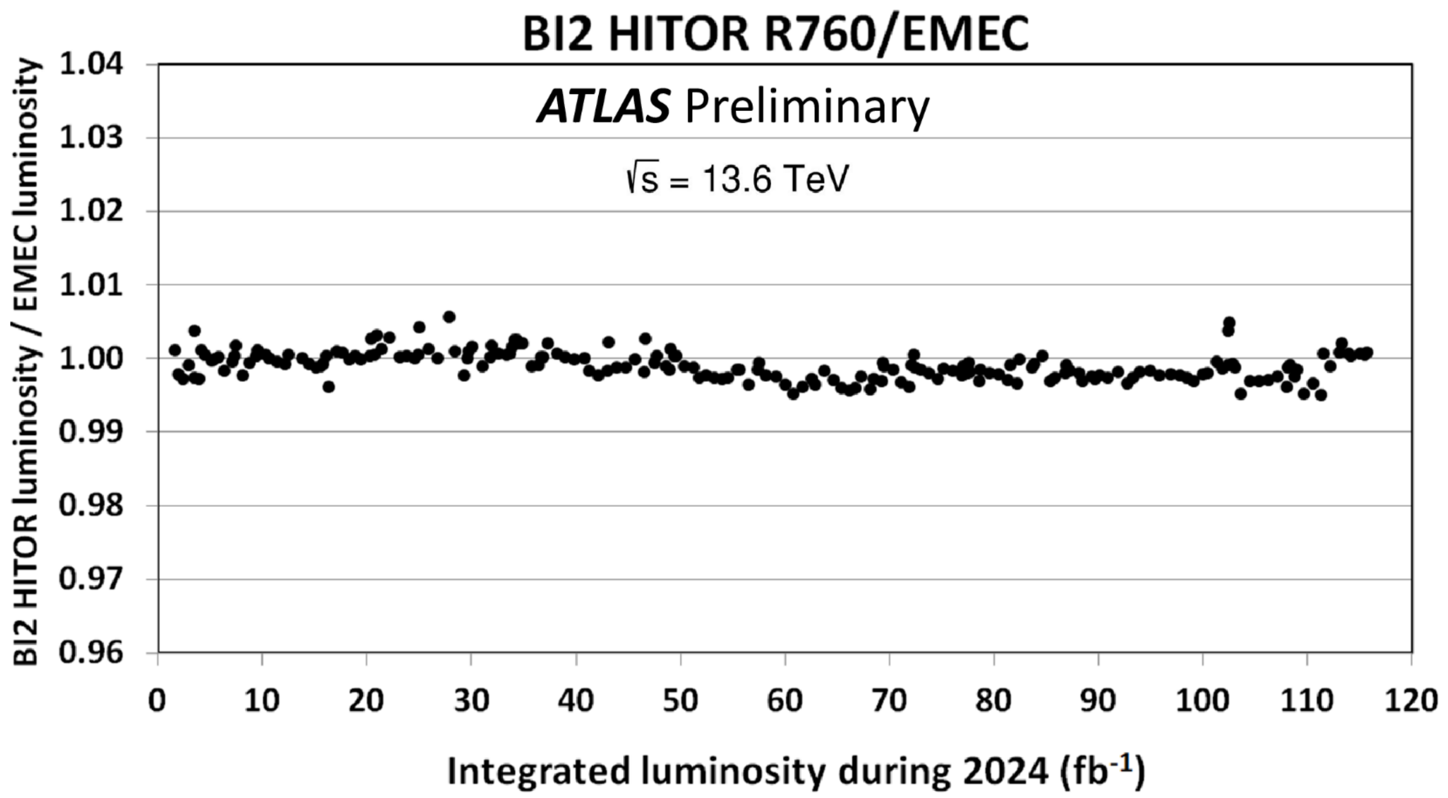


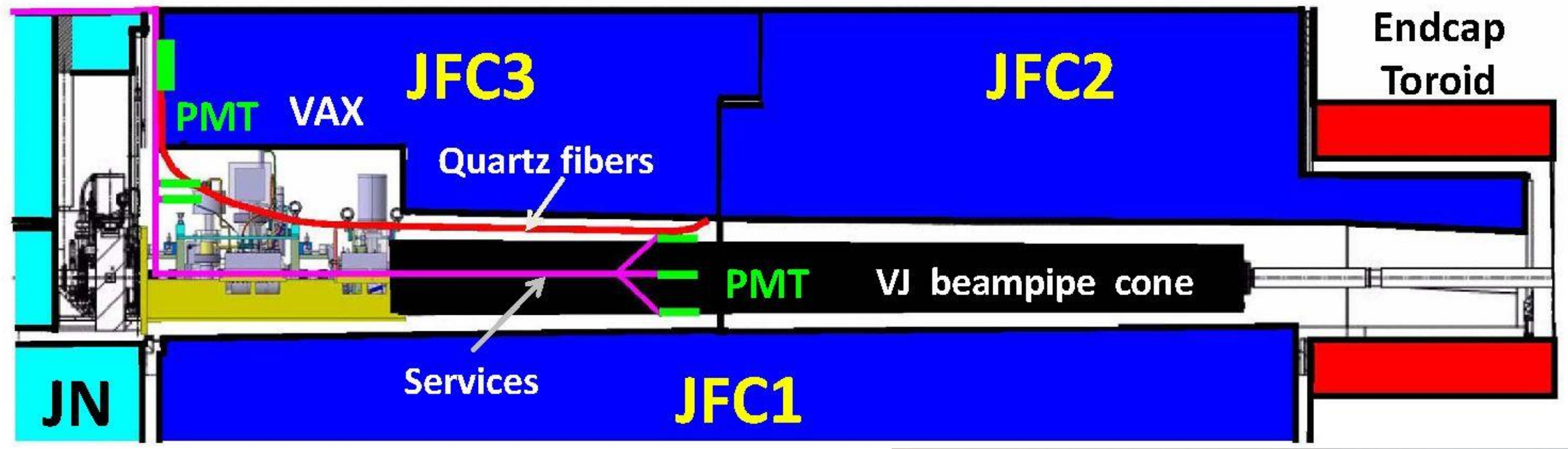


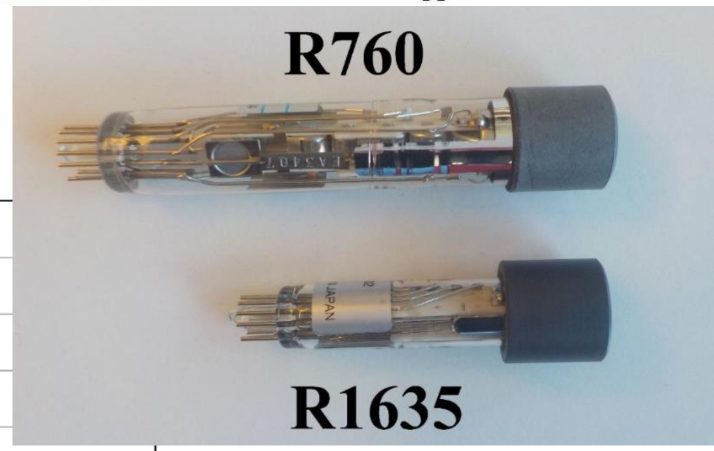


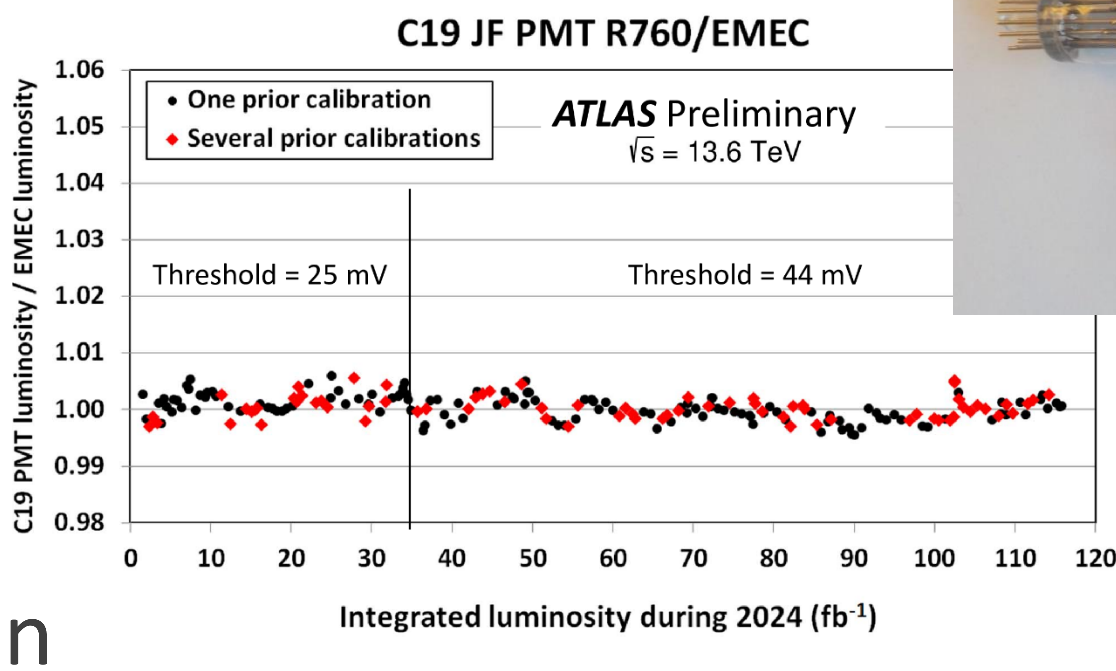
Conclusions

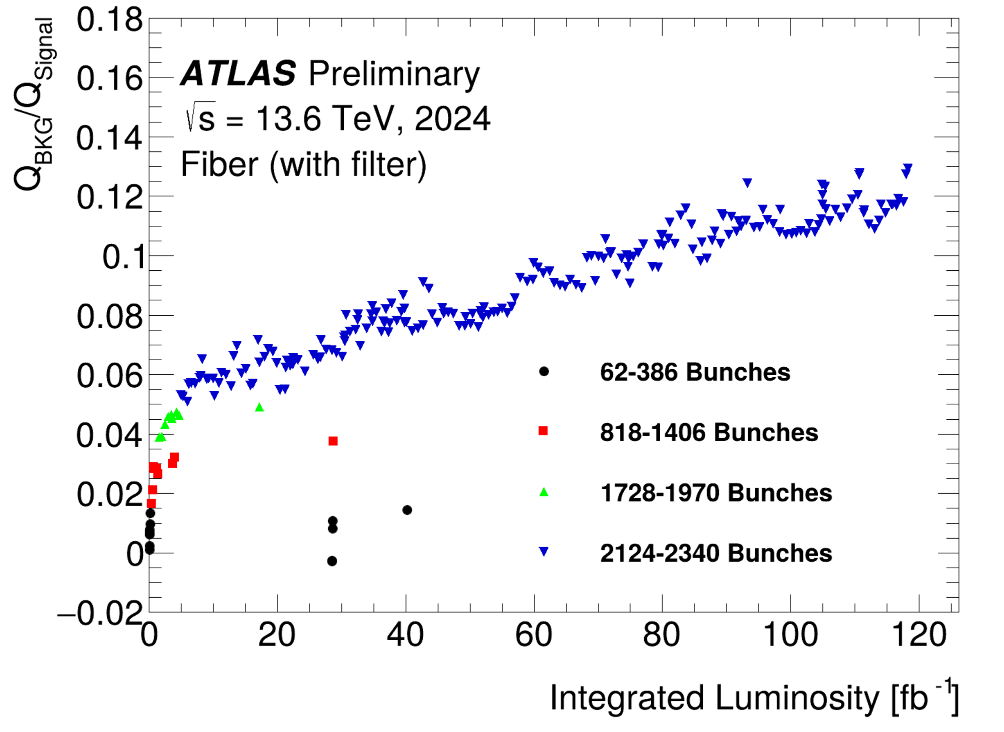
- LUCID 2 performed with exceptional precision and stability over Run2 and Run3
  - Thanks to the simplicity and redundance of the system, as well as the continuous adjustments in operation and extensive analysis work
- A new design will be necessary to cope with HL-LHC μ=200
- Prototypes were introduced in Run 3 to study their performance
  - Small modified R1635 PMTs -> stability issues under investigation
  - JFC detector performs as expected with R760s, investigating higher threshold behaviour
  - JN detector showed good linearity and stability -> working on optimization
  - The fiber detector showed good linearity, working on stability
    - Interesting effects discovered, under investigation











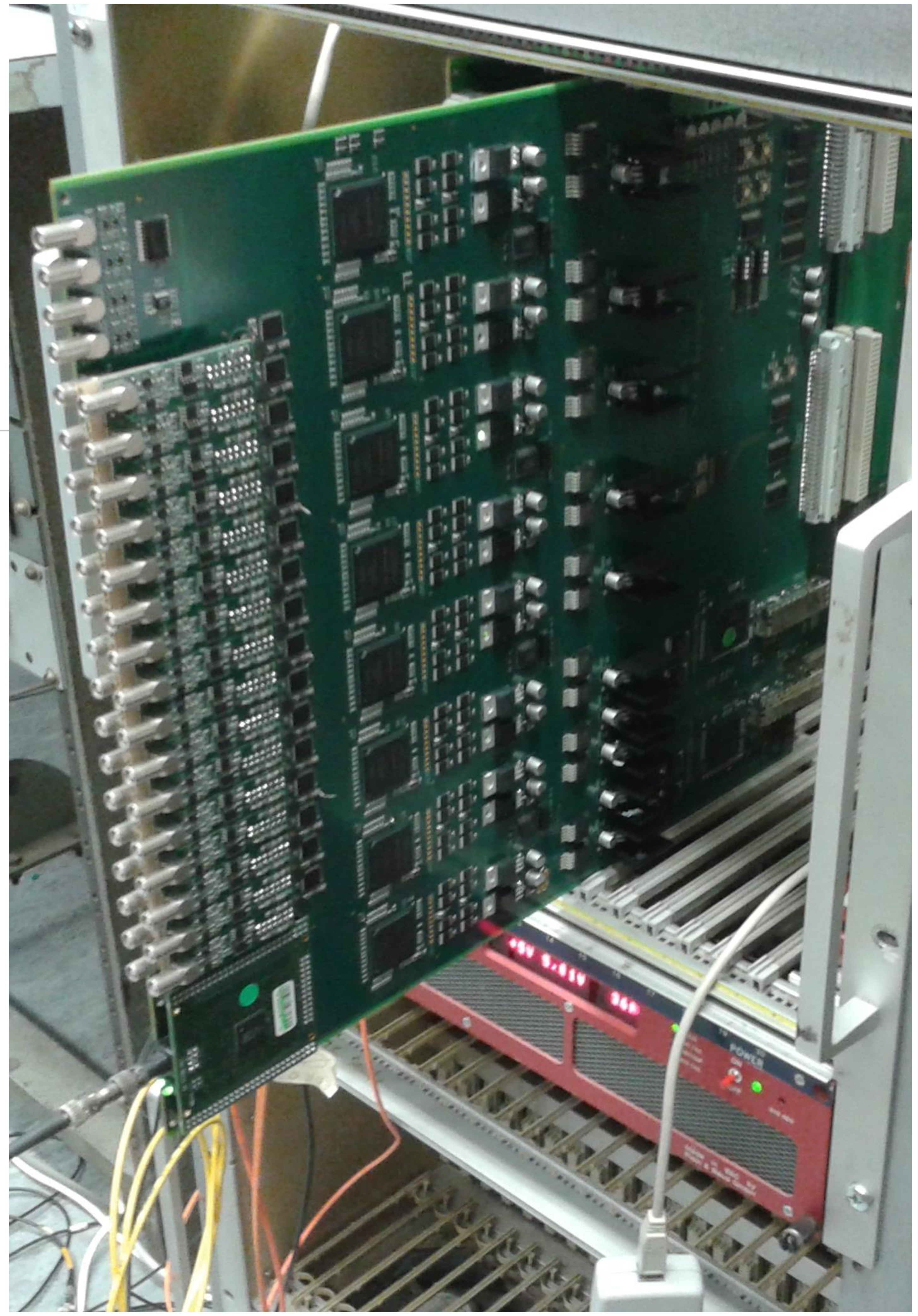
Merci de votre attention!

The LUCROD board

Each board has 16 input channels, each connected to a different PMT or other analog input. Positioned close to the detector.

Main components of the LUCROD board:

- a low noise amplifier and a 320 MHz FADC for each input channel
- a FPGA for each pair of inputs, integrating the input signal over each bunch crossing and discriminating hits
- an additional FPGA implementing luminosity algorithms and optical link communication
- an optical link to transmit the defined signals (hits) to the LUMAT board
- an analog amplified output for each input



Flow: digitization -> hit definition -> charge integration

- Single-PMT algorithms published, greatly increasing the flexibility and control

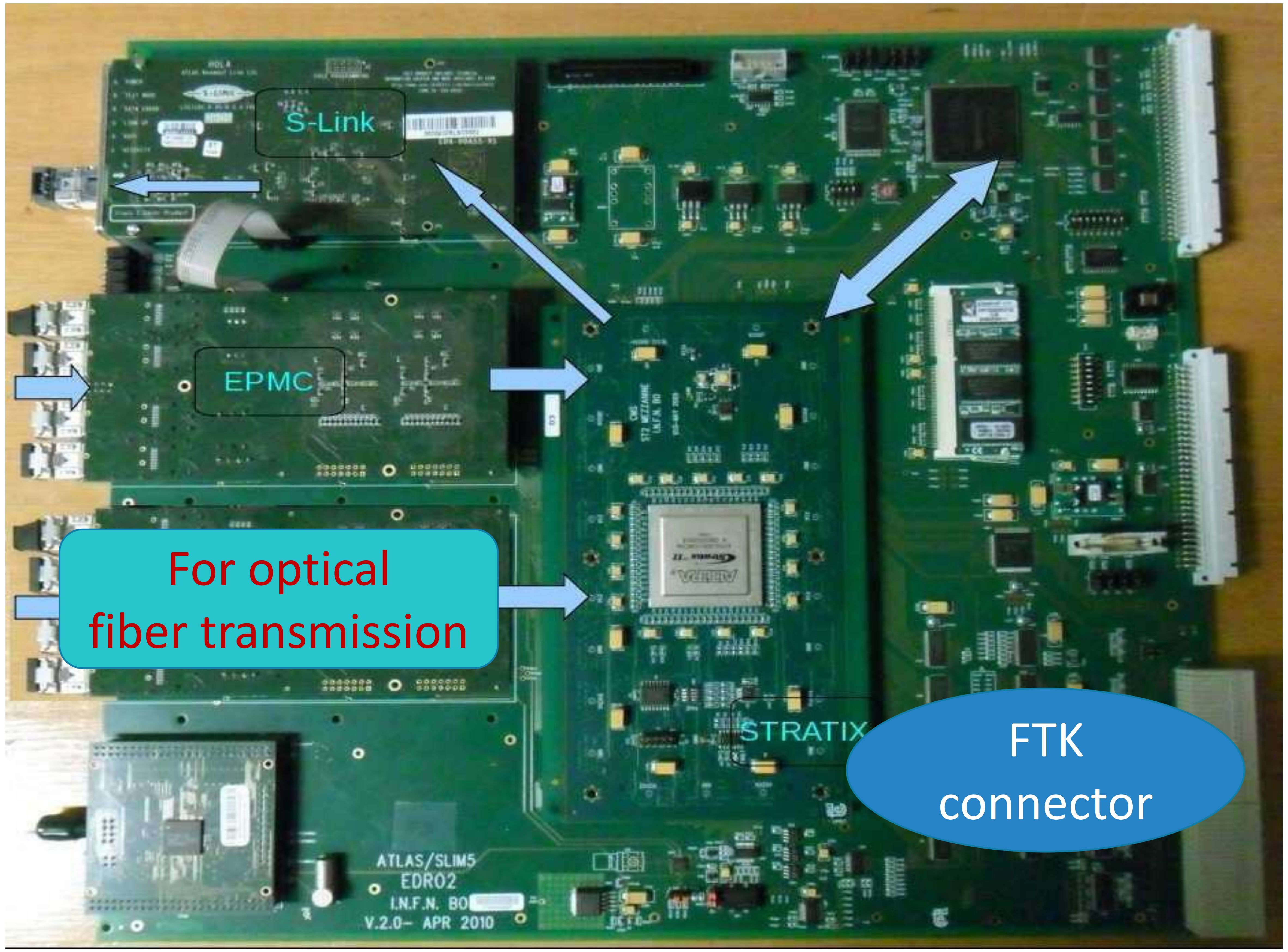
Not rad-hard, but in shielded area: occasional Single Event Upsets have been observed.
Operative solution: cross-check counters and trigger a firmware reload automatically in case of SEU

The LUMAT board

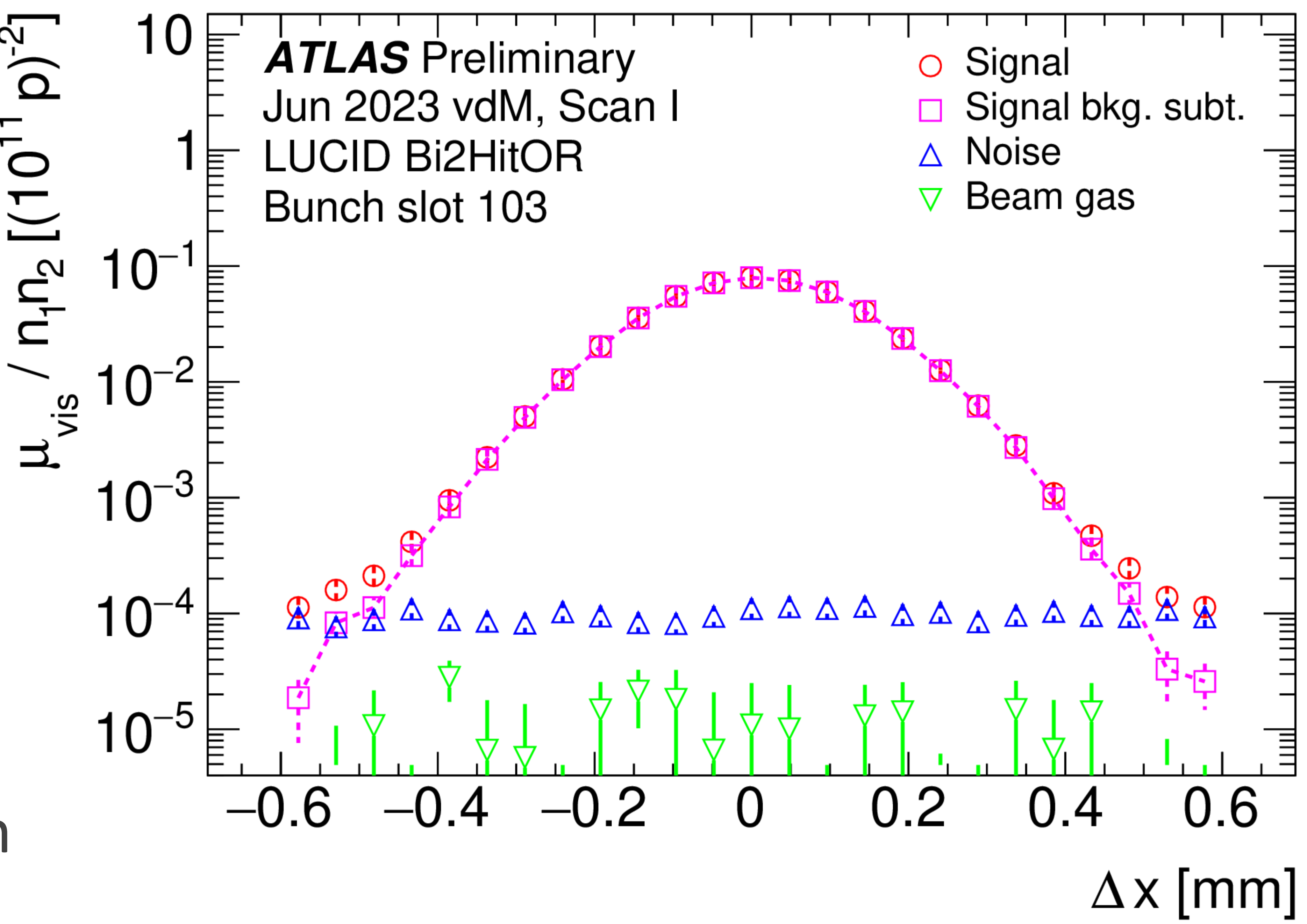
- Fiber communication with LUCROD's, over 100 m, using 100 MHz transceivers → hit patterns
- Time alignment of side A and C inputs, with performance monitoring
- Computing luminosity algorithms @40 MHz:
  - Based on hit counting and event counting
  - With combination of information from both detectors (12 algorithms)
- Algorithms are published:
  - Every LB, differentiating each BCID
  - Every LB, integrating all BCID's (12 + single-PMT's)
  - Every 2 s, to ATLAS and LHC for online luminosity (12 + single-PMT's)

Both boards publish hit patterns online, which are then processed for luminosity.

Developed with Fast Tracker!

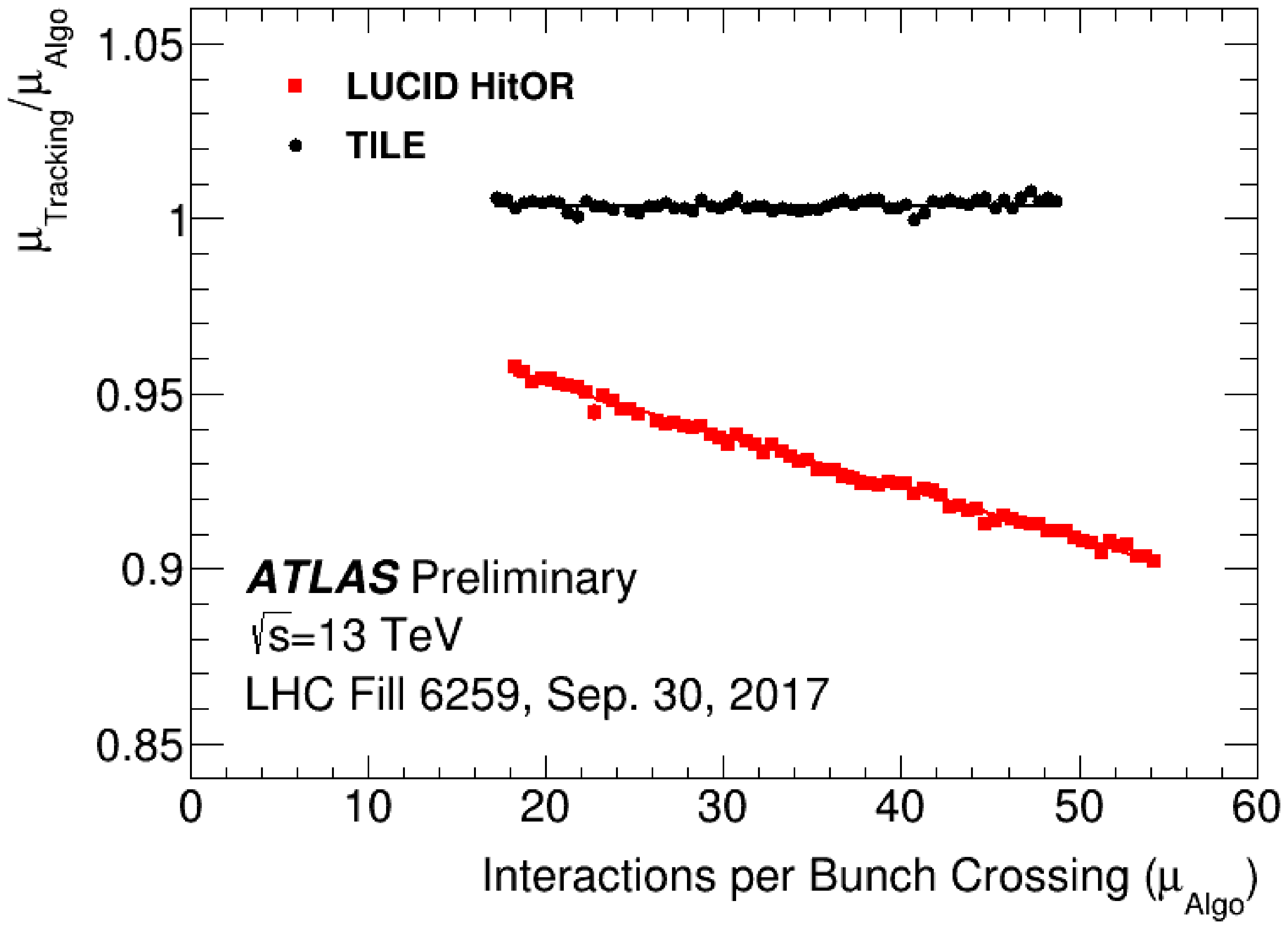


Luminosity measurement: Absolute calibration



Van der Meer Scan: dedicated calibration run

- Beam separations are shifted in steps of 50 µm in the horizontal & vertical directions
- At each step the visible interaction rate µ-vis is measured
- Convoluted beam width is measured, detector calibrated using beam paramenters



LUCID suffers from µ-dependence (not linear with µ)

- LUCID needs another detector to calculate a correction ->
  - It cannot operate completely stand-alone!
- Using tracks for the correction
- Absolute Calibration transfer: transfer VdM scan result from calibration (low-µ) to physics (high-µ)
- Measured µ corrected to be valid in the full µ range
- Charge integration linear with µ

µ = average number of interactions per BC

Threshold tests on R760 PMTs

Threshold studies:

- μ -dependence increses with Threshold
- Saturation under study