PLUME Cherenkov Luminometer for LHCb

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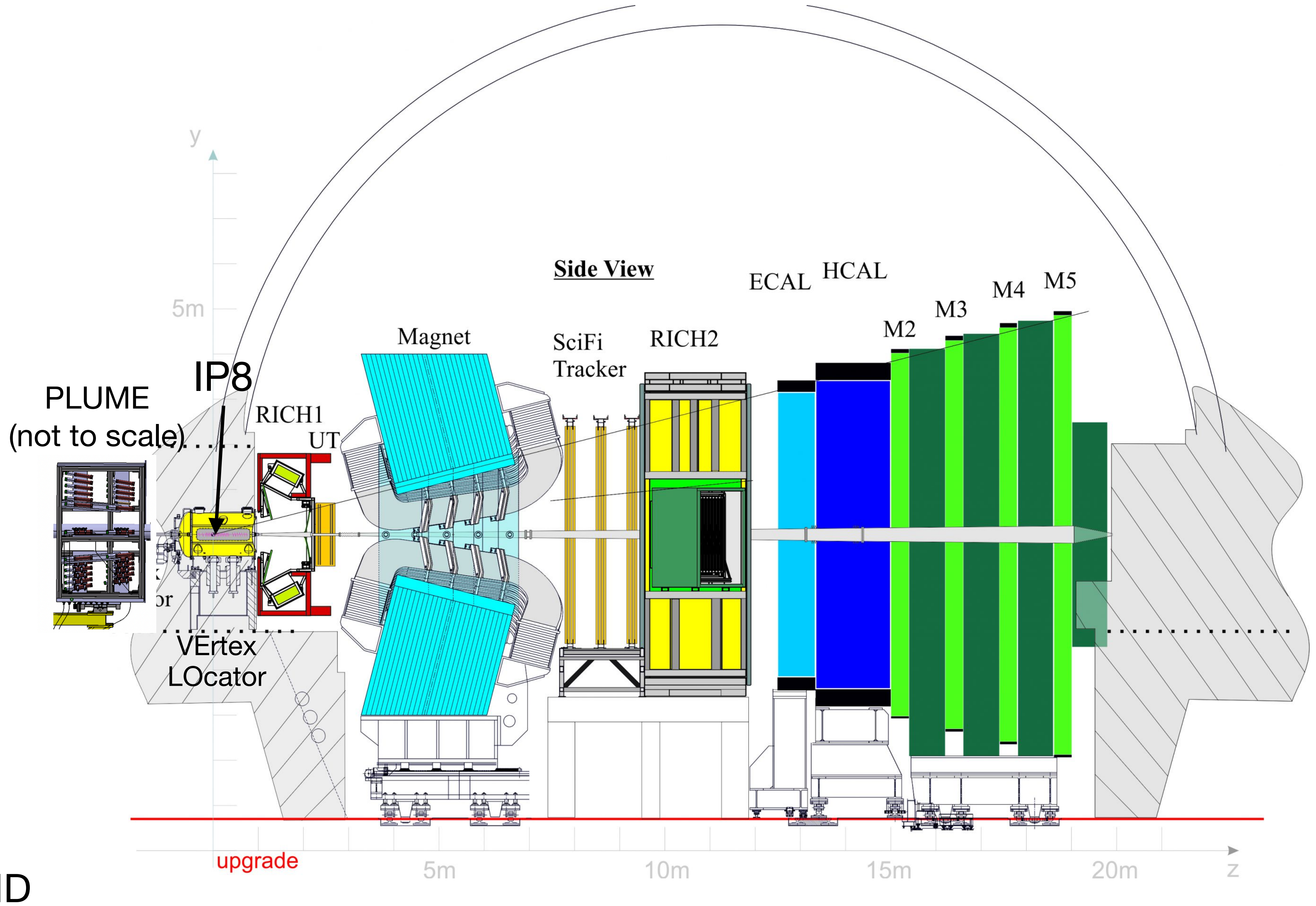
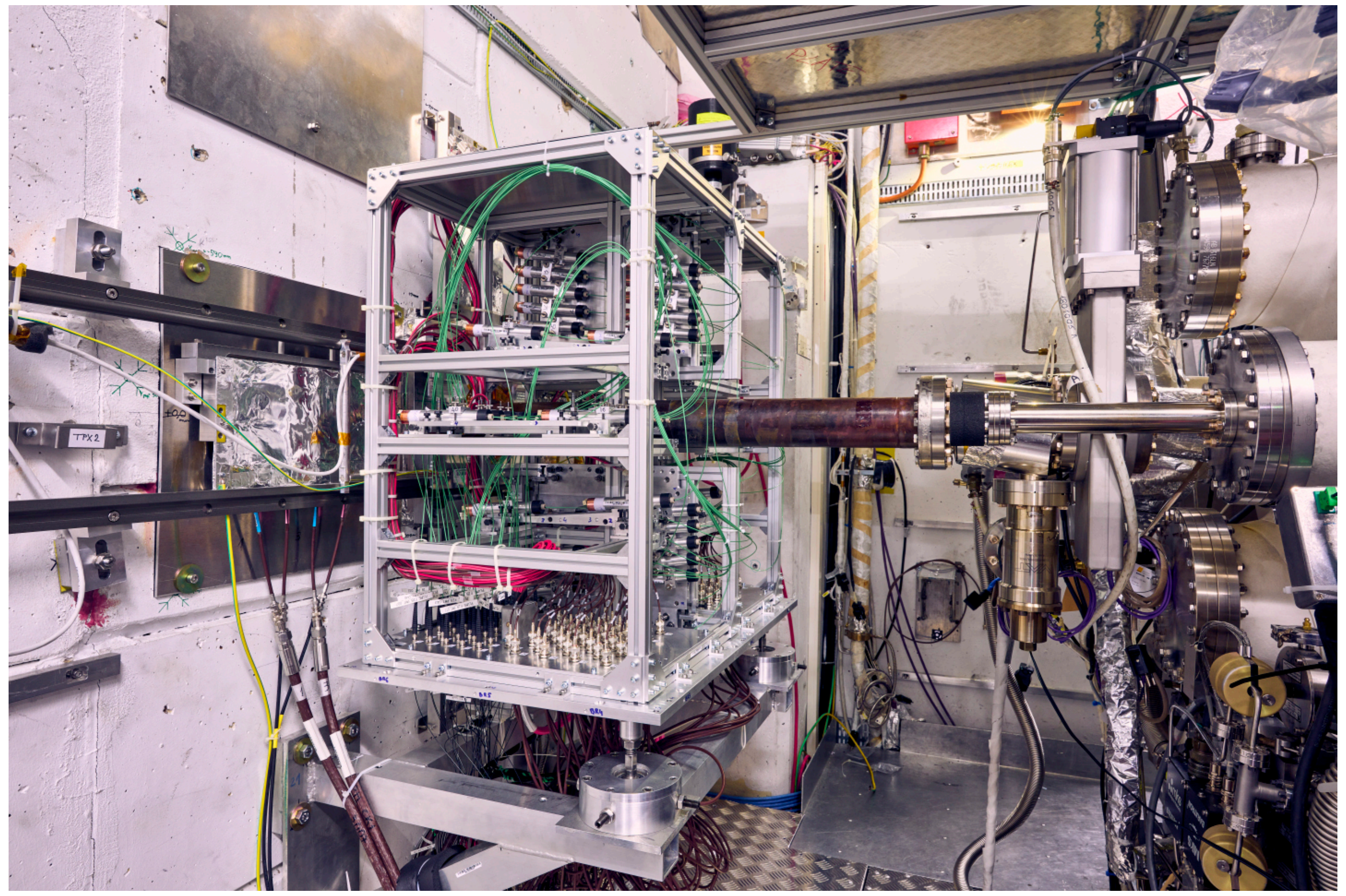
LHCb detector in a nutshell

- Single-arm forward spectrometer at **LHC at CERN**
  - For **heavy flavour studies** at high rapidity
  - Collisions pp, pA, AA; fixed target with SMOG(2)
- Massive **Upgrade** during LS2
  - **Wide range of technological solutions**
- **Trigger**
  - Switched to full **40 MHz read-out** with GPU real-time analysis
    - L0 hardware trigger removed
- Vertex Locator **VELO**
  - Silicon microstrips -> **silicon pixels**
- **Tracking**
  - Tracker Turencis -> Upstream Tracker UT
    - **Silicone microstrips**, upgraded resolution
  - Inner Tracker (removed) - silicon microstrips
  - Outer Tracker -> SciFi tracker
    - Straw drift tubes -> **Scintillating fibres with SiPM**



- PID
  - RICH1/2: **Gas radiator** (+aerogel in Run 1) with Hybrid PD -> **MaPMT readout**
- Calorimetry (sampling calorimeters with Pb/Fe and organic scintillators)
  - SPD/PS (removed): scintillating pads with Pb converter in between
  - ECAL: **Shashlik** geometry with WLS and PMT readout, Pb absorbers
  - HCAL: **Tiles** with WLS and PMT, Fe absorbers
- Muon system
  - Gaseous detectors: **MWPC** (low-occupancy) and **GEM** (high-occupancy)
- Luminosity and beam monitoring
  - **PLUME**, RMS, BCM

Probe for LUminosity MEasurement - PLUME

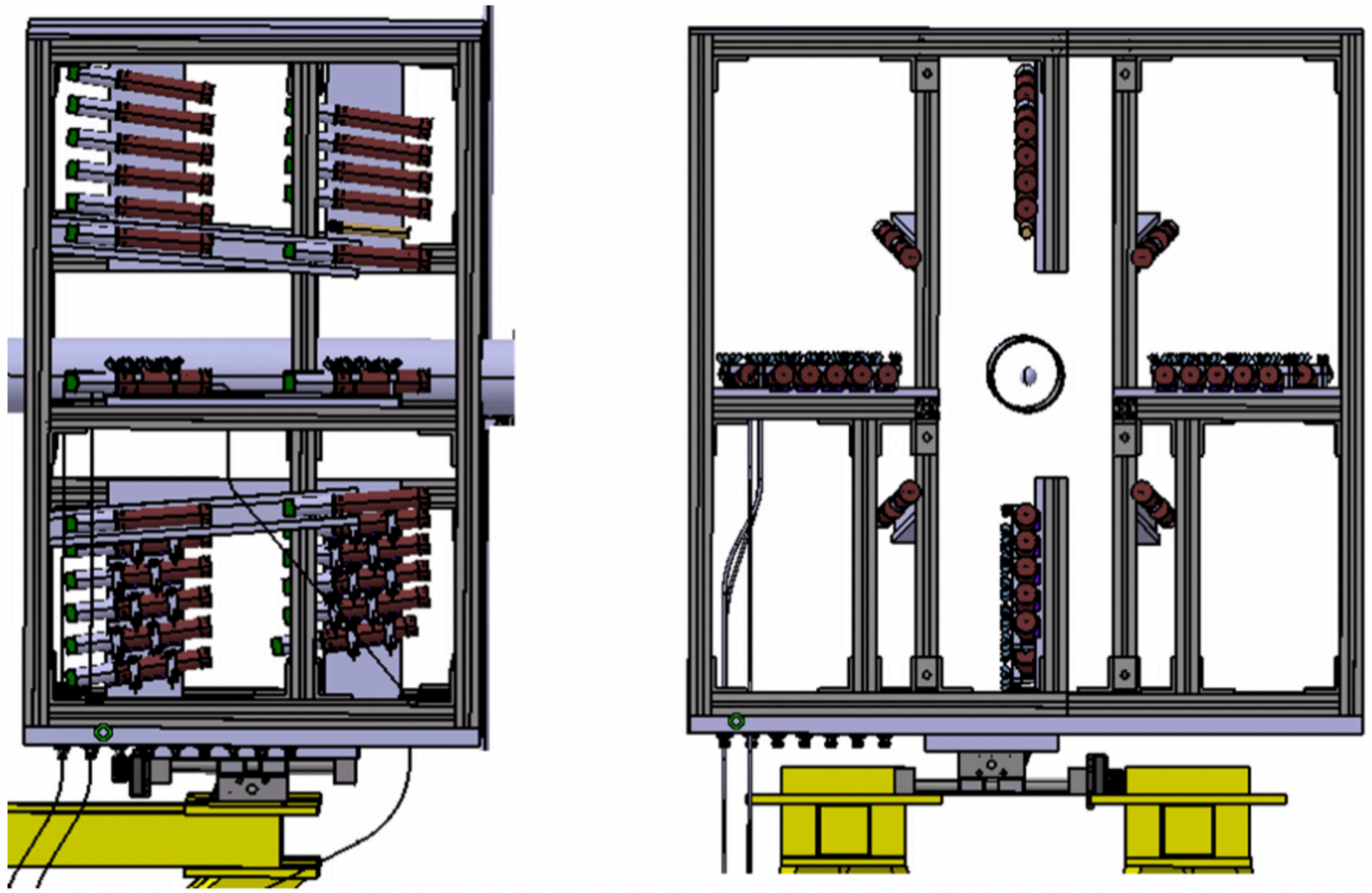


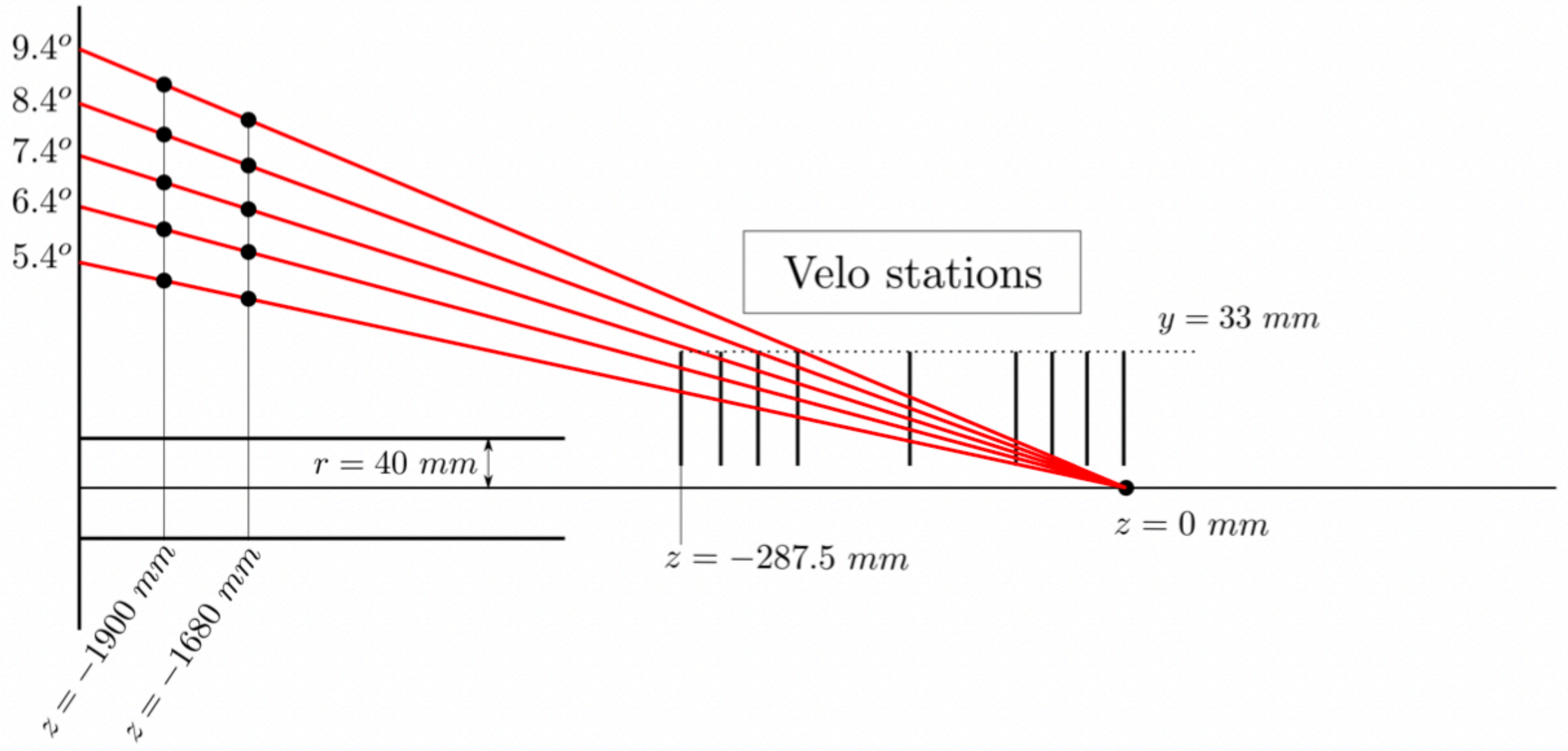
- **New dedicated luminometer for Run 3**
- Main goals
  - Producing **fast alarms**
  - **Online/offline luminosity** measurement
  - **Feedback to LHC** for luminosity leveling
  - Contribute to centrality determination for **heavy-ion** and **fix-target** programme
- Challenges
  - Highly **radioactive environment**
  - **Restricted space** available
  - **Integration** in LHCb detector
- **Technical design report**

- Collaborating institutes
  - **IN2P3 IJCLab Orsay**: production, installation, alignment, front-end electronics…
  - **EPFL Lausanne**: DAQ, monitoring
  - **INFN Bologna**: PMT characterisation, calibration, back-end electronics
  - **LLR Palaiseau**: luminosity
  - **TSNUK Kyiv**: simulation, prototypes, test beam
  - **ISMA Kharkiv**: irradiation tests, prototypes
  - **CERN-LHCb**: software, infrastructure

Detector design

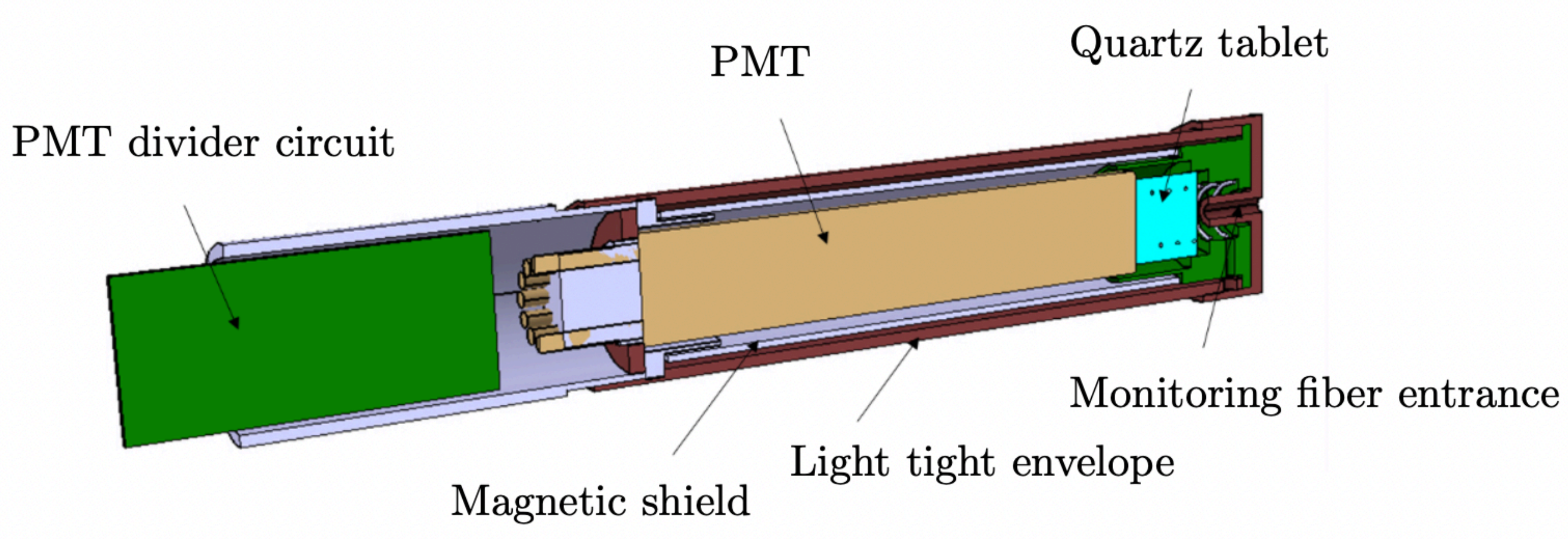
- **Two projective hodoscope layers** of elementary modules detecting **Cherenkov light** from charged particles going upstream from the interacting region
  - **2*24 PMTs** in a "snowflake" shape
  - Cover angles 5°-10° ($2.4 < \eta < 3.1$ in rapidity)
- Elementary modules
  - PMT with **quartz window** and attached **quartz tablet** for increased light yield
  - Measure **integrated charge per bunch crossing,** and **yes/no** response
- Calibration and monitoring
  - Tracks reconstructed with upstream **VELO**
  - Signal amplitudes at **single MIP**
  - **Light from LED** carried to PMTs by **quartz fibers**



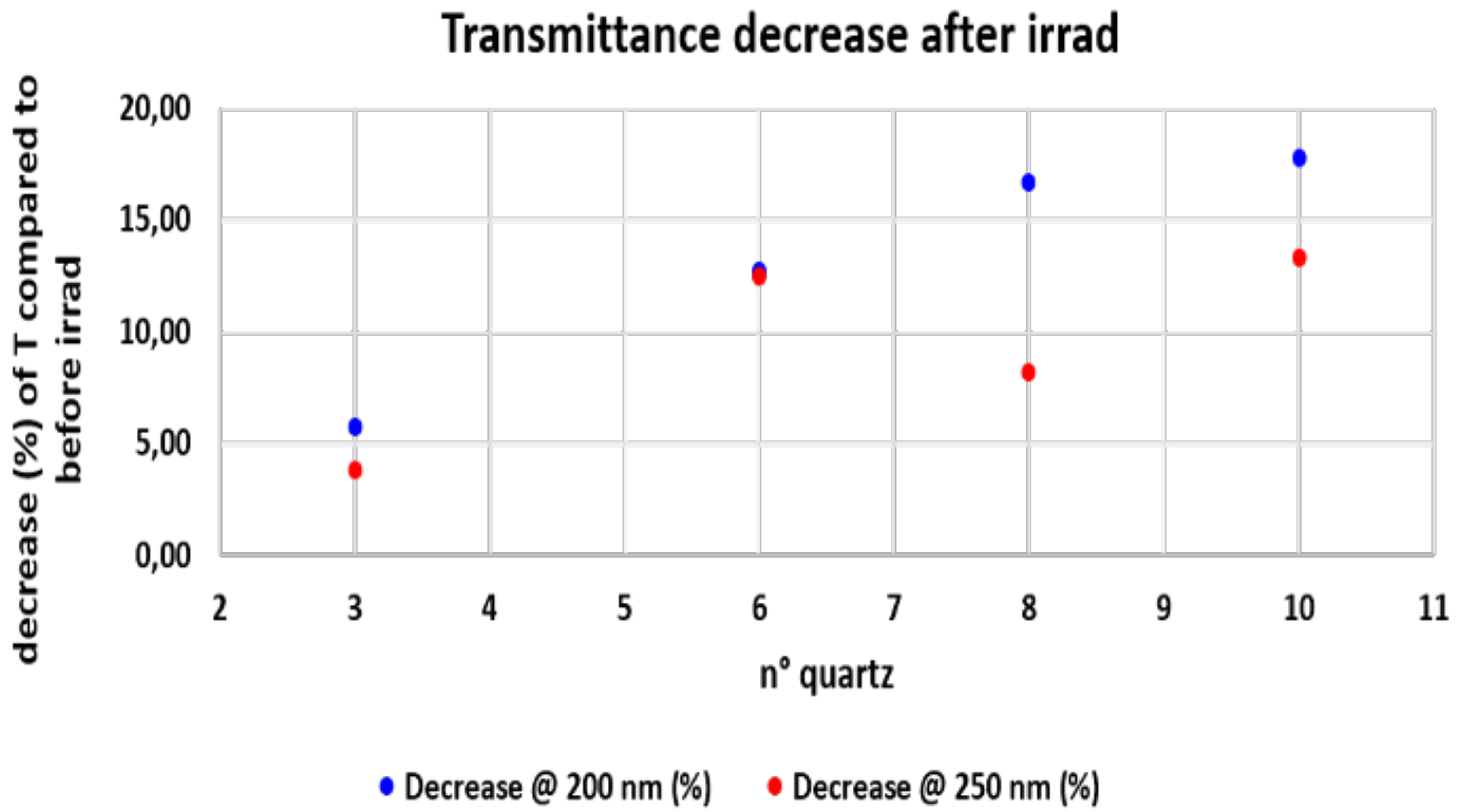


Elementary module

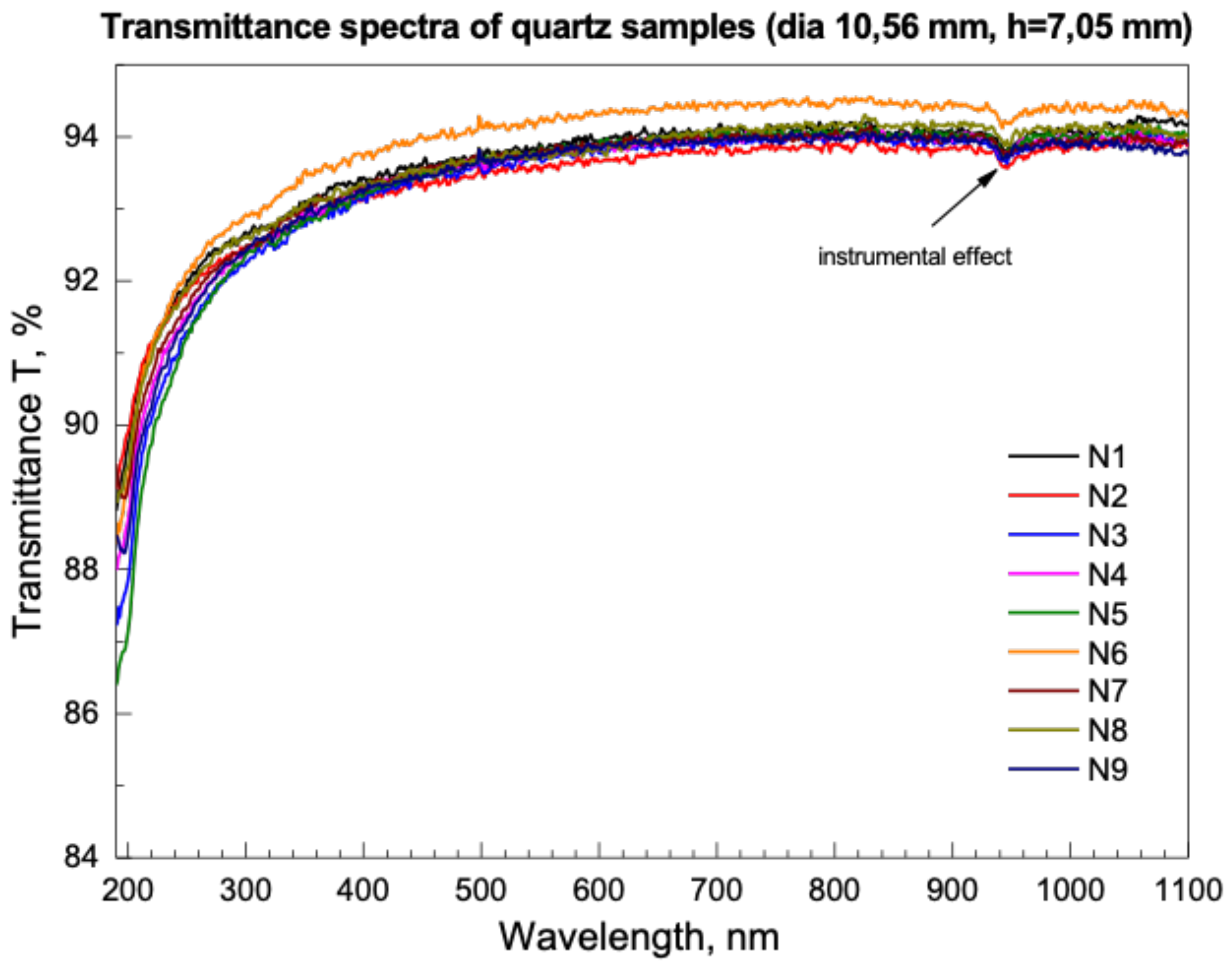
- PMT R760 with quartz tablet **optically coupled**
- Custom-designed divider circuit
- Light tight module



- Irradiation test of Corning HPFS 7980 quartz tablets



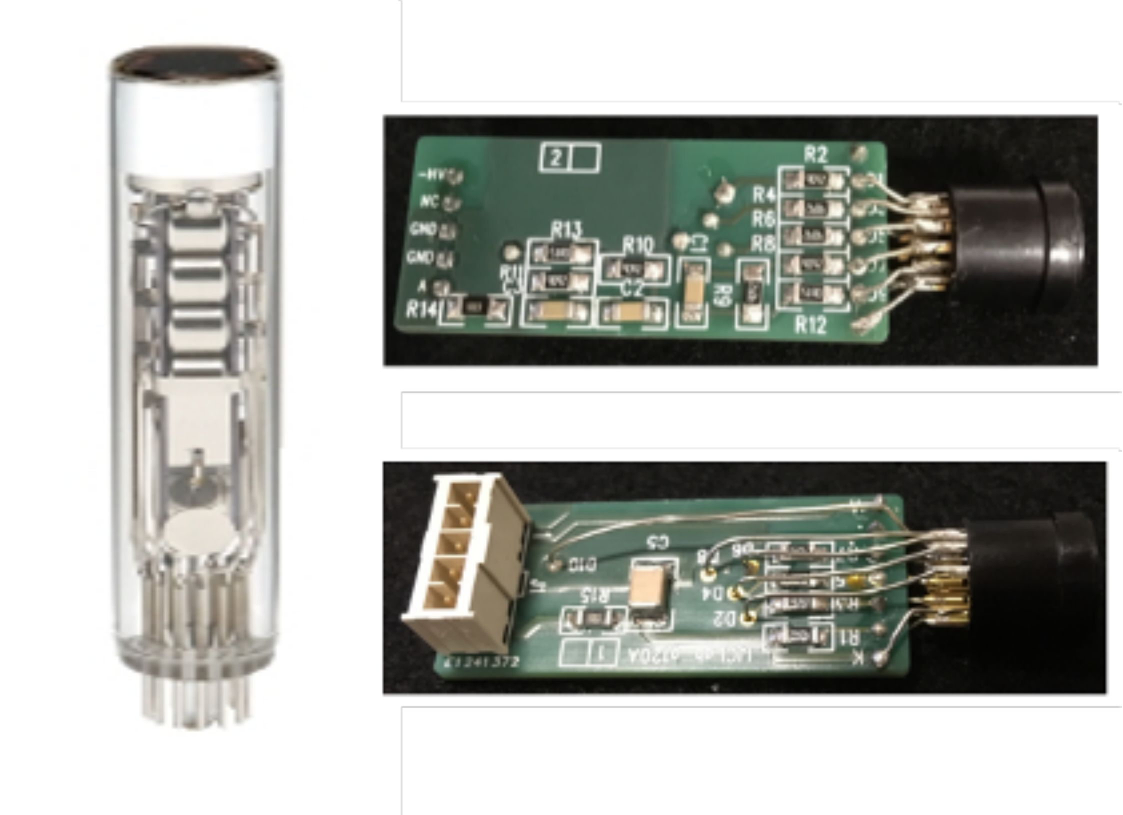
- Quartz tablets, first batch of Heraeus Spectrosil 2000



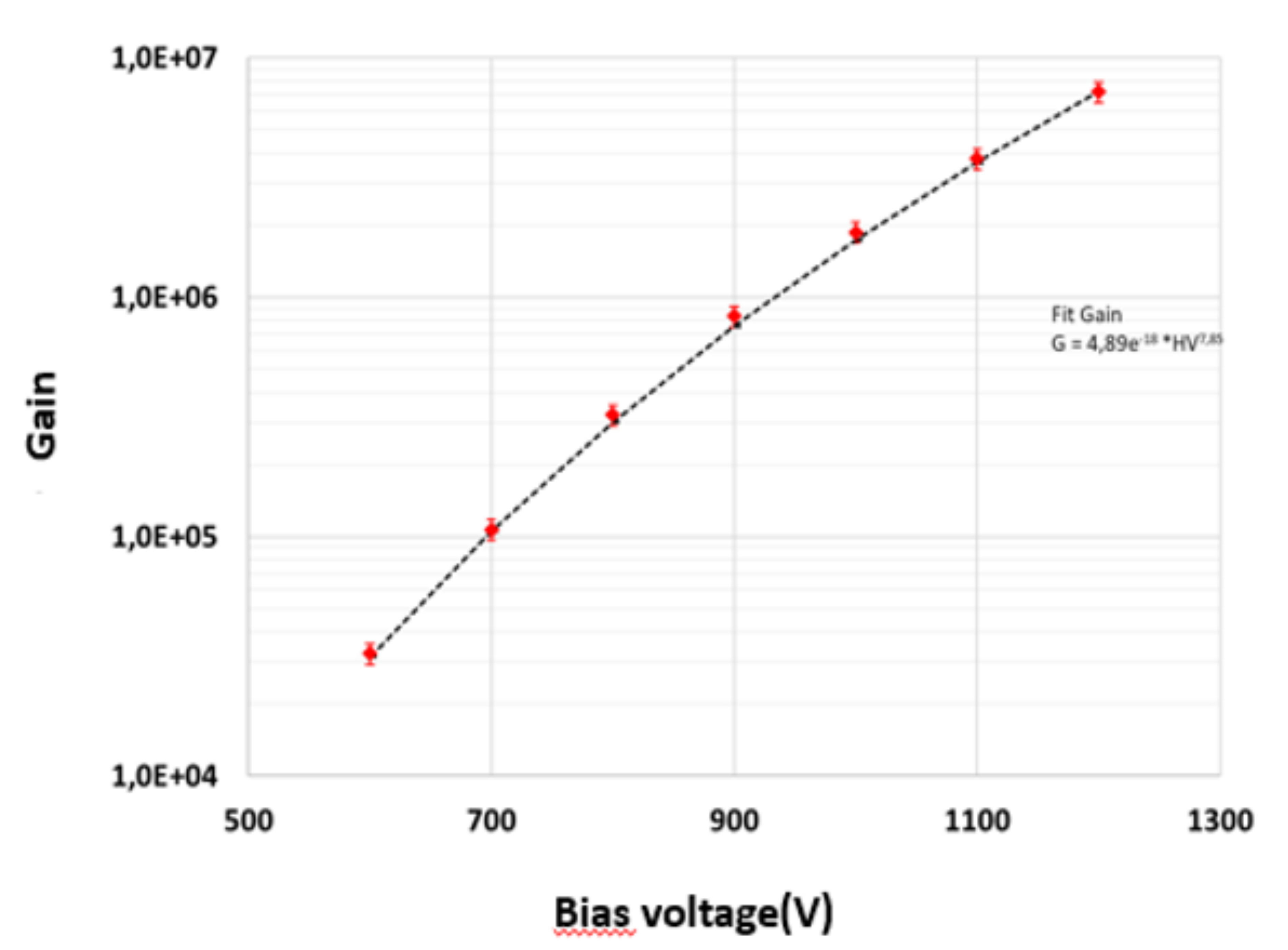
Elementary module

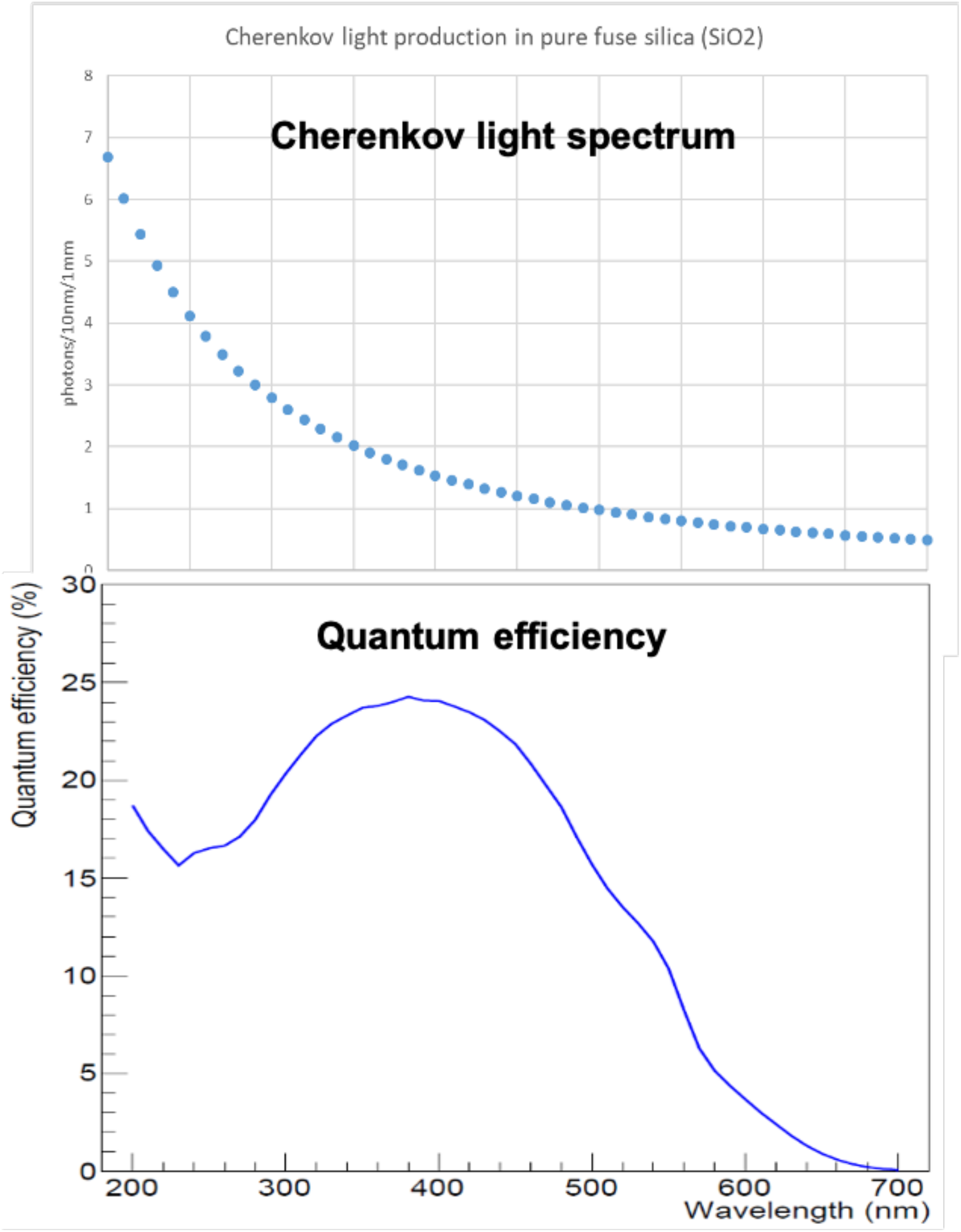
- PMT Hamamatsu R760
  - Robust technology and materials (borosilicate, quartz and metal – all **radiation resistant**) **already used by LUCID** (ATLAS)

PMT R760 and divider circuit



Gain curve for PMT R760

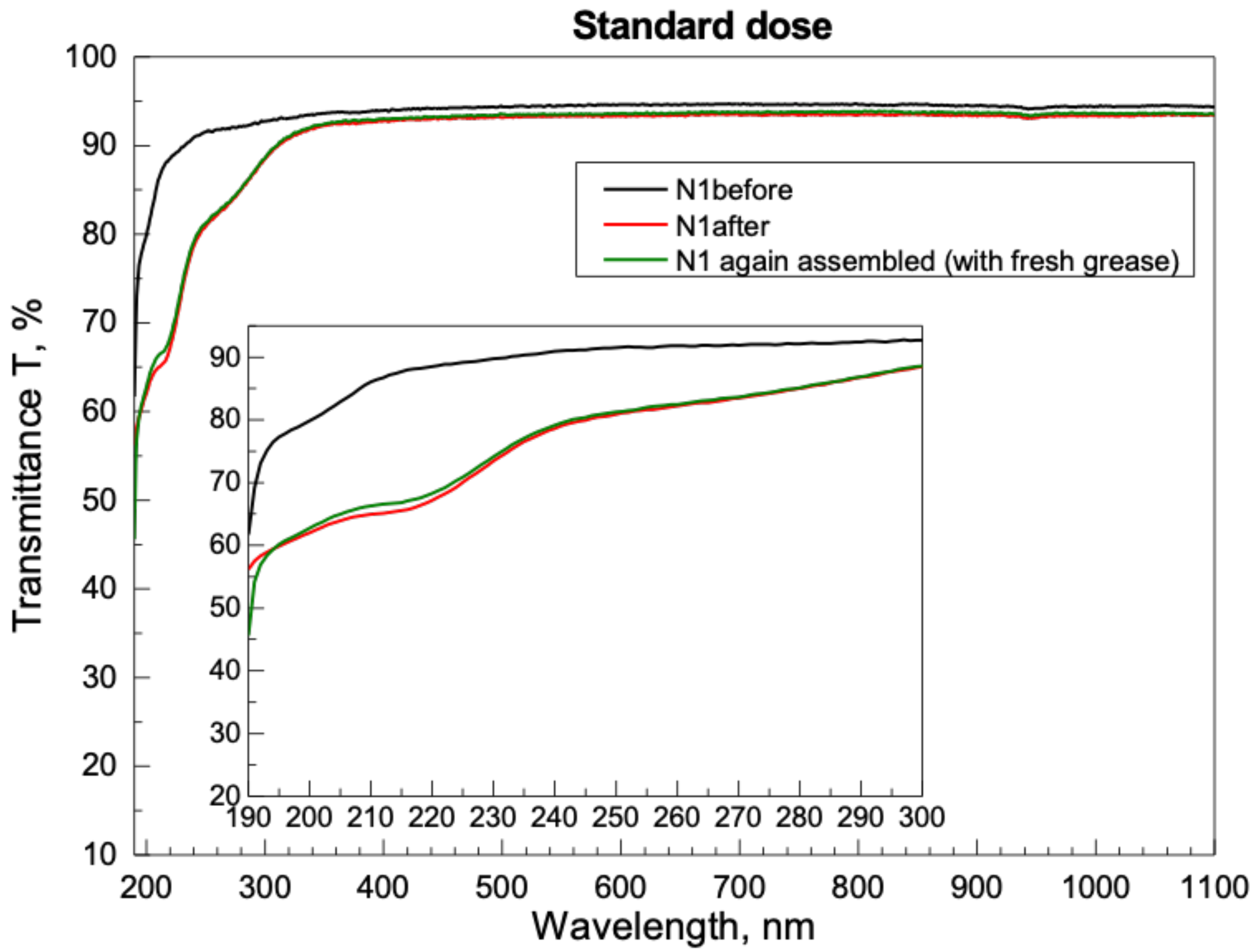




Elementary module

- Study radiation resistance of optical contacts: **grease vs glue** samples
- Irradiation @ KIPT with **e on Ta/W target** (γ and neutrons) of sandwiches:

Corning HPFS 7980 quartz tablets



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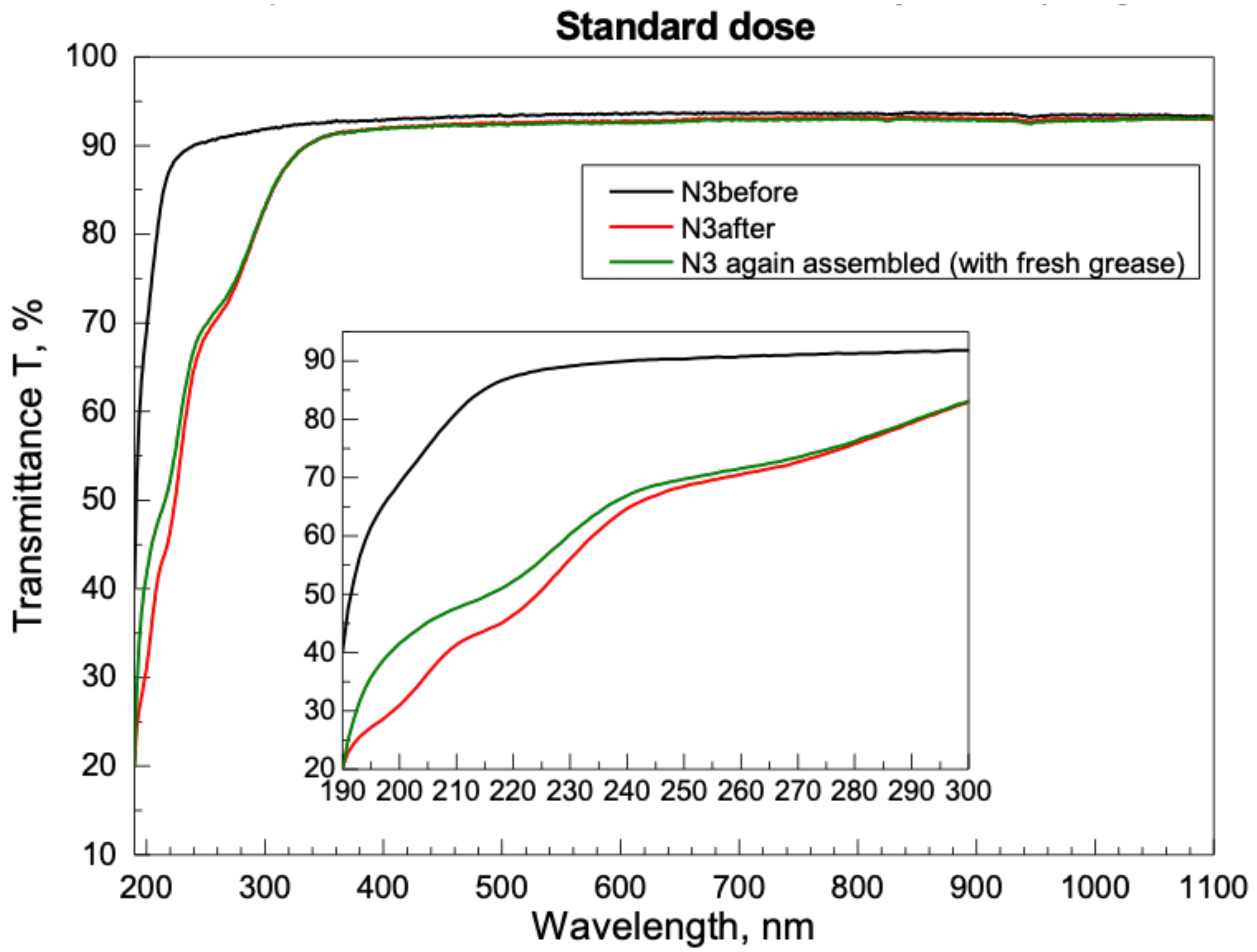
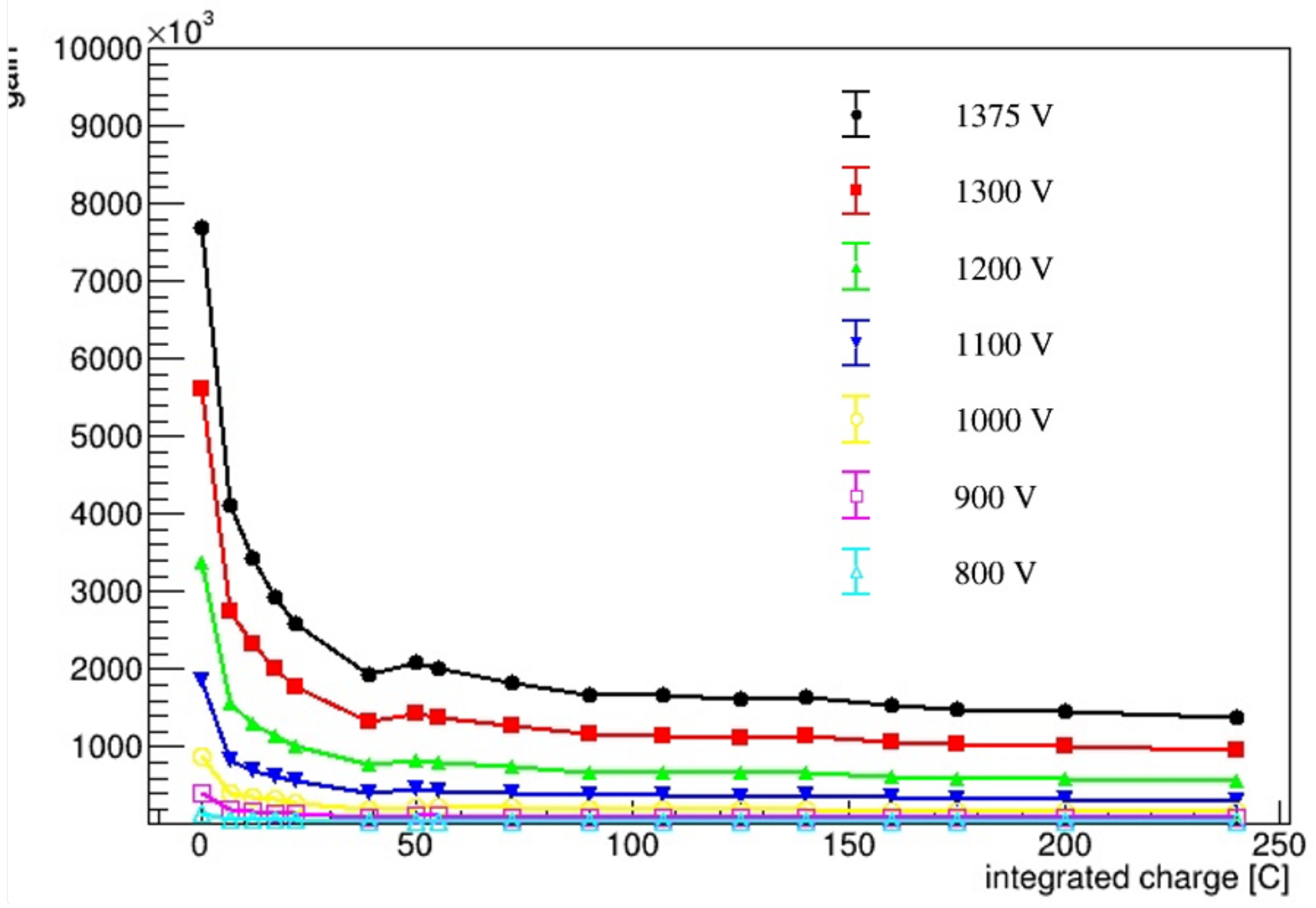


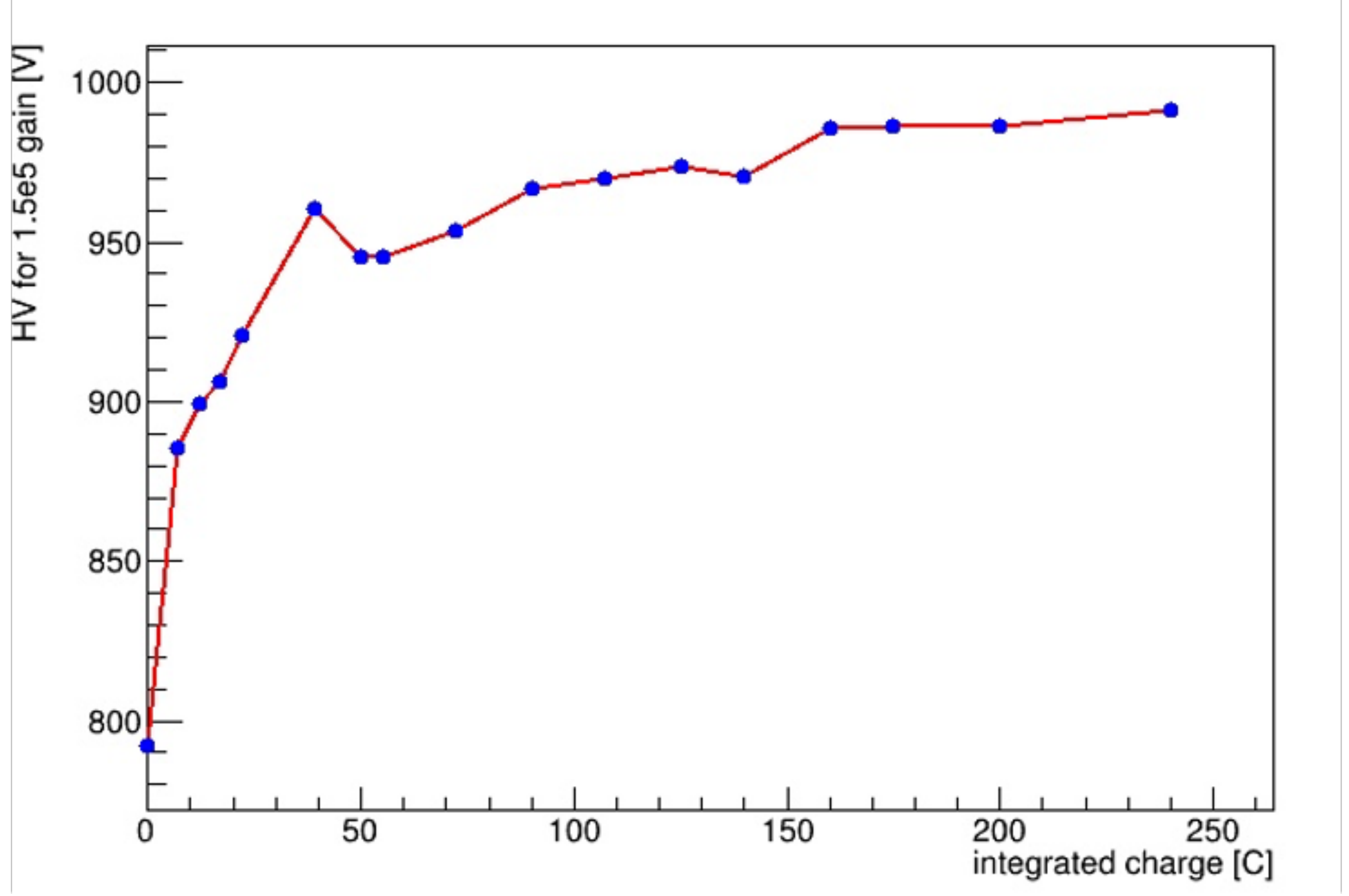
PMT Ageing studies

- **Ageing** tests wrt **integrated charge**
  - Laser and PMT with at 1200V
  - Up to **200 C of charge** - approx **3 years** of nominal data taking
  - Several stops to measure **single p.e. gain**
- Gain drops **3 times at first 17C**, then reaches "plateau"
- Possible to replace innermost modules during winter shutdown

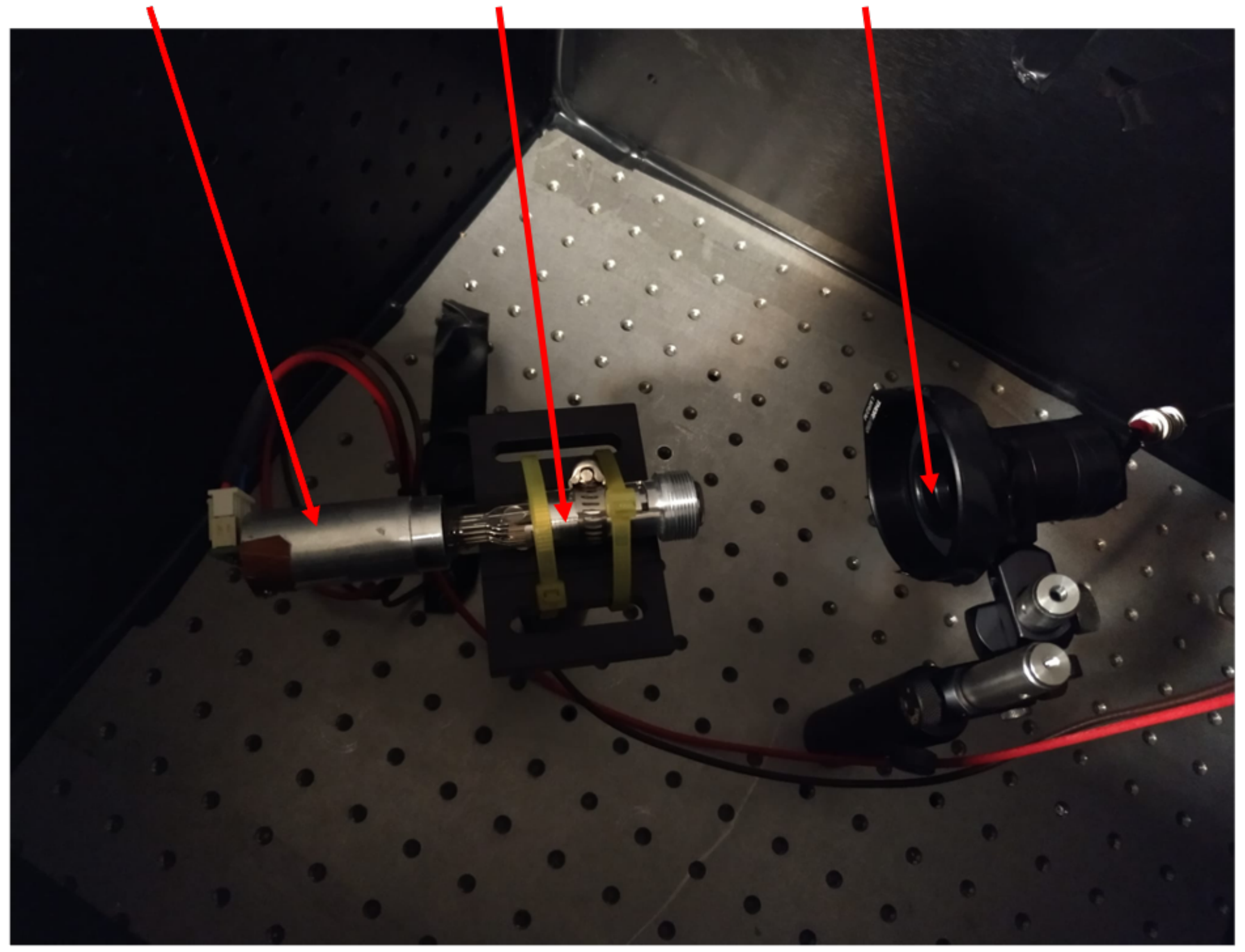
PMT gain as function of integrated charge



HV required to keep the constant gain as function of integrated charge



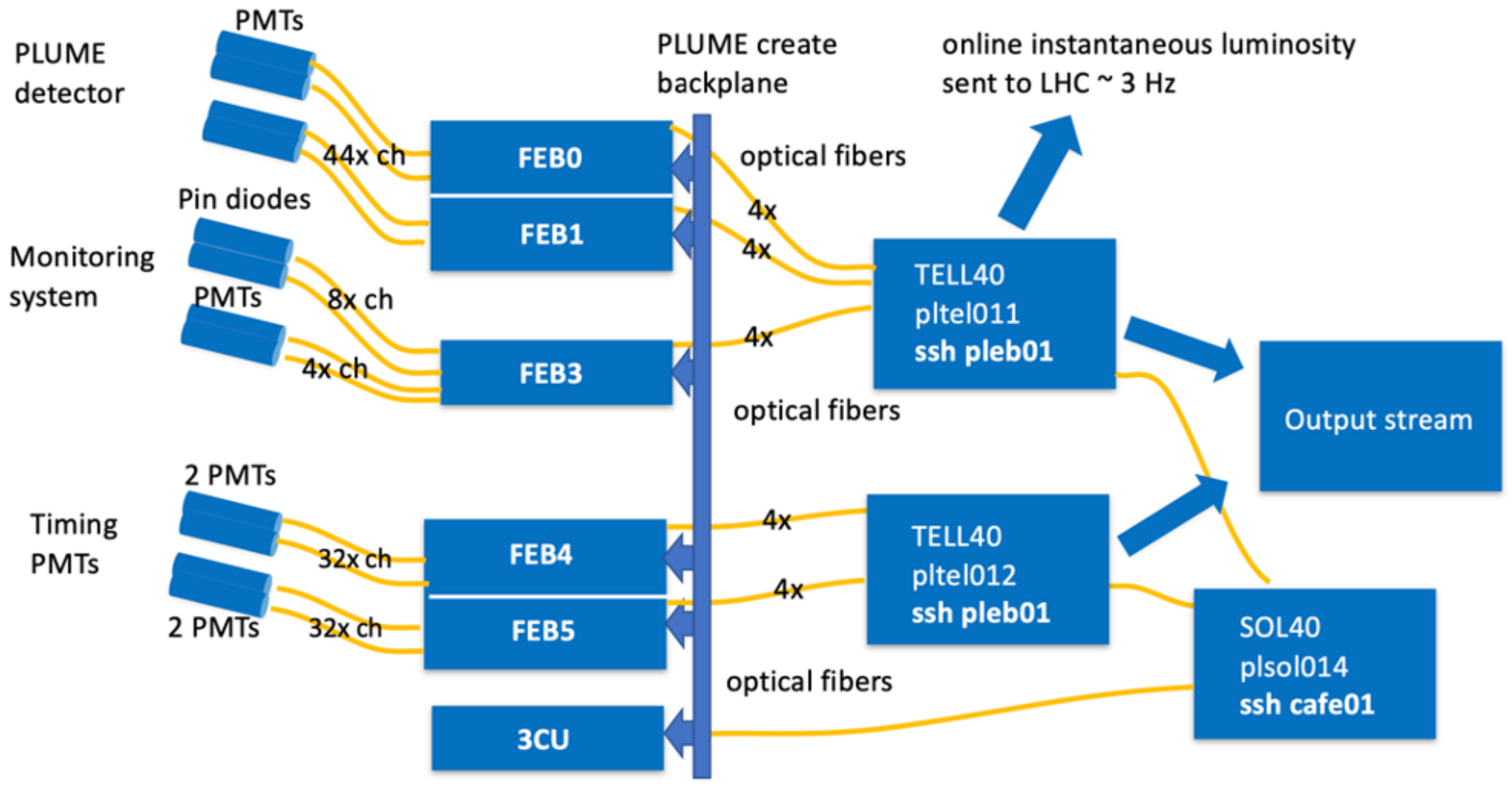
Experimental setup in the lab ->



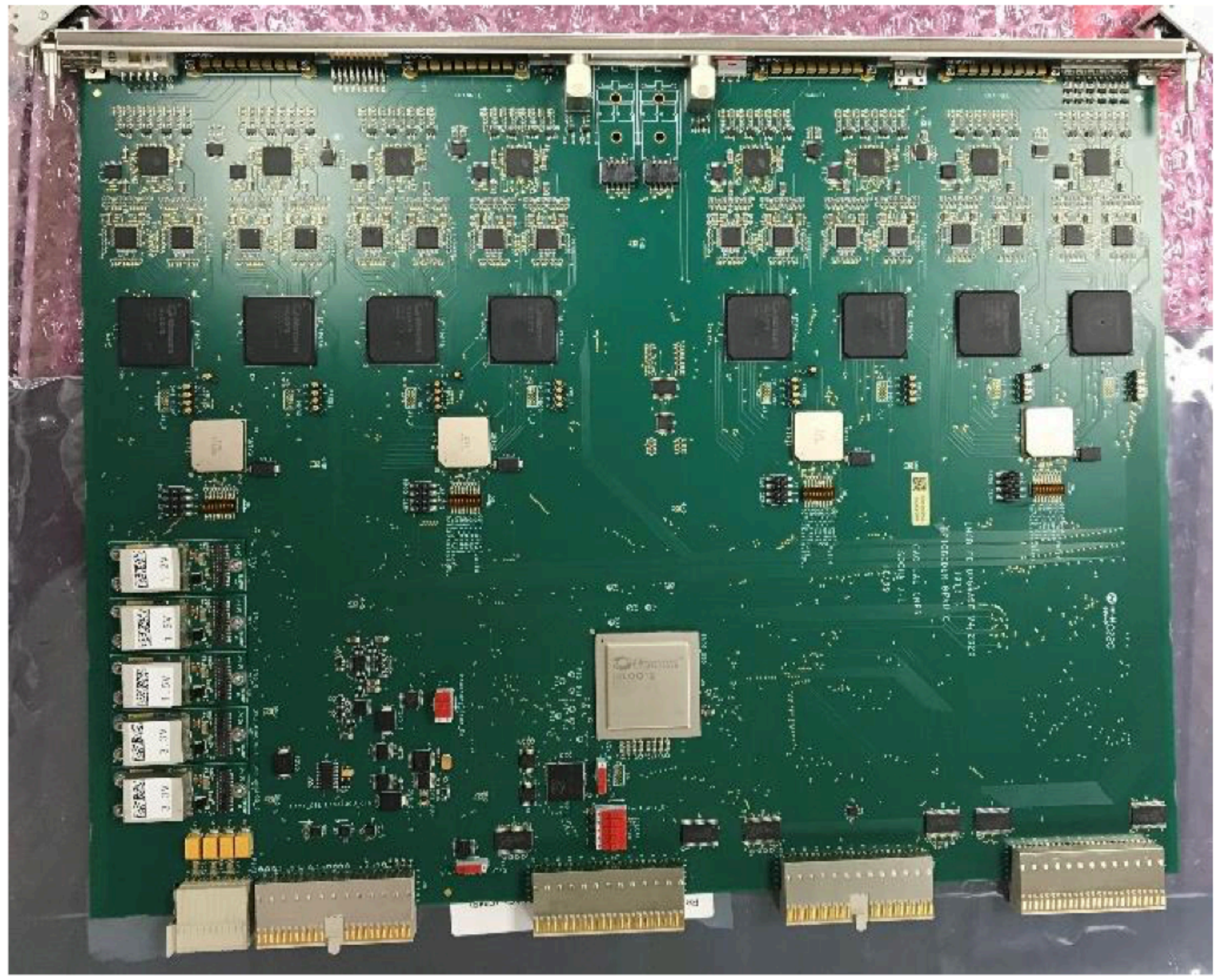
Readout electronics

- IJCLab Orsay is responsible for **LHCb calorimeter** front-end electronics
- Read-out is done by reprogramming front-end boards from calo
  - **32 input channels**
  - Analogue shaping and integration with **ICECAL chip**
    - **2 subblocks per channel** - even and odd bunch crossings
  - **12-bit conversion on commercial ADC**
  - Digital processing in radiation tolerant **FPGA Microsemi** (ACTEL) **Igloo2** family
    - **Pedestal subtraction** using information from previous bunch crossings (per ICECAL subblock)
    - **Numerical correction** and **event formatting**
    - Over-threshold computation (for **yes/no counting**)
  - Communication with other boards via **backplane** and with LHCb DAQ via **optical fibre**
- Followed by a shared LHCb processing chain (**PCIe40**) and control system (**WinCC**)

Schematics of the PLUME data flow



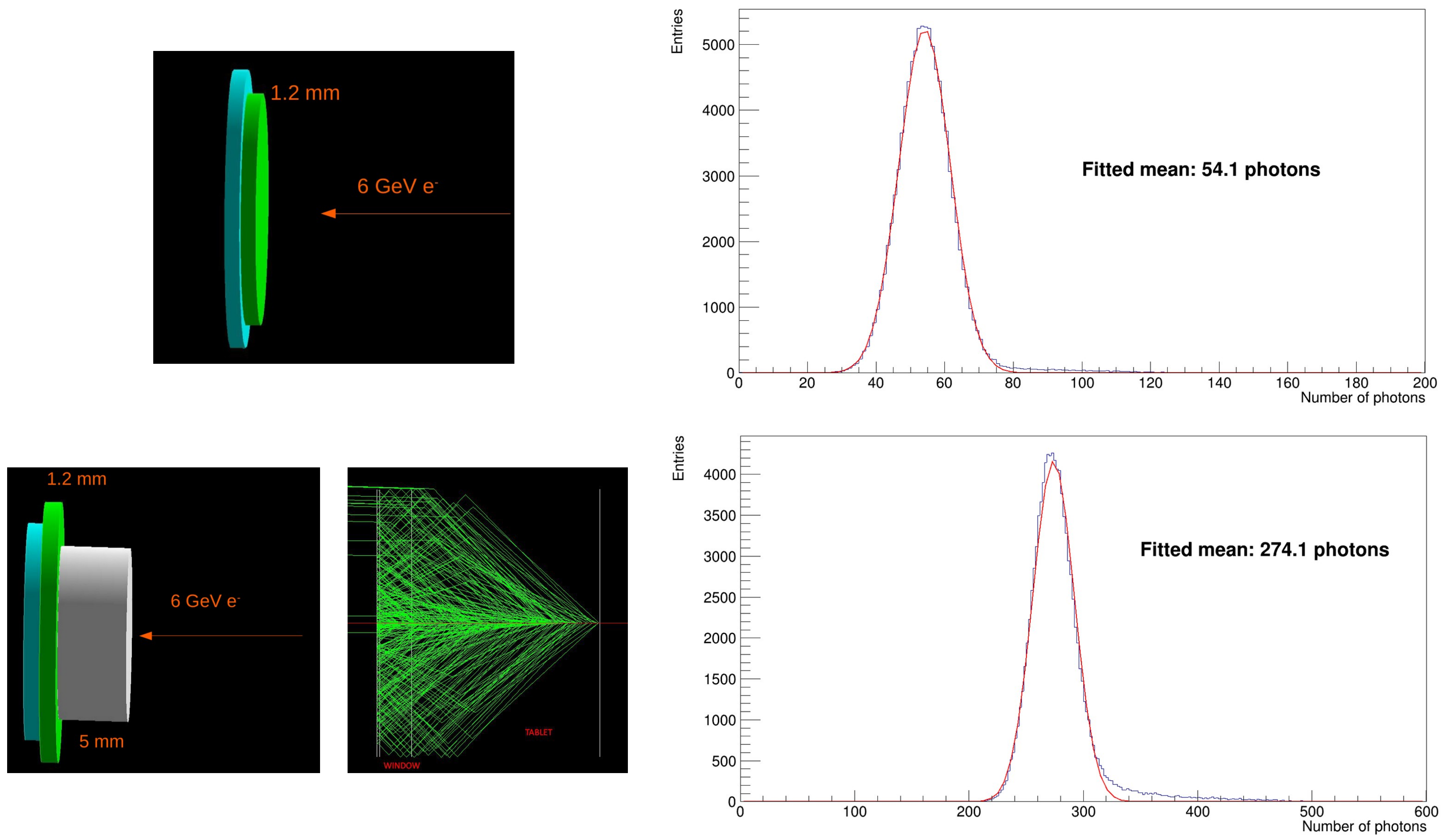
LHCb calorimeter front-end board



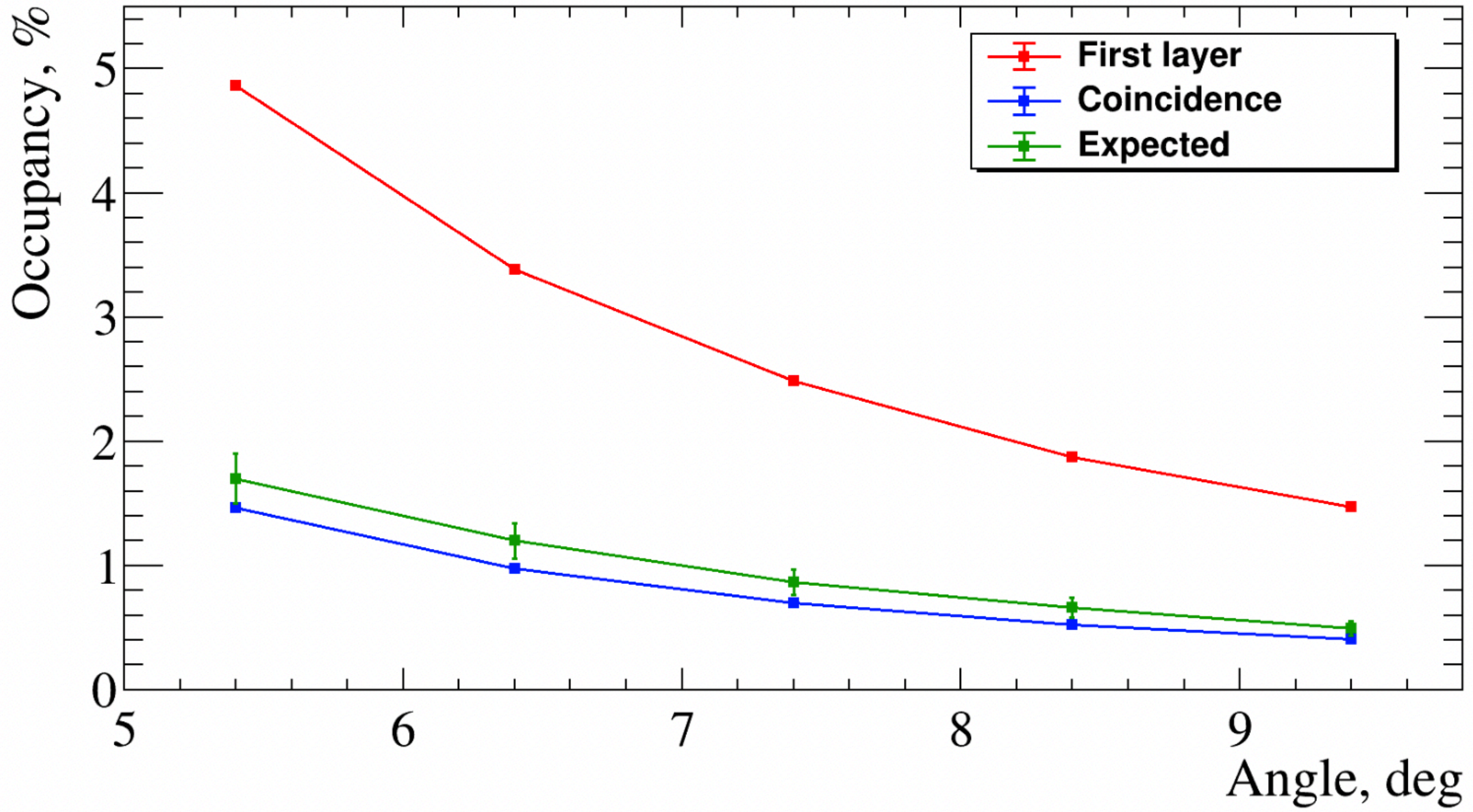
Geant4 Simulation

- Simulation using **Geant4 with Cherenkov light** and simplified geometry were done
- Key simulation studies
  - **Single module studies**:
    - total expected **light yield**
    - **angular dependency** for evaluation of possible background
    - coupling simulation for **optical grease study**
  - Simplified upstream **LHCb geometry with Pythia8** event generator
    - Study of **expected occupancy**
    - Acceptance study for **early luminosity estimation**
- Results compared with expected due to no bias event **multiplicity** and further validated with **test beams**

Simulation of the quartz window and window+tablet for test beam



Simulated occupancy and coincidence rate compared to projected values from Run 1 measurement



Calibration and monitoring

- PMT gain is expected to vary depending on **integrated charge**, **irradiation**, **annealing** during stops
  - **Monitor the gain** and apply **HV corrections** to recover the reference value
- Custom **LED system** for gain monitoring
  - **LEDs** and controls installed in the moderate radiation environment in the cavern
  - **Trigger** received from **FE electronics** in specific **bunch slots**
  - LED light transported to the PMTs via **quartz fibers**, monitored by **PIN diodes**
  - **Monitoring PMTs** close to LEDs - monitor fibre ageing
- **Track reconstructed in VELO** - select the events with charged tracks in acceptance
- **MIP calibration** - fit the charge per event spectra to determine the gain with constant MIP light yield

LED system with fibres to PLUME (left), trigger modules (centre), monitoring PMTs (right)

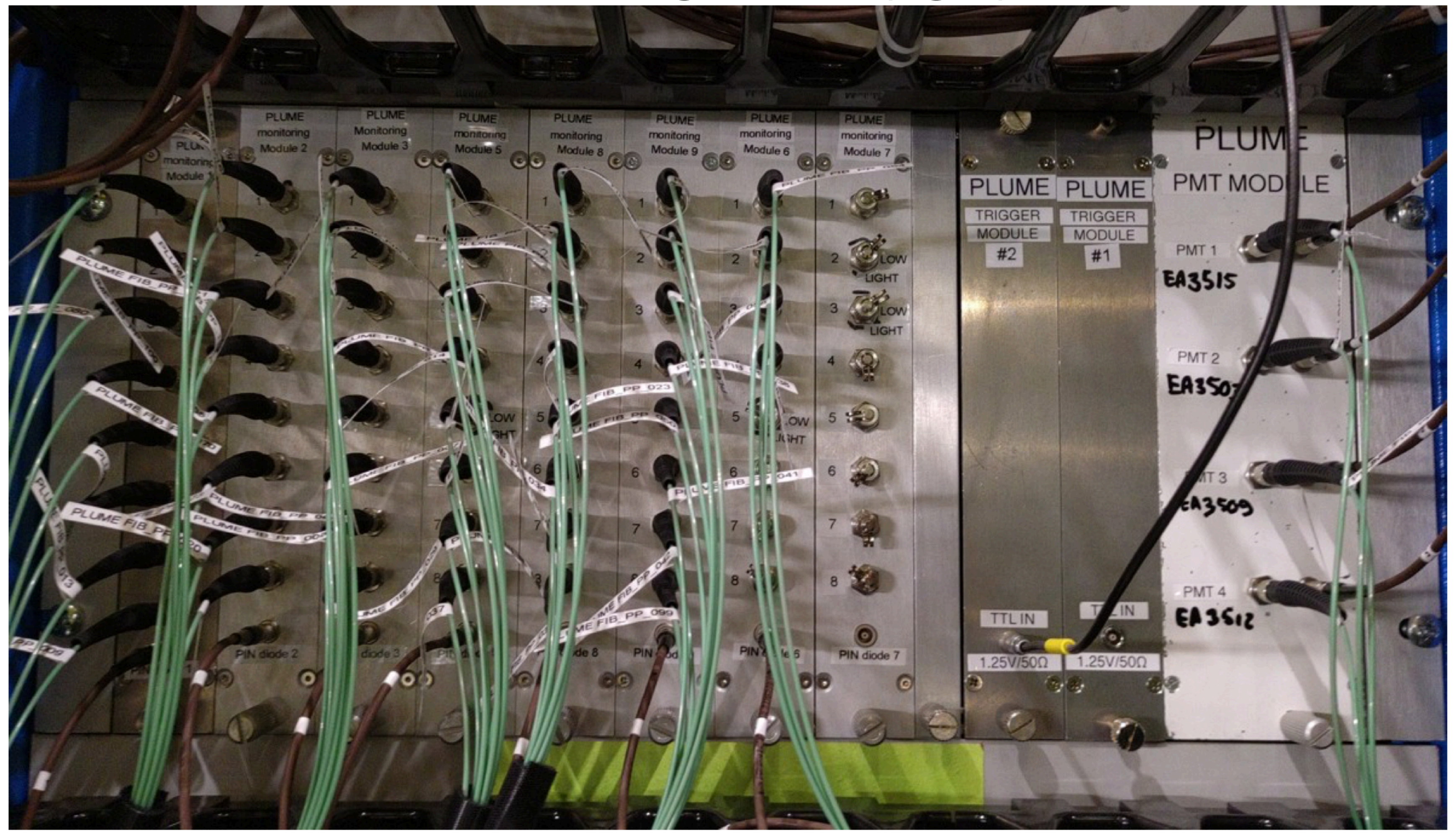
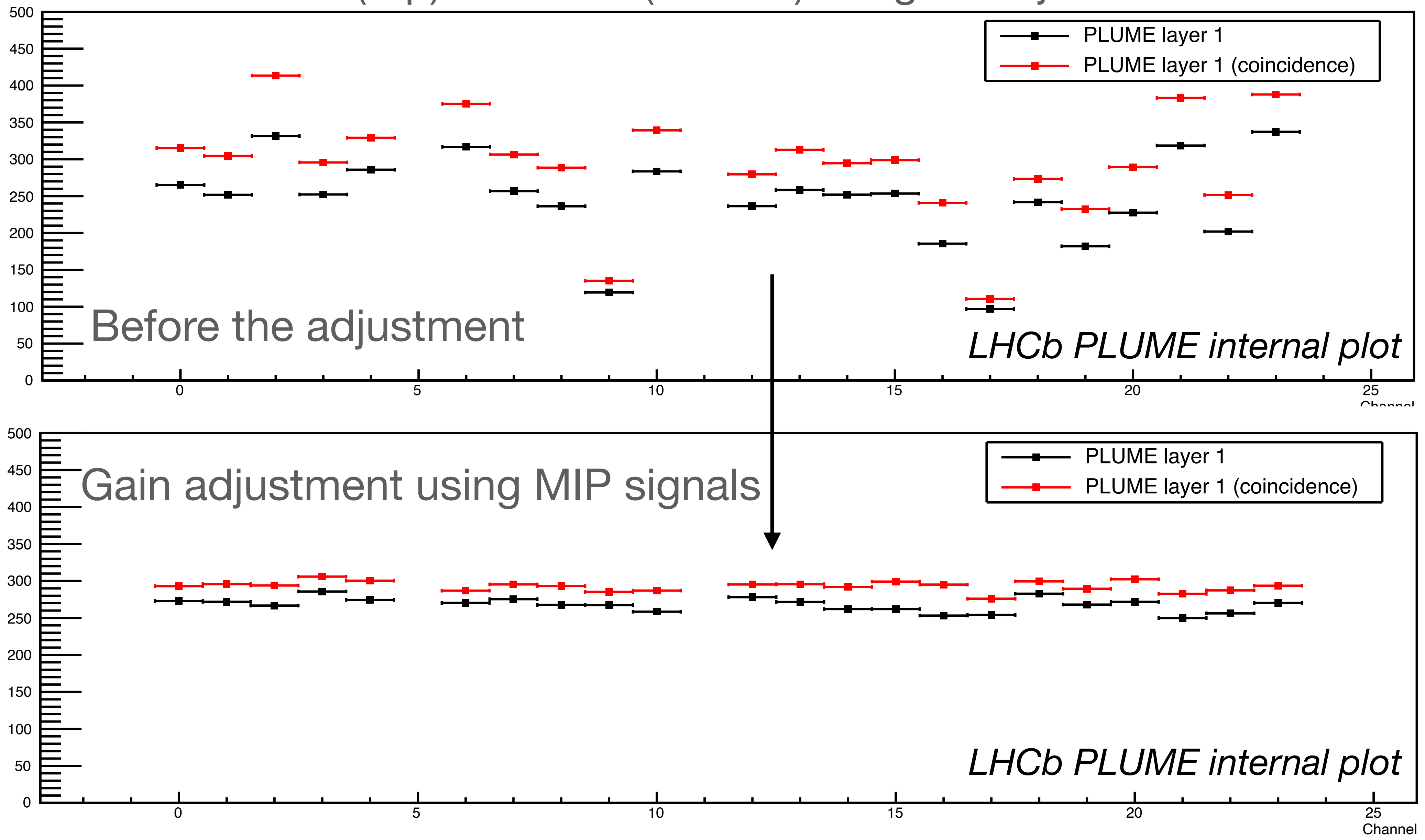


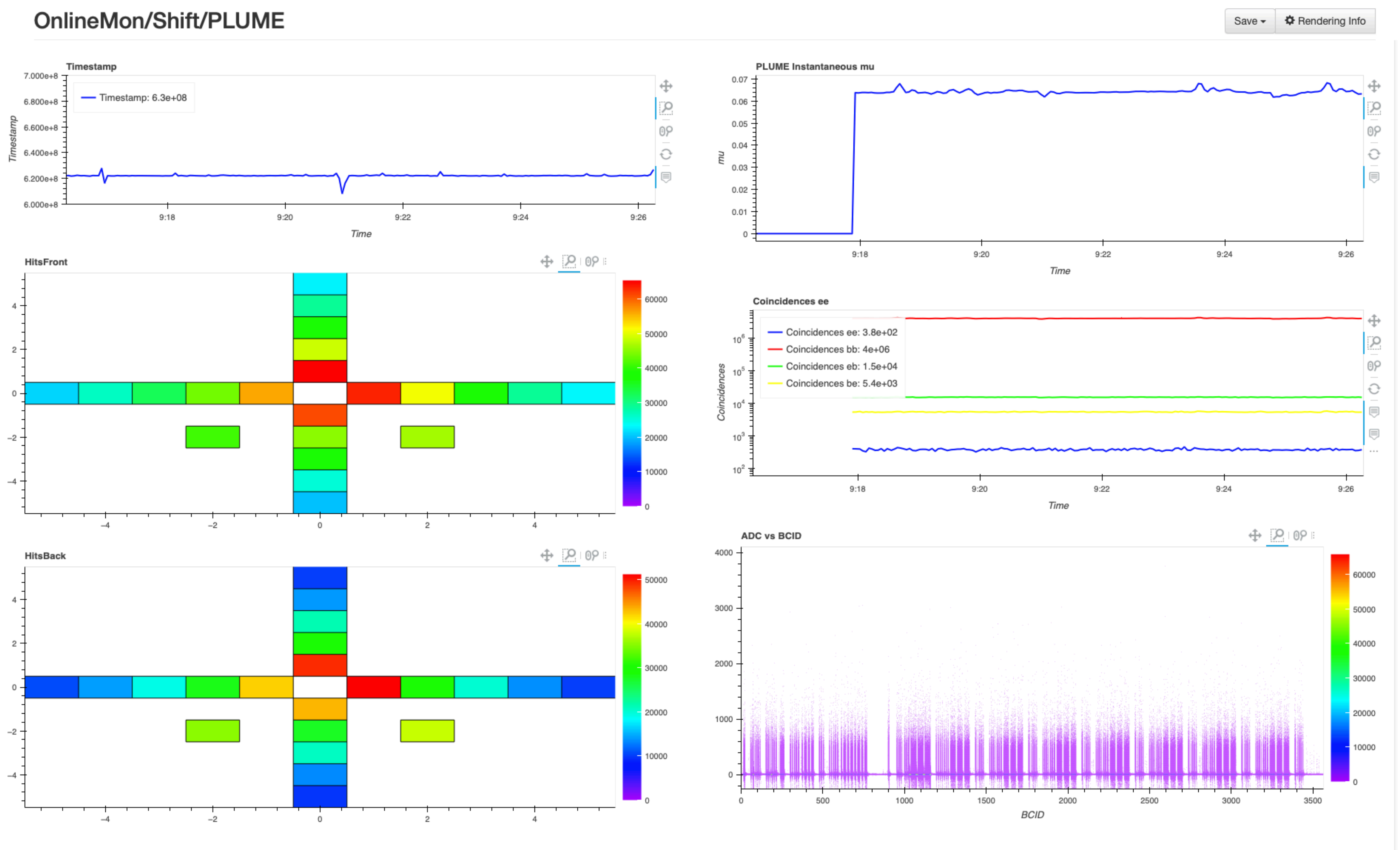
Illustration of the average MIP amplitude in ADC counts before (top) and after (bottom) the gain adjustment



LHCb online monitoring

- **PLUME online monitoring** is based on **LHCb Monet** platform
  - Dedicated **online stream** with low frequency and **low-level reconstruction** for **monitoring the detectors' state** available via the **web page** online
- Provides essential information to the **shift crew**
- Debug **information for experts**
  - Charge spectra for all PMTs
  - BCID information for time alignment
  - Luminosity data points
  - Monitoring for timing reconstruction

Screenshot of the Monet page with PLUME information for shifter

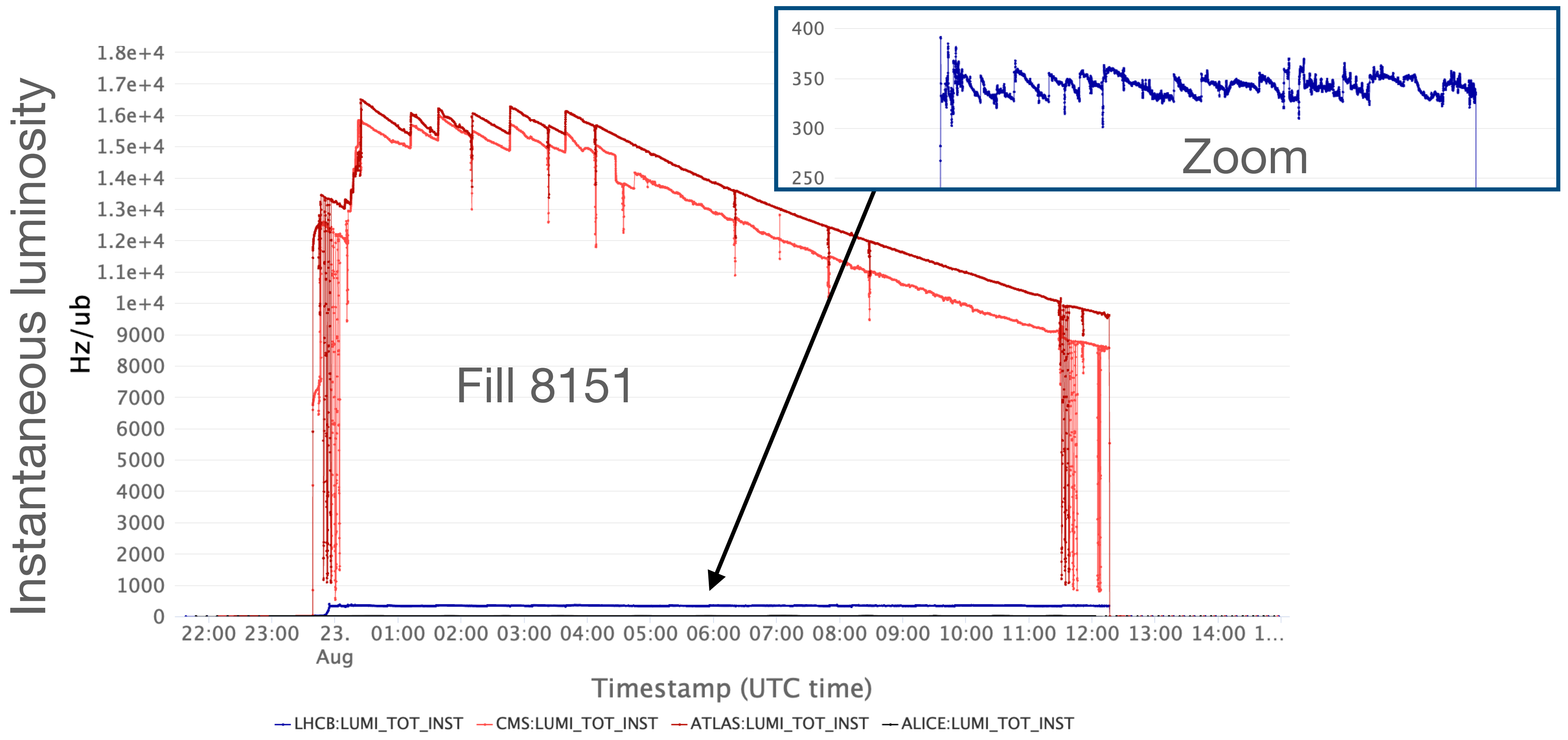


Luminosity determination

- Instantaneous luminosity per bunch: $$\mathscr{L}_{bunch} = \frac{f_{LHC} \times \mu_{vis}}{\sigma_{vis}}$$
- $f_{LHC} = 11245\ Hz$: LHC revolution frequency
- μ_{vis}: average number of visible interactions per event (counter specific)
  - Relative luminosity - values are monitored continuously
  - **Linear**, **LogZero** methods
- σ_{vis}: visible cross-section of a counter of interactions
  - Absolute calibration - performed periodically (once a year per energy)
  - Van der Meer scan (**vdM**), beam-gas imaging with SMOG (**BGI**)
- Luminosity counters in LHCb
  - Online: **PLUME (main)**, VELO clusters, Muon hits/currents, RICH1 currents, SciFi currents, RMS currents
  - Offline: all the detectors

- **Luminosity leveling at LHCb**: keep **stable luminosity** for stable detector performance

Luminosity leveling at LHCb



Absolute luminosity calibration (van der Meer scan)

- **Van der Meer scan** - moving beams against each other and measuring μ **as a function of beam separation**

- Absolute calibration of the counter μ:

$$\sigma_{vis} = \int \frac{\mu(\Delta x, \Delta y)}{N_1 N_2} \, d\Delta x \, d\Delta y$$

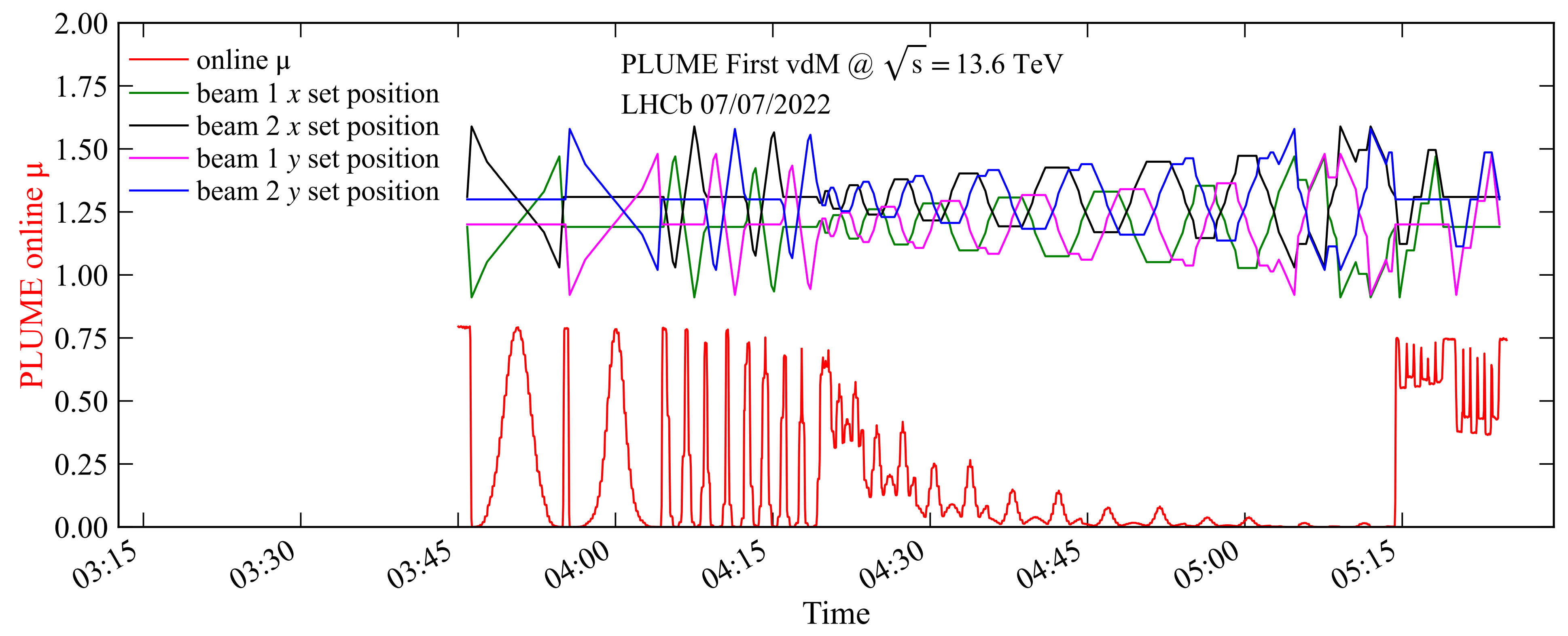
Obtained from the accelerator beam monitors

- First vdM scan at $\sqrt{s} = 13.6 \ TeV$ on July 7 2022

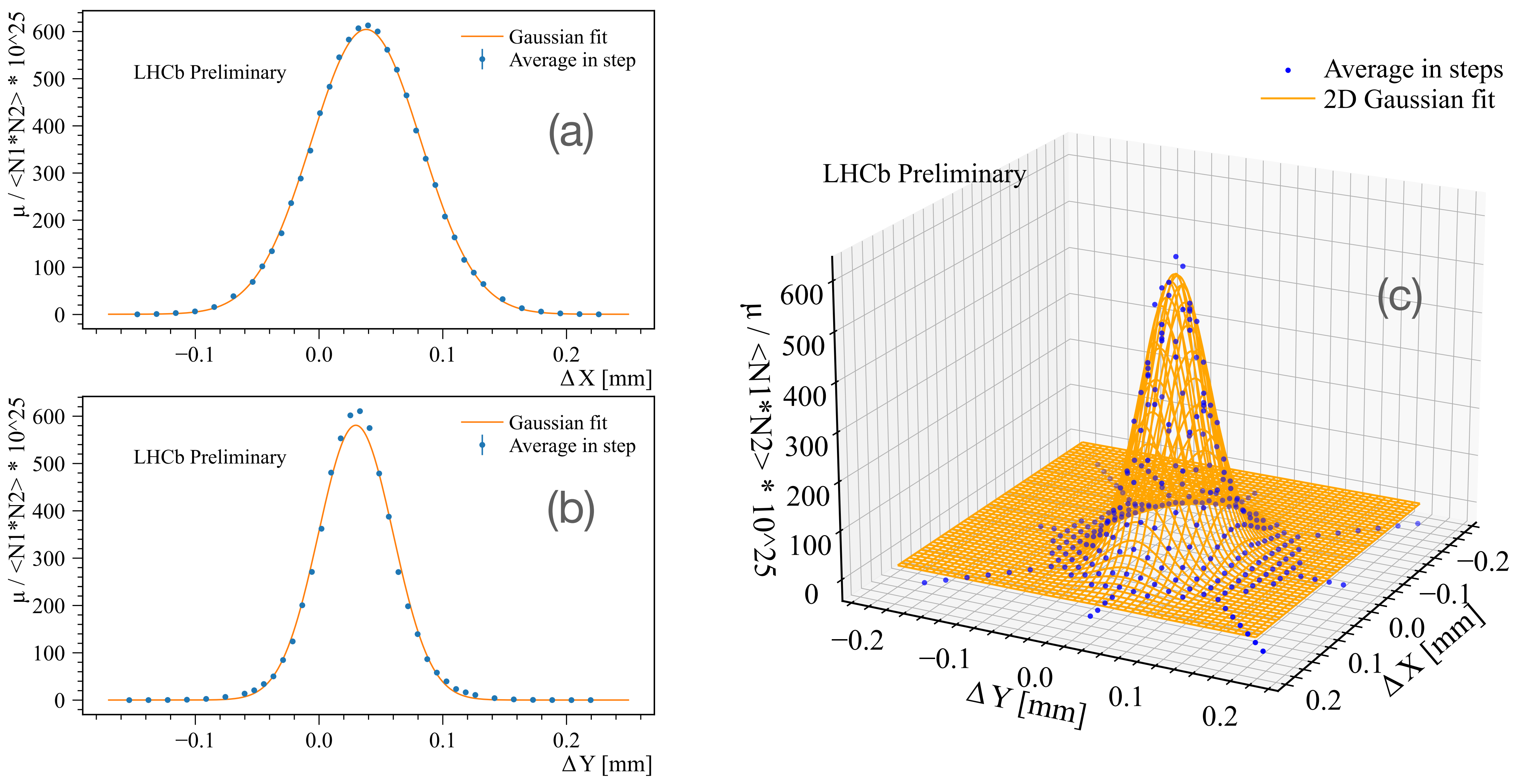
- PLUME online counter cross-sections from vdM:

$$\sigma^{online} = (3.65 \pm 0.01_{stat}) \ mb$$

- Obtained cross-section allows measuring **absolute luminosity** using **observable values** independently of the **beam parameters**



PLUME online μ as a function of time during the vdM sequence. Beam positions are in arbitrary units for illustrative purposes only



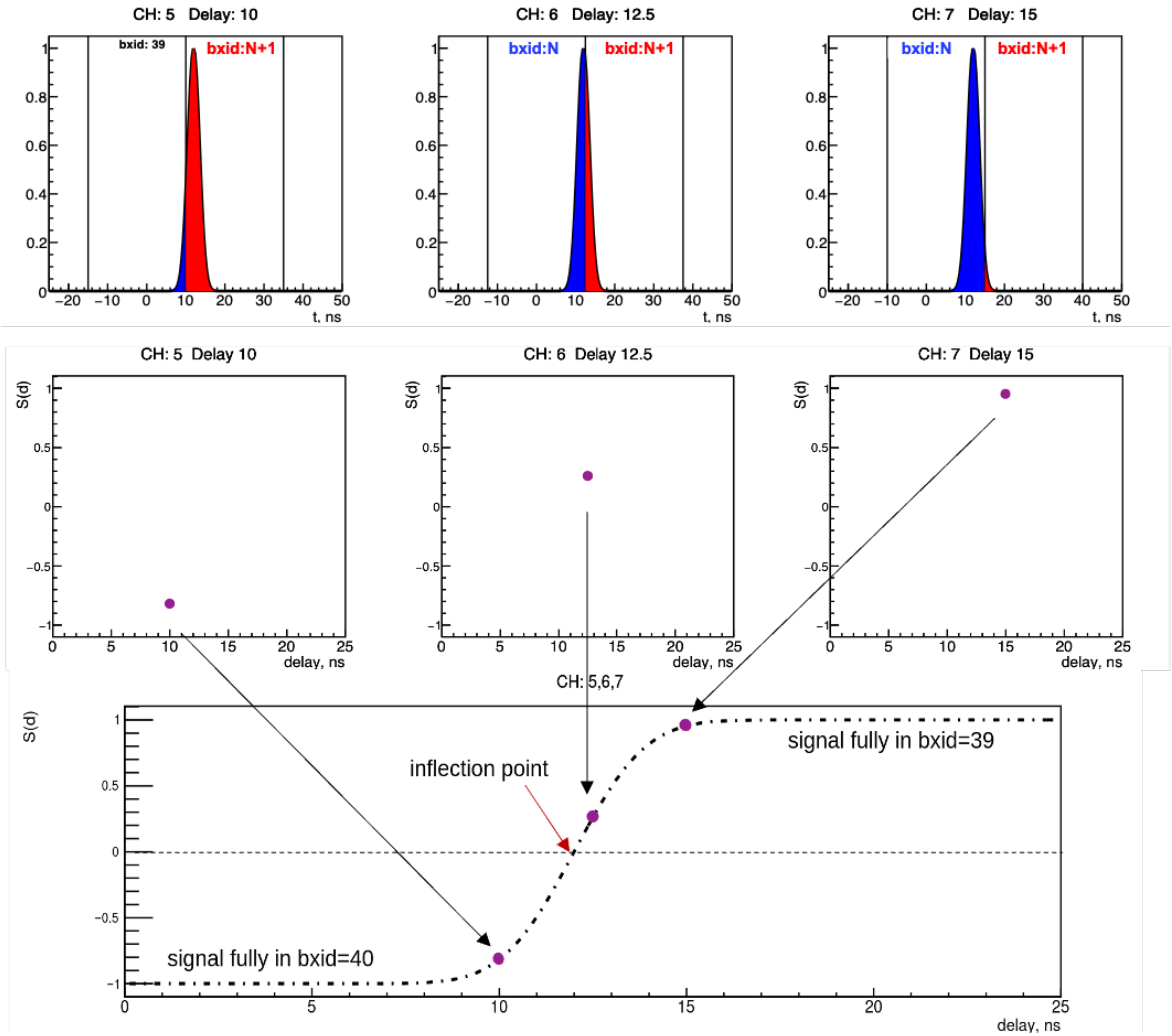
Preliminary fits of the PLUME data in the vdM sequence in three scans: (a) along X-axis, (b) along Y-axis, and (c) in 2D scan.

PLUME timing: s-shape and offline algorithm

- S-shape algorithm inspired by position reconstruction in calorimeters
- The goal is to measure the **time of input signal** from **S-shape**
  - **split signal into 8 copies**
  - each copy is sent to different calo FEB channels **with increasing delay**.
  - for each channel get the **integrated value** of signal per each bunch crossing (**sampling**, 25ns time window).
  - save the value from **the previous bcid** in another FEB channel (16 FEB channels per PMT in total)
  - **S-shape** is obtained by **subtracting** the values in two **consecutive samplings** for each channel:

$$\boldsymbol{S}(\boldsymbol{d}) = ch_{bxid=N}(\boldsymbol{d}) - ch_{bxid=N+1}(\boldsymbol{d}), \quad where\ \boldsymbol{d}\ - delay$$

- Final steps:
  - fit with an error function
  - find a **S-shape**'s inflection point (derivative changes sign).



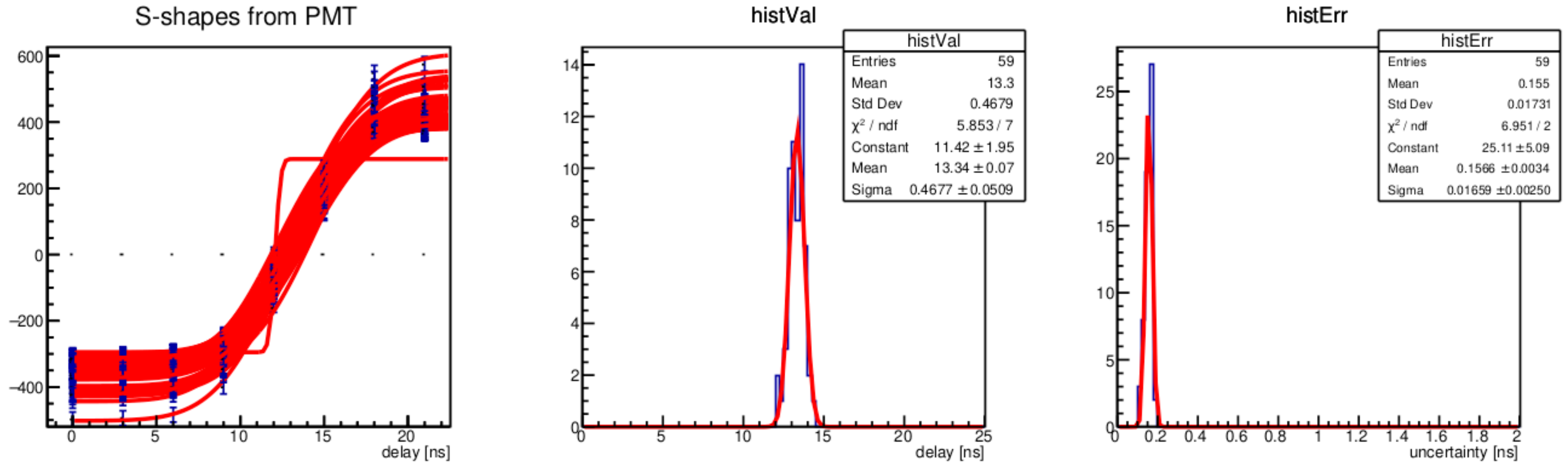
Timing analysis and results

- **Simulated events**:
  - only one PMT with laser as a signal source
  - resolution of **~70 ps / track**

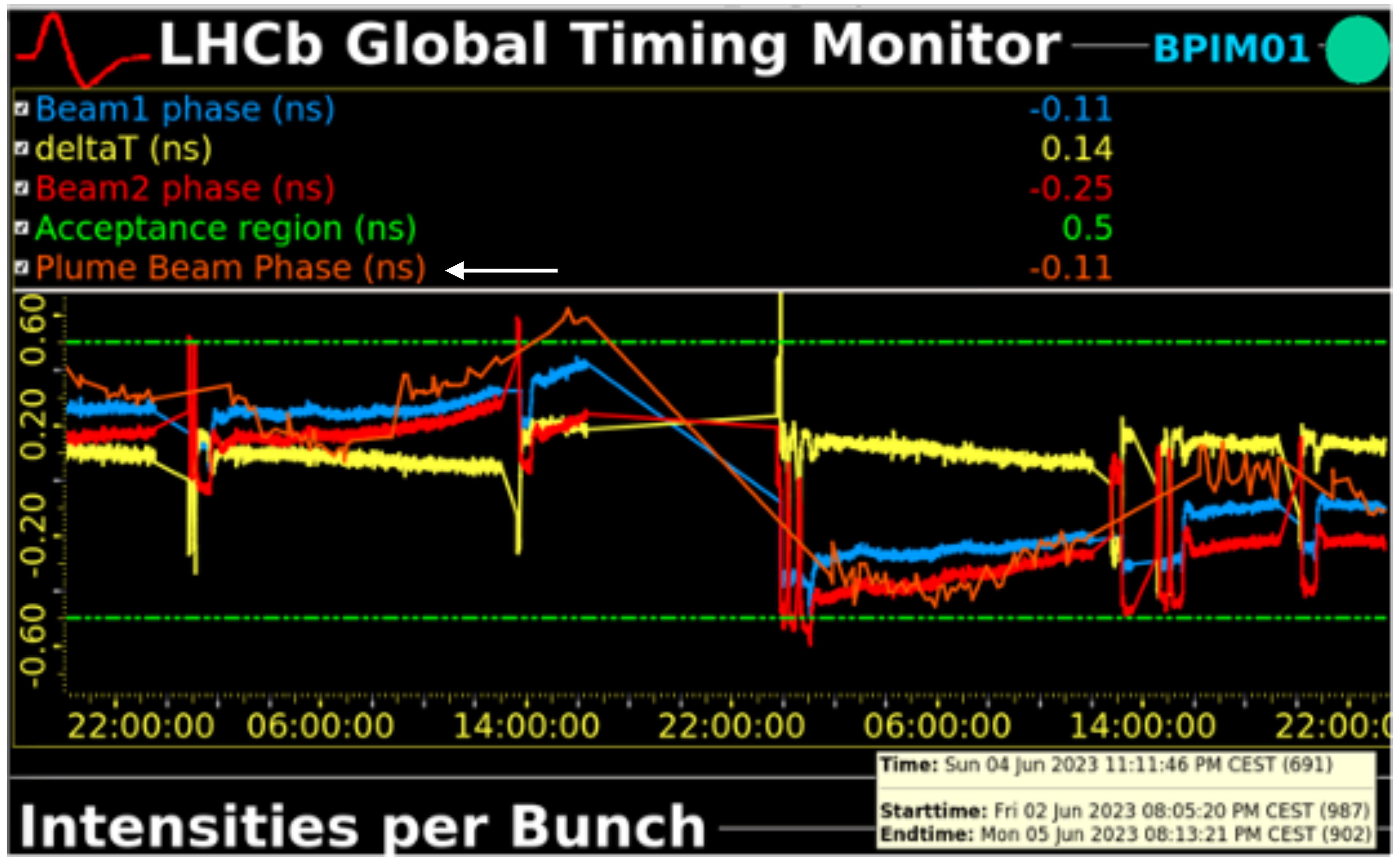
- **Data from collisions at LHC**:
  - two projective PMTs with **coincidence** required
  - time difference between PMTs is fixed and extracted from the data
  - resolution of **~100 ps / track**
  - resolution of **~400 ps / bunch** comparable with luminous region σ_z ~ 200 ps

- **Possible application**:
  - timing measurements of interactions wrt. LHC clock
  - beam-gas measurement of parasitic charges in "empty" RF buckets in VdM scan

S-shapes from a single PMT



LHCb timing pannel for shifter with PLUME timing trend



Summary

- **Simulations** were done, **validated with tests** with beams and in the lab
- **Calibration and gain monitoring** technique was developed and implemented
- **Luminosity calibration** was done with vdM scan at full energy
  - **First detector in LHCb to have absolute luminosity calibration in Run 3**
- Technique for precise **collision time determination** developed for **LHC clock correction**
  - Tests and validation are ongoing
- PLUME was designed, tested, installed and commissioned for LHCb Upgrade 1 in **less than 3 years**
  - **Running routinely without experts involvement since 2022**

Thank you!