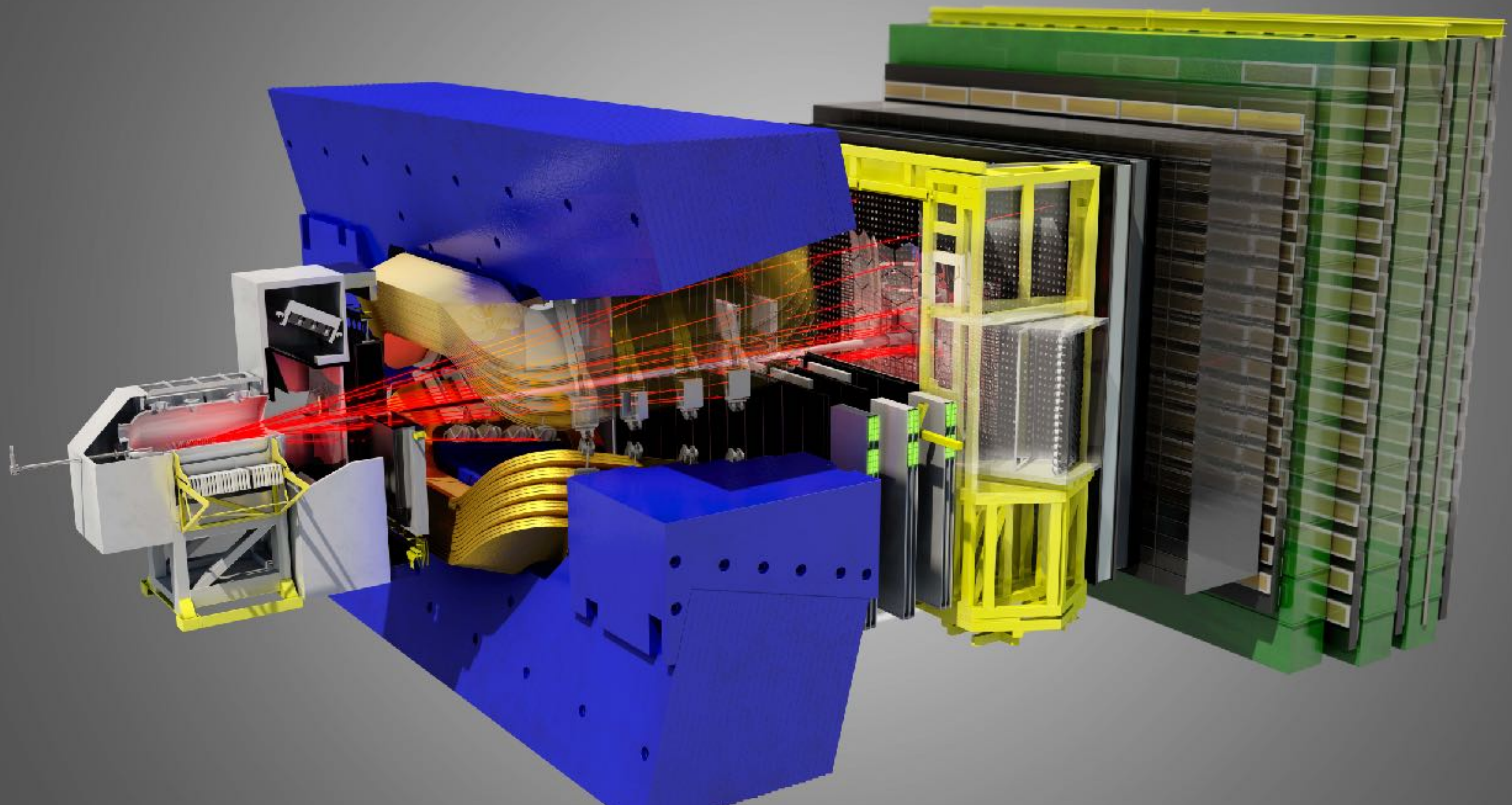
Latest feasibility studies of LAPPD as a timing layer for the LHCb Upgrade-2 ECAL

13th workshop on picosecond timing detectors
Isola d'Elba, 31st May 2023



F. Ferrari, D. Manuzzi, S. Perazzini, V. Vagnoni on behalf of the LHCb PicoCAL group

Outline

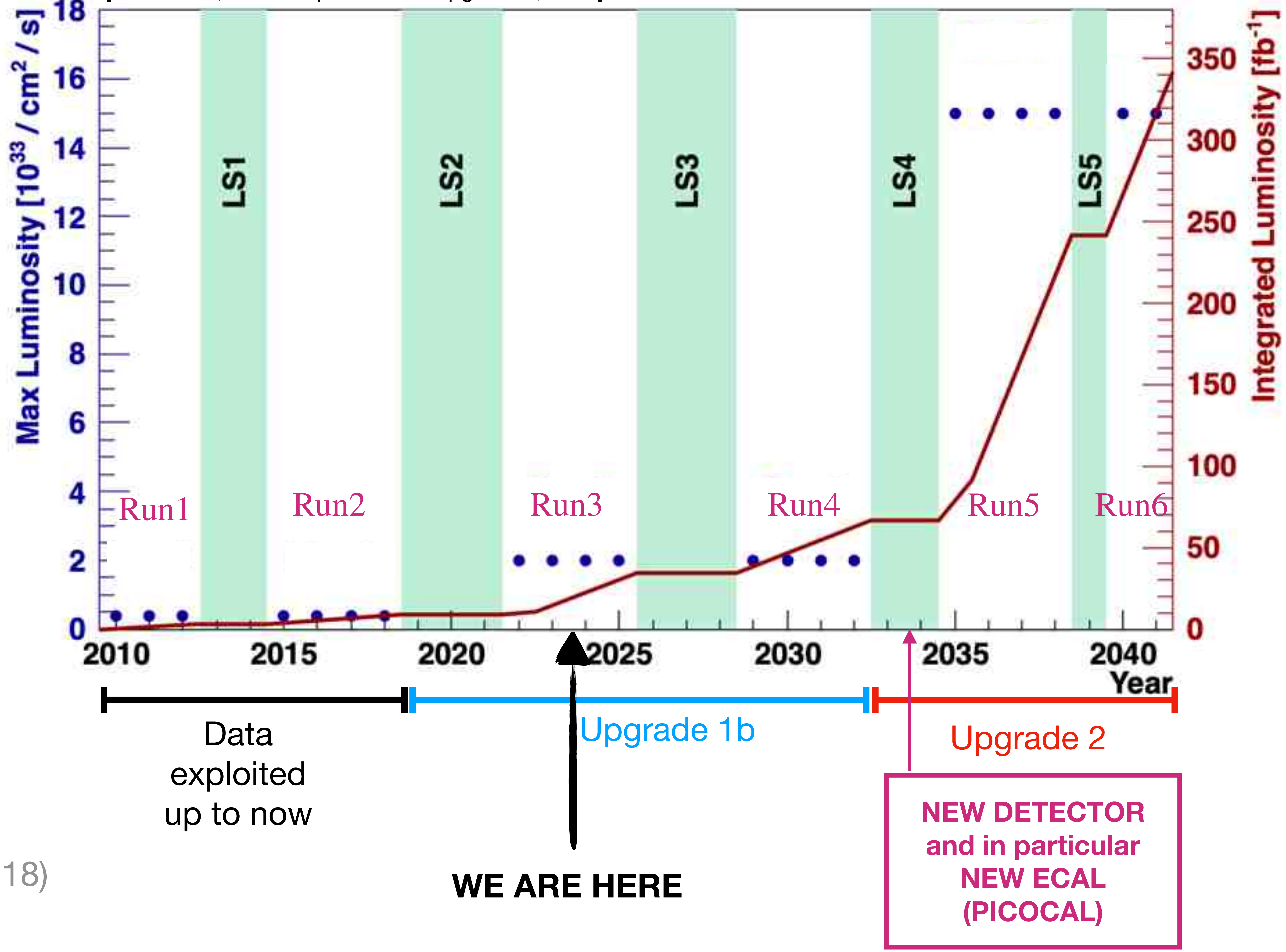
- Introduction
  - The future of LHCb and its Electromagnetic Calorimeter (ECAL)
  - Motivations for a MCP-based timing layer in the ECAL
- R&D status
  - The **L**arge **A**rea **P**icosecond **P**hoto**D**etector
  - Time resolution
  - Radiation hardness and lifetime
  - High rate
- Summary and conclusions

Previous results presented at the last edition of this workshop
[Stefano Perazzini, Zurich 2021]

A luminous future for LHCb

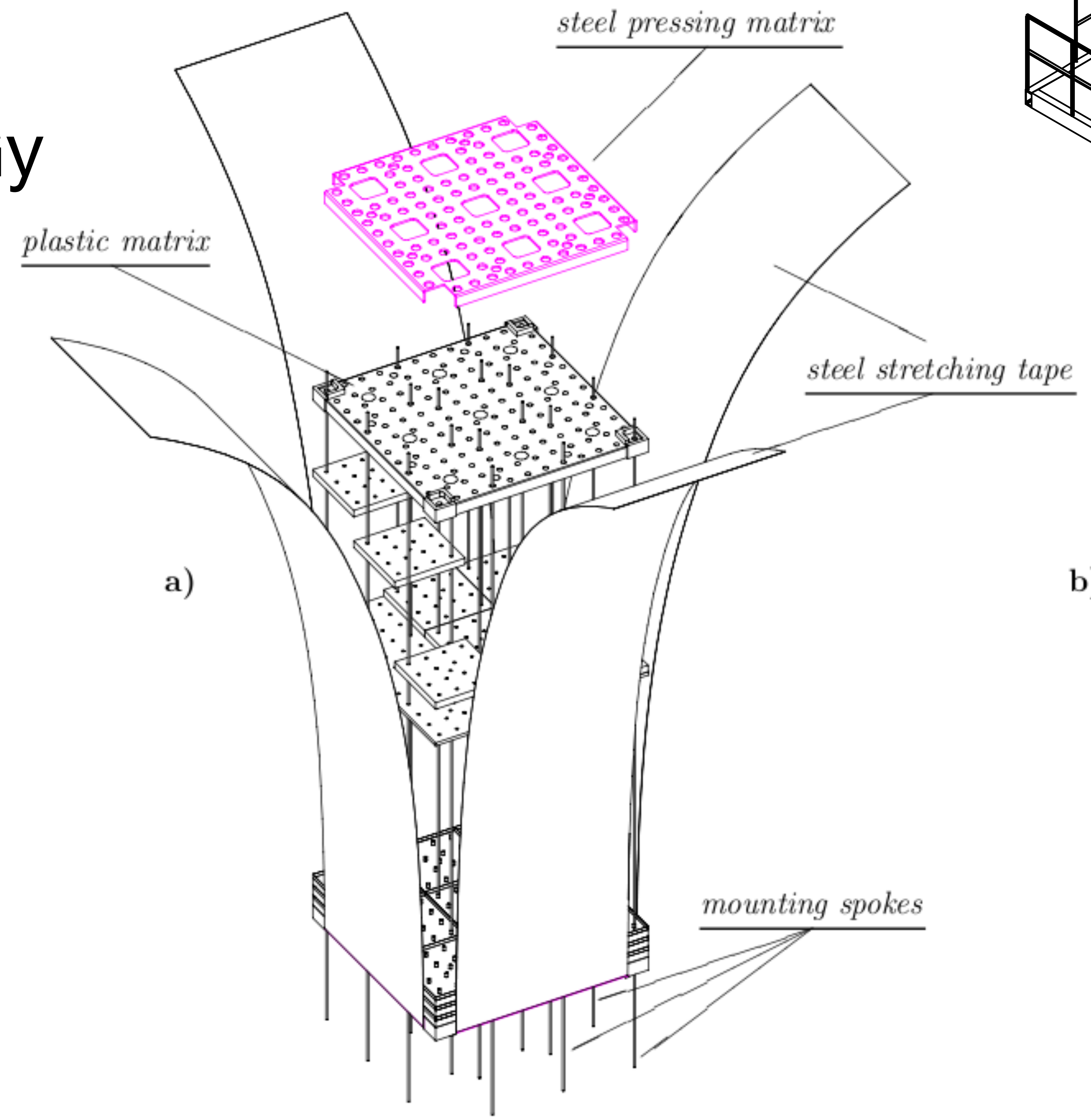
- Major upgrade of the whole detector foreseen in the **LS4**
- **Peak inst. luminosity:** $\times 7$ compared to now (Run3)
- **Integrated luminosity:** $> \times 30$ compared to recorded data
- **New ECAL** mandatory to pursue the physics programme
  - CPV, FCNC, hadron spectroscopy, forward physics, fixed target, LFV, …
  - Details:
    - Physics Case for an LHCb Upgrade 2 (2018)
    - FTDR for LHCb Upgrade 2 (2021)

[M. Palutan, Workshop for LHCb Upgrade 2, 2023]

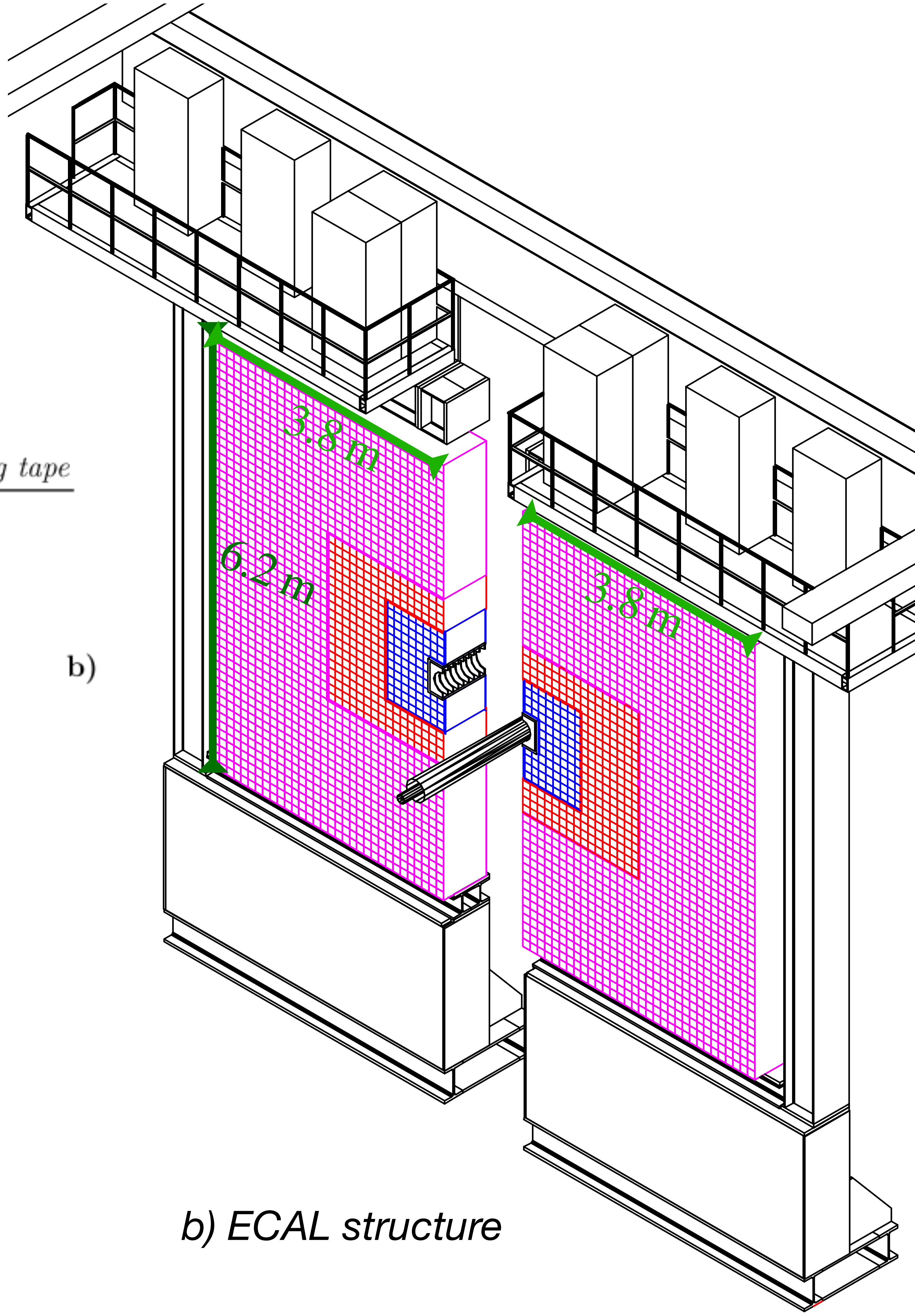


Context: the current ECAL

- Large array of shashlik cells
- Radiation tolerance up to 40 kGy
- Three rectangular regions with different cell sizes
  - 4, 6, and 12 cm
- Optimised for $\mathscr{L}_{\text{inst.}} = 4 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$
- γ, π^0, $e^{\pm}$ from few-GeV up to 100-GeV



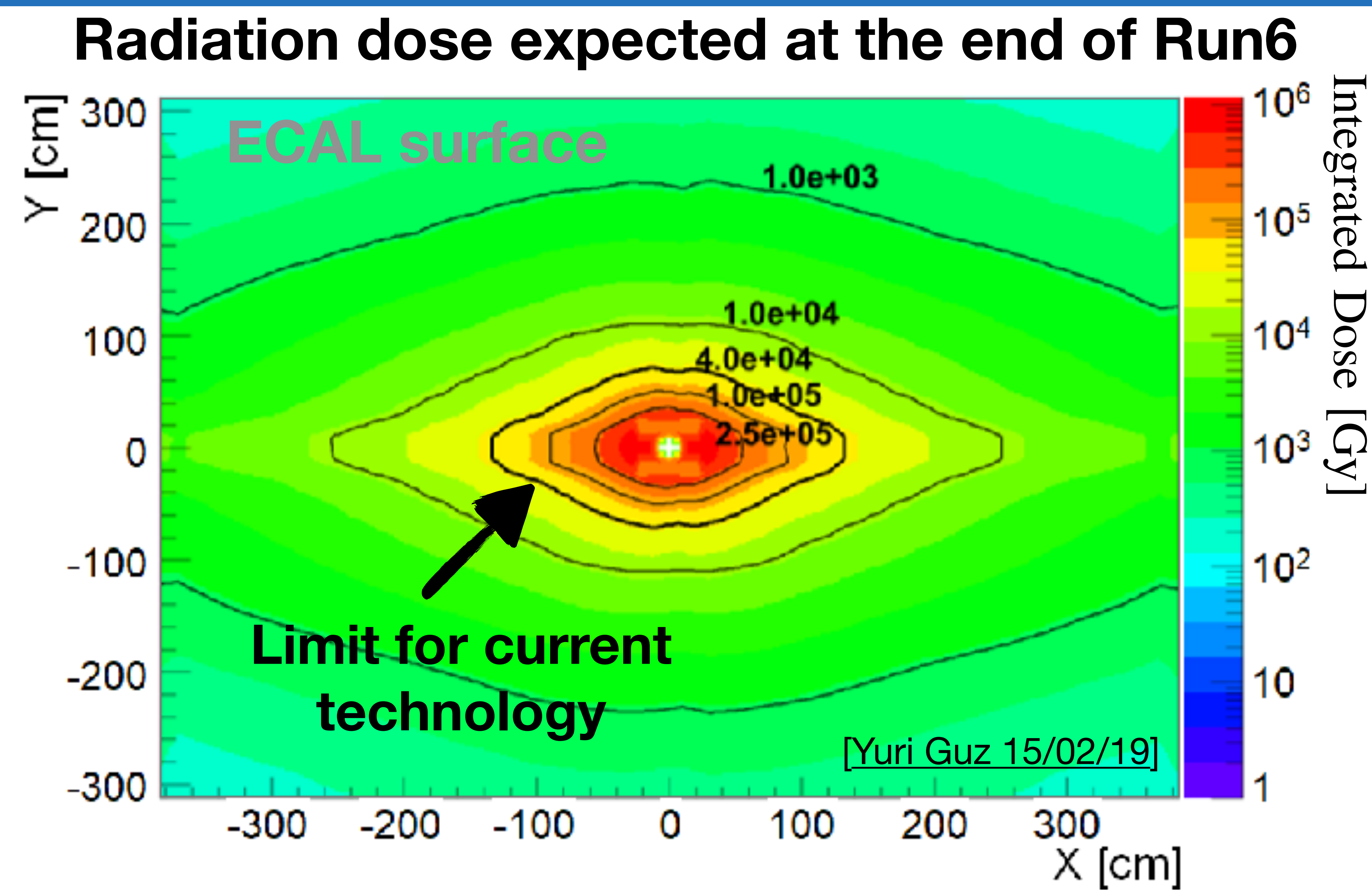
a) Exploded view of Shashlik cell



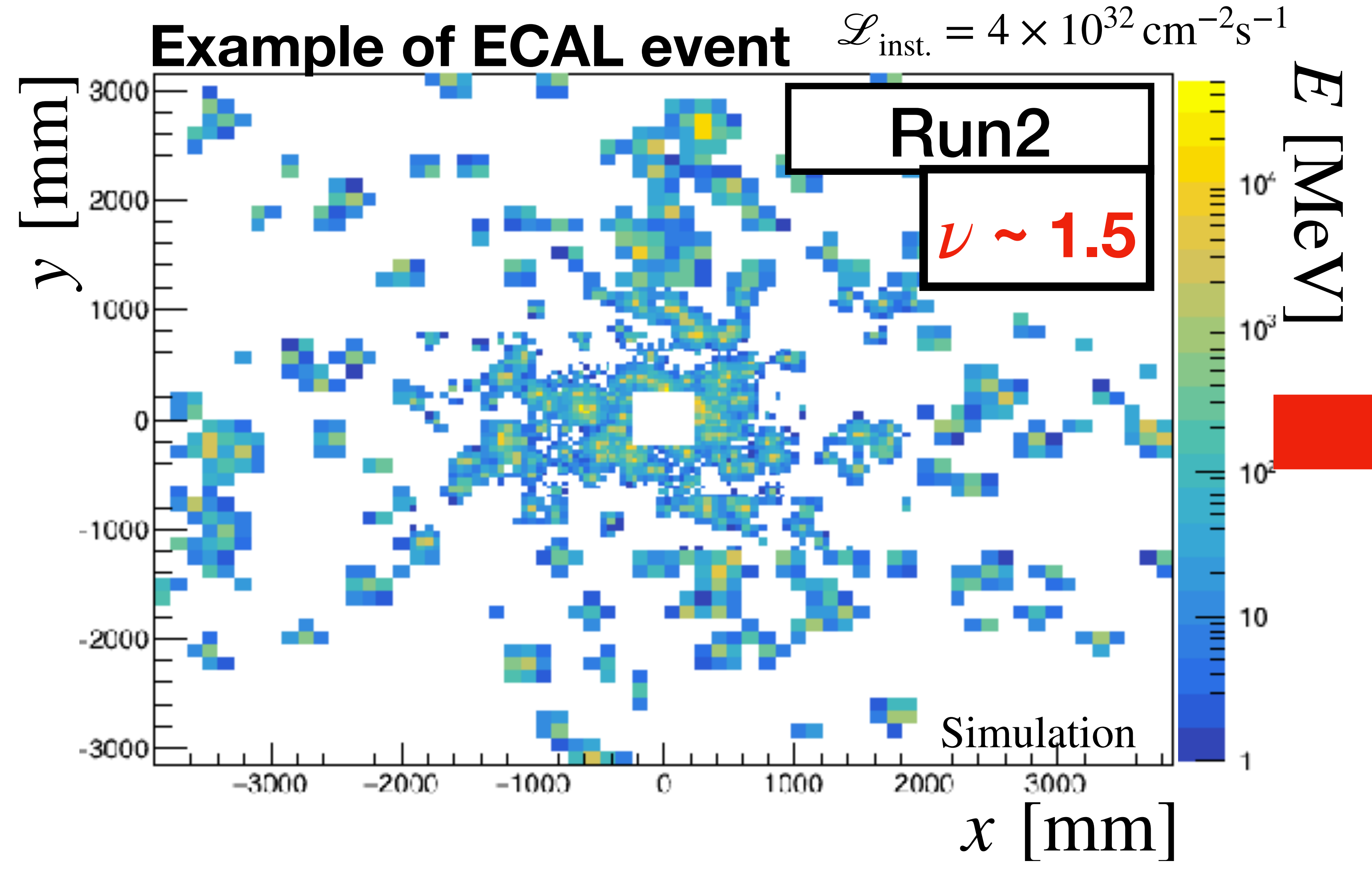
b) ECAL structure

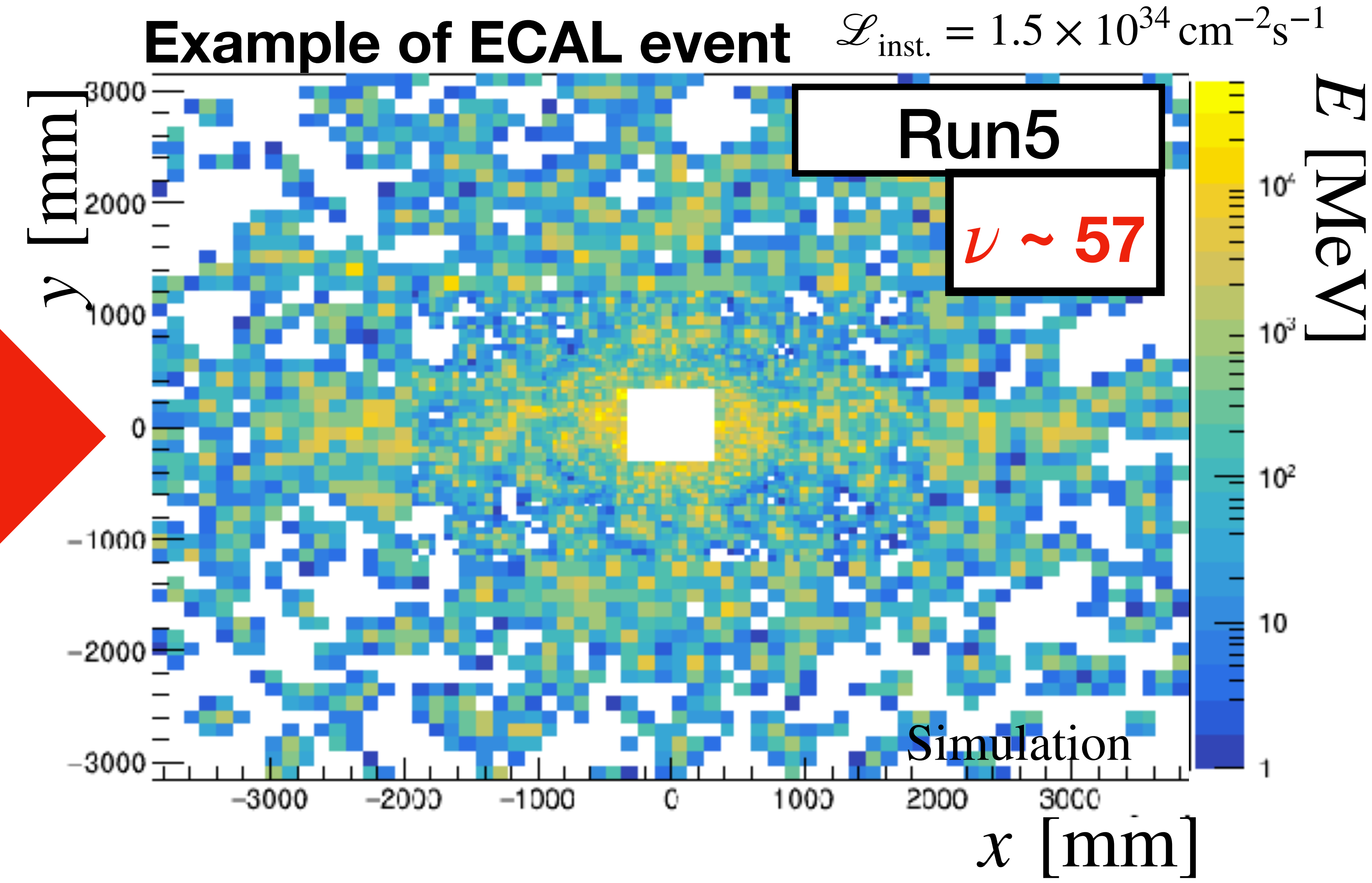
Context: challenges for the new ECAL

- Radiation hardness



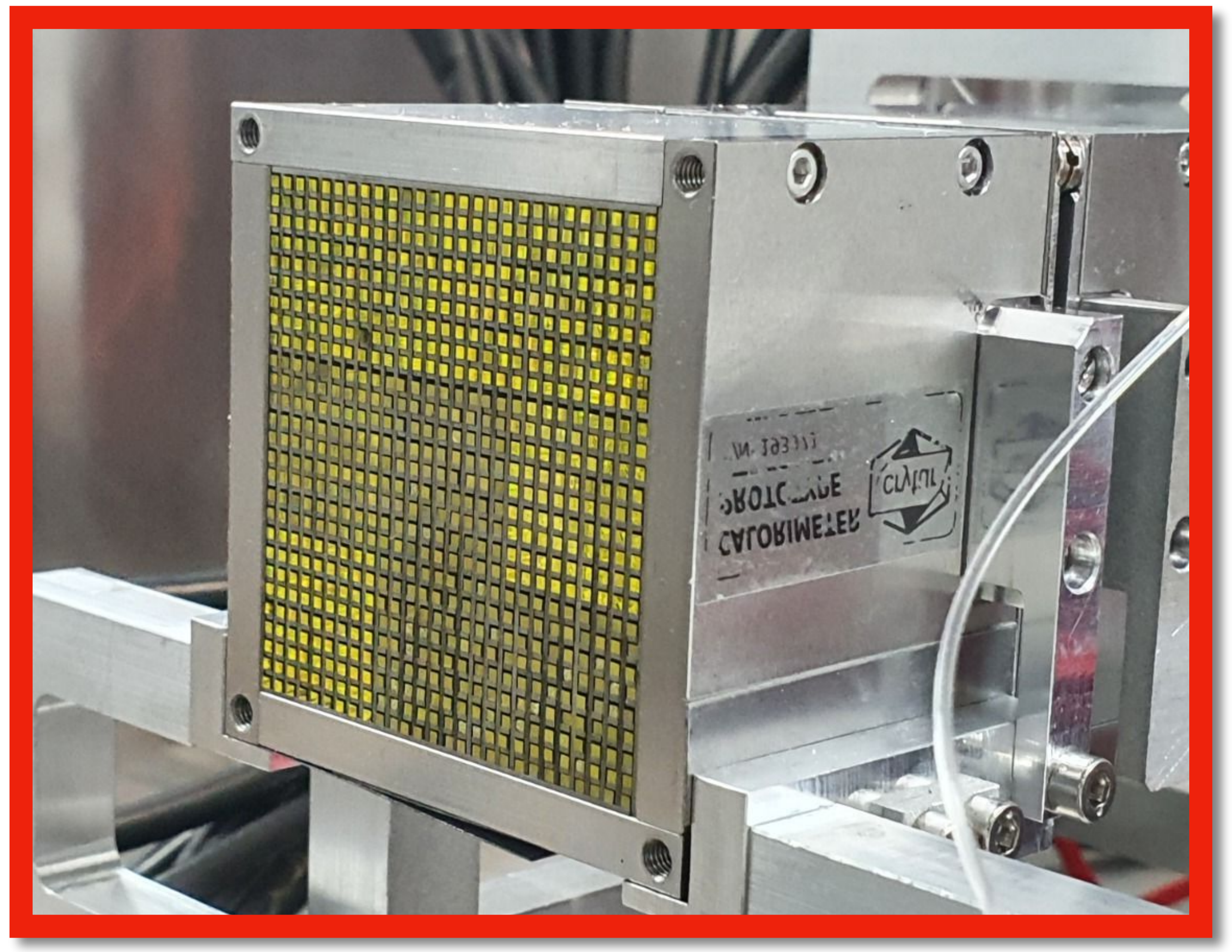
- Occupancy



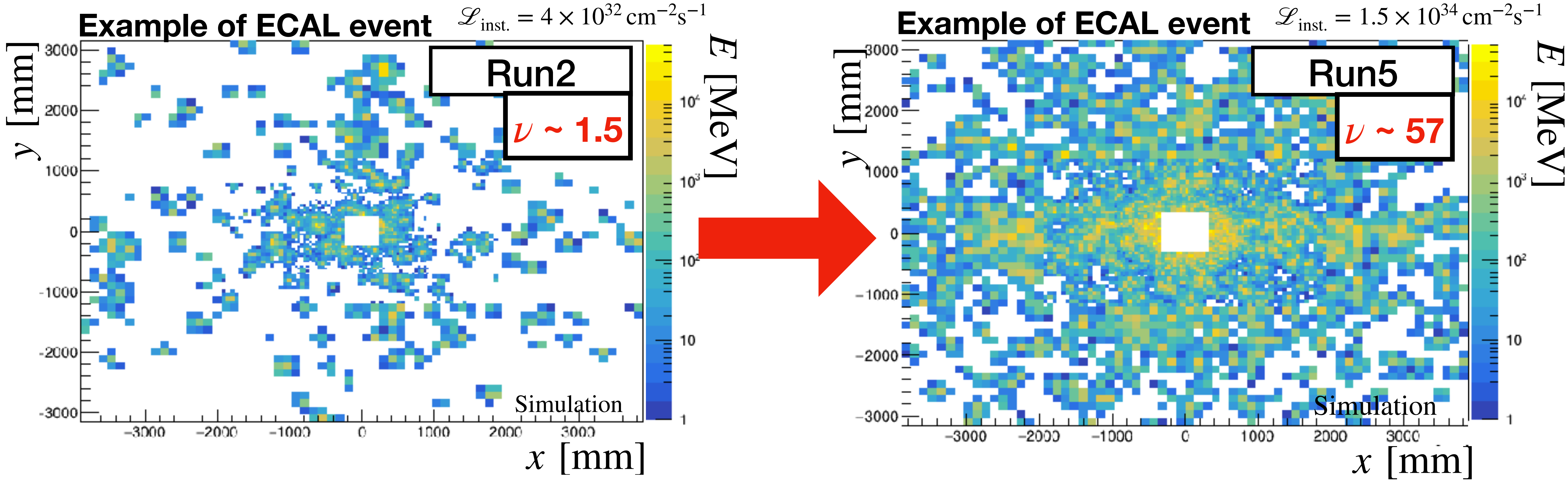


Context: challenges for the new ECAL

- Radiation hardness
  - SPACAL for the innermost regions
    - Absorber: Pb or W
    - Scintillator: Polystyrene-based or GAGG ($Gd_3Al_2Gd_3O_{12}$)



- Occupancy



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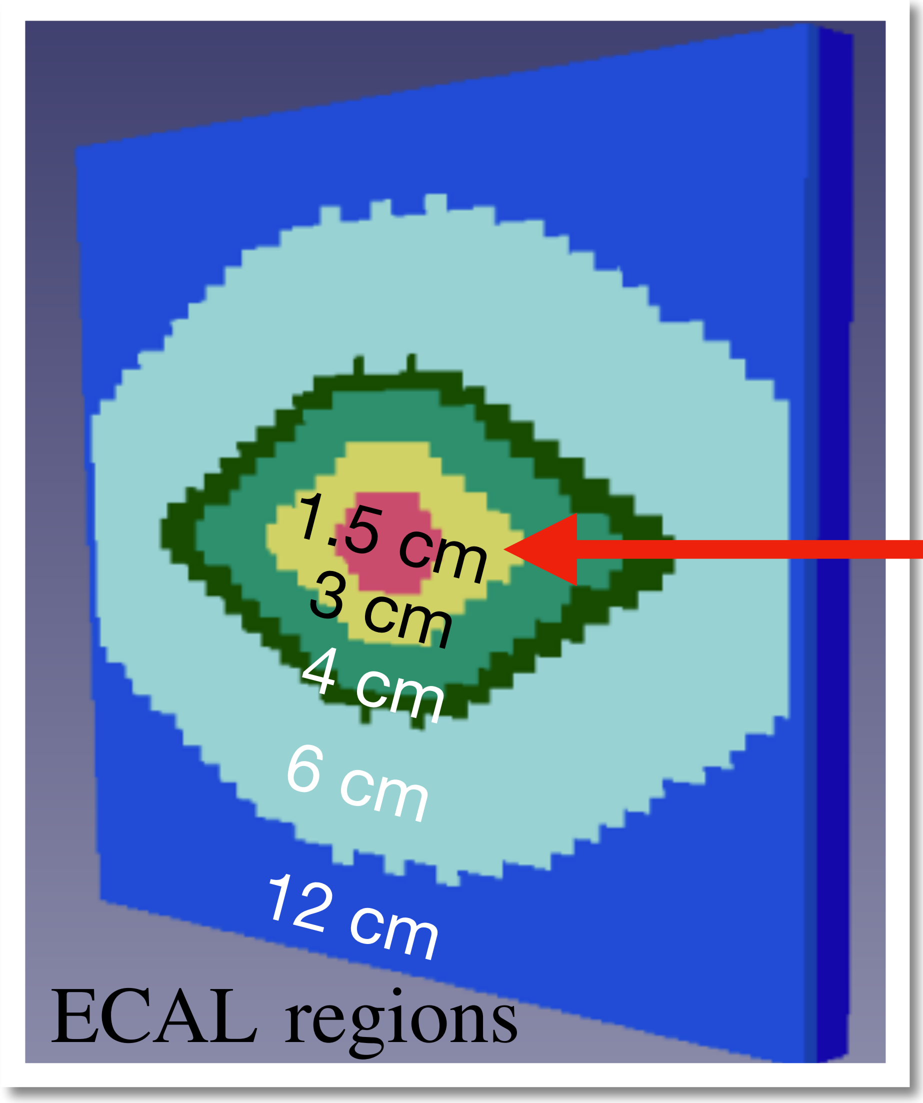
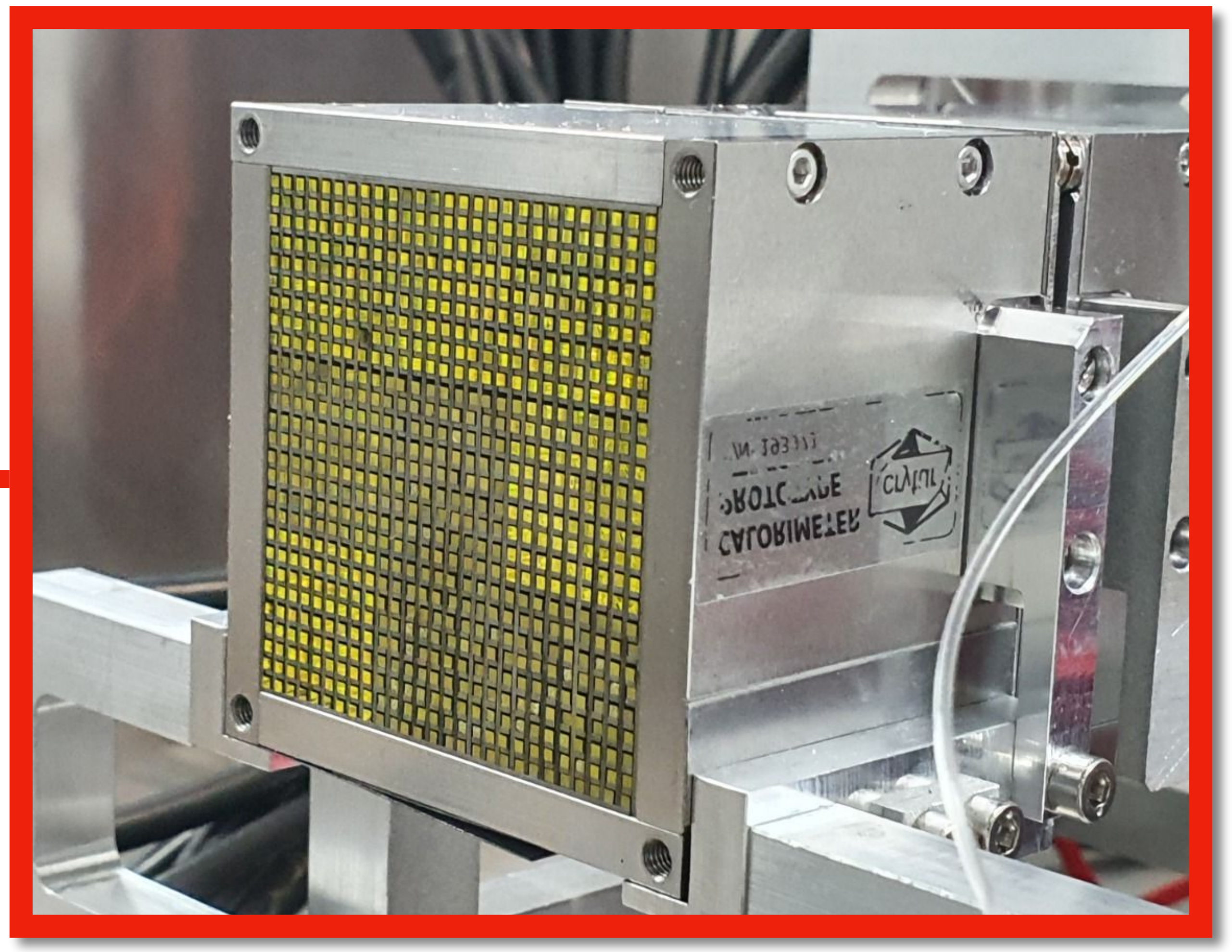
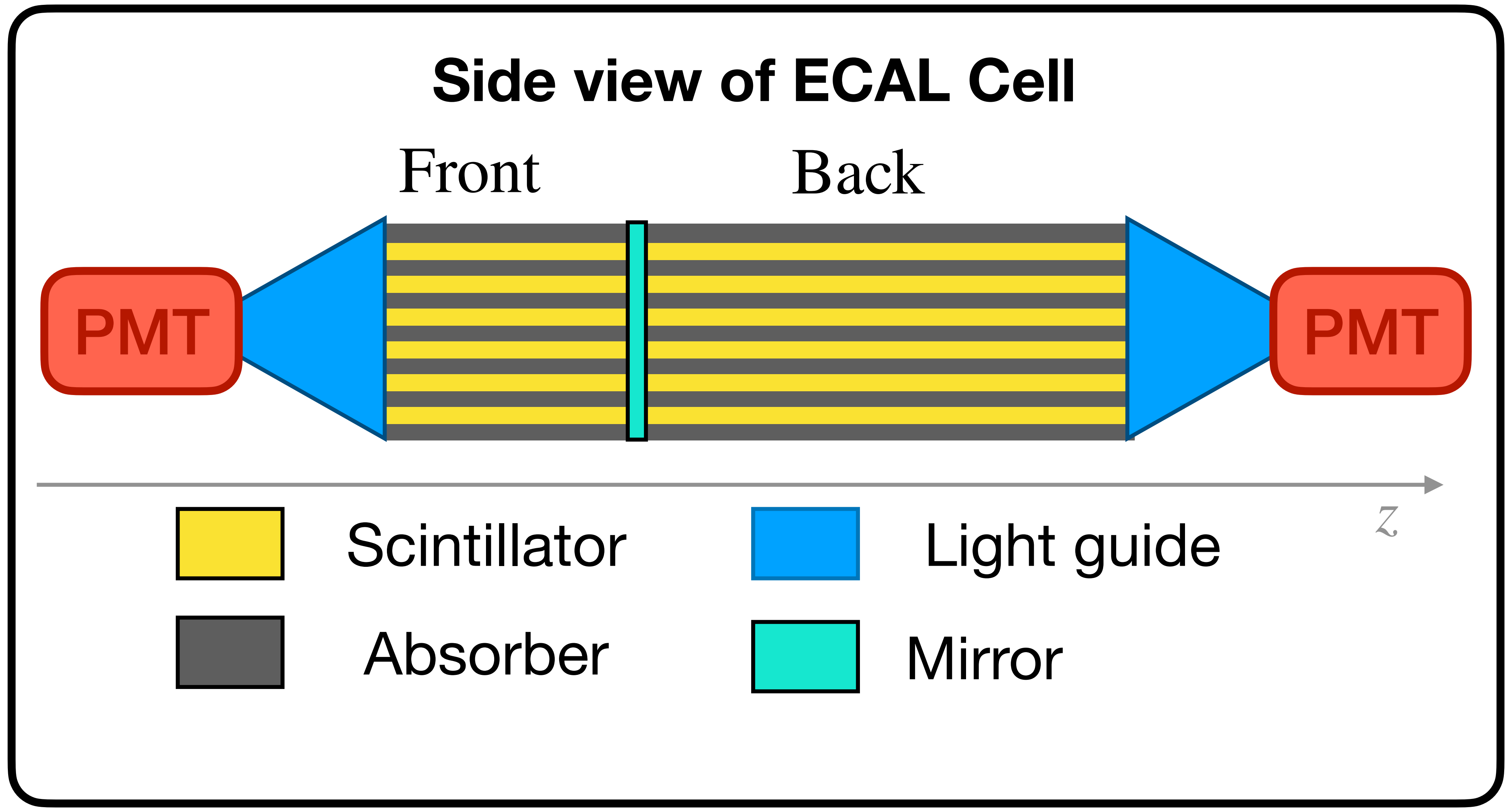




- Occupancy
  - Higher granularity
  - Double readout



Context: time information

- Radiation hardness
  - SPACAL for the innermost regions
    - Absorber: Pb or W
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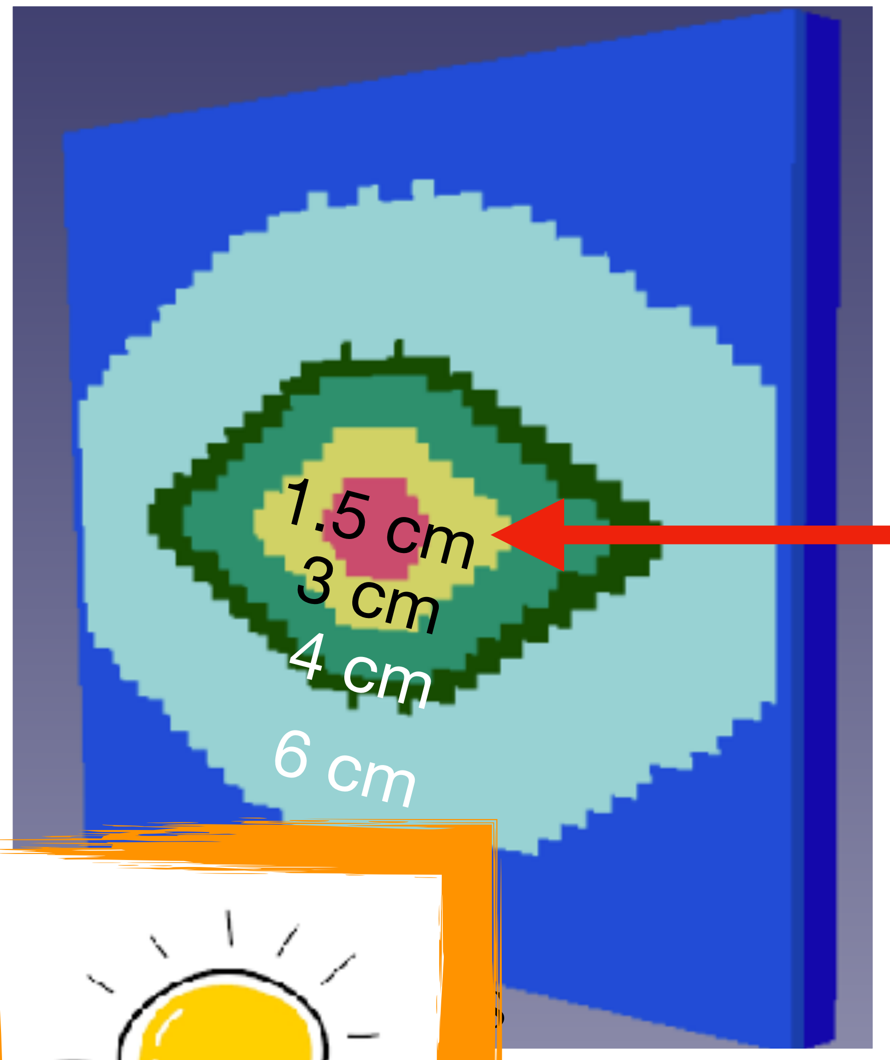
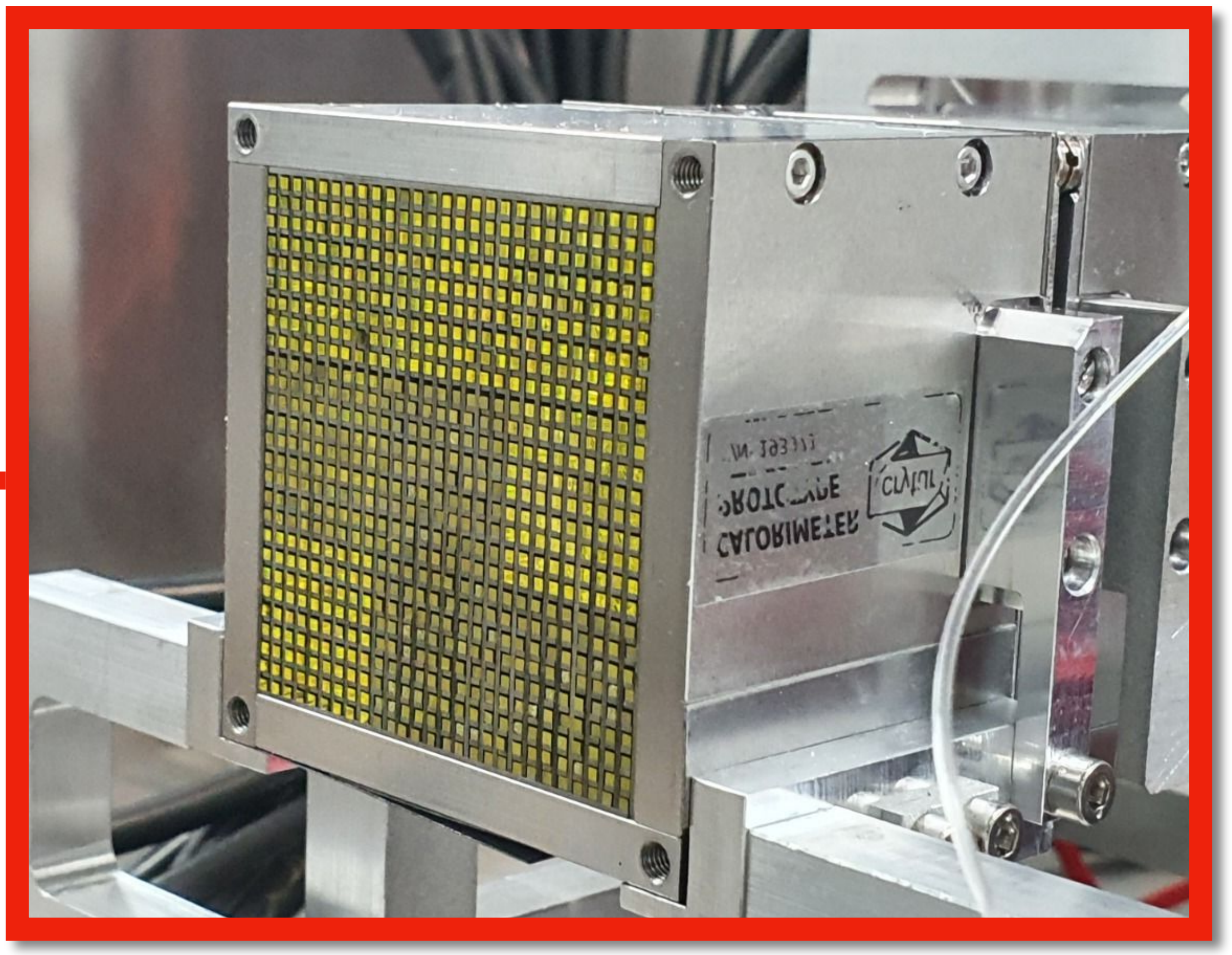
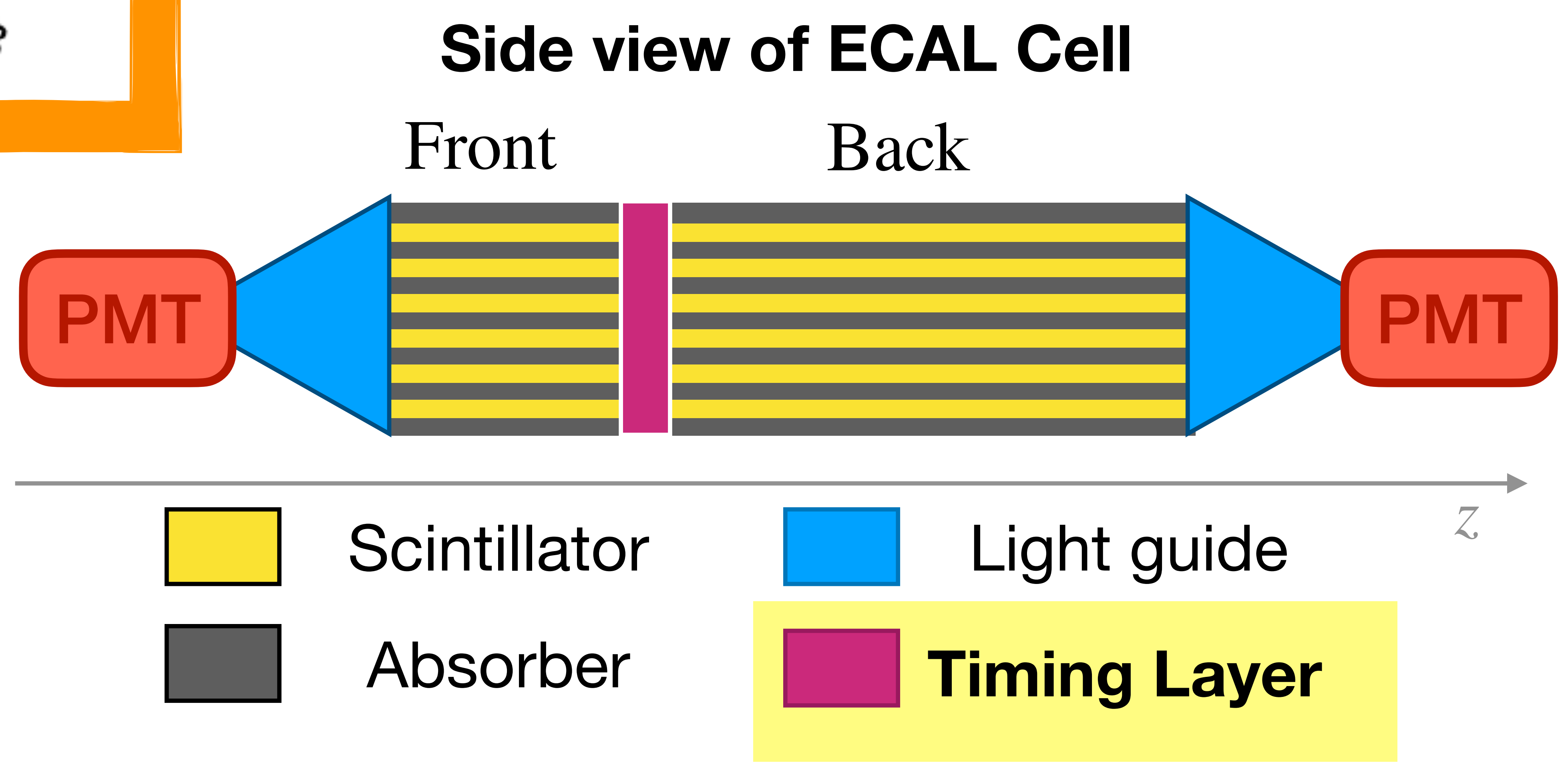




- Occupancy
  - Higher granularity
  - Double readout
  - **Time information**

Effective to suppress the combinatorial background and resolve the pile-up

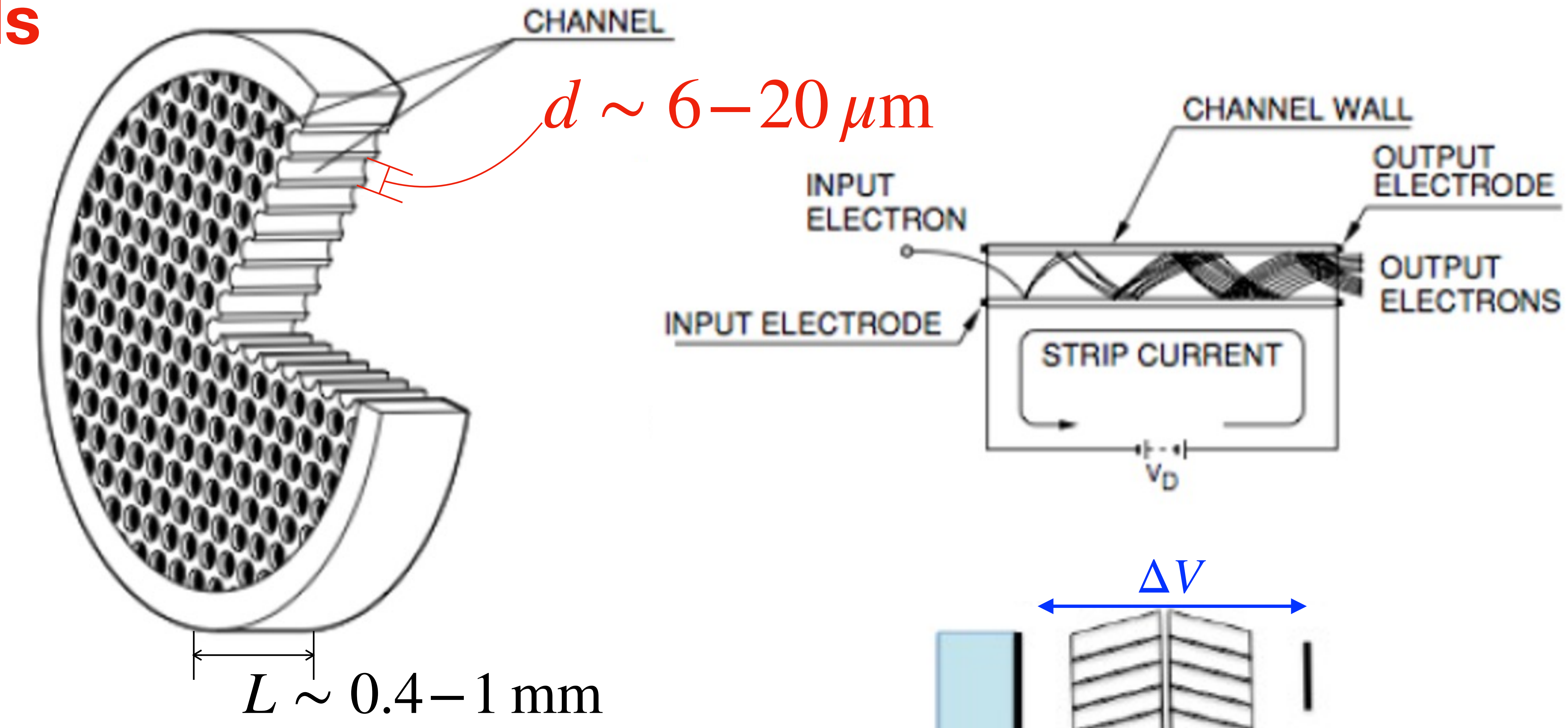
Required resolution below 20 ps

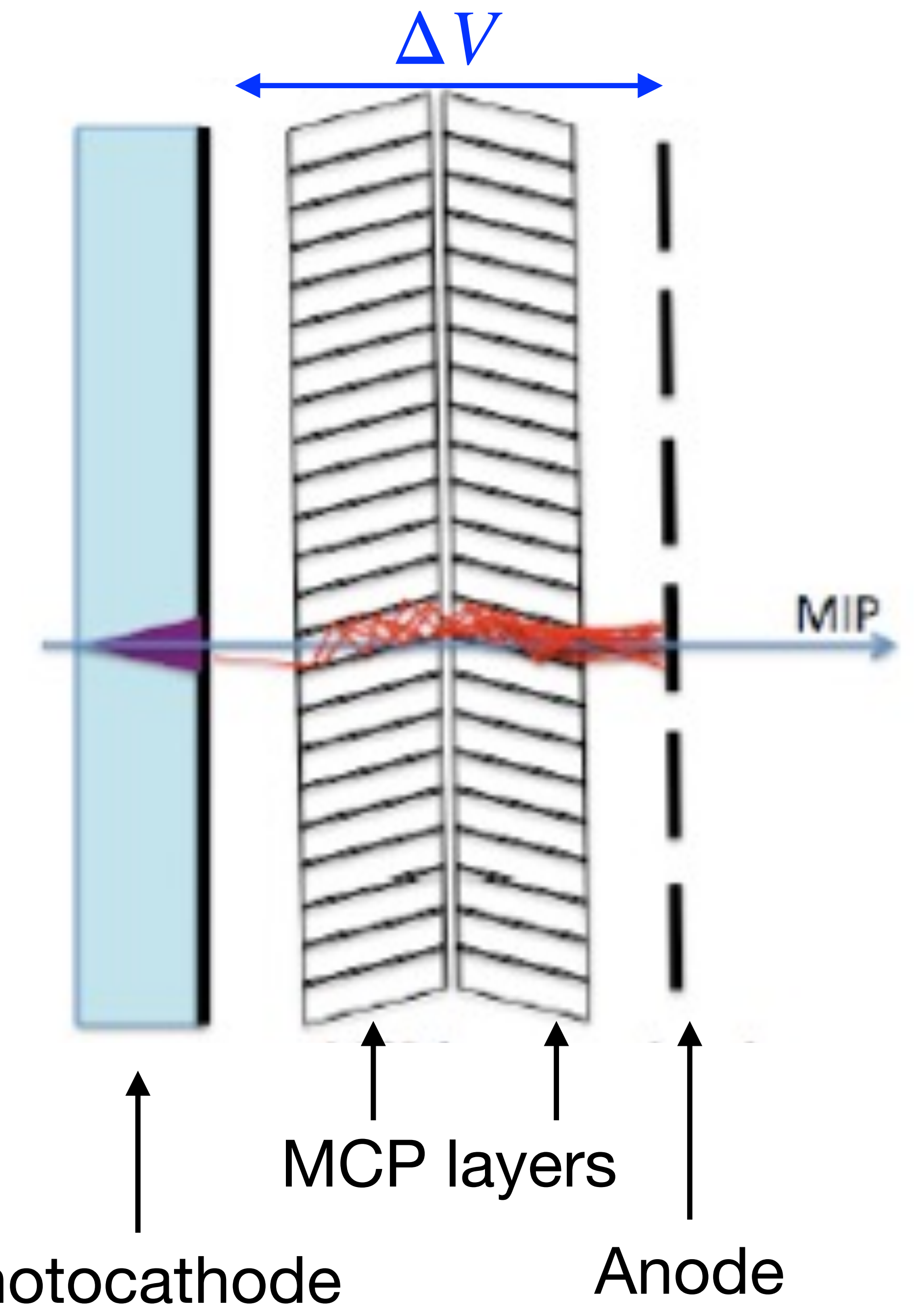


PicoCAL performance in beam tests are encouraging, but more R&D is necessary

Why MicroChannel Plates

- An MCP is a matrix of **micrometrical channels** able to multiply electrons
  - Traditionally produced from stacks of optical fibres with lead-glass cladding
  - **Photocathode**:
    - Photon detection
    - Good efficiency with single particles
- Easy to obtain gain of order $10^6 - 10^7$ with two MCP layers
  - $\log(G) \propto L/d$
- **Excellent time resolution:** $10 - 15$ ps
  - Several vendors available
- Original idea to use MCPs to sample EM-showers dates back to ‘90s
  - [A. Ronzhin et al., IFVE 90-99, Protvino, 1990]
- Recent work focused on Phase 2 HL-LHC Upgrades
  - [A. Ronzhin et al.] [A. Barnyakov et al.]



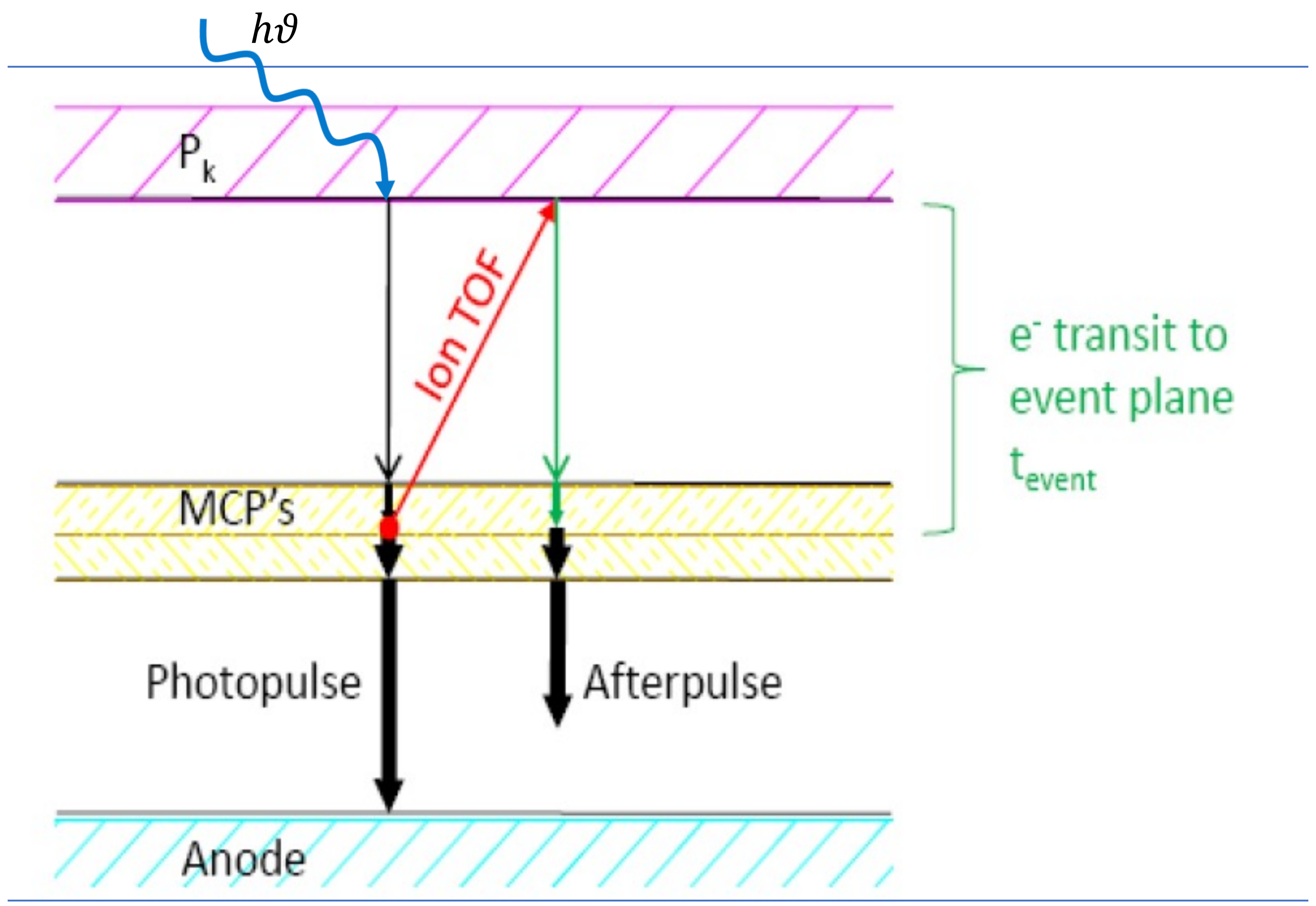


MCP limits

- **Cost**
  - Difficulties to build large-area MCPs with the traditional technology
    - ECAL area: $\sim 47\,\mathrm{m}^2$

- **Photocathode** fragility
  - Ion-feedback ruins the photocathode and spoils the quantum efficiency
    - Max. Integrated charge in literature: $\sim 35\ \mathrm{C/cm}^2$
    - 10 times less the requirements of LHCb ECAL

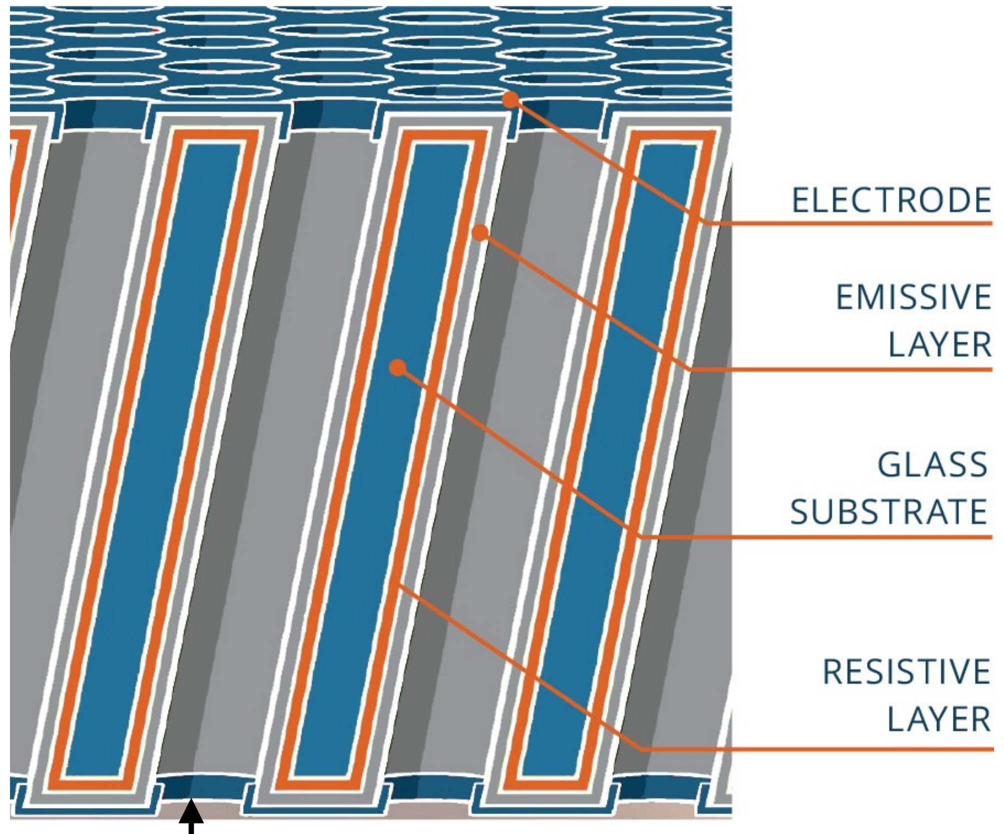
D. Miehlin et al., Nuc. Inst. and Methods in Physics Research A, Vol. 1049, 2023



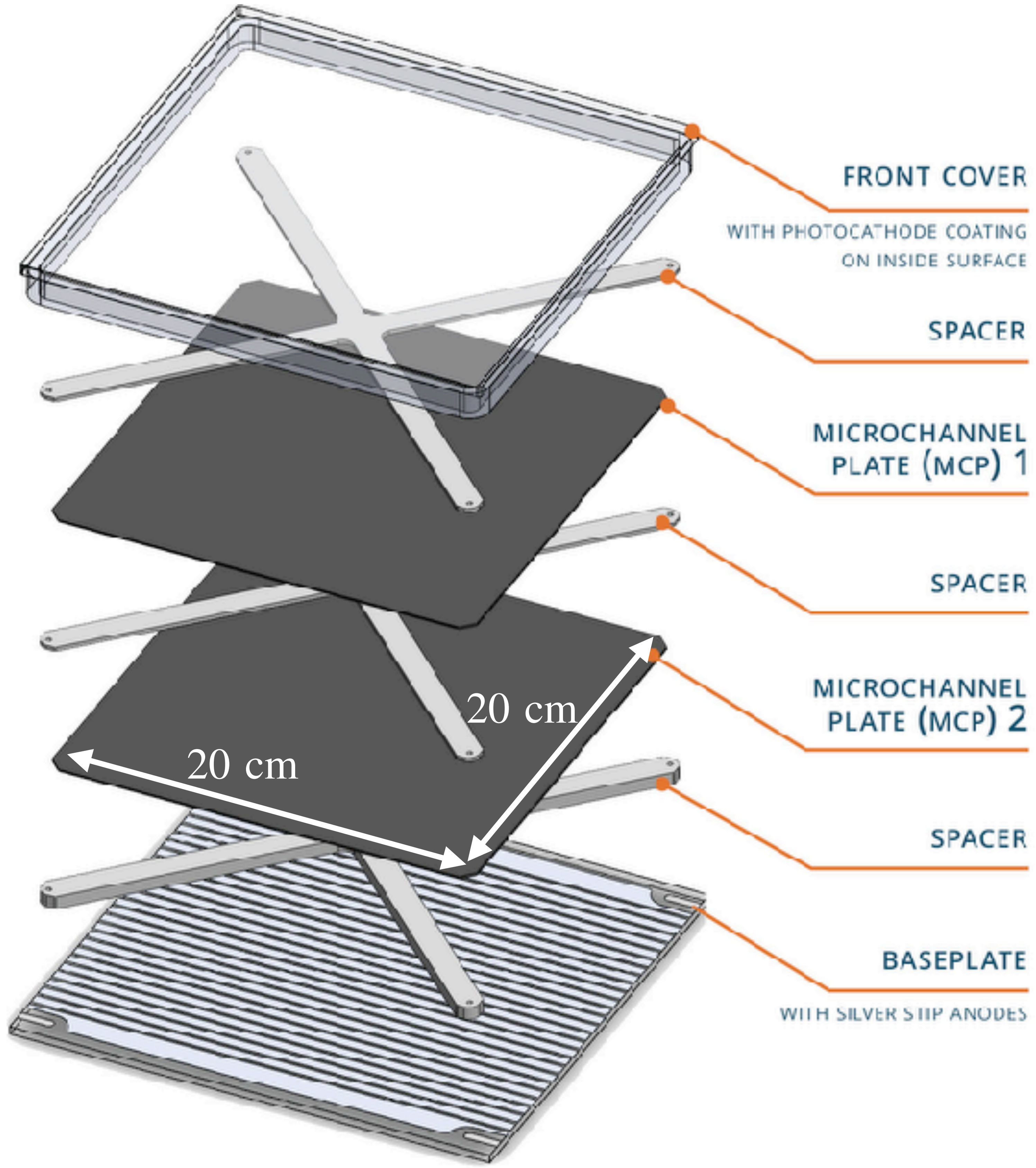
V. A. Chirayath & A. Brandt

MCP limits

- **Cost**
  - LAPPD™ by INCOM
    - Porous structure of the MCP made of **common borosilicate**, then activated through deposition of **resistive** and **emissive** layers (**A**tomic **L**ayer **D**eposition)

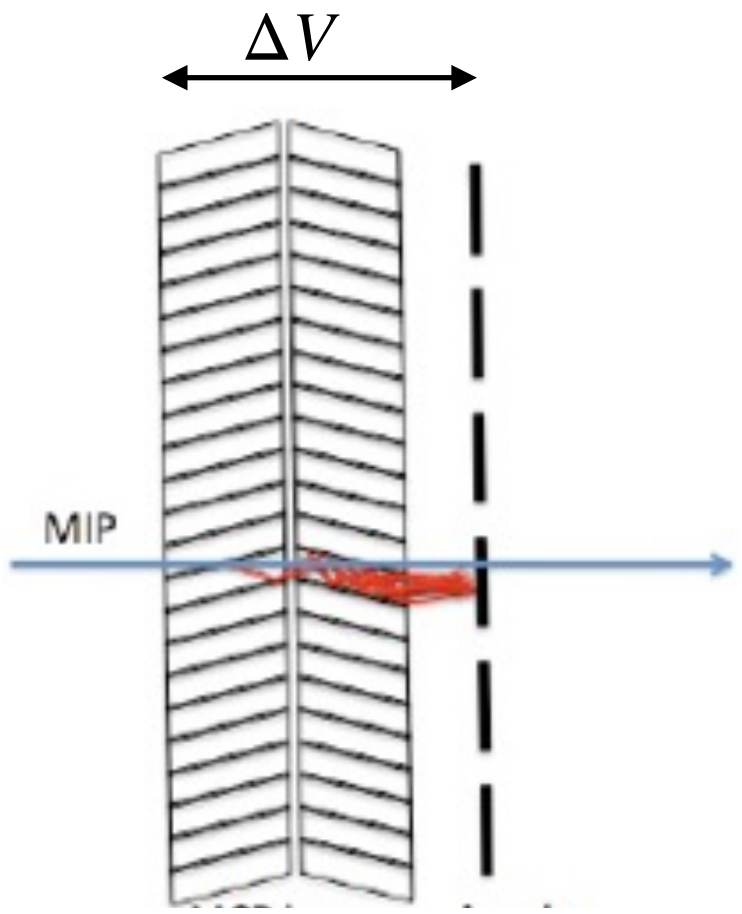


Exploded view of LAPPD, Gen I



- **Photocathode** fragility
  - Remove the photocathode
    - At the shower maximum, the number of $e^{\pm}$ is high
    - Exploit primary ionisation
      - **Further complexity and cost reduction**

[i-MCP Collaboration]
[arXiv:1504.02728]



Largest MCP-PMT available on the market

LAPPD = **L**arge **A**rea **P**icosecond **P**hoto**D**etector

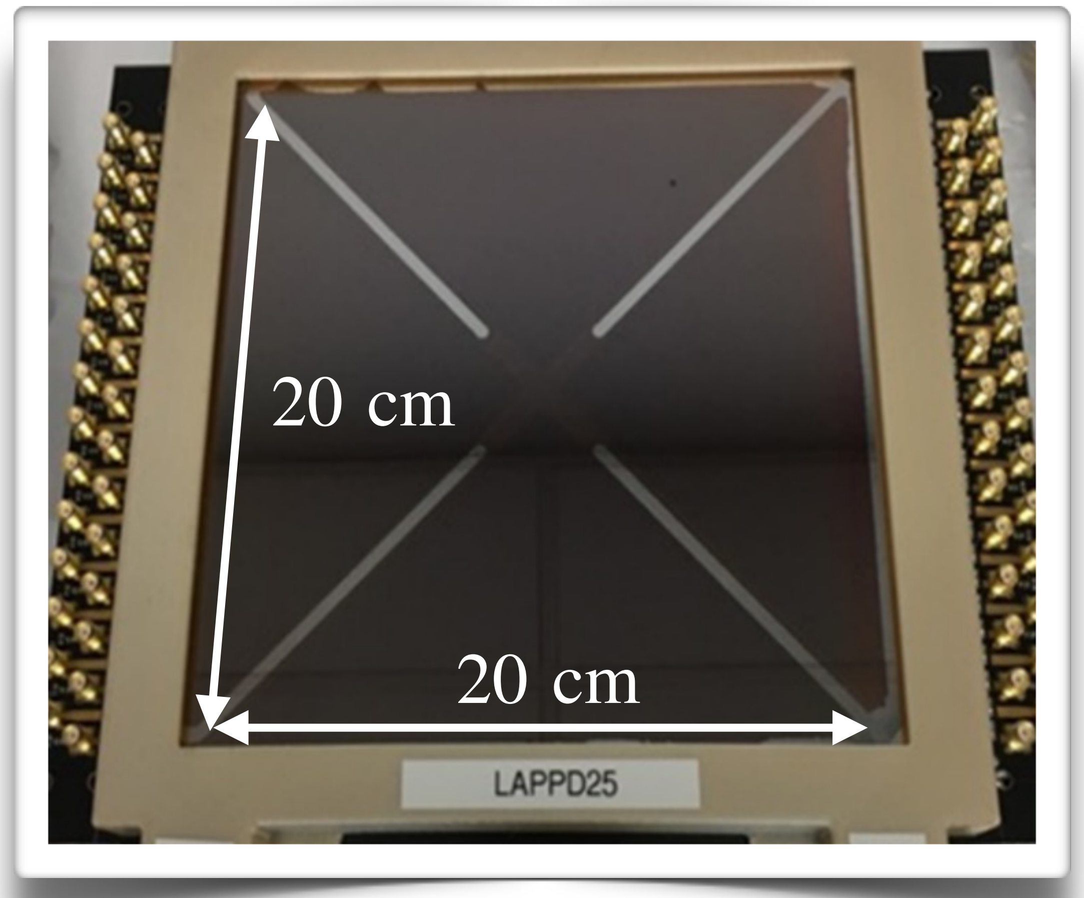
Prototypes

LAPPD versions

FAST 2021 → #69, #87

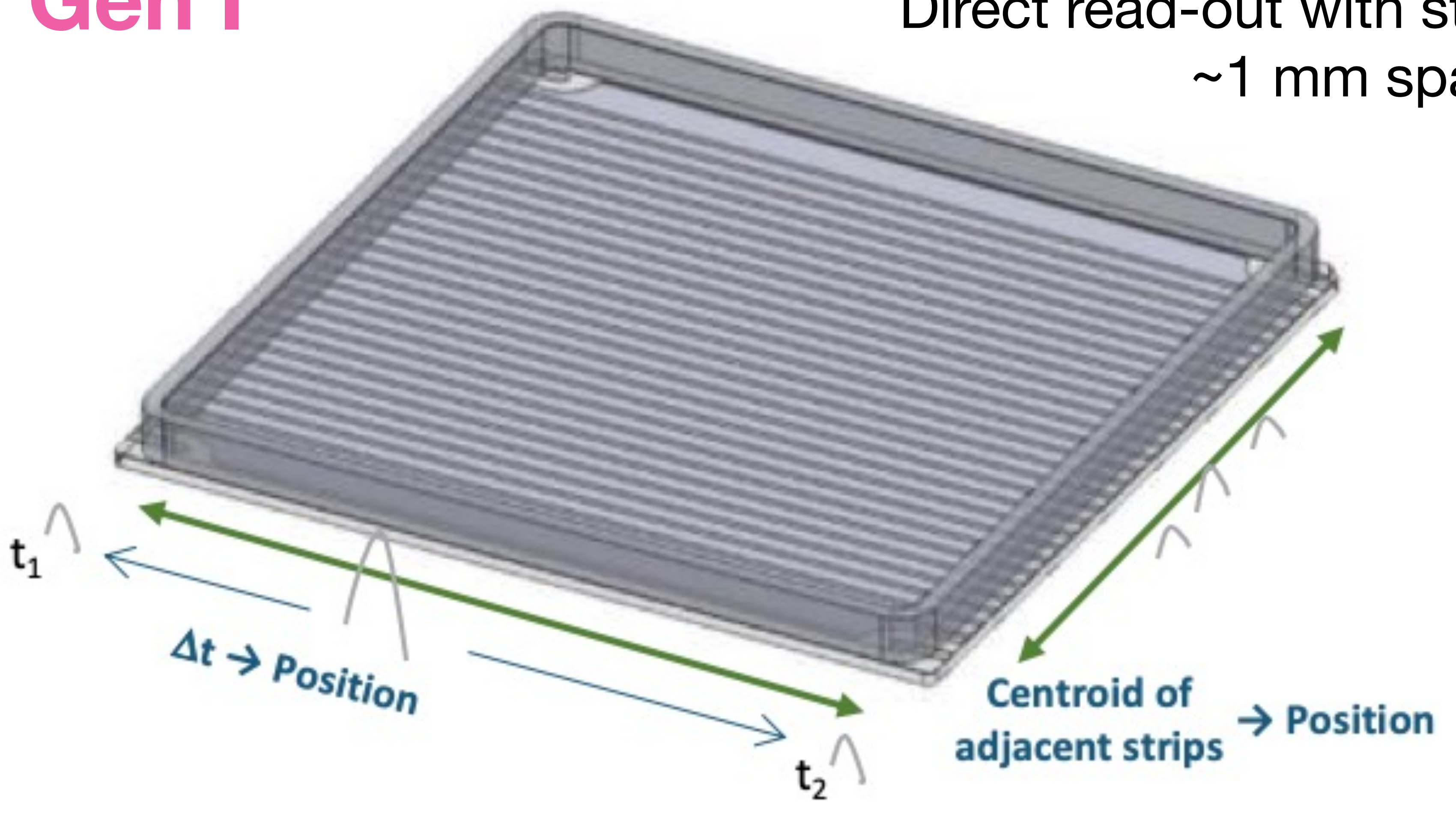
TODAY → #89, #119, Z-stack

Name	pore d [μm]	# MCP layers	Anode
#69	20	2	strip
#89	10	2	strip
#87	20	2	pixel
#119	10	2	pixel
Z-stack	10	3	pixel



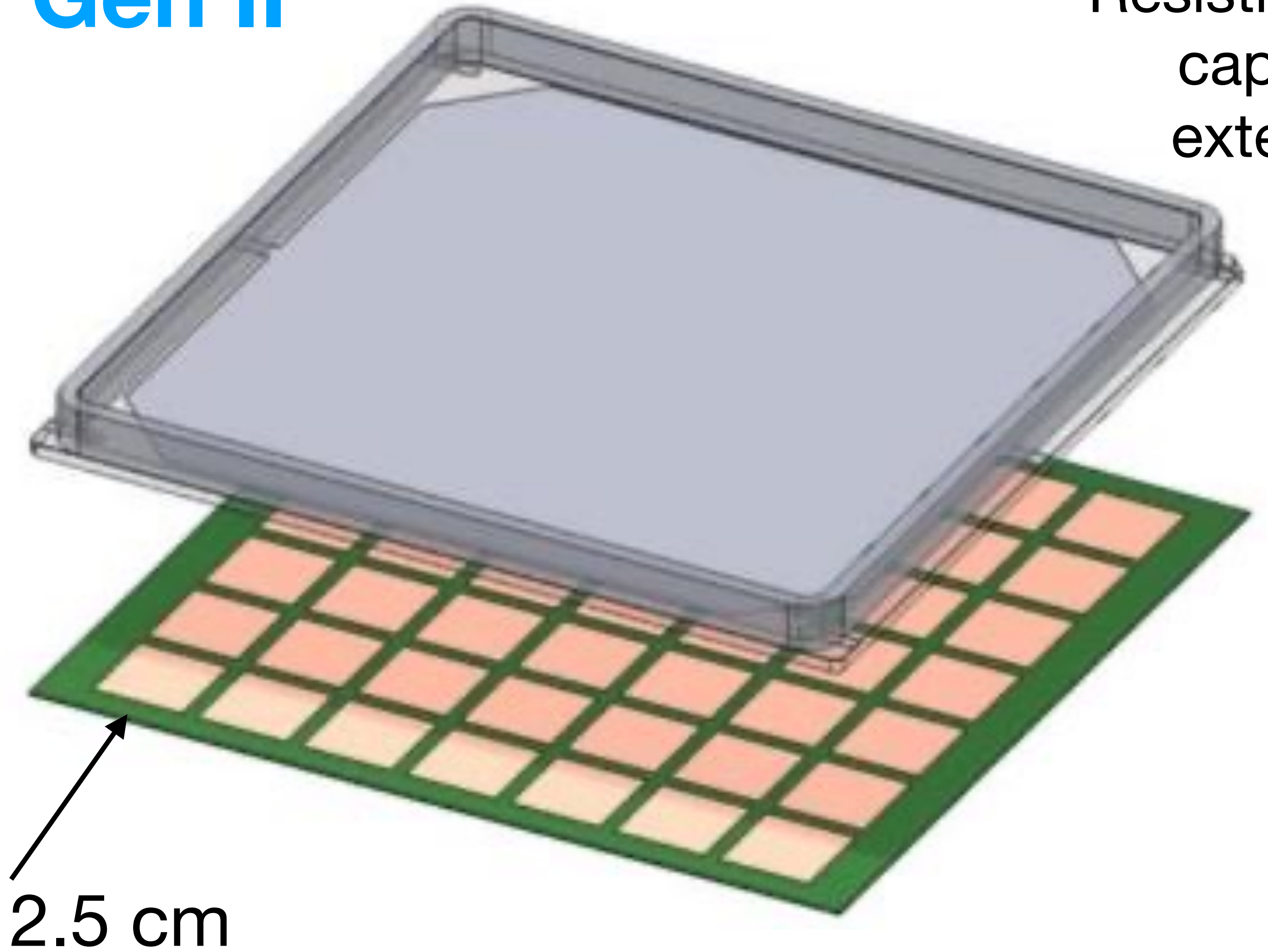
Gen I

Direct read-out with strip-line anode
~1 mm spatial resolution



Gen II

Resistive interior anode,
capacitively-coupled
external-anode PCB,
customisable
pixel pattern



pixel side: 2.5 cm

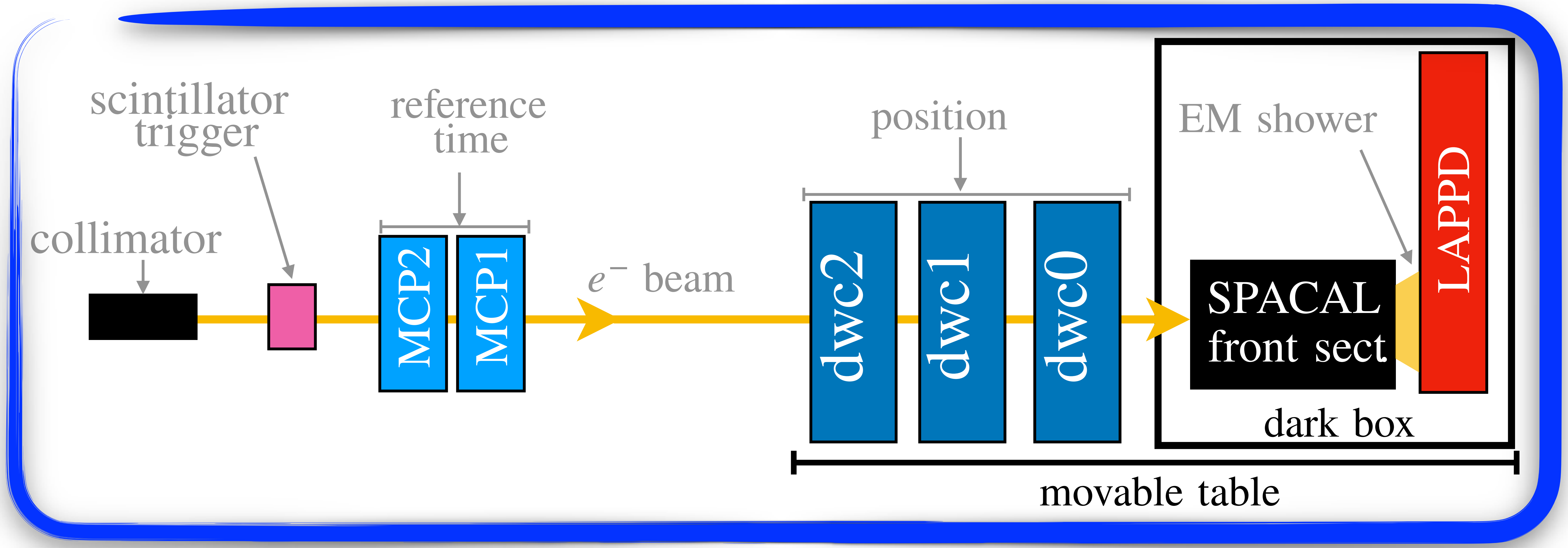
more suitable for high occupancy

Test Facilities

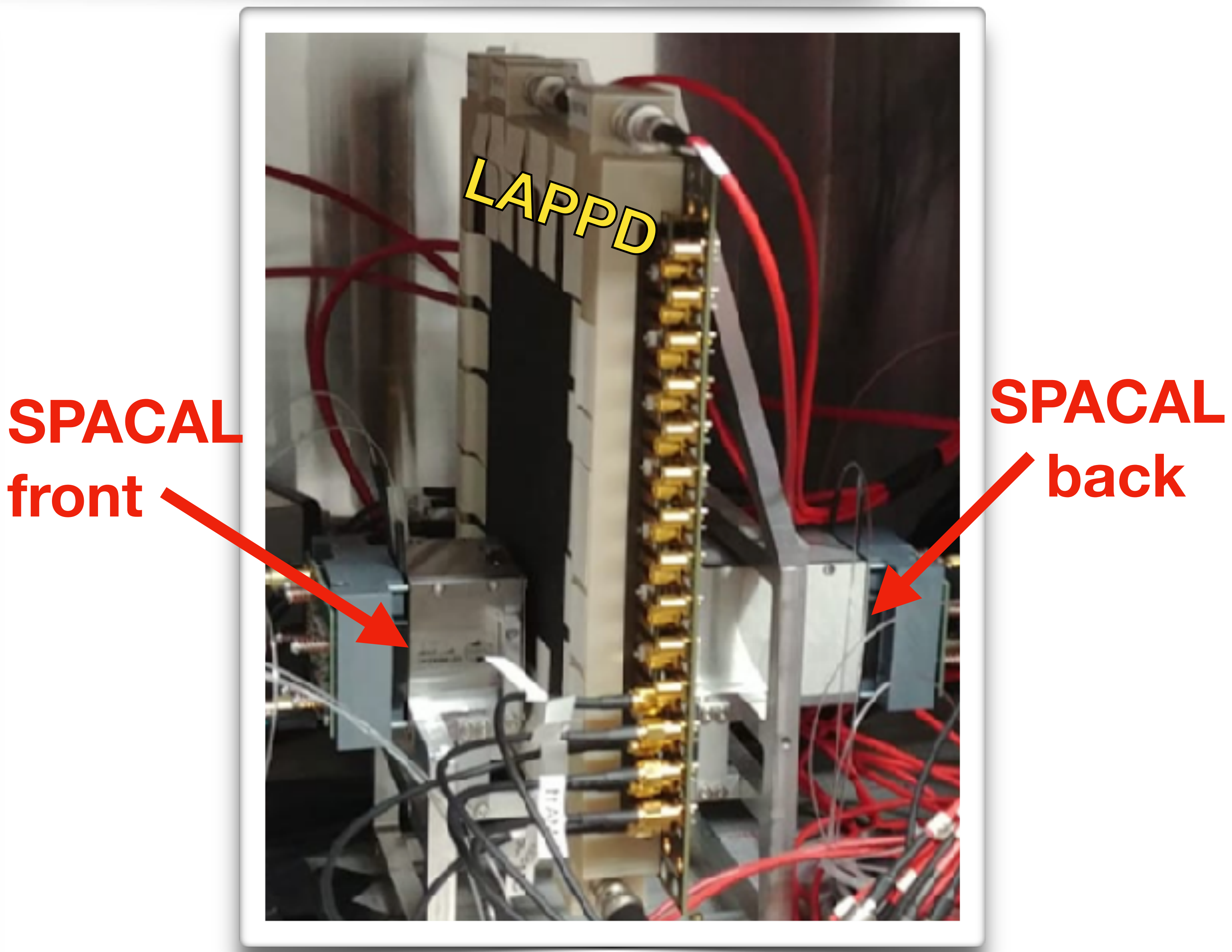
- At **accelerators:**
  - Electrons → **Time resolution**, Efficiency, Spatial resolution
    - DESY: $1-5.8\ \mathrm{GeV}$
    - SPS: $20-100\ \mathrm{GeV}$
  - Protons → **Radiation hardness**
    - IRRAD: $24\ \mathrm{GeV}$

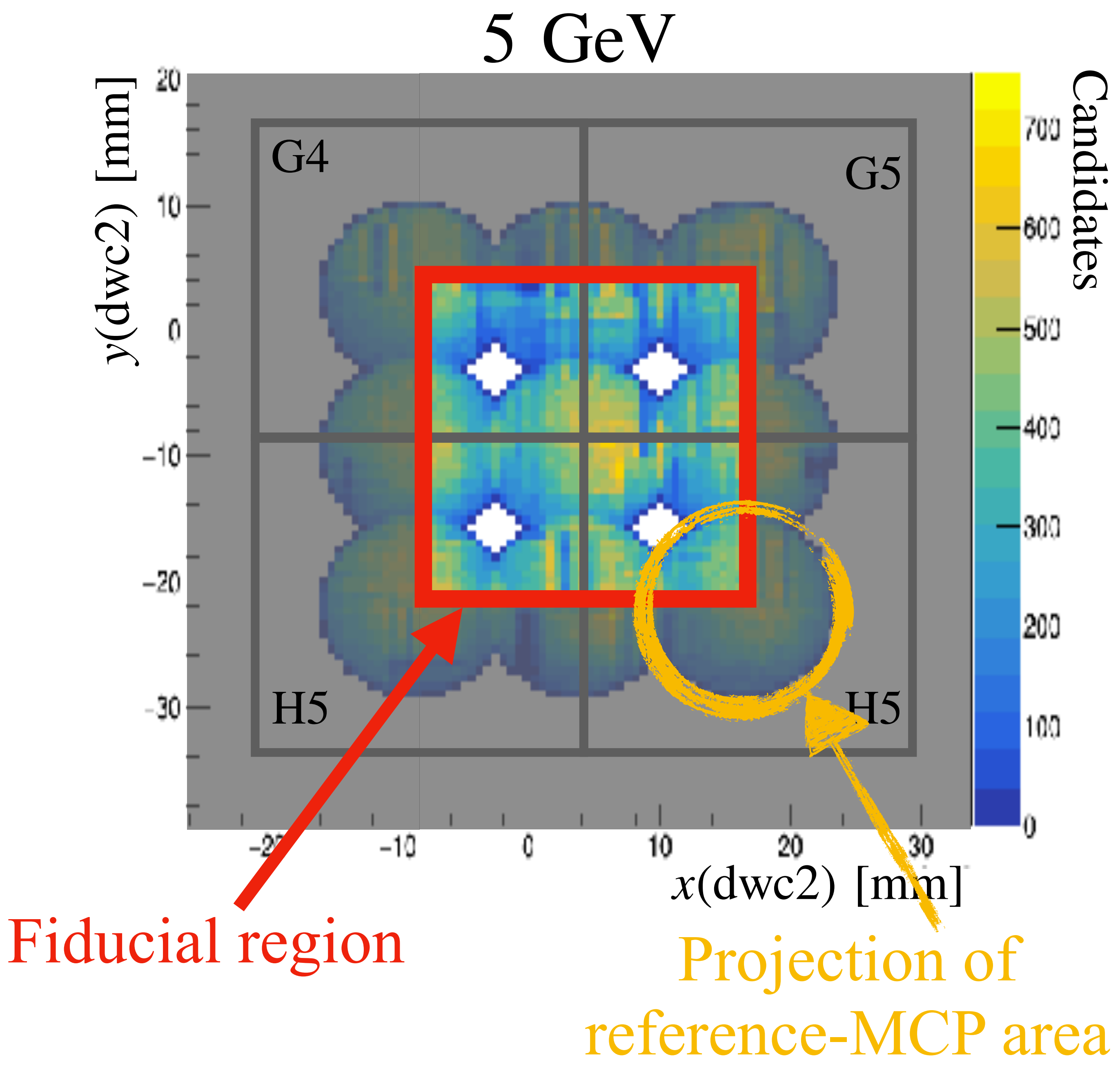
- In the **laboratory**
  - UV lamp → **Ageing**
  - Laser $(\lambda = 405\,\mathrm{nm})$ → Studies of operation in **high-flux environment**

Test beam setup



- Today: results with **LAPPD Z-stack**
  - Gen-II, d = 10 μm, 3 MCP layers available
  - Photocathode: alway inhibited
- Signals digitised with: `CAEN v1742` (5 GS/s)
  - Details in the backup
- Resolution of reference time from the MCPs: ≈ 12 ps
- Fiducial region involving **4 pixels**
  - G4, G5, H4, H5





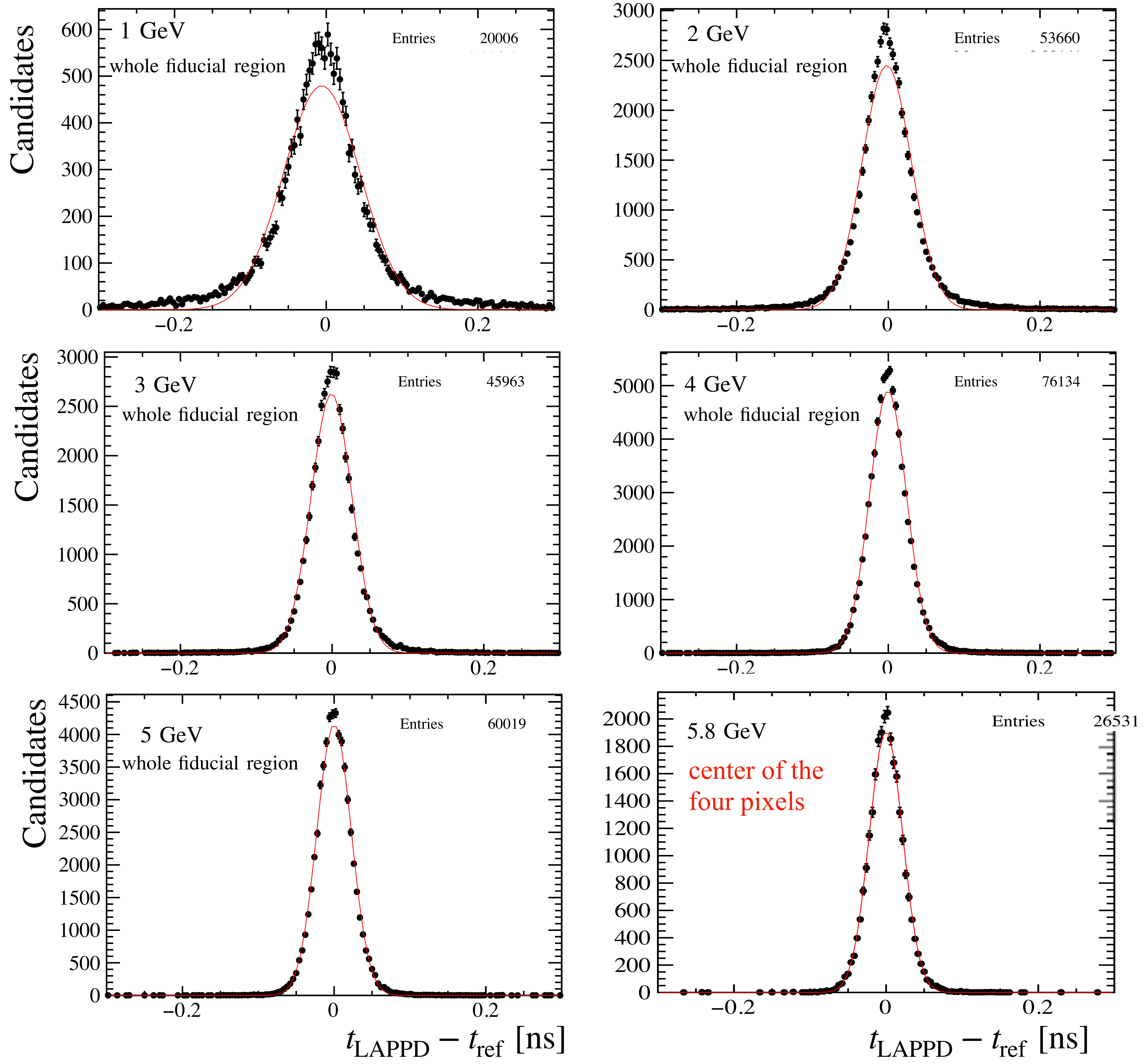
Pixel combination

- Information from the 4 pixels combined using a **Random Forrest Regressor**
  - **Inputs:**
    - from LAPPD pixels:
      - Signal amplitudes
      - t_{CFD} at 10%, 50%, 90%
    - Position from DWC2
  - **Target**: mean time of reference MCPs (t_{ref})

- Gaussianity improving with increasing energy

- Results in the next slide

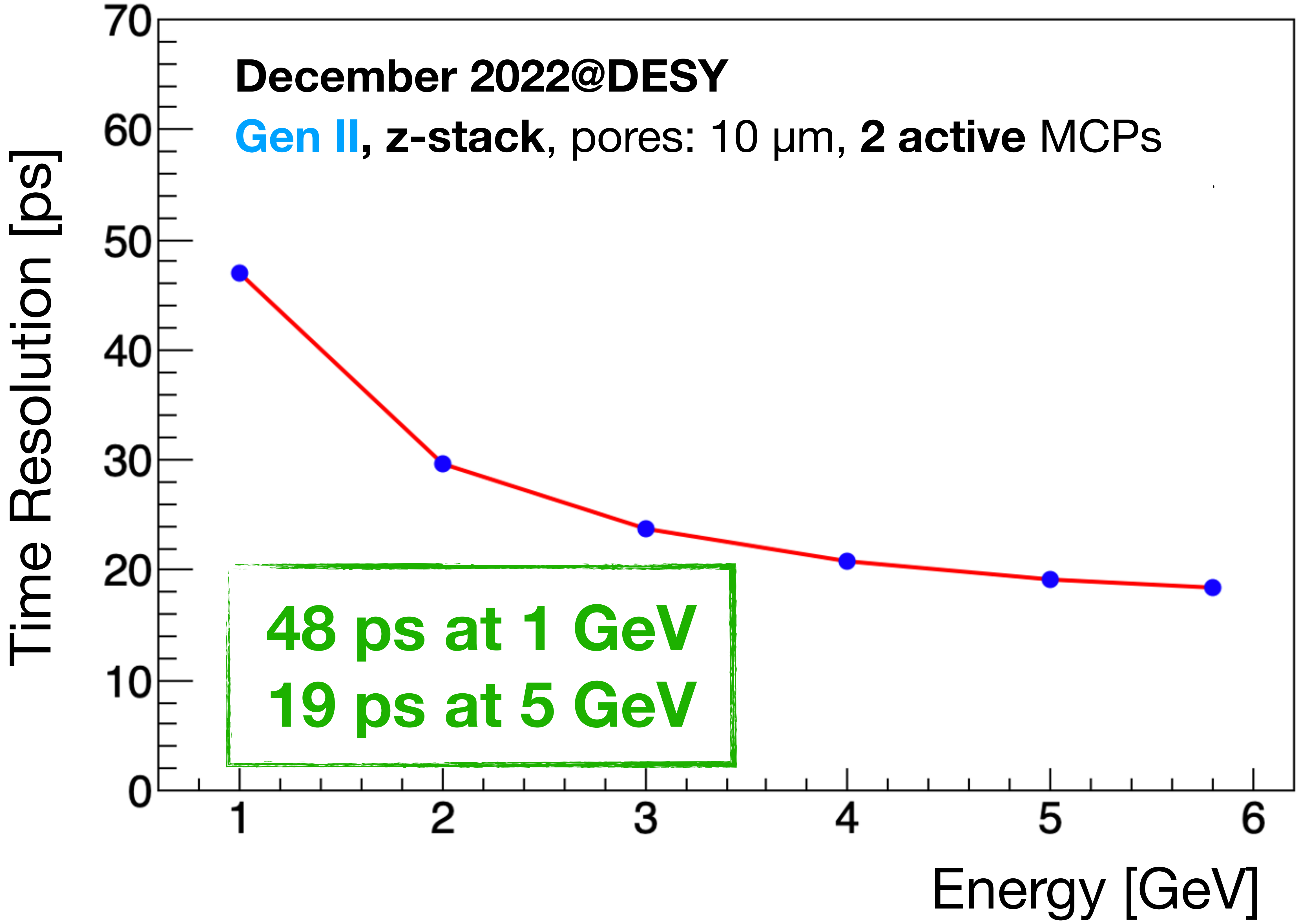
Gen II, z-stack, pores: 10 µm, **2 active** MCPs



Corresponding distributions at 20, 40, 60, 100 GeV in the backup

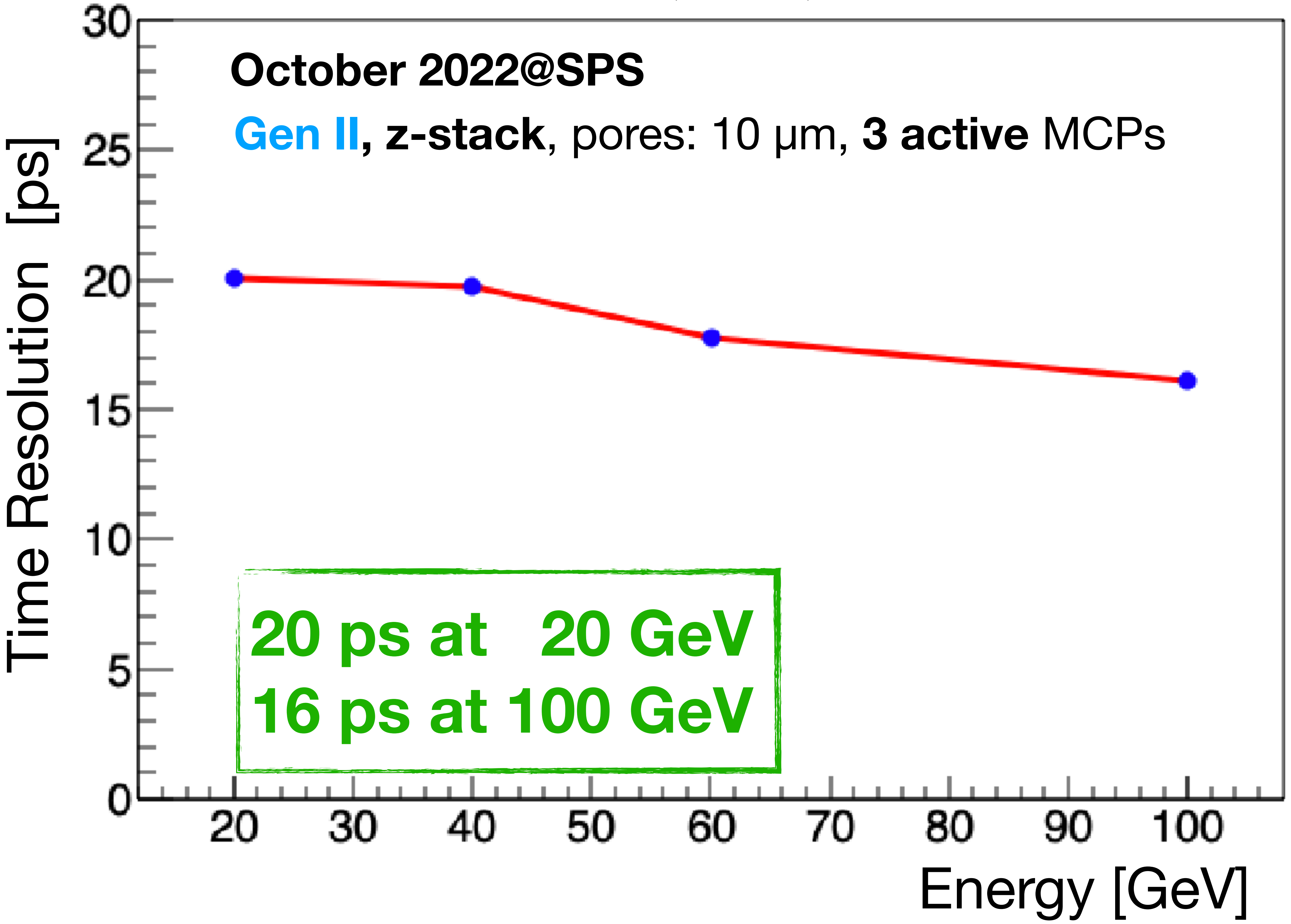
Time resolution

Voltage settings: PC and MCP1: OFF, GAPs: 200 V,
MCP2 and MCP3: 875 V



σ_t = 30 ps at 5 GeV, with 3 active MCPs

Voltage settings: PC: OFF, GAPs: 200 V,
MCP1, MCP2, and MCP3: 685 V



Improvement expected with 2 active MCPs

Resolution of reference MCPs already subtracted in this slide

Backup slides: performances of Gen-I prototypes

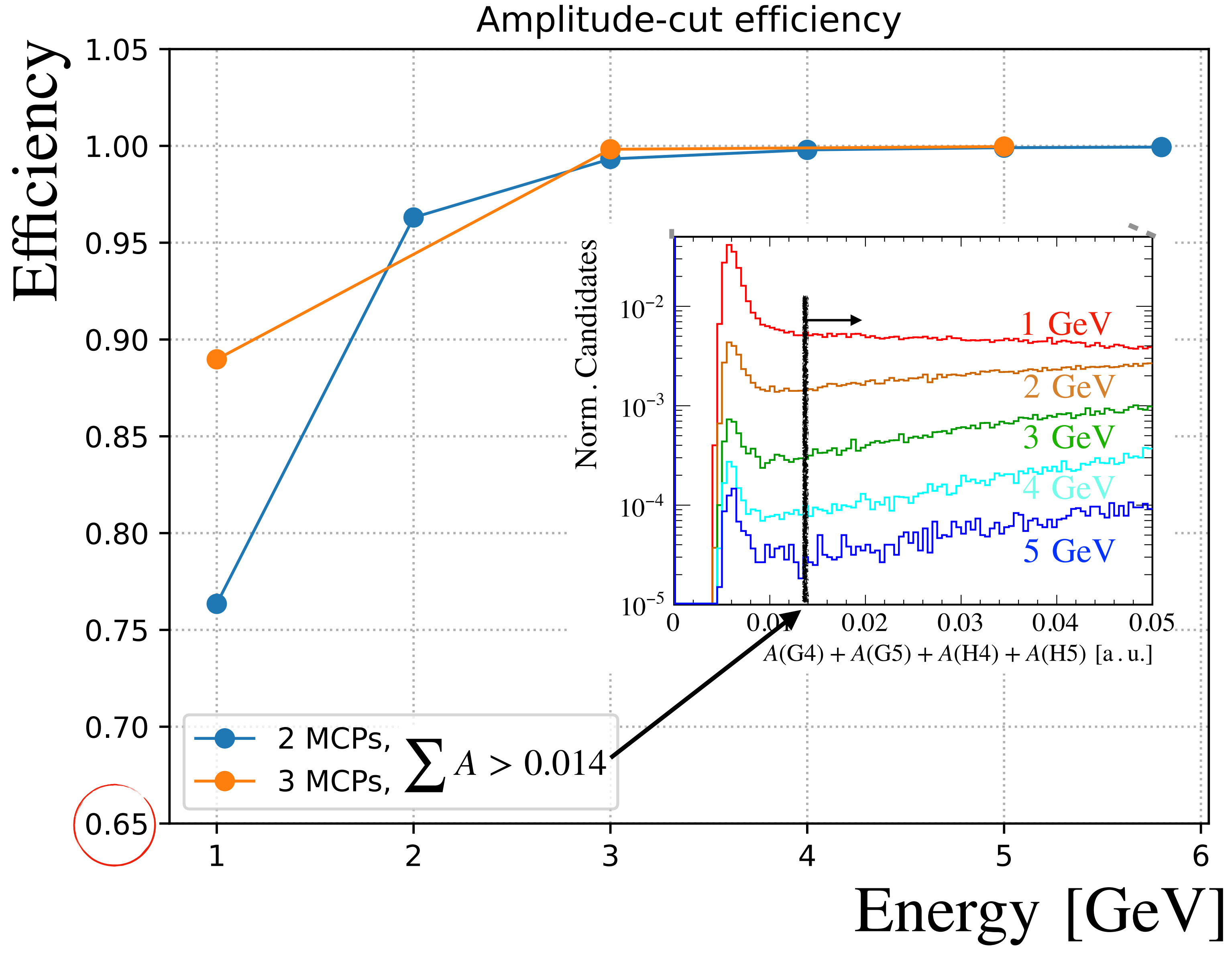
Efficiency and spatial resolution

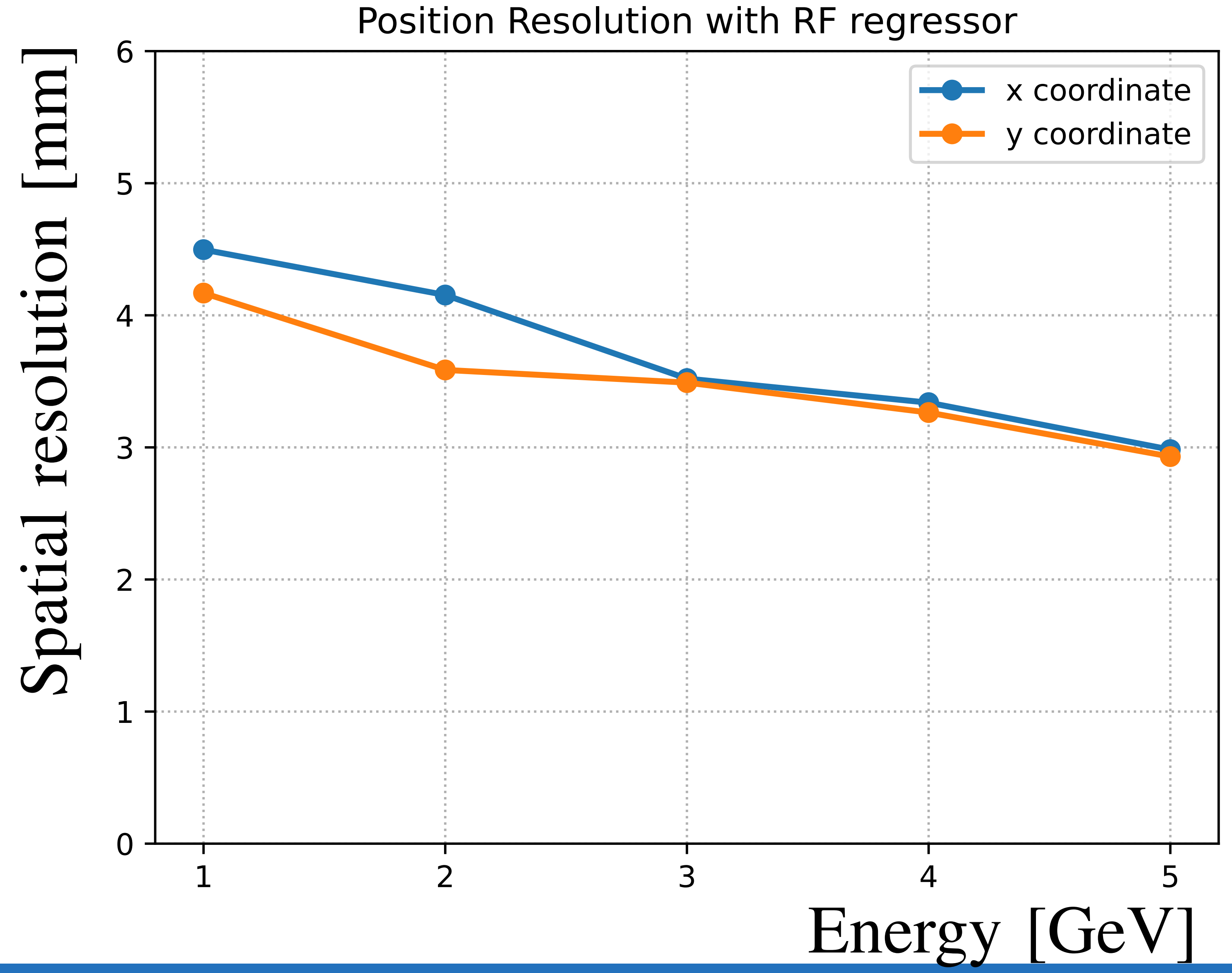
- December 2022 @ DESY, LAPPD z-stack, $(d = 10\ \mu\text{m})$

- **Efficiency**
  - 2 MCPs: Efficiency drop at 1 GeV: $\varepsilon = 76\,\%$
    Almost recovered at 3 GeV: $\varepsilon = 99\,\%$
  - 3 MCPs: Inefficiency mitigated at 1 GeV: $\varepsilon = 89\,\%$

- **Position** reconstruction
  - 2 MCPs layers
  - Random Forrest Regressor
    - Inputs: signal amplitudes
    - Target: position from DWC2 $(\delta x < 1\ \text{mm})$
  - Resolution goes from 4.5 mm at 1 GeV to 3 mm at 5 GeV
  - Improvements expected from a wider fiducial region

- More details in the backup slides



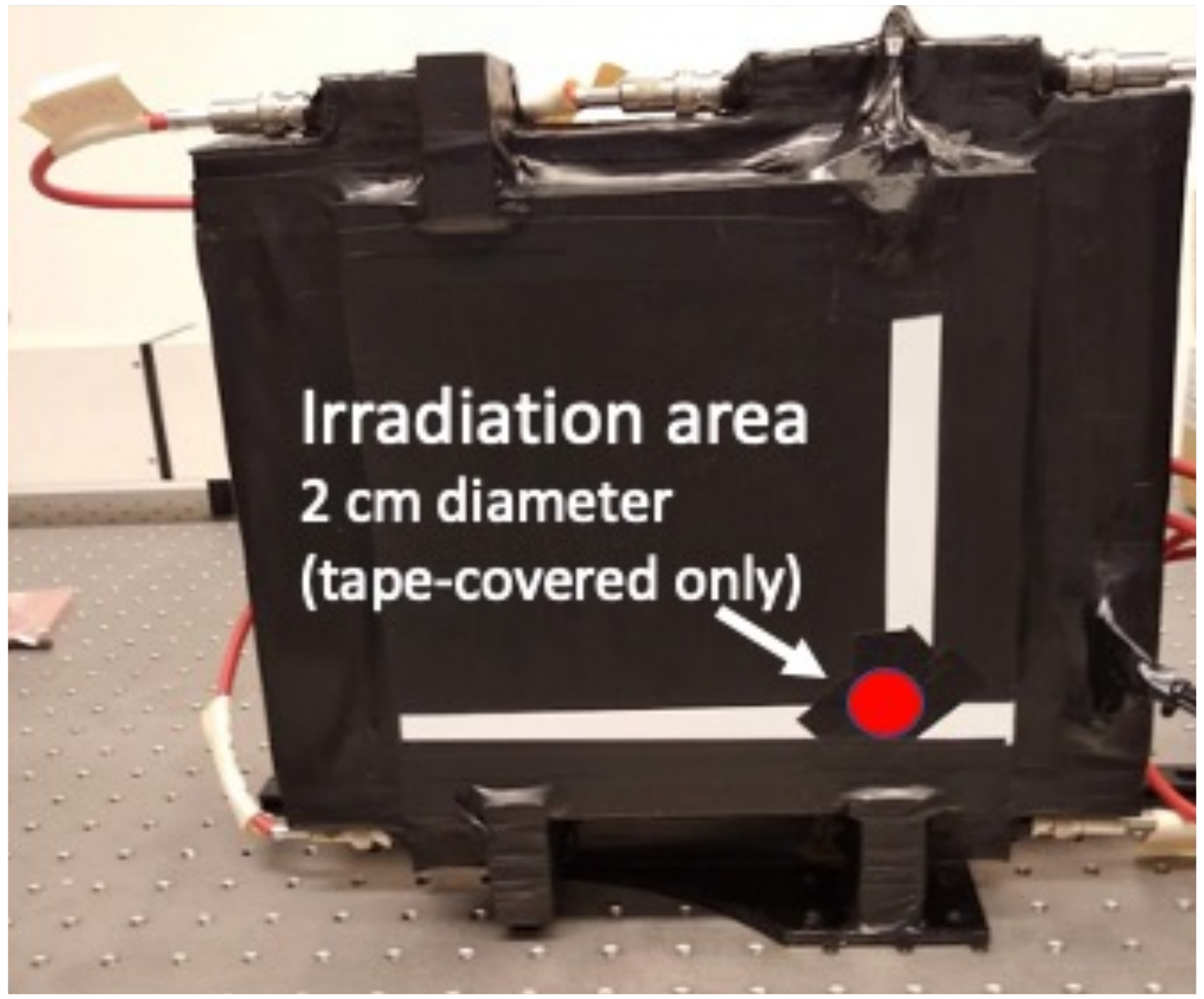


Proton Irradiation

- Device
  - LAPPD-#119, Gen-II, 10 μm pores
  - light tight with black paper sheets, plastic, and tape

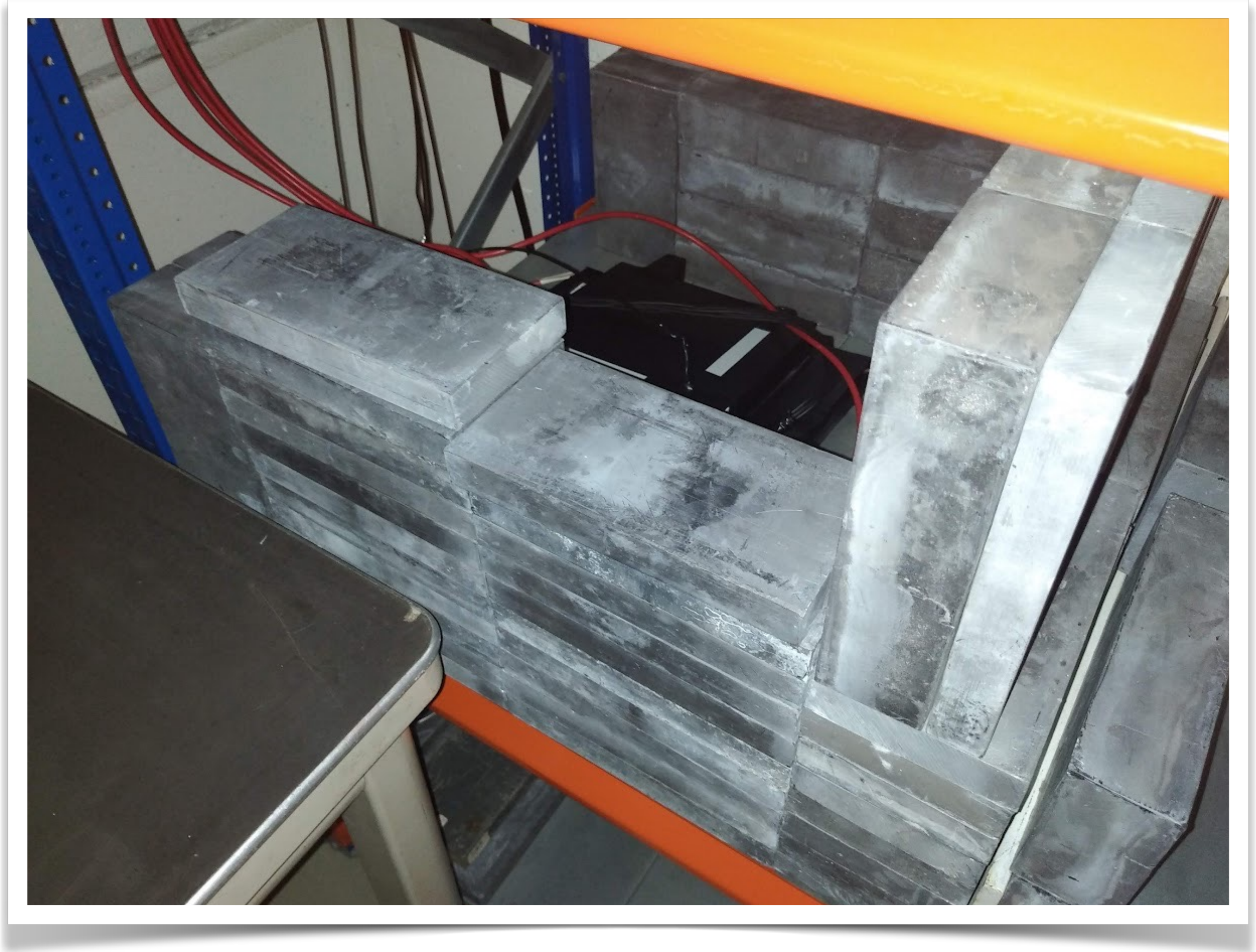
- IRRAD parameters
  - 24 GeV protons from CERN protosynchrotron (PS)
  - Beam spread: $FWHM_{x,y}$ ~ 1 cm
  - **10^{16} protons** integrated in about 1 week
    - Corresponding to roughly 5×10^{15} 1MeV neq.

- **During** the irradiation
  - high voltage
    - 900 V/mcp, 200 V/gap



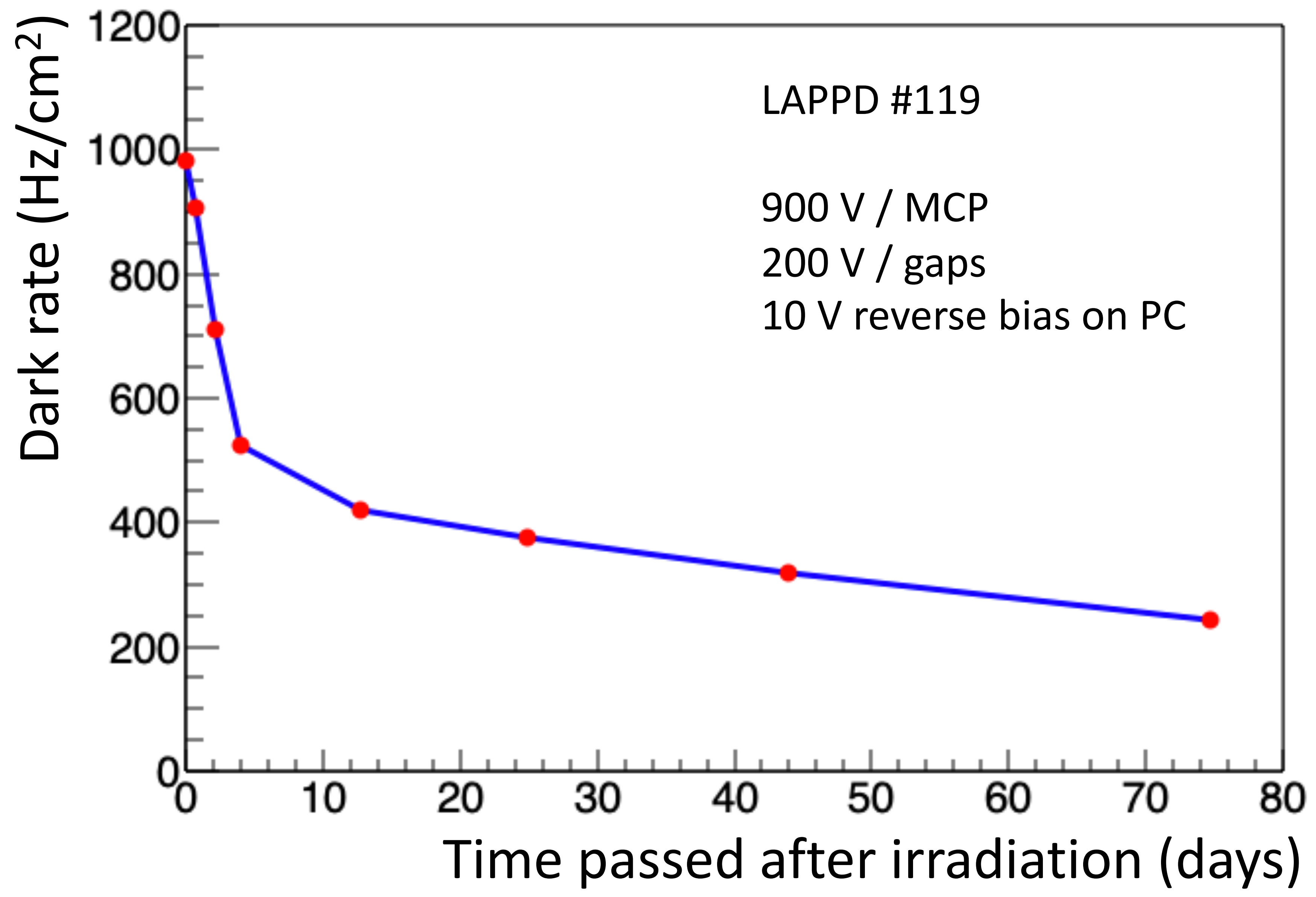
Cool down

- **After the irradiation:**
  - LAPPD moved to storage area
  - A blue LED was inserted in front of the irradiated area
    - Light sent to a square of 1 cm^2 centred at one LAPPD pixel
    - LED powered by a pulse, whose width and amplitude were tuned to produce **single isolated photoelectrons**
  - **Dark** rate and **gain** measured for 75 days

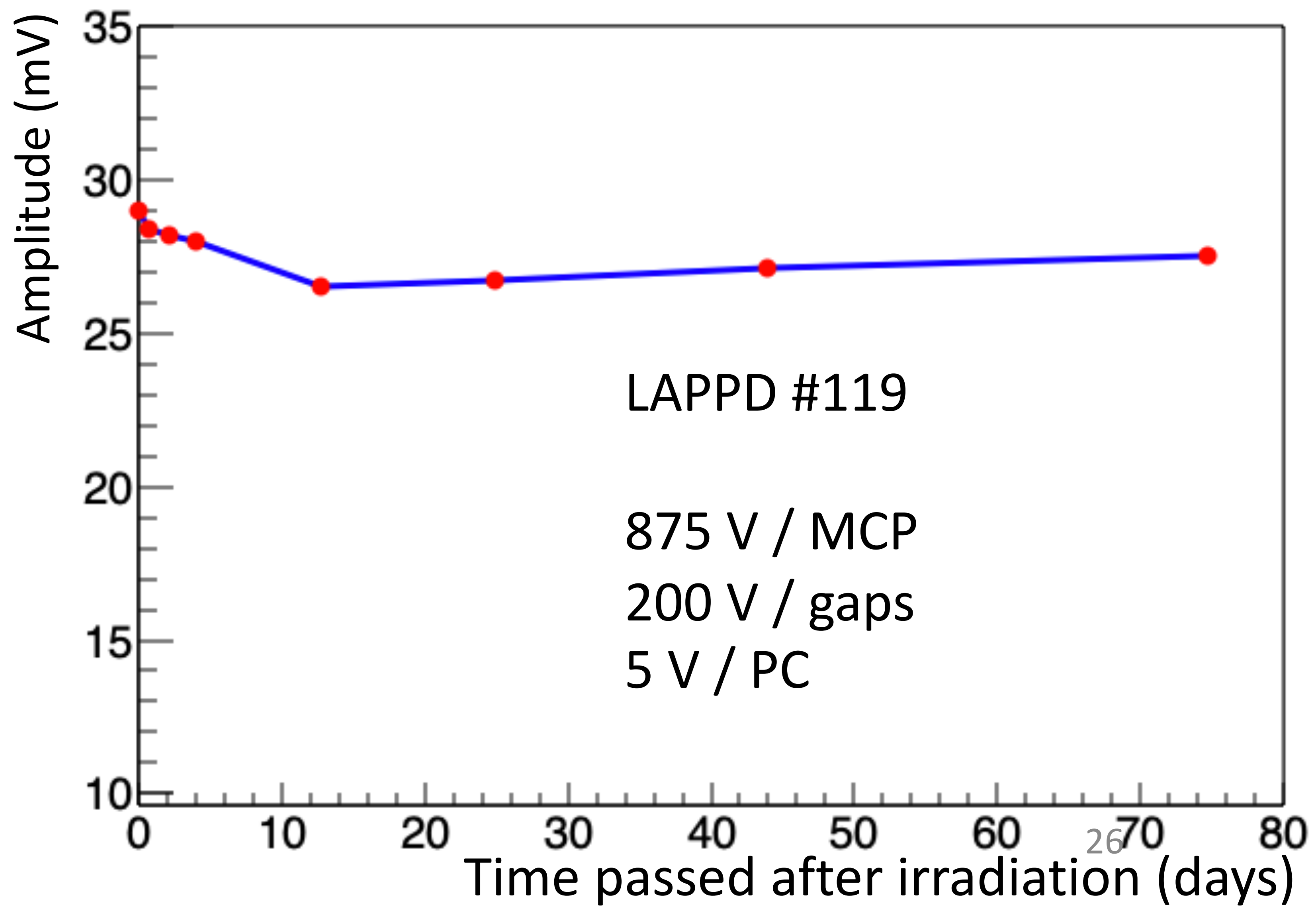


Irradiation results

- **Dark rate:**
  - **Prior to irradiation**, dark rate was about 10 Hz/cm2
  - **Right after irradiation**, it increased by 2 orders of magnitude
  - **Then**, it decreased steeply in the first few days, with a much slower long-term trend
    - remaining significantly higher than prior to irradiation,
  - Such a level of dark rate is (by far) **not problematic for our purposes**
    - still below average dark counts from PC, when activated



- **Gain:**
  - Slight reduction of gain observed right after irradiation (**30→29 mV**), with some small variations
    - Our best guess: not stable temperature in IRRAD storage area



MCP lifetime: setup

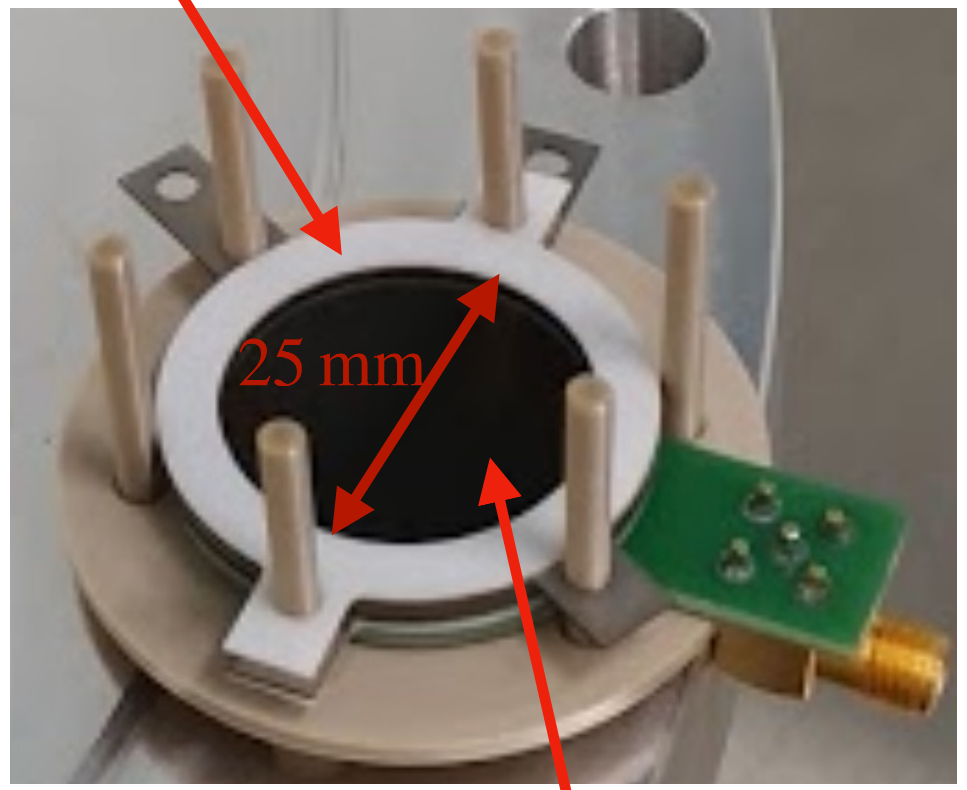
- Chevron stack of **2 round MCPs** placed in a **vacuum chamber**
  - upper flange equipped with a viewport
    - MCPs provided by Incom

- **Mercury lamp** placed on top of the viewport
  - The UV light triggers the extraction of primary e^- from the top MCP
    - low but nonzero quantum efficiency (useful UV line at 185 nm)

- Electrons are multiplied by the MCP stack and charge is collected by a metallic anode
  - Very high currents ⇒ large emitted charge is collected

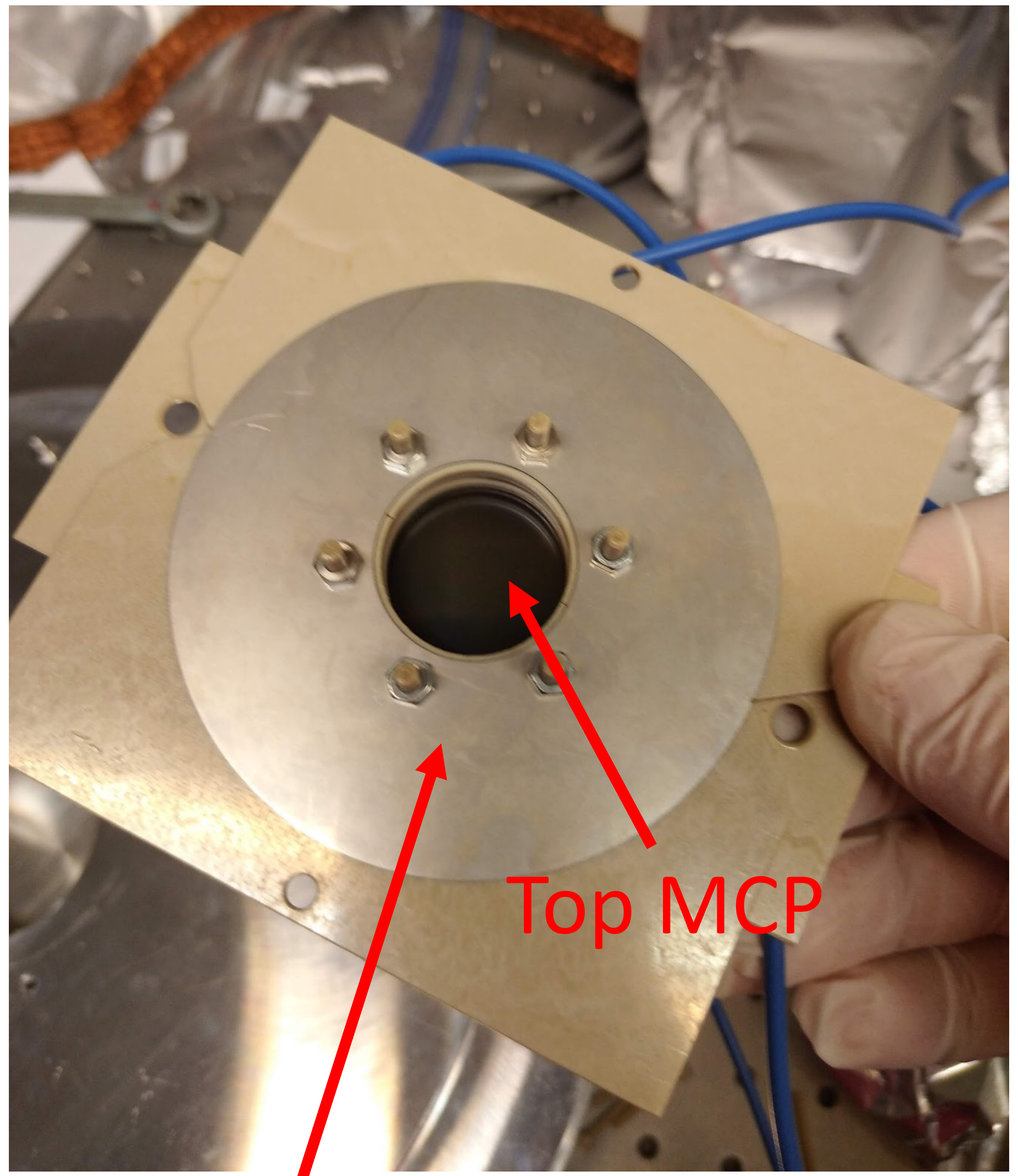
Partial assembly

Spacer



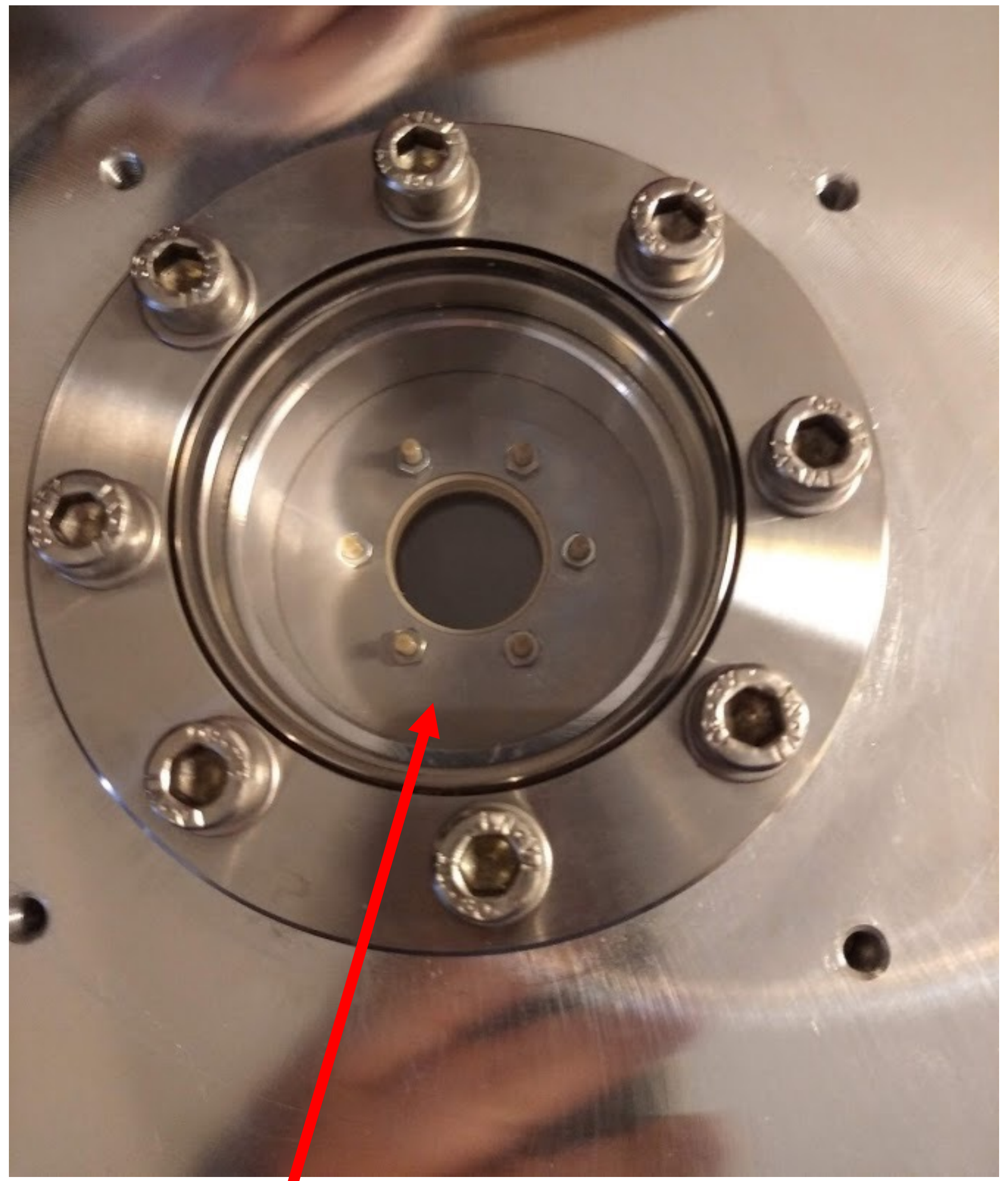
Bottom MCP

Final assembly



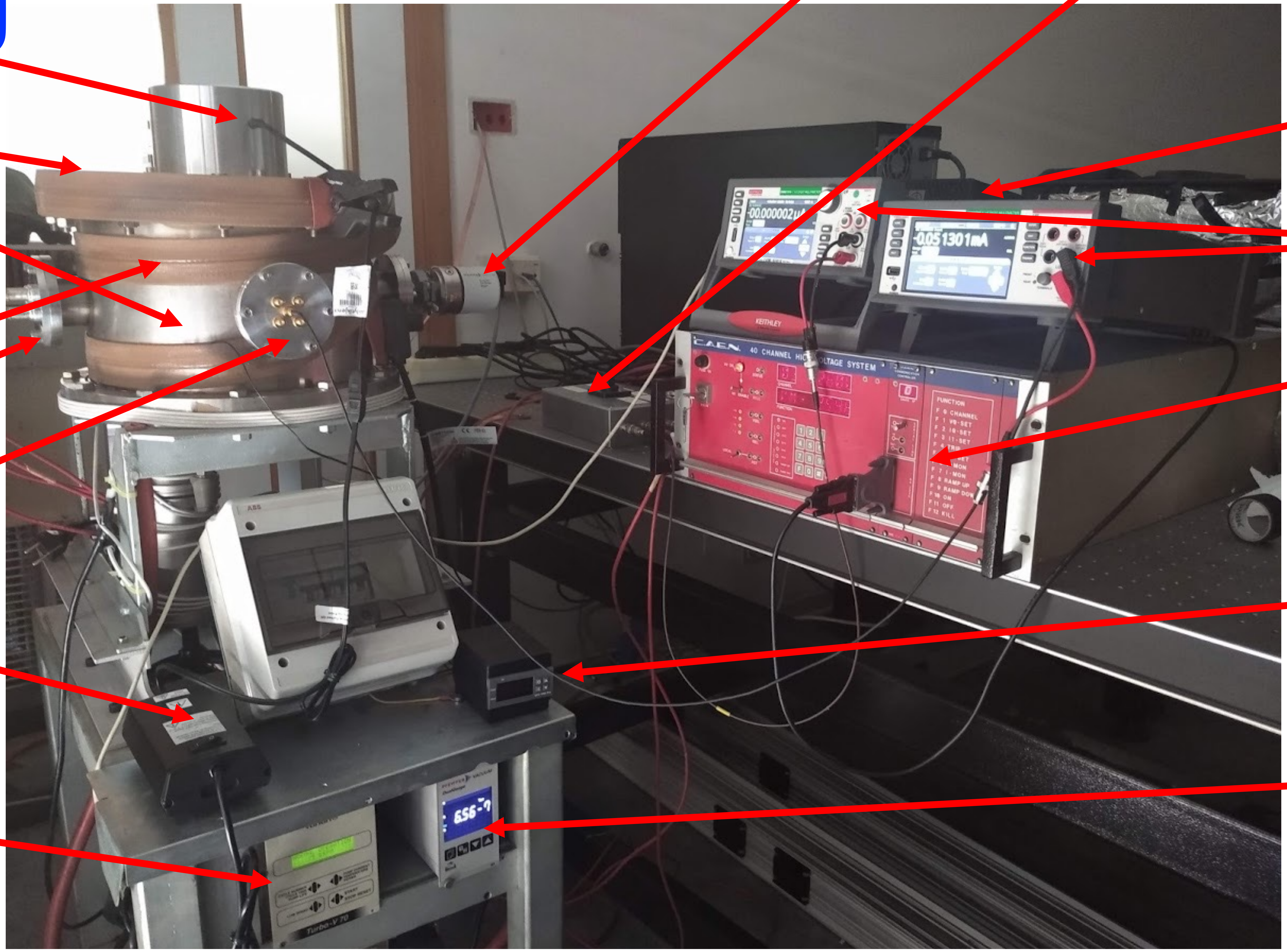
Metal contact to the vacuum chamber to avoid creating charge on the PEEK support by UV light

Viewport on the top flange



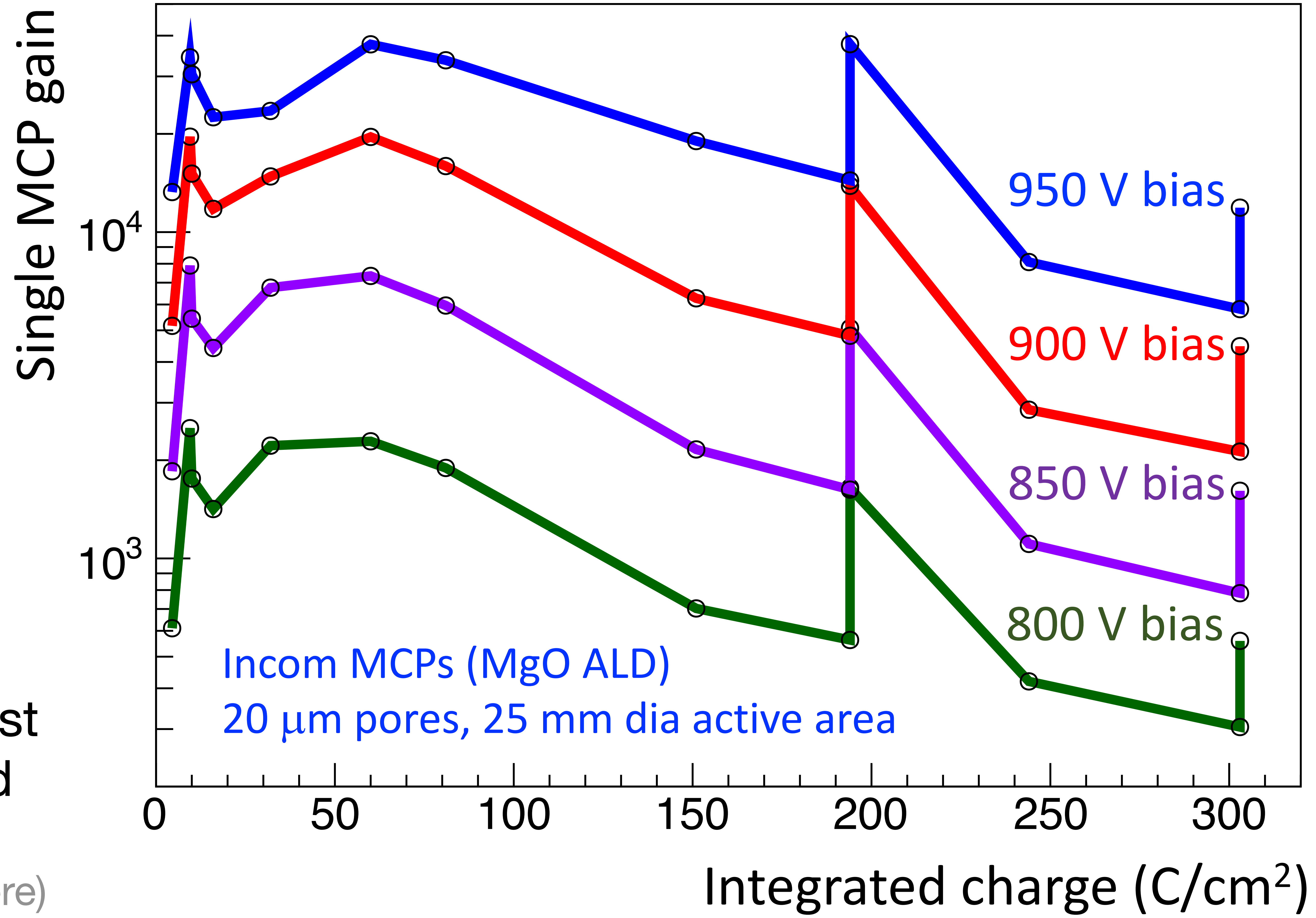
Corning HPFS 7980 excimer-grade fused-silica window with 90% external transmittance at 185 nm

MCP lifetime: whole setup

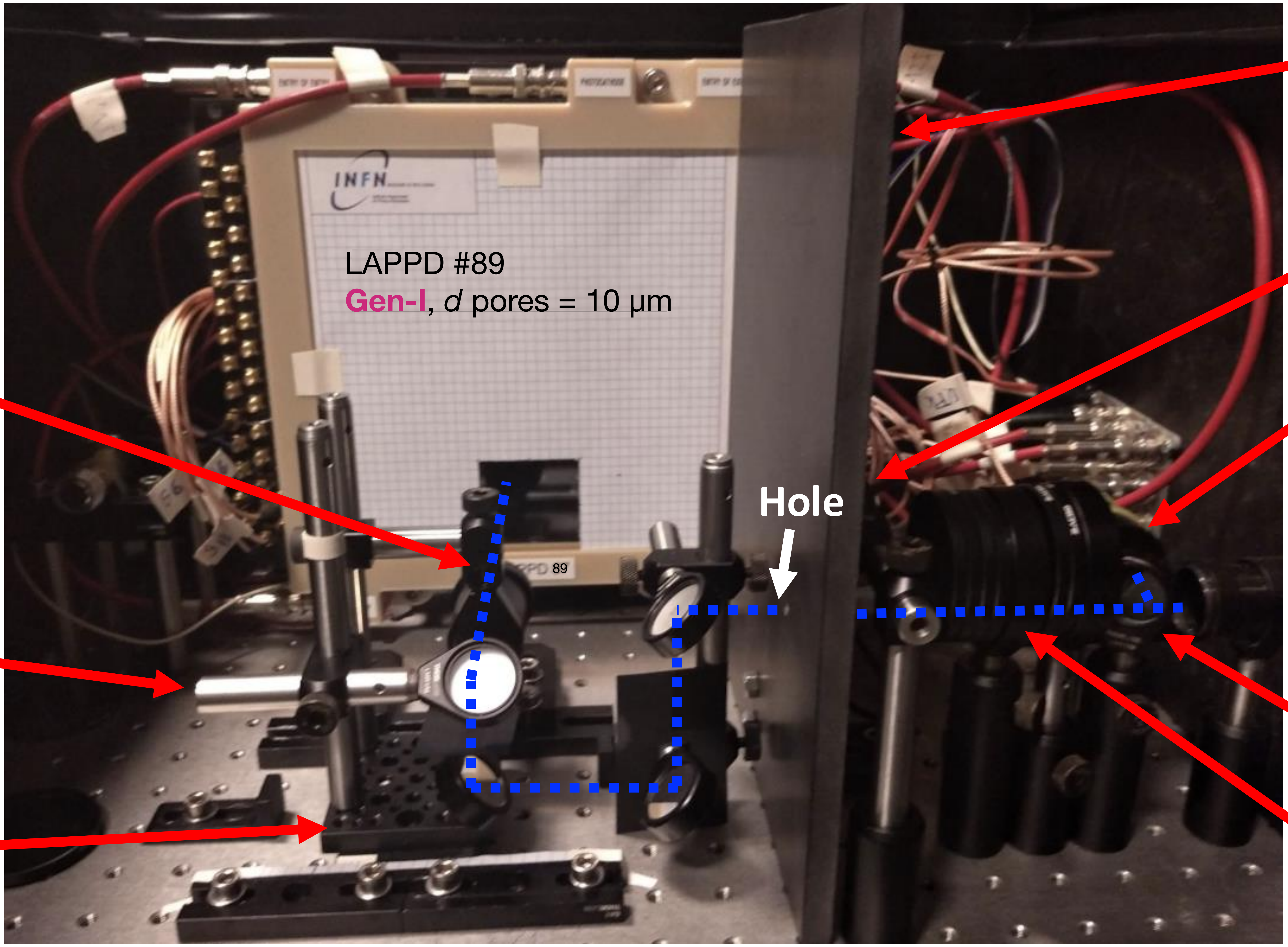


MCP lifetime: results

- Max integrated charge: $300\ \mathrm{C/cm^2}$
- Gain reduction: factor 7
  - Recovered with $+100\ \mathrm{V}$
- Discrete jumps at 200 and 300 C/cm^2:
  - Gain measurement repeated after turning off the UV light for about a week
  - The rest makes the MCPs recover part of the lost gain, but then it goes back to the previous trend
    - It happens within the subsequent 30 C/cm^2, as shown by anodic current monitoring (not showed here)



LAPPD in the Lab.: baseline setup



Screen to separate high from low luminous regions

Retractable calibrated Si photodiode

UFK-5G-2D

Laser head

Beam splitter

ND filters

Beam diffuser and shutter

Upper mirror can be moved for vertical translations

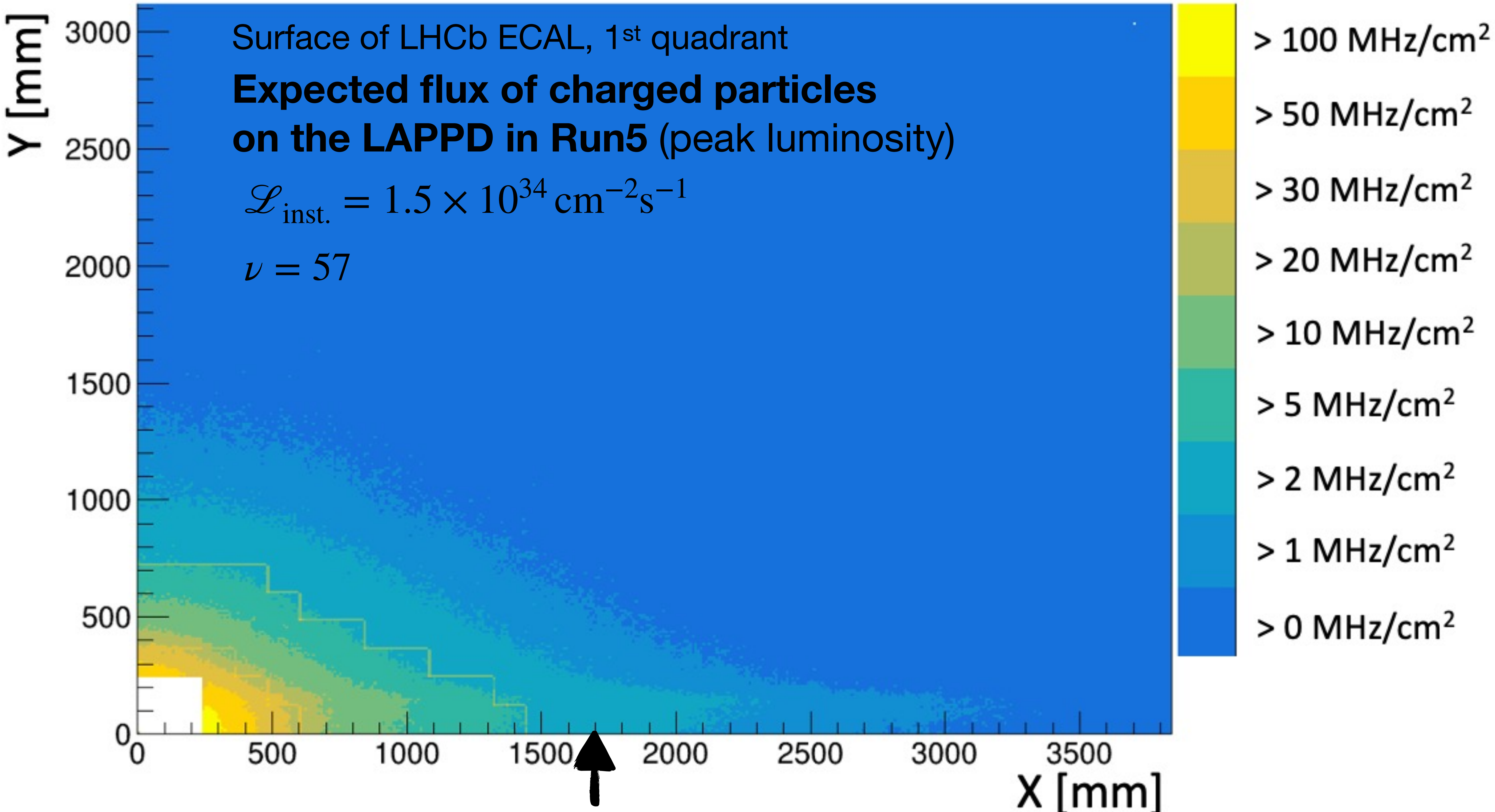
Two of the mirrors movable on rail for horizontal translations

Details about laser and DAQ in the backup

High rate: requirements

- A high input rate is expected to degrade the MCP performances
    - Each multiplication depletes the pores of e^-
    - Dead time (per each pore)
    - Signal amplitude decreases
    - Worse time resolution

- The Run5 of LHCb demands operations at high rate



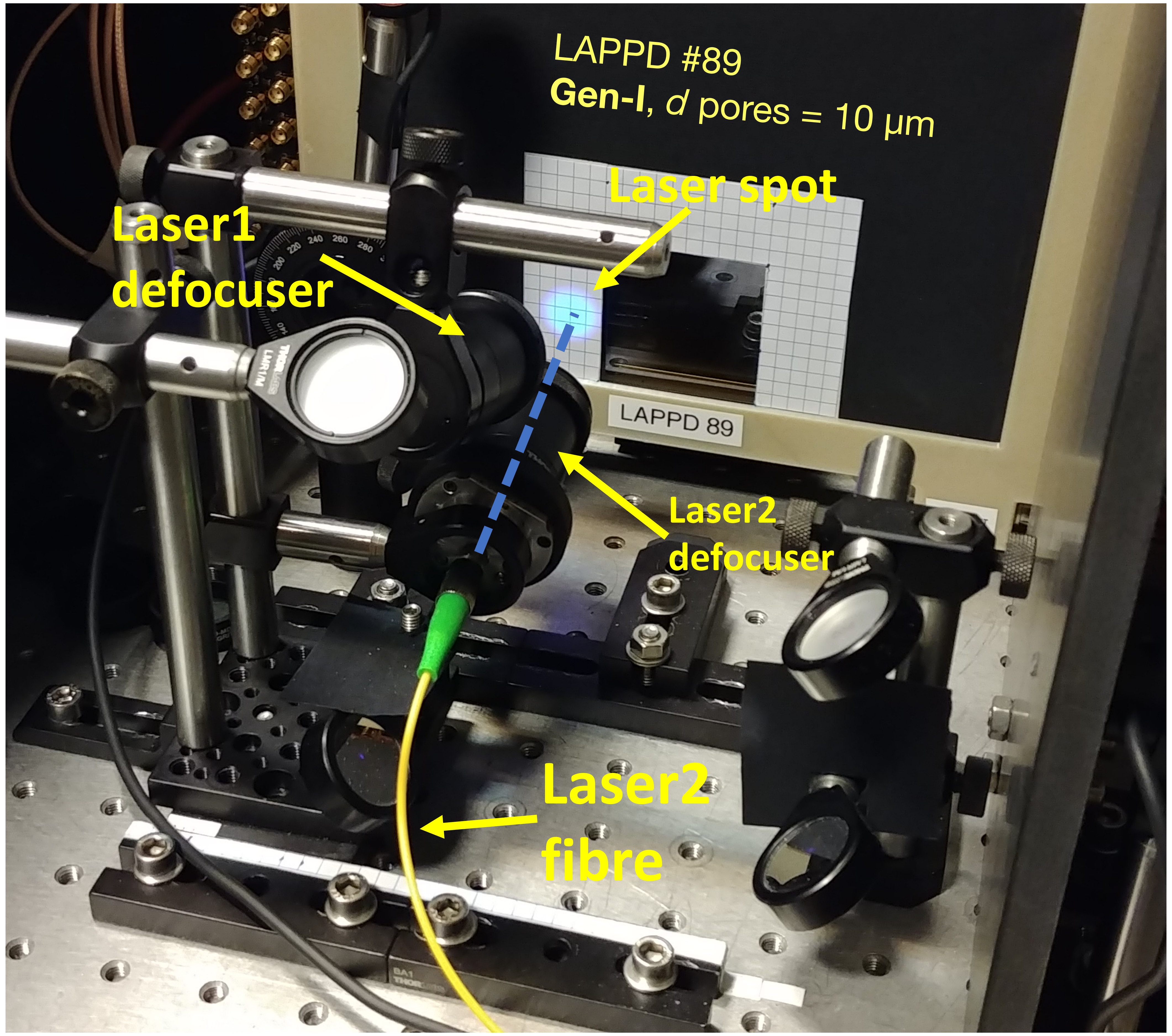
- Geant4 simulation used to determine the flux of charged particles entering the LAPPD when inserted within the two sections of the ECAL
    - Input flux from LHCb full simulation
- Between 30 and 100 MHz/cm^2 expected in the hottest region

Mimicking high-occupancy environment

- Each charged particle entering the LAPPD is expected to produce order of 1 photoelectron (PE) with the photocathode (PC) inhibited

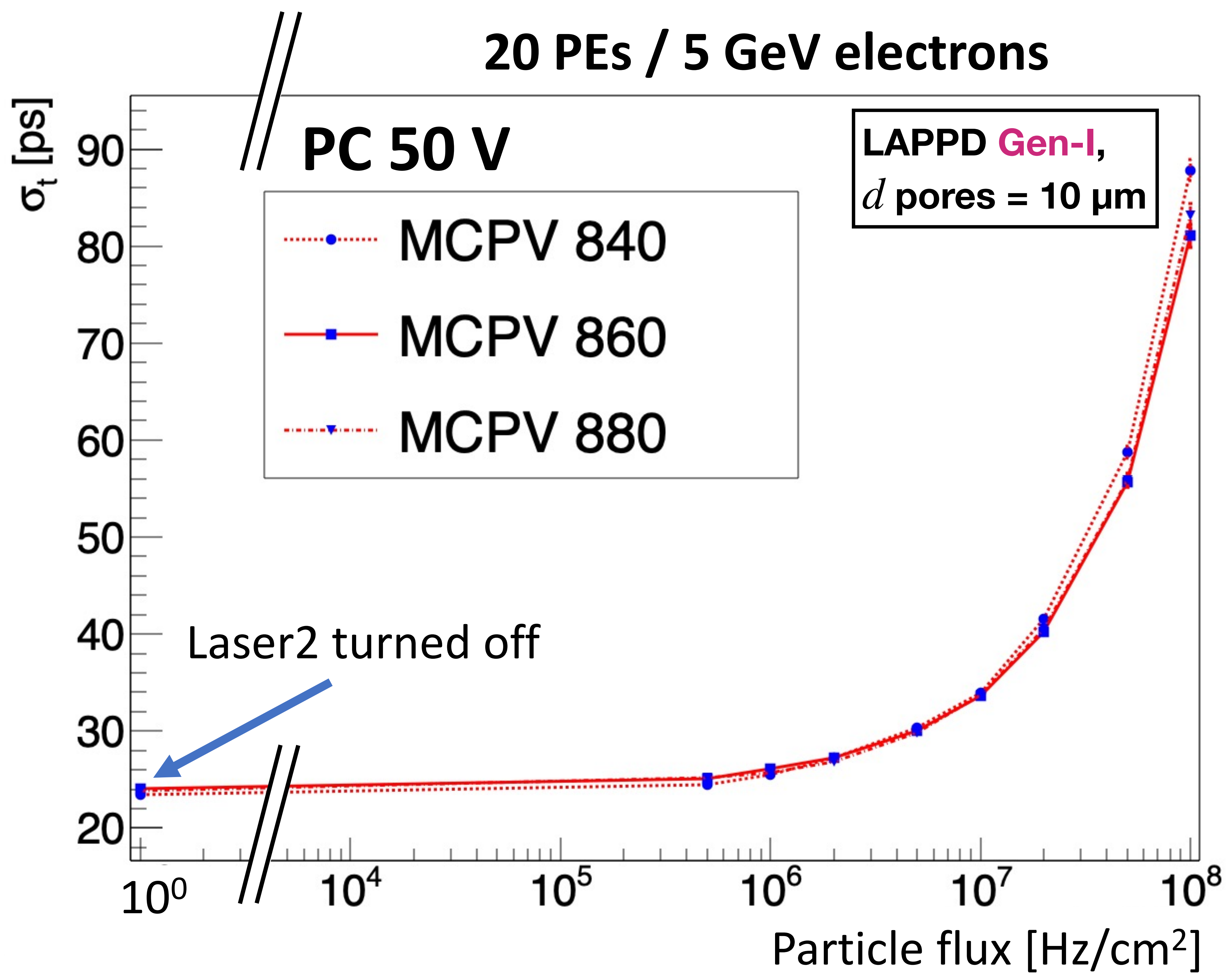
- **Two lasers** are operated simultaneously
  - PC: ON with $\Delta V = 50\ \mathrm{V}$ to get low kinetic energy for the PEs
- `Laser1` used to mimic the signal EM showers
  - Beam defocused and centred between two strips
    - ∅ = 15 mm
  - Pulse power varied to mimic showers with different energies
    - From simulations: 5 GeV → 20 PEs, 10 GeV → 40 PEs
- `Laser2` used to mimic the background flux
  - Beam defocused and centred on the same spot
    - ∅ = 15 mm
  - Pulse power adjusted to have 10 PE/cm^2 in the illuminated area
    - Pulse rate varied from 50kHz to 10MHz to mimic the particle flux in different regions of the calorimeter
    - e.g. pulsing the laser at 100kHz would mimic 1MHz/cm^2 of PEs

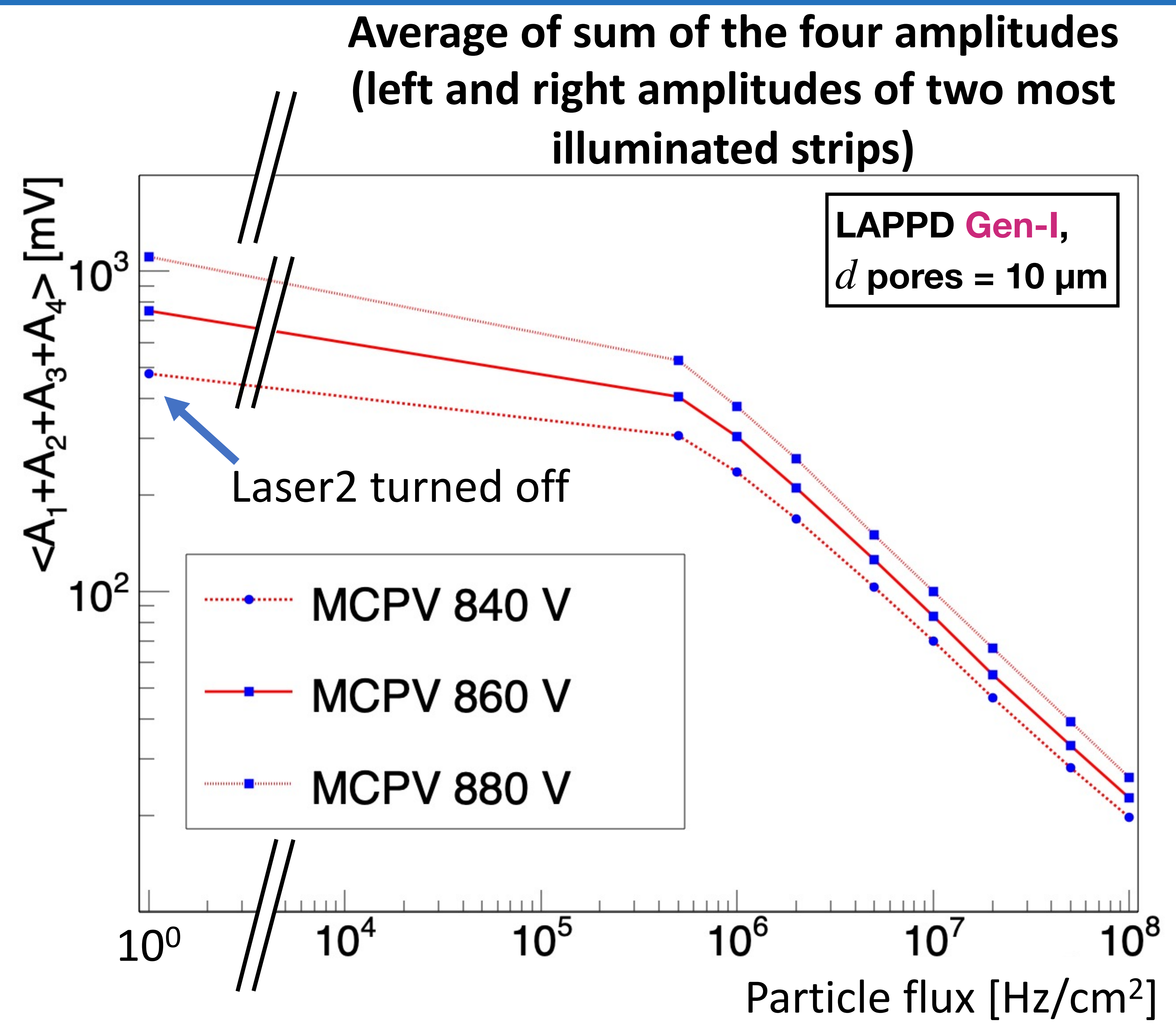
- Study time resolution for the signals produced by the first laser as a function of the pulse rate of the second laser



Details about lasers and DAQ in the backup

Performance in high-occupancy (1)

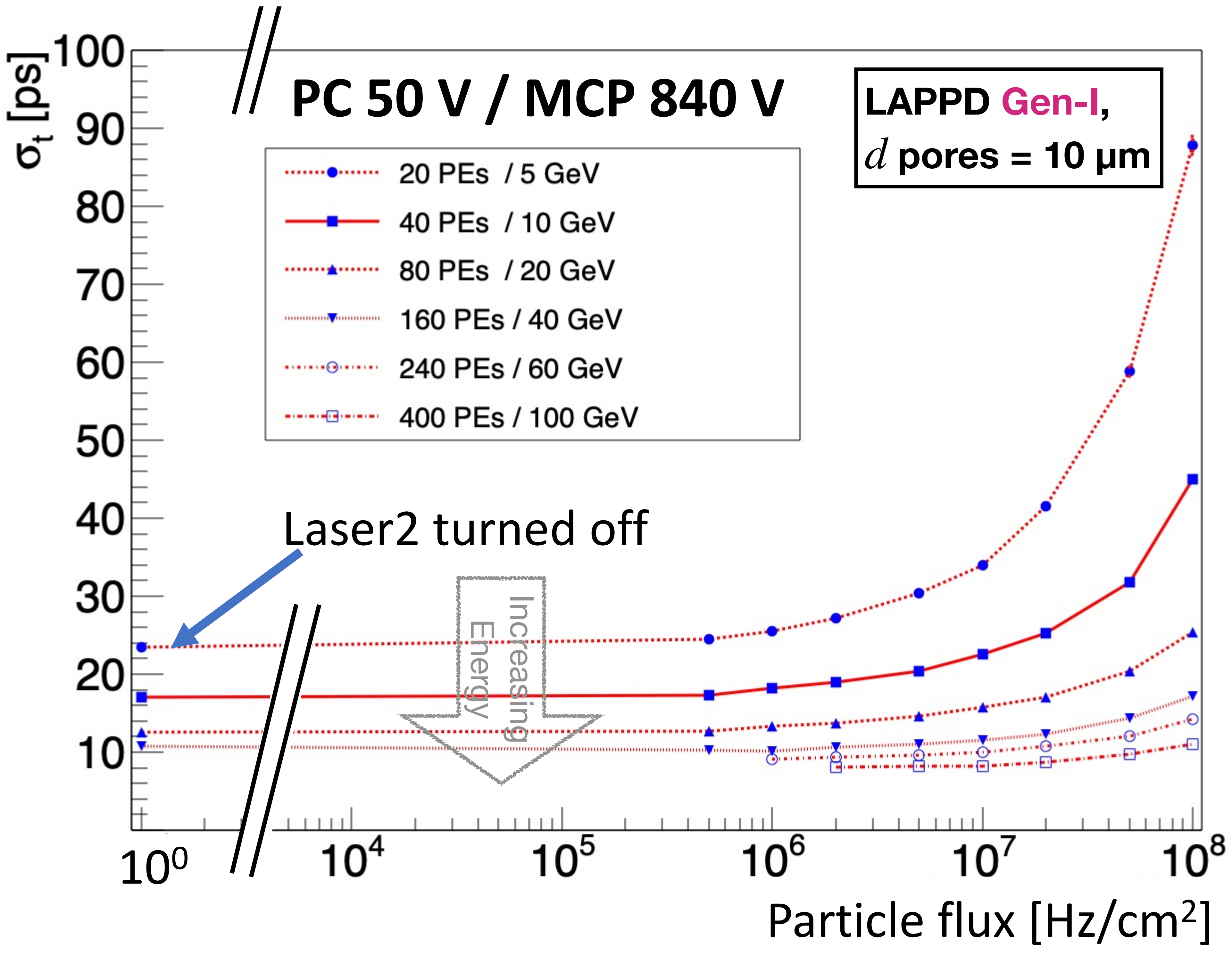


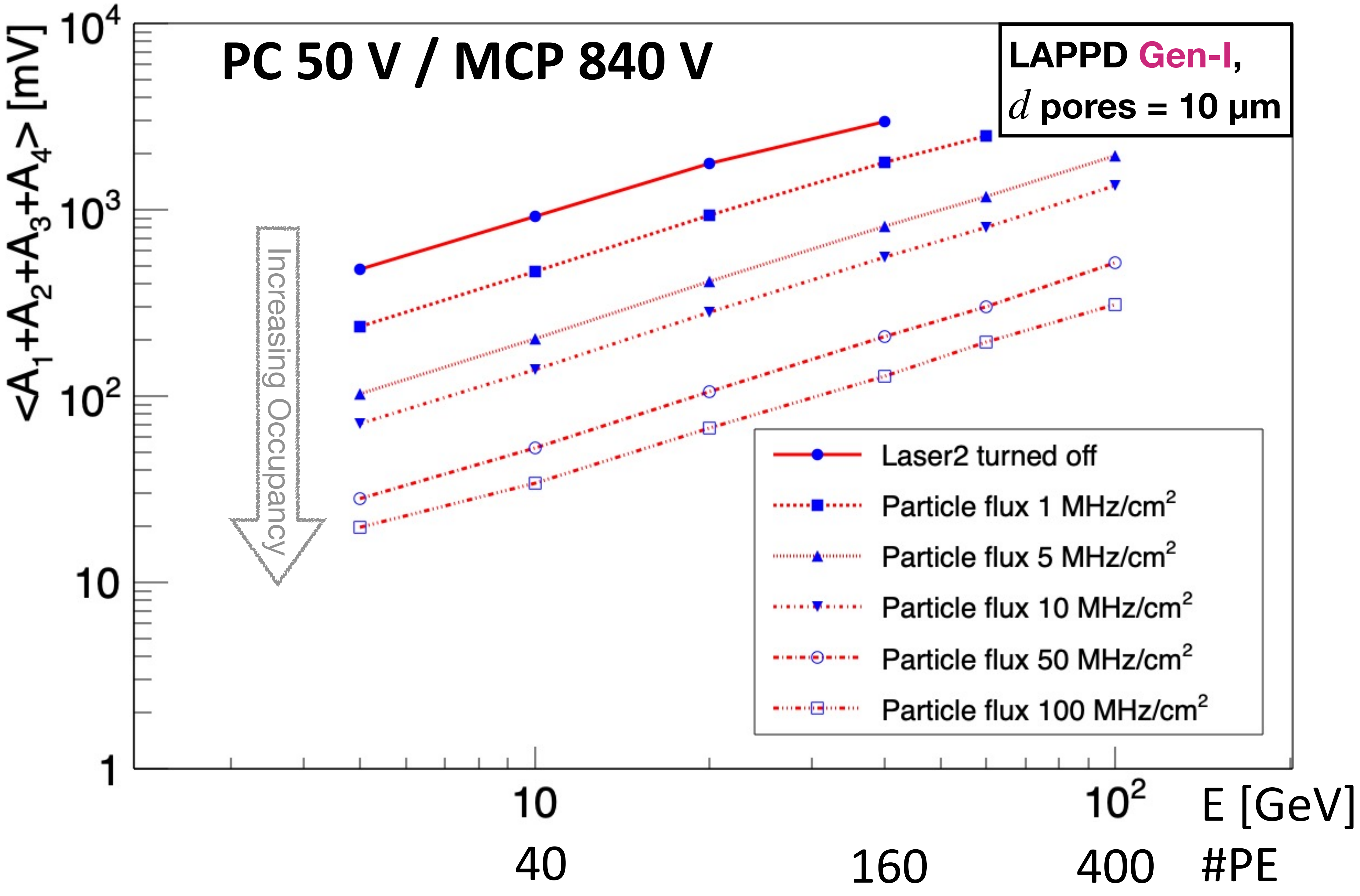


- Relevant **degradation** of time resolution for particle flux **above few MHz**
- Corresponding drop in signal amplitude
- Same behaviour modifying the MCP bias

PC = PhotoCathode, PE = PhotoElectron

Performance in high-occupancy (2)

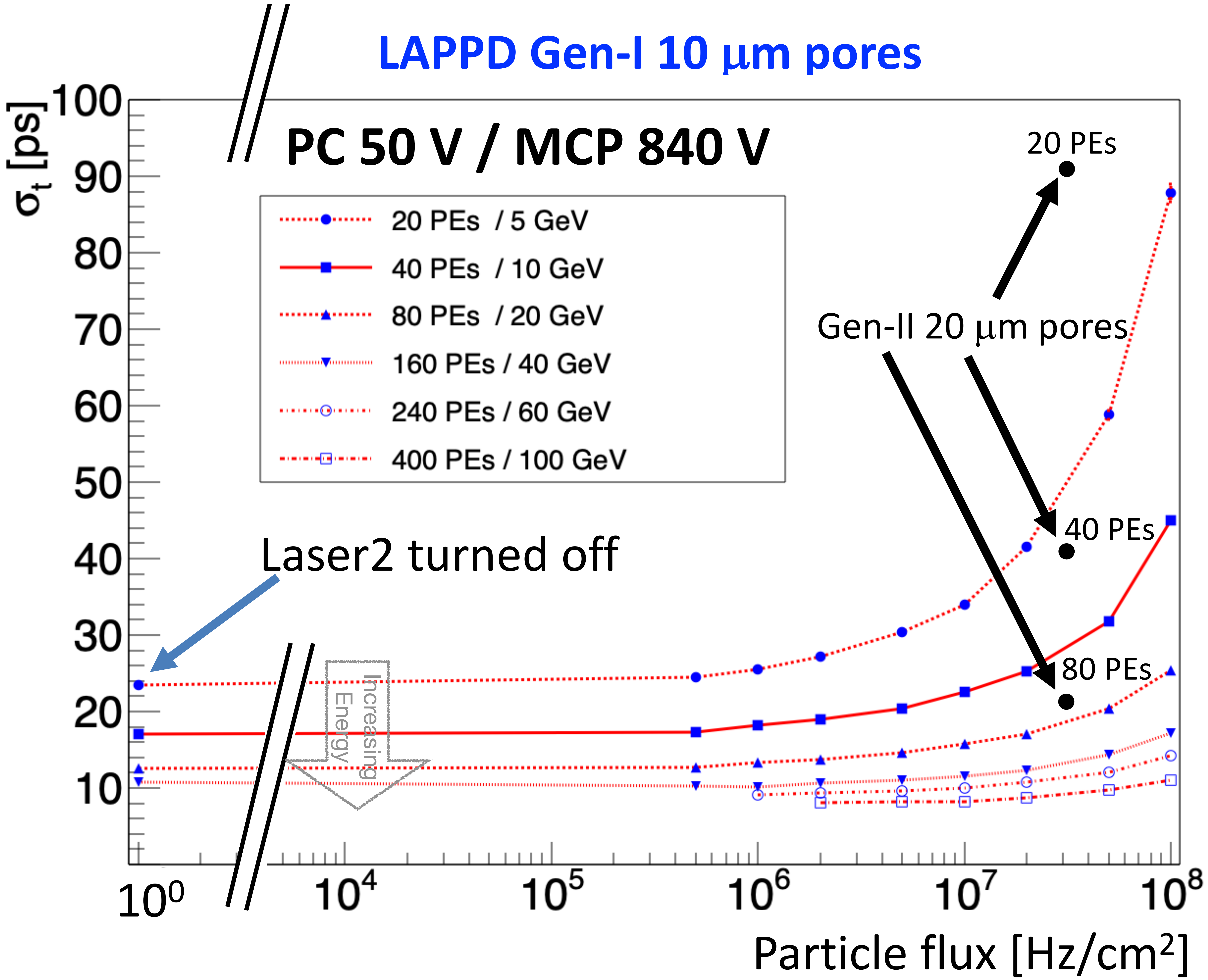




- Same study, but changing the pulse width of `Laser1` to simulate different energies
  - Time resolution degradation is much less pronounced at higher energy
  - Linear dependence of signal amplitude from the energy

PC = PhotoCathode, PE = PhotoElectron

Performance in high-occupancy: pore size



Energy [GeV]	Time resolution [ps] at 30 MHz/cm²	
	Gen-II, **20 μm pores**	Gen-I, **10 μm pores**
5 (20 PEs)	90	50
10 (40 PEs)	40	28
20 (80 PEs)	21	18
	details in backup slides (FAST 2021)	interpolation at 30 MHz/cm²

- As expected, a benefit from the reduced the pore size is observed at high rate
- Still R&D to do to meet the LHCb-Run5 requirements at low energy

PC = PhotoCathode, PE = PhotoElectron

Conclusions

- A LAPPD-based timing layer is currently one of the candidate components for the Upgrade-2 of the LHCb ECAL
  - Cost reduction compared to traditional MCPs
  - Several test already done both in the lab. and at beam facilities
  - Effective **radiation hardness** for the LAPPD
  - **Lifetime** of MCP wafers tested and found to meet the requirement of 300 C/cm2 of integrated charge
  - Good **time resolution**, even without the photocathode

- Intense R&D is ongoing
  - Current focus: performances at high incident flux
    (smaller pixels, smaller pores, z-stack, …)

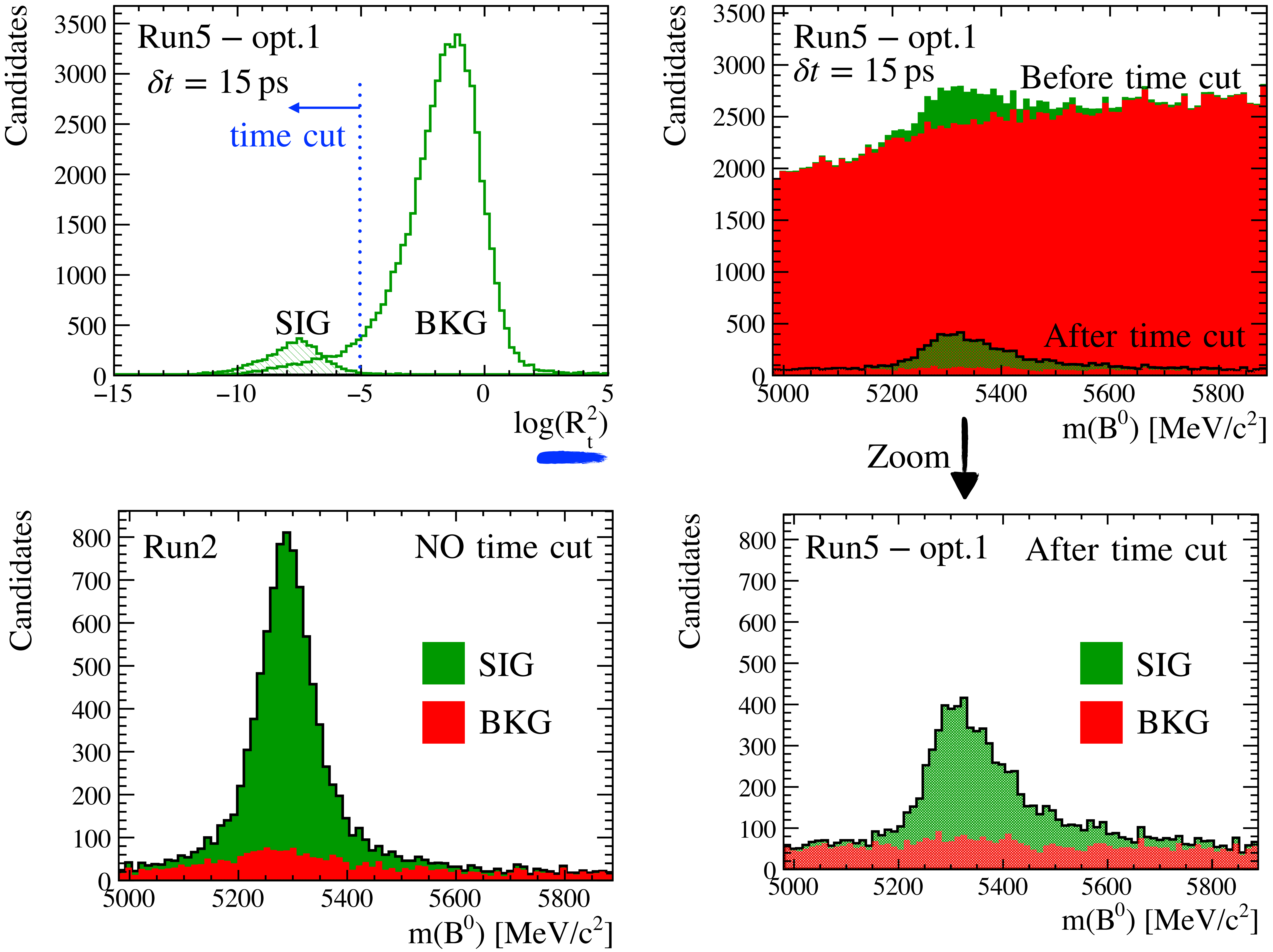
- LLMCP project for R&D on robust and cheap photocathodes activated by INFN

- **Our warmest acknowledgments to Income Inc. for the support, availability and guidance**

BACKUP SLIDES

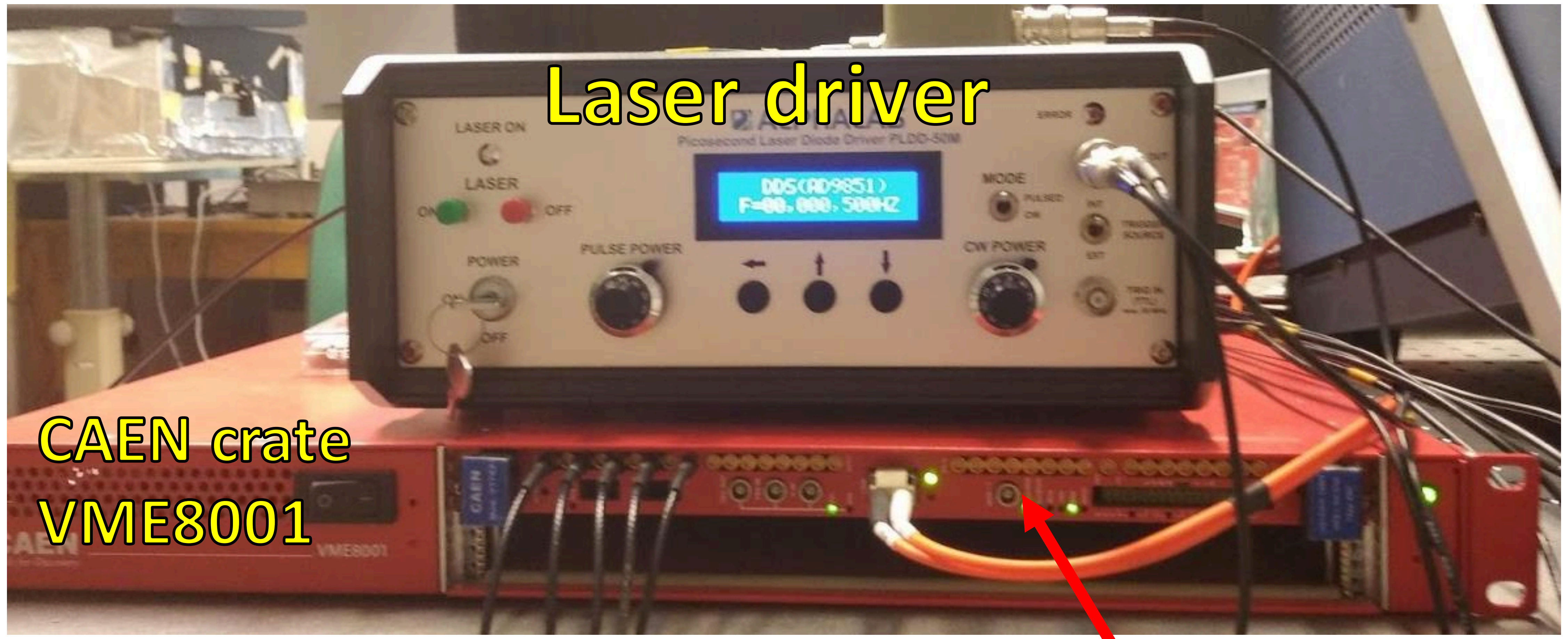
Relevance of time: $B^0 \to \pi^+\pi^-\pi^0$ simulation

- True information for $\pi^+\pi^-$
  - “perfect tracking”
- *ONLY* background from π^0
- Time Info. used to reject the background in Run5
  - $R_t^2 \equiv (t_1 - t_1^{exp})^2 + (t_2 - t_2^{exp})^2$
- Preformante in Run5 compared to those in Run2
  - Hypotheses on the rest of the detector canceled out by the comparison



Lab. Apparatuses

- **Laser** system
  - PICOPOWER™-LD by ALPHALS
  - Class 3B with **405 nm** wavelength
  - Repetition rate tunable from **1Hz to 50 MHz** (in steps of 1 Hz)
  - Pulse width with optimal settings measured at the factory before shipment **11.7 ps (RMS)**
  - Trigger **jitter** measured in the lab to be **3.4 ps**



CAEN digitizer v1742

- **Digitiser** CAEN v1742
  - VME board with 32 channels based on **DRS4 chip**
  - Maximum sampling rate is **5GS/s** with 1024 cells per channel (full acquisition window of 204.8 ns), and **500 MHz** bandwidth
  - Calibration performed in the lab based on [D. Stricker-Shaver et al., IEEE Trans. Nucl. Sci. 61 (2014) 3607]
    - Time resolution of the digitiser is negligible compared to the LAPPD one
    - Details in the backup

used both in the lab. and at test beam

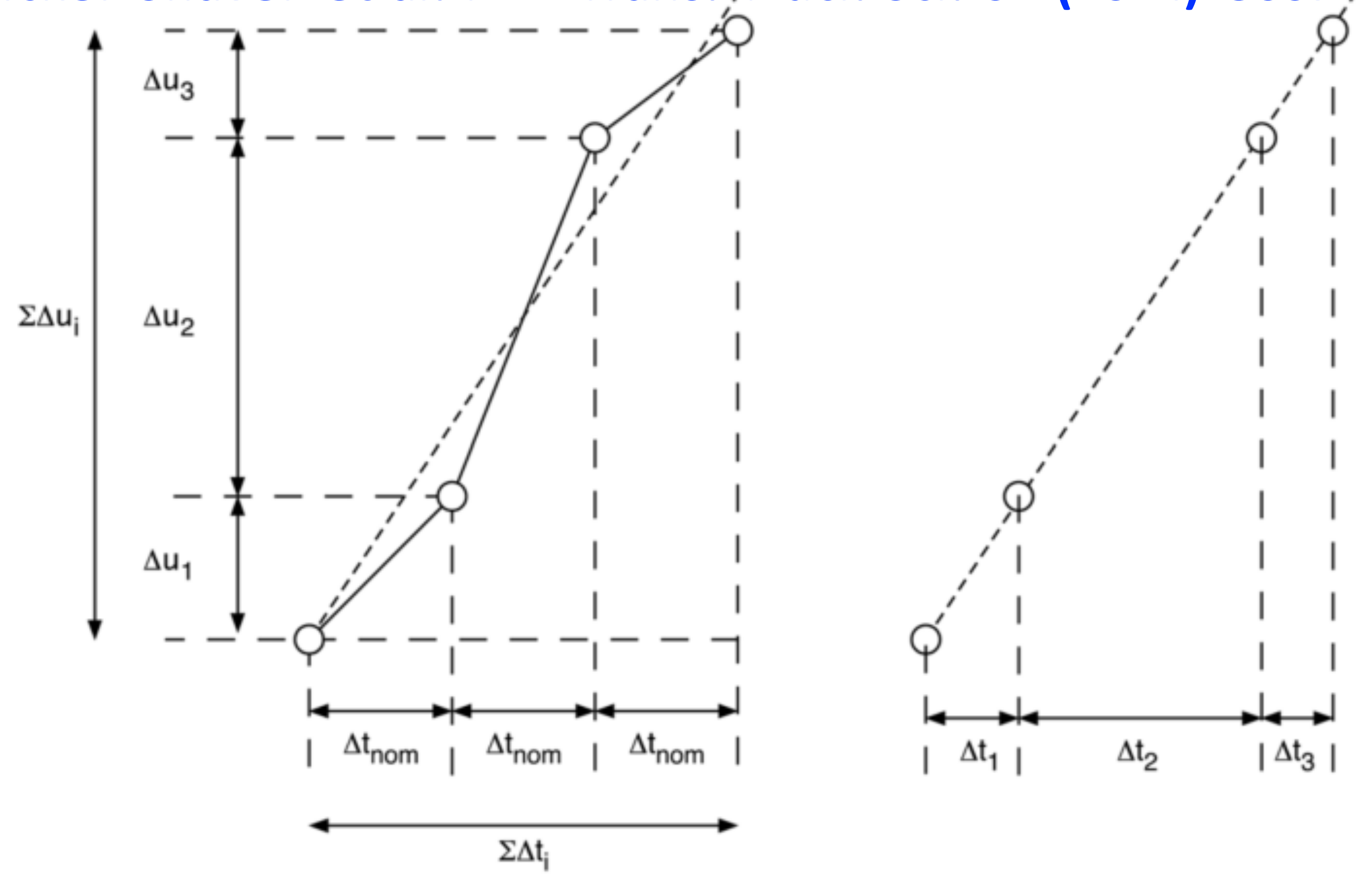
Digitizer calibration

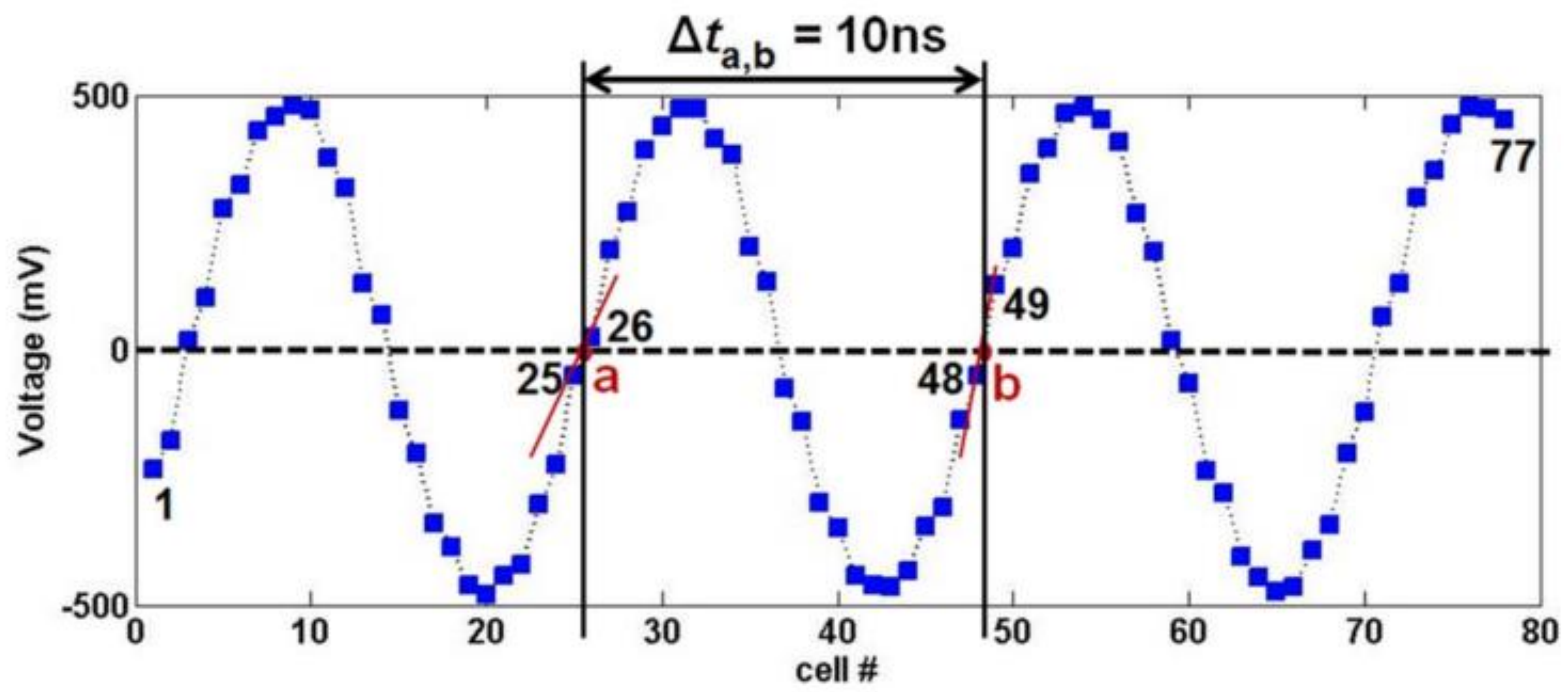
D. Stricker-Shaver et al. IEEE Trans. Nucl. Sci. 61 (2014) 3607

- Voltage offsets calibration
  - Injected into each channel a set of **constant voltages**
  - Use a **linear fit** to parameterise the correspondence between voltage and the average or registered ADC counts for each cell of each channel

- Local calibration of cells time widths
  - Injected into each channel **50 MHz saw-tooth waveform**
  - Exploit **linear correlation between voltage difference and time difference of two adjacent cells**

- Global calibration of cells time widths
  - Injected into each channel a **100 MHz sinusoid waveform**
  - Measure the time **difference between zero crossings** for one or multiple periods, and use this difference to correct the time widths of all intermediate cells

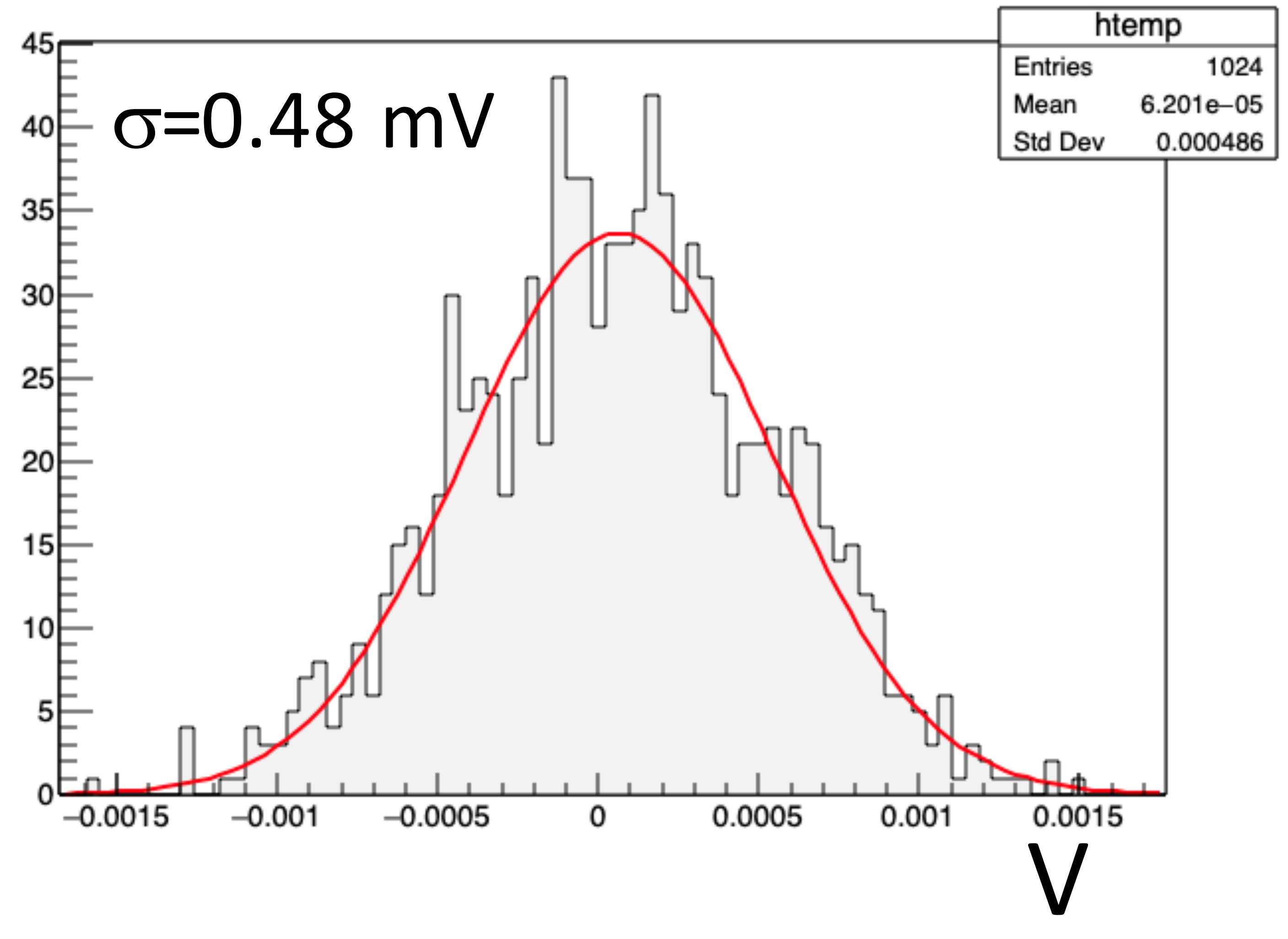


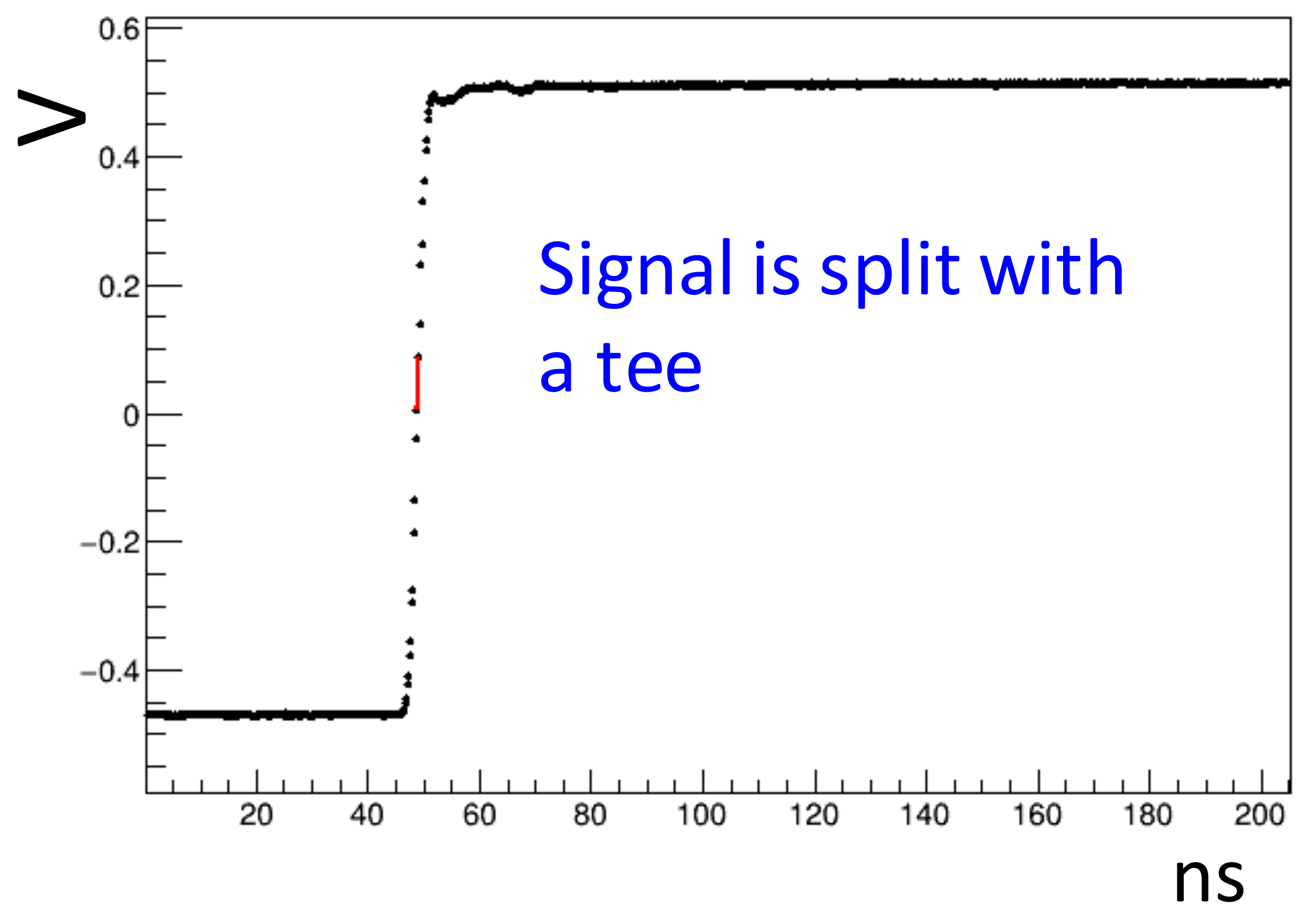


Goodness of calibration

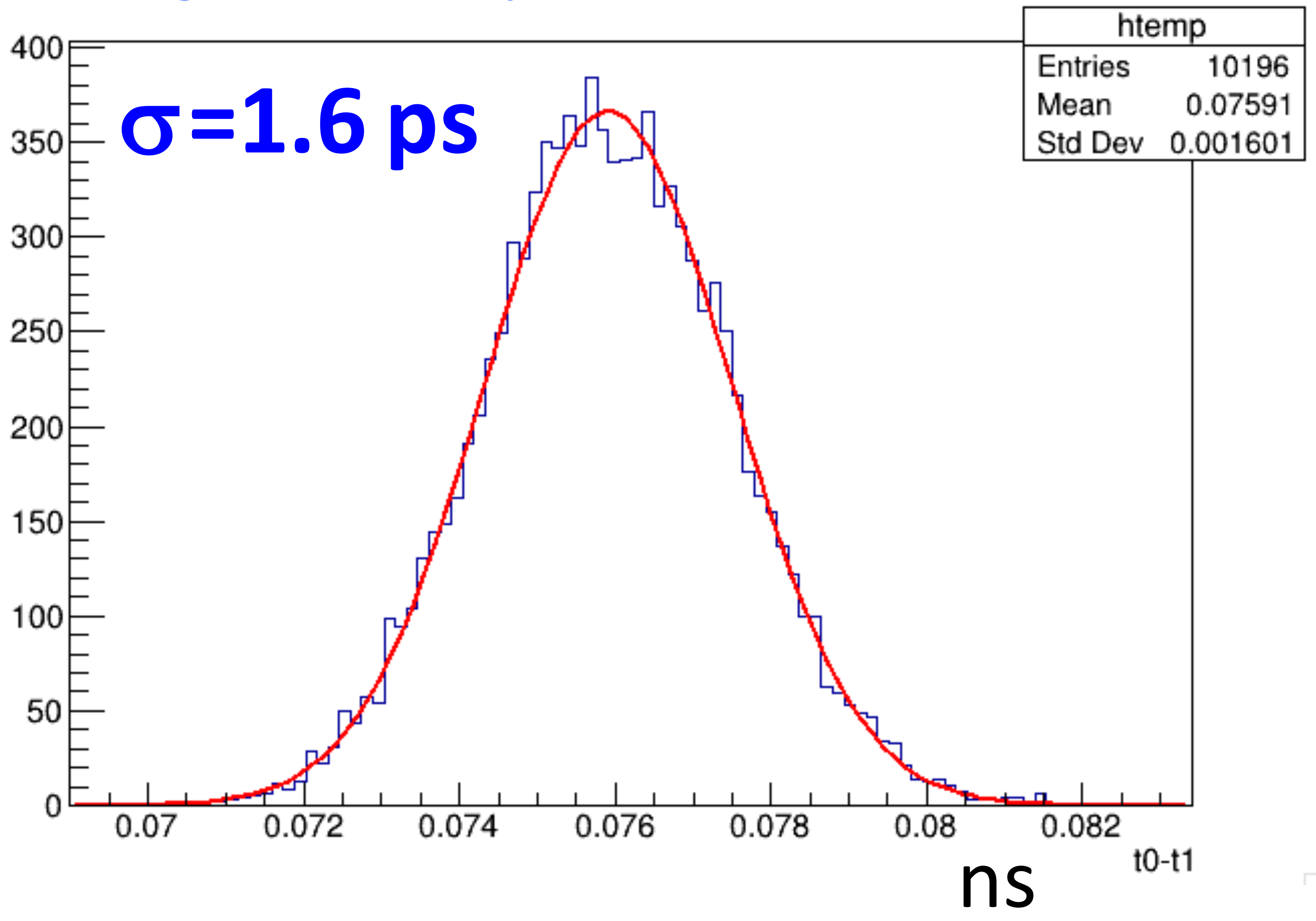
- Calibration check is performed with a **signal split test**
  - A rising edge is generated via waveform generator, split in two and sent to two distinct channels of the board
  - One of the two signals is also delayed wrt the other via a longer cable
    - Effect of small miscalibrations of cells widths adds up for signals separated in time
  - Difference between the two signals is used to determine time resolution

Residual noise after calibration

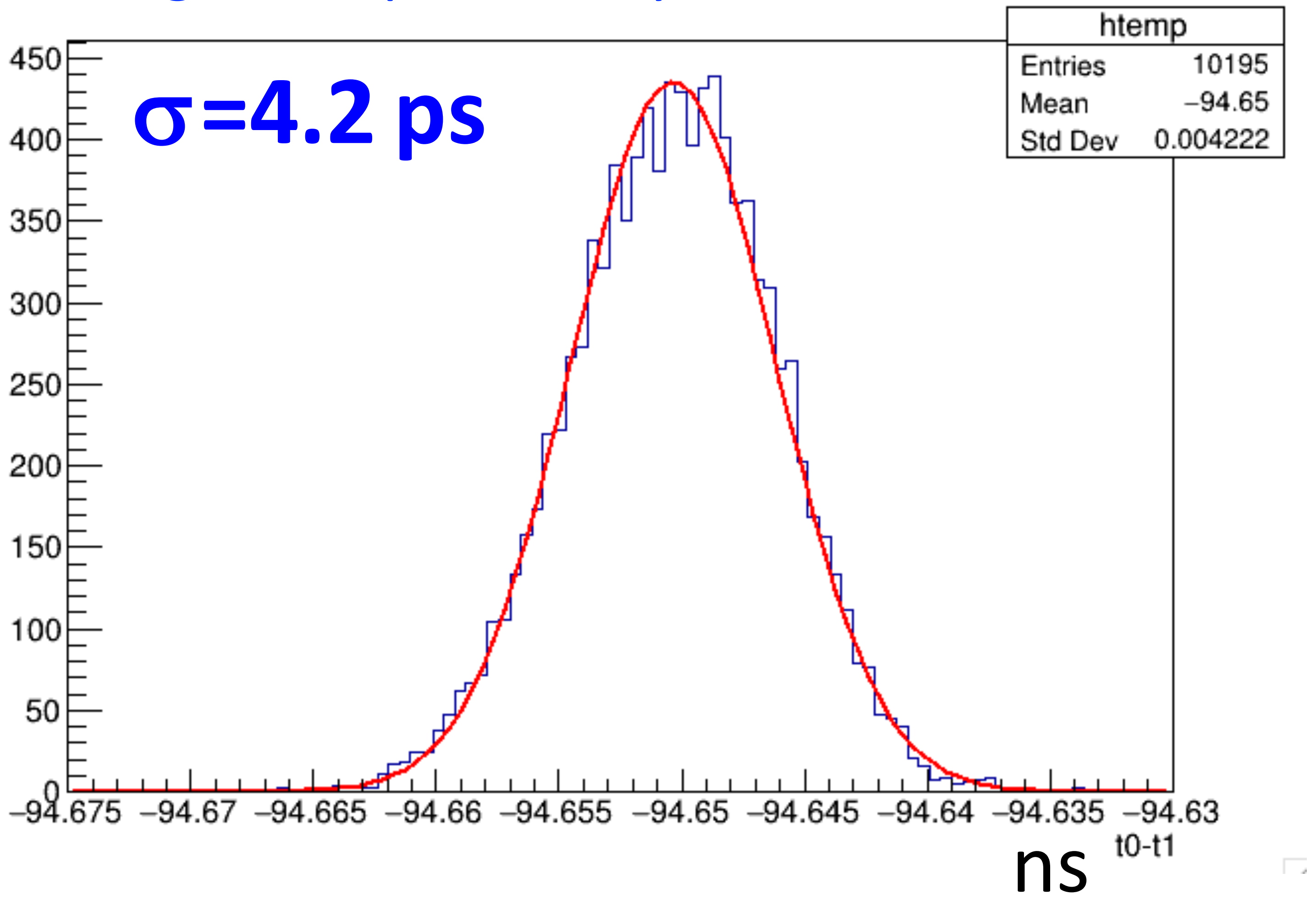




Signals not separated in time

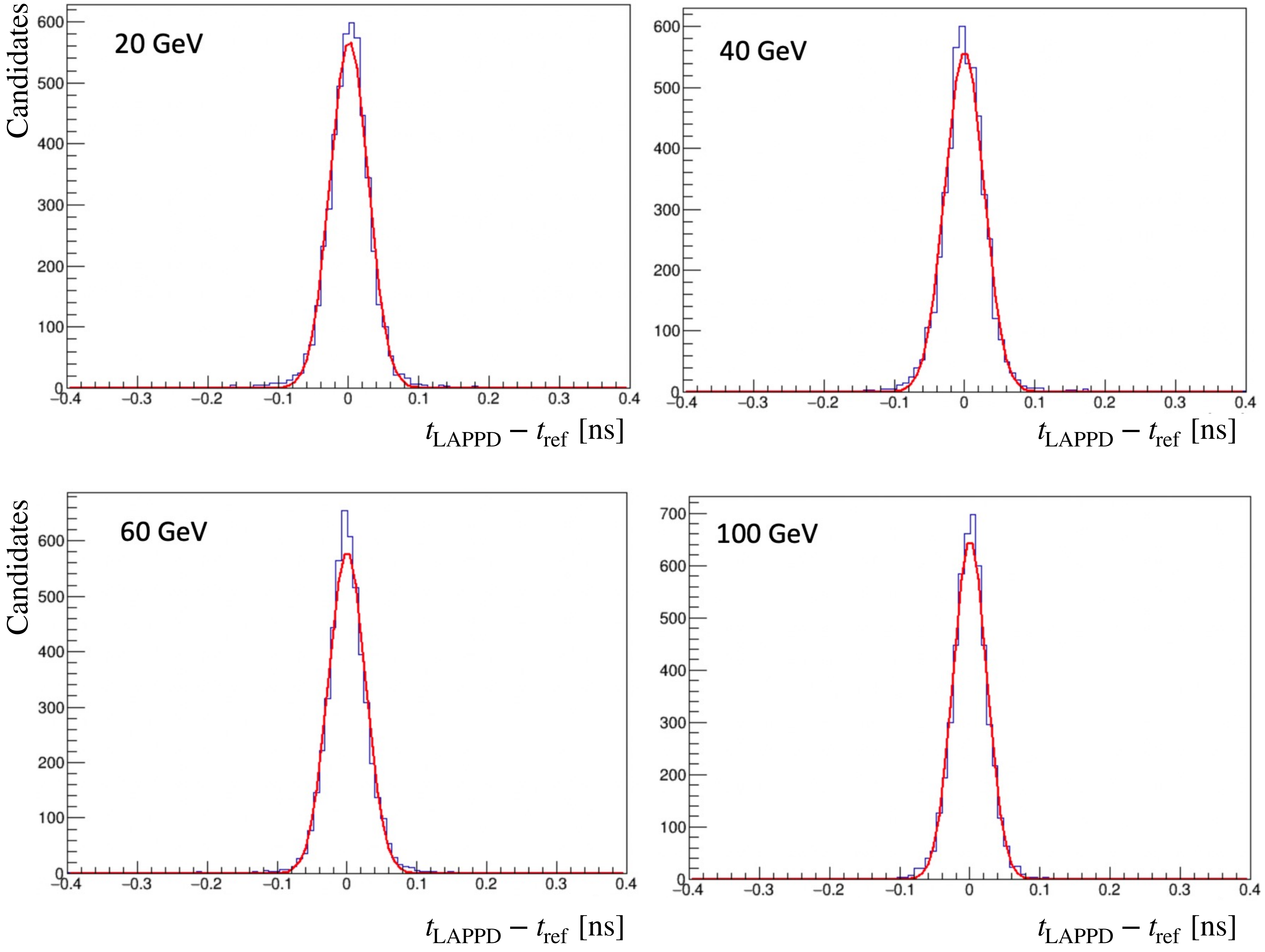


Signals separated by ~100 ns



Pixel combination at SPS

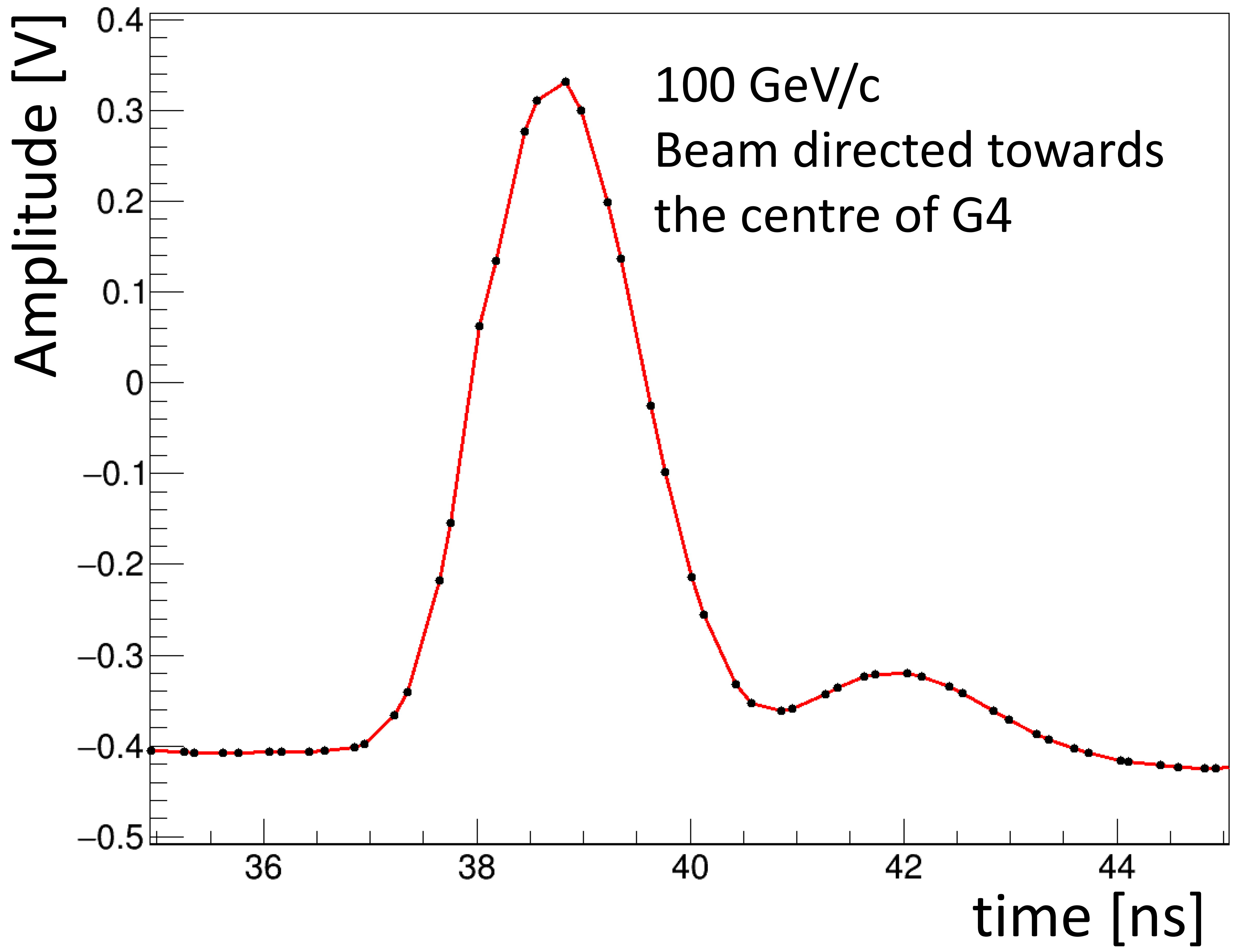
- Information from the 4 pixels combined using a **Random Forrest Regressor**
  - **Inputs:**
    - from LAPPD pixels:
      - Signal amplitudes
      - t_{CFD} at 10%, 50%, 90%
    - Position from DWC2
  - **Target**: mean time of reference MCPs (t_{ref})



- Gaussianity improving with increasing energy

Typical LAPPD signal

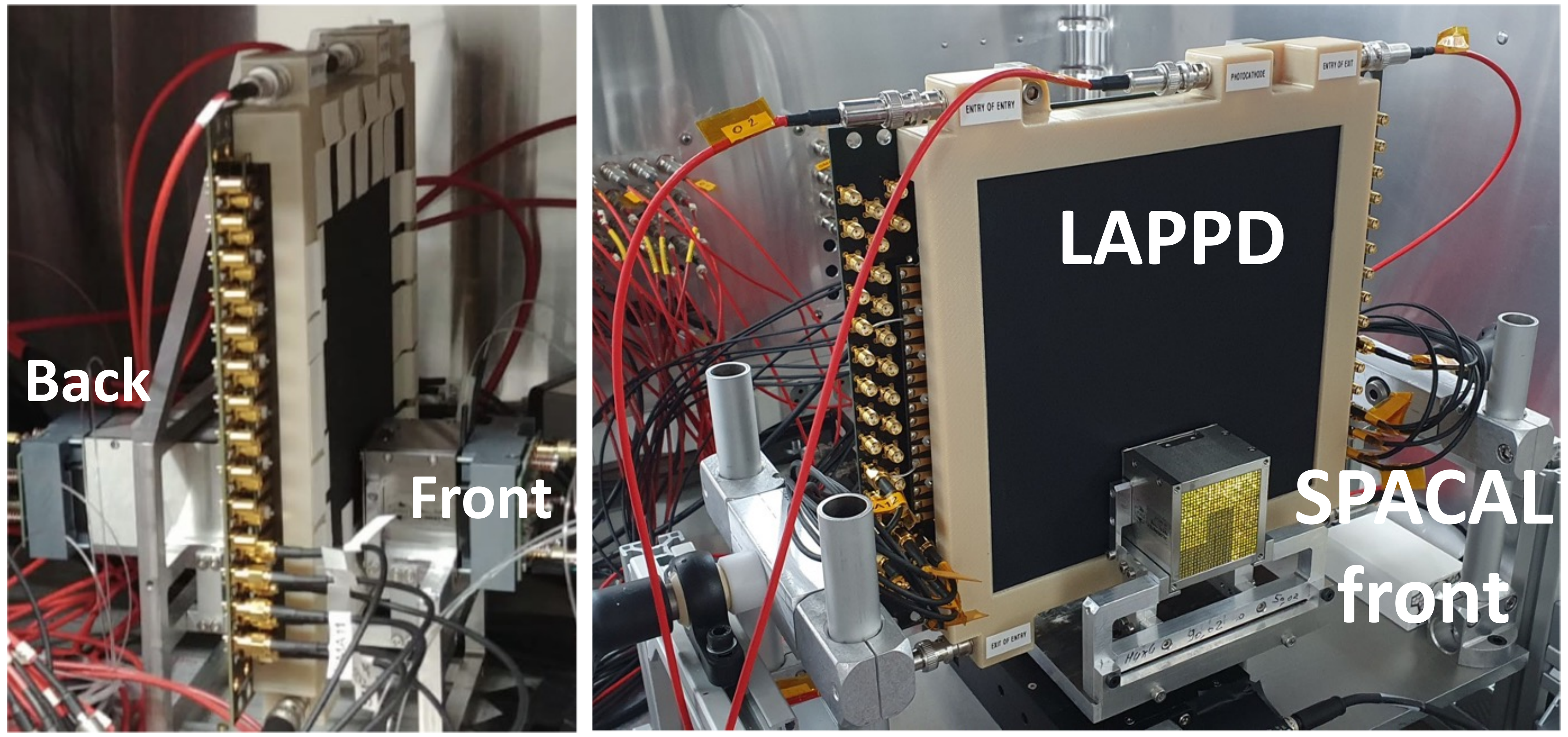
- Rise time between 10 and 90% measured in CERN SPS data to be about 1.1 ns
- Full width at half maximum of signal shape is about 1.7 ns

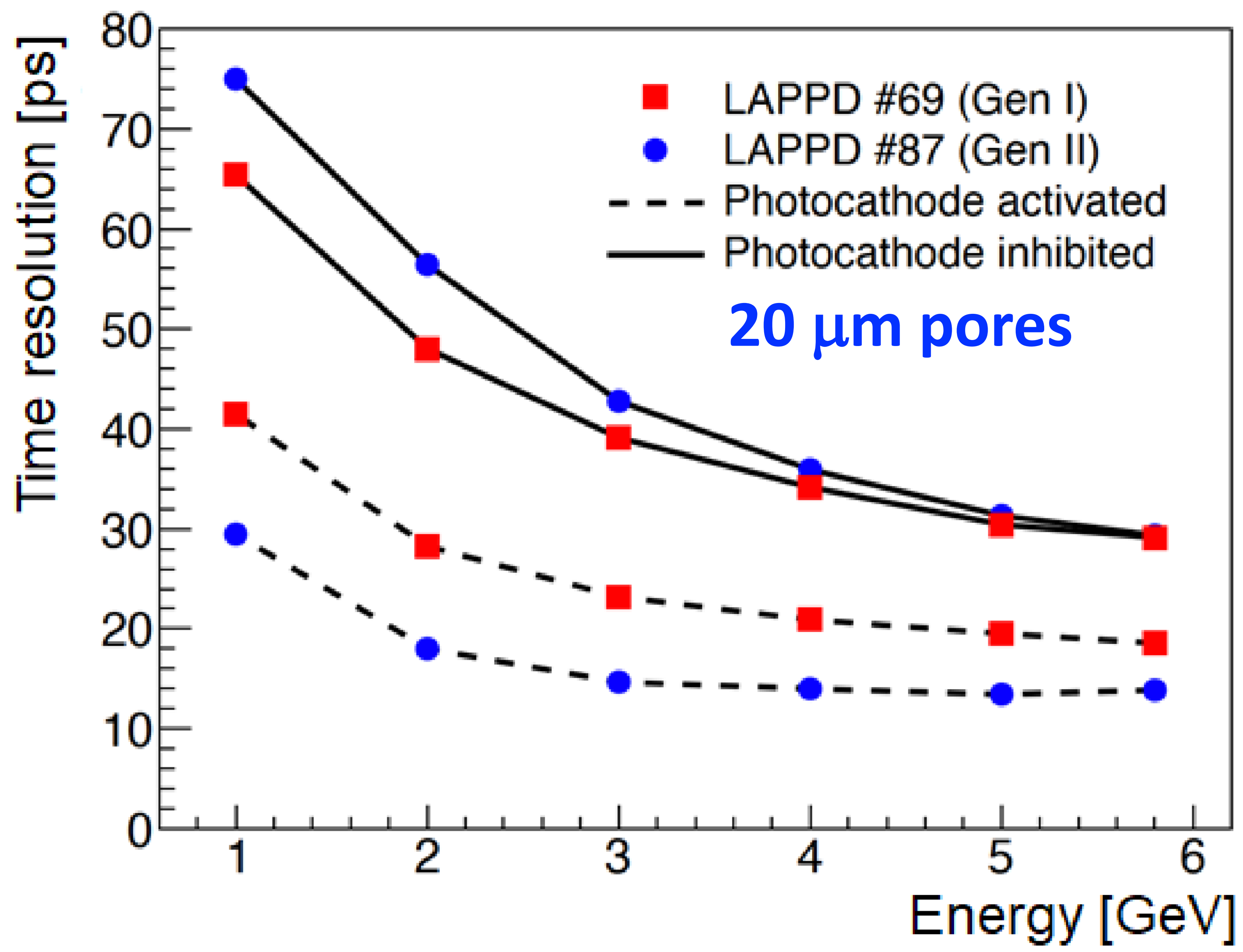


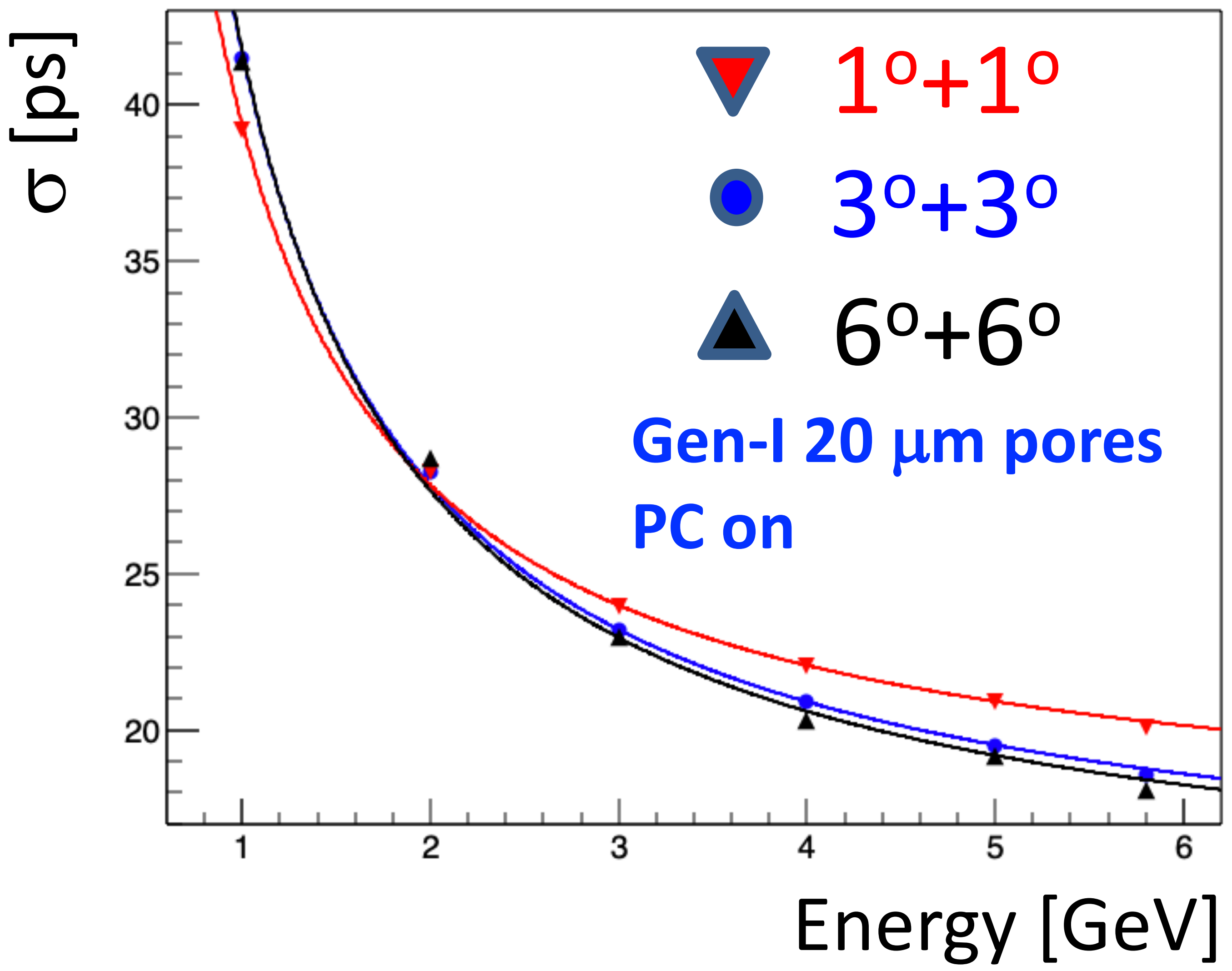
Test beam at DESY: November 2020 e May 2021

LAPPD Gen. I e II, 20 μm pores
Time resolution:
- Photocathode ON: 23 ps (Gen-I), 14 ps (Gen-II) at 5 GeV
- Photocathode OFF : ~30 ps at 5 GeV

Small differences depending on the beam-axis orientation
- due to SPACAL geometry

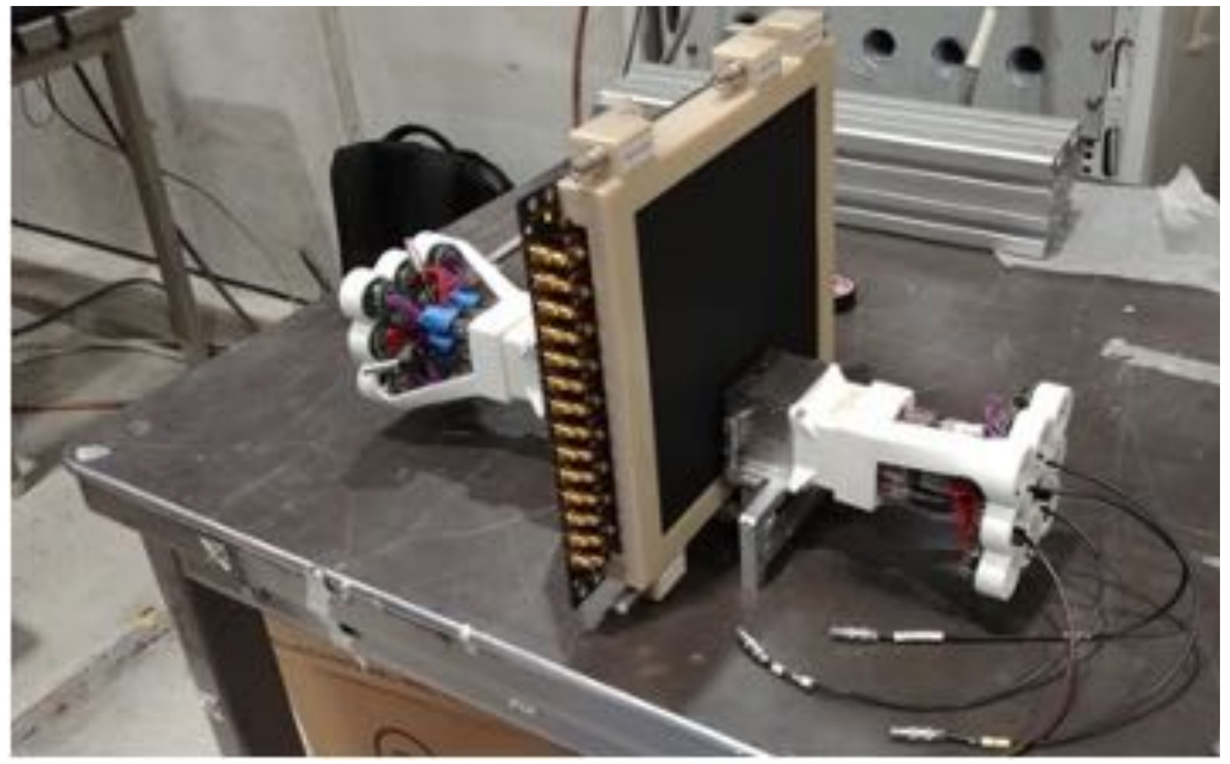


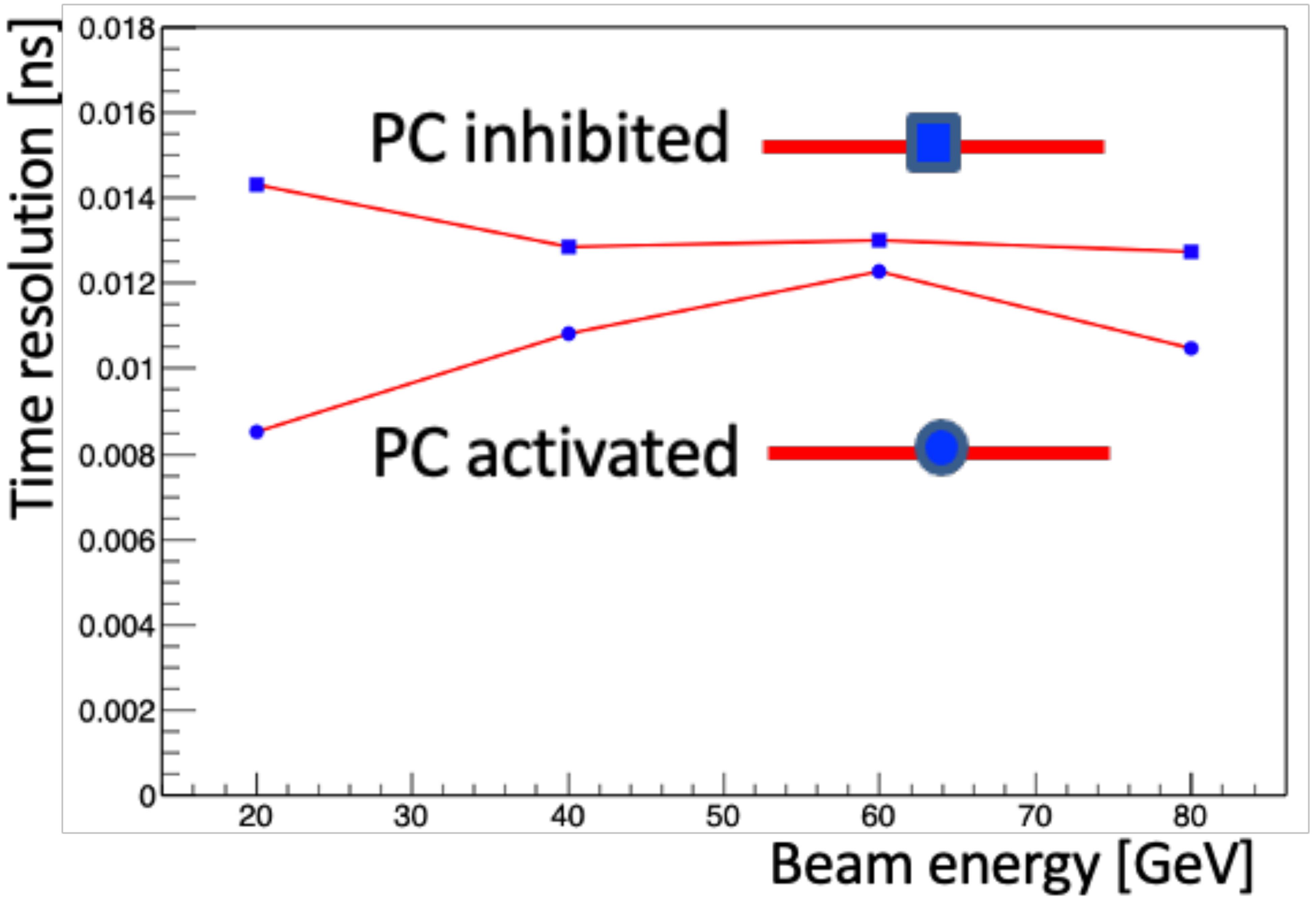


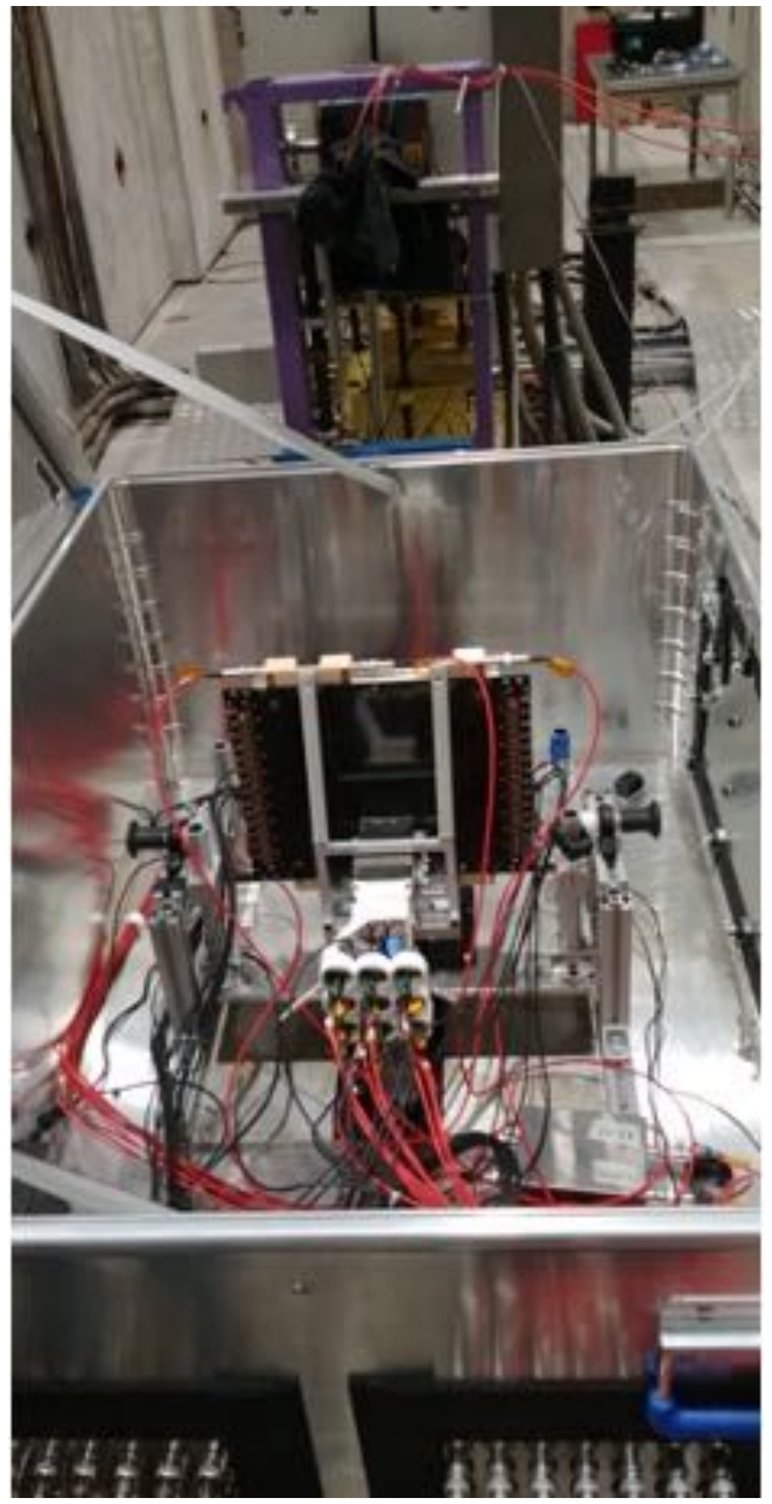


Test beam at SPS: November 2021

- LAPPD Gen-I, $10\,\mu m$ pores
- Time resolution with inhibited photocathode similar to the one with active photocathode
  - Photocathode ON: 8 - 12 ps
  - Photocathode OFF: 13-14 ps

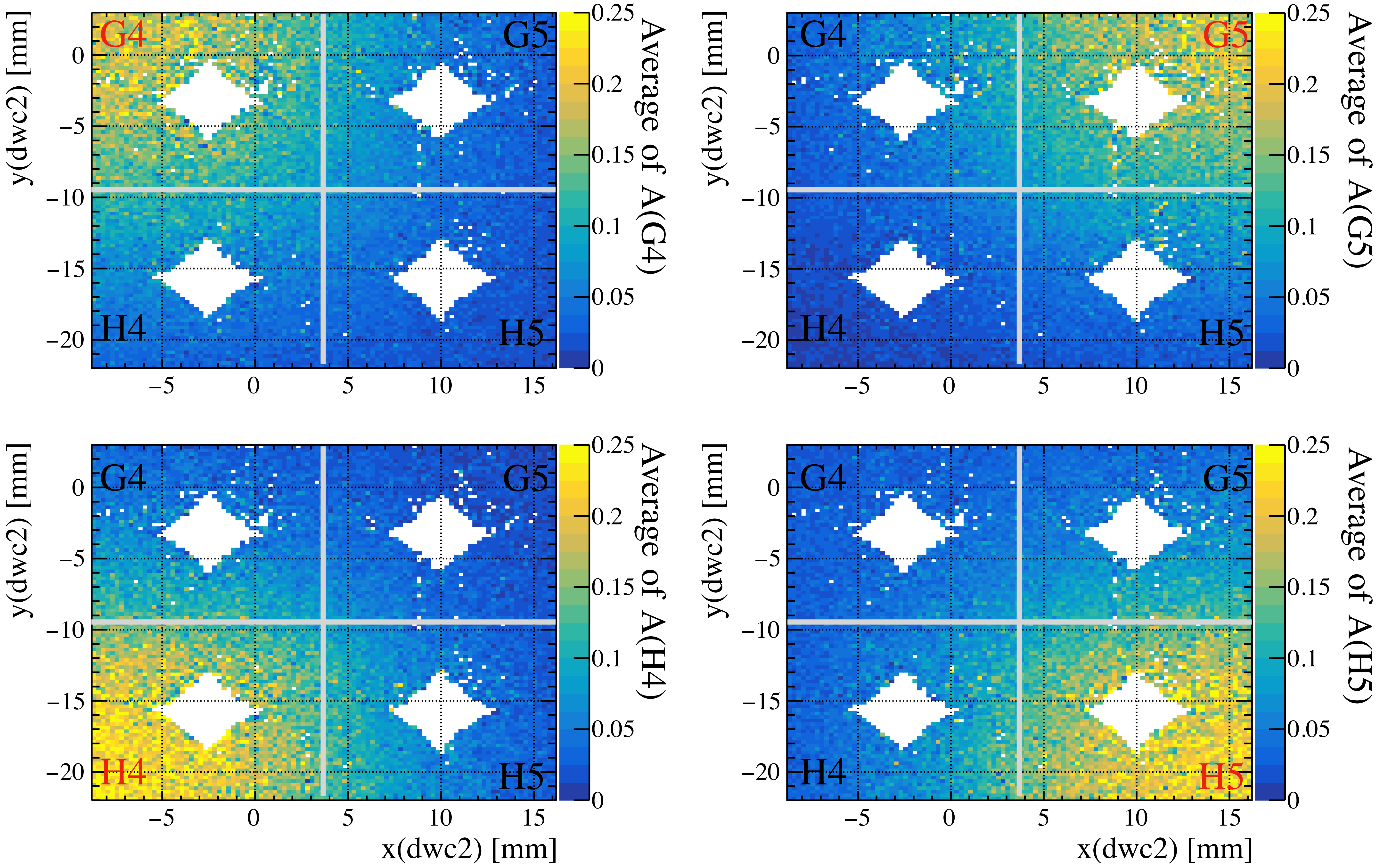






Position from the LAPPD

Average amplitudes of the LAPPD signal channels @ 5 GeV
depending on the DWC2 measurements

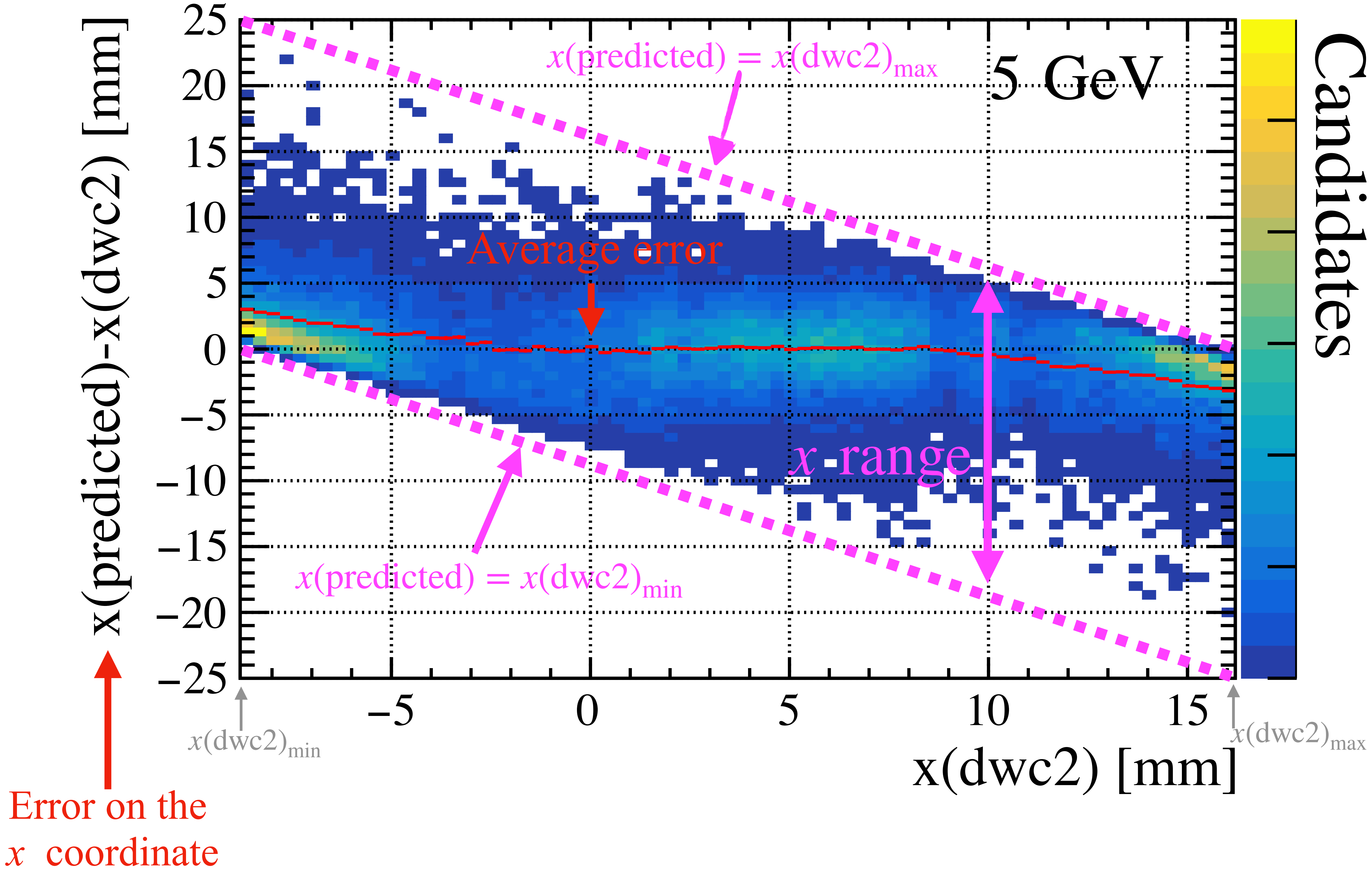


The signal amplitude encode information about the position of the impinging electron

- Also hit position estimated combining the information from the 4 pixels
- A dedicated Random Forest Regressor was trained:
  - **Targets**: x(dwc2) and y(dwc2)
  - **Inputs:** signal amplitudes from the 4 pixels
  - **RF Configuration:** Default
    - NO remarkable improvement from including the signal areas, time infomation or changing configuration of the RF algorithm from the default
- Same fiducial cuts as before for the training sample
  - See slides 5 and 7
- More about the test sample in the following slides

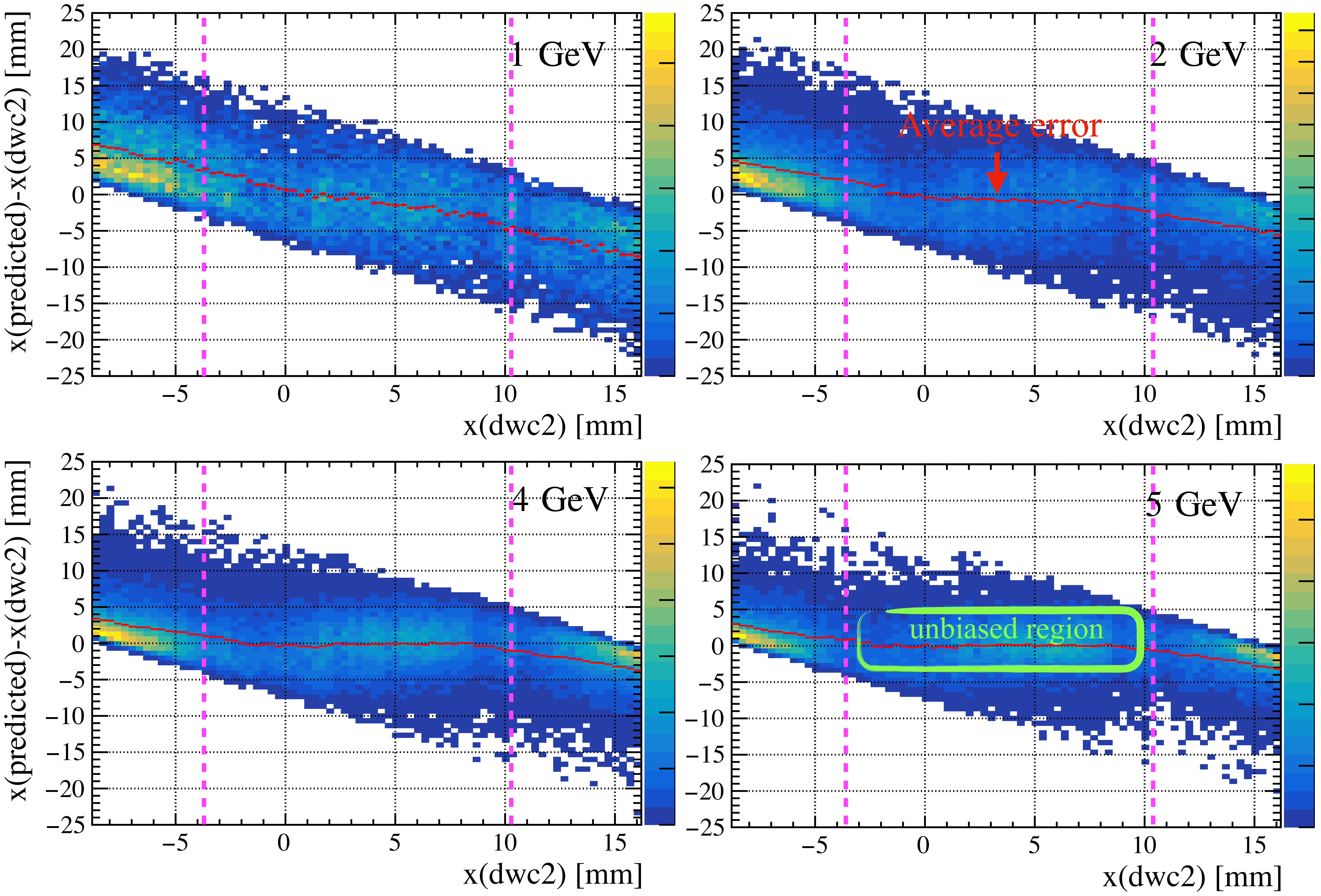
Position-reconstruction features

- **A deviation of the reconstructed coordinates is observed** when x(dwc2) and y(dwc2) have low or high values
- On average, the predicted coordinates deviate towards the center of the allowed region
- Behaviour due to the limited spatial range of the training events
  - Not-gaussian distribution of the errors close to the borders: tail on the only possible side



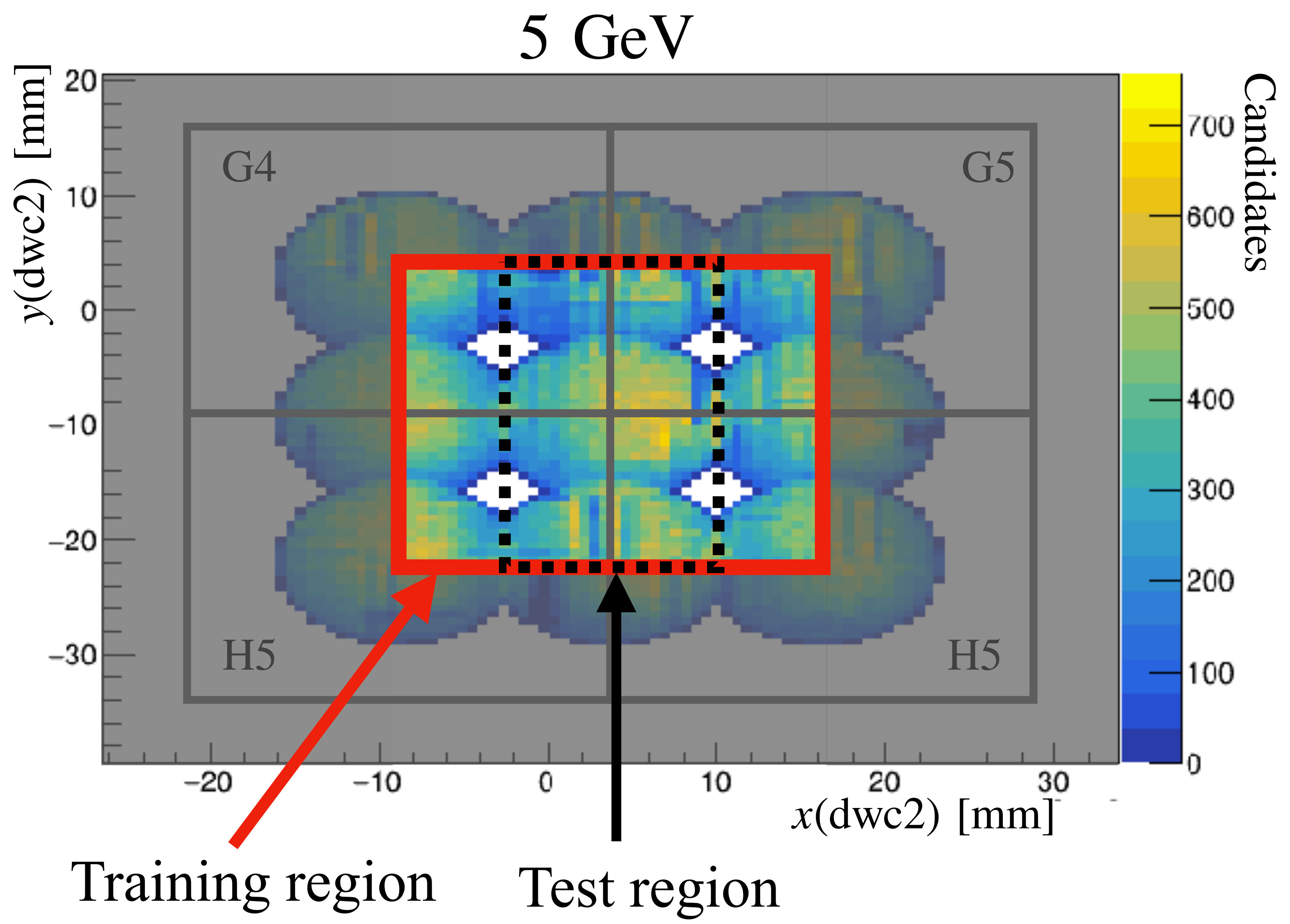
The same features are observed in the y-coordinate reconstruction

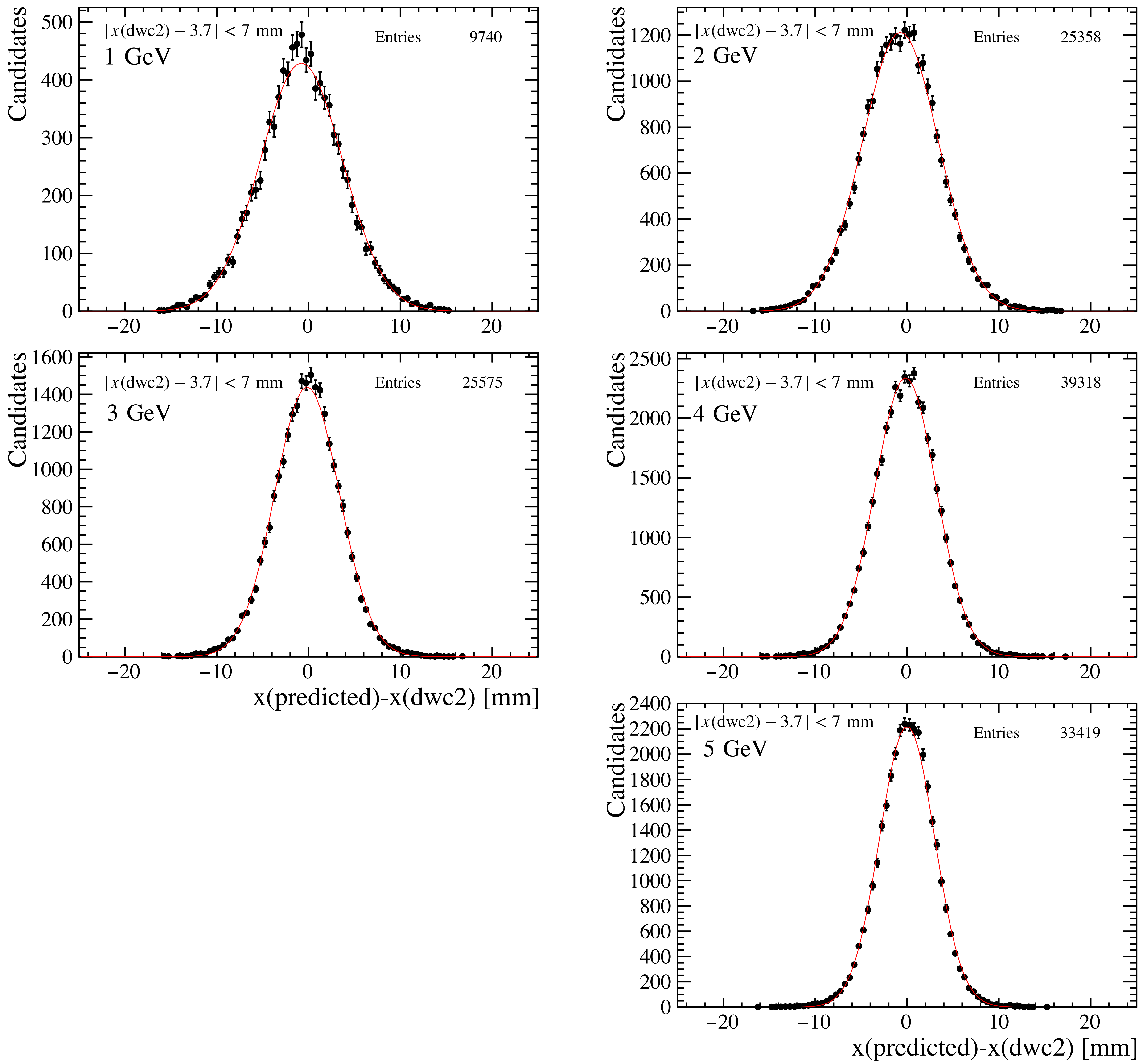
Position bias depending on E



- The lower the energy,
  1. the smaller the unbiased region
  2. the larger the maximal deviation
- Hence, performance evaluated in the central bands
  - For x coord.: $|x(\mathrm{dwc2}) - 3.7| < 7$ mm
  - For y coord.: $|y(\mathrm{dwc2}) + 9.5| < 7$ mm

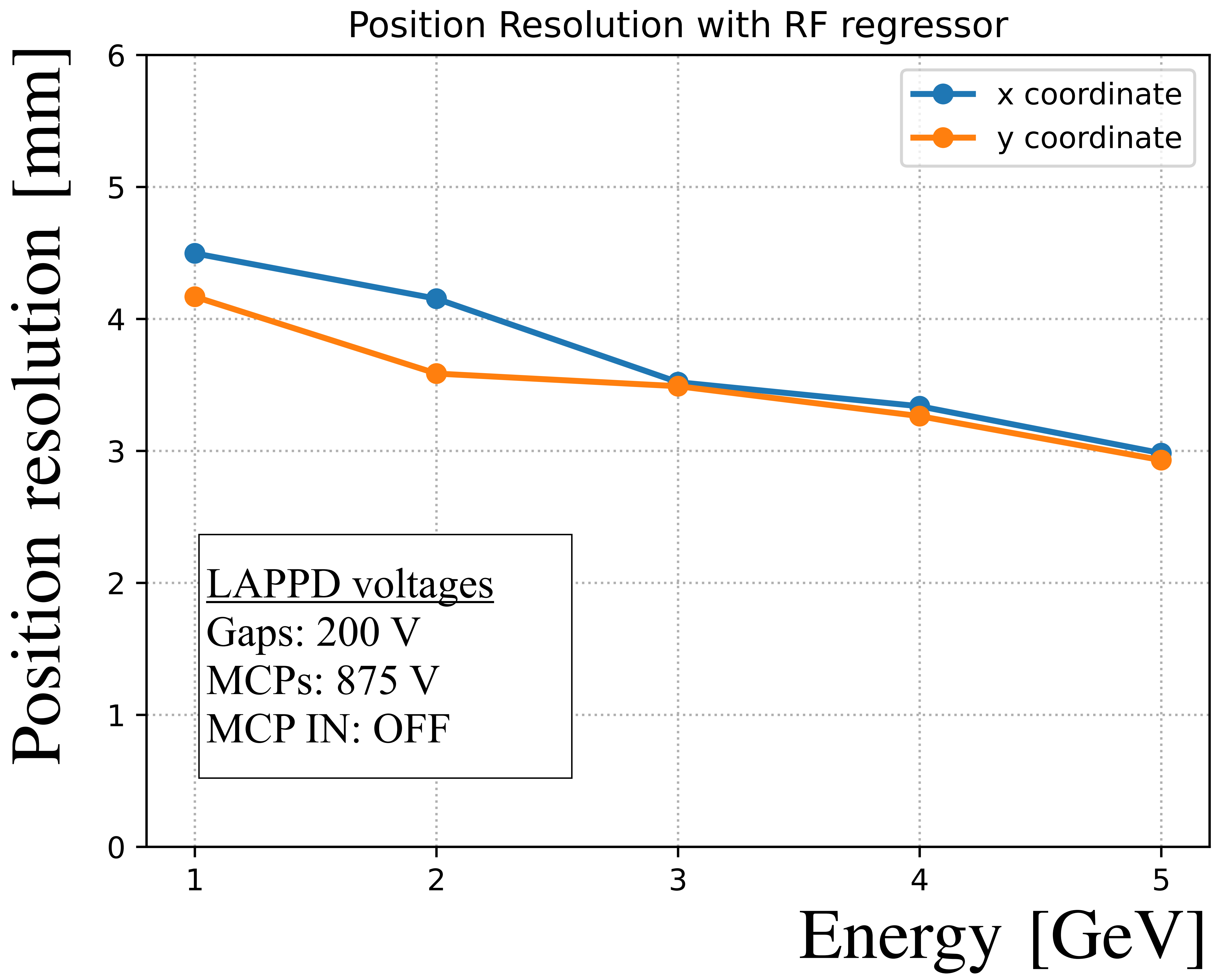
Position resolution: δx distributions





- Good gaussianity in this reduced test region for all energies
  - Results in the next slide
- Analogous distributions for the y coordinate

Position resolution: results



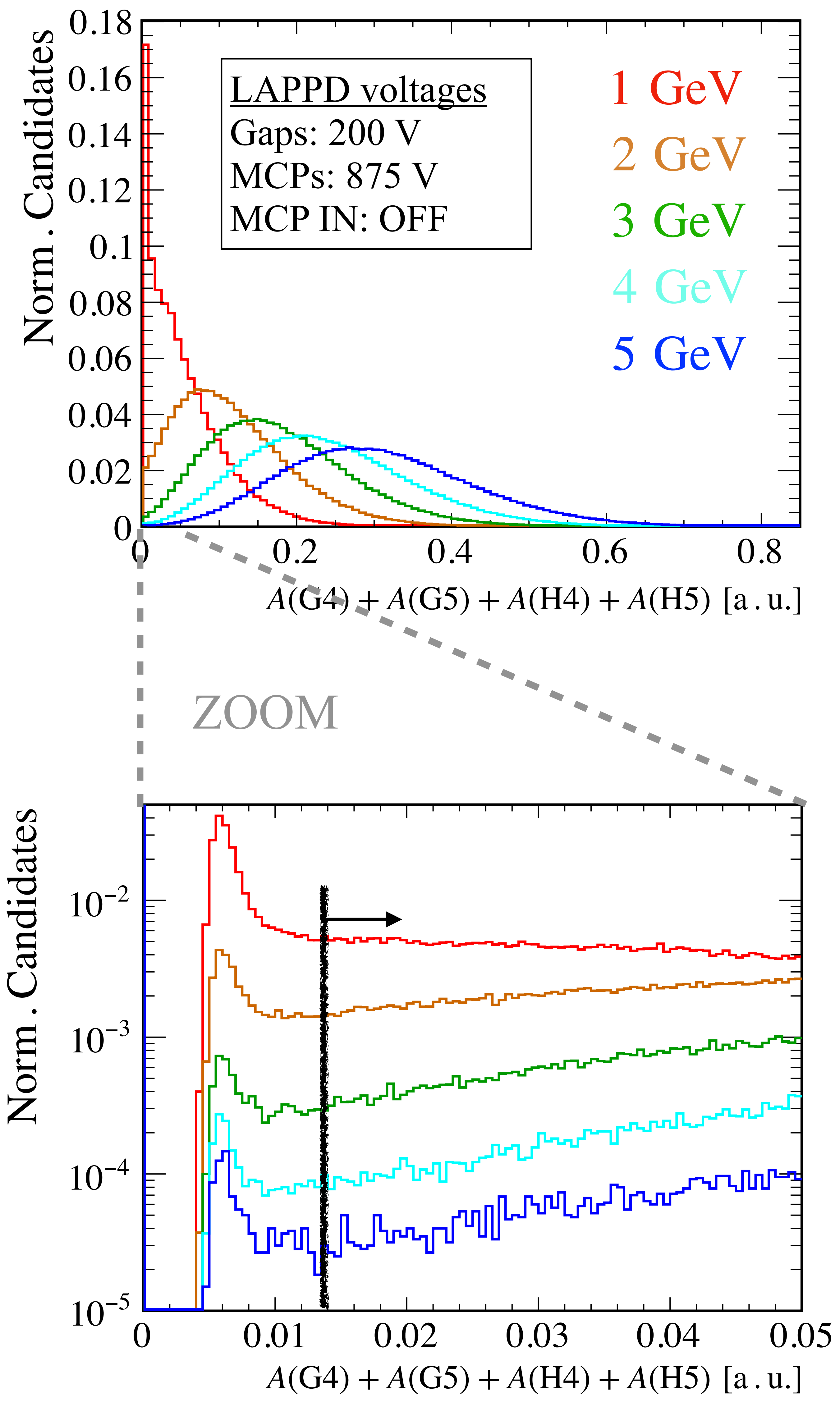
- Position resolution **4-4.5 mm at 1 GeV** and **3 mm at 5 GeV**

Efficiency

- Want to study the cases when no actual LAPPD signal is produced
  - Due to EM shower fluctuations and/or LAPPD intrinsic inefficiency

- Basic strategy: consider as empty events those gathering at minimum values in the distribution of the sum of the 4 pixel amplitudes

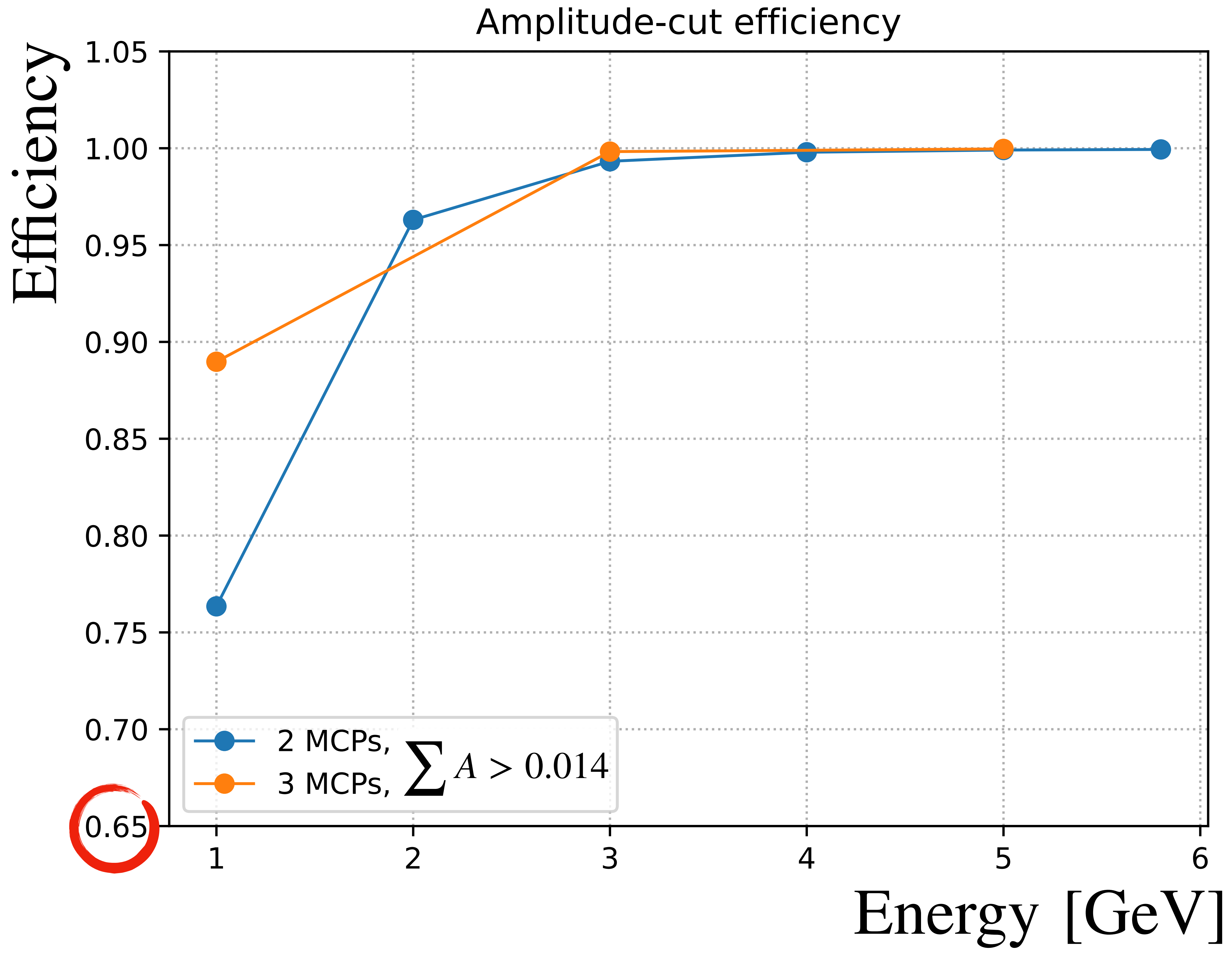
- Selection cut:
  $A(\mathrm{G4}) + A(\mathrm{G5}) + A(\mathrm{H4}) + A(\mathrm{H5}) > 0.014$



Efficiency Results

- <u>Efficiency numerator</u>: number of candidates, whose total signal amplitude is higher than 0.014

- <u>Efficiency denominator</u>: number of candidates passing the baseline fiducial cuts (slide 7)



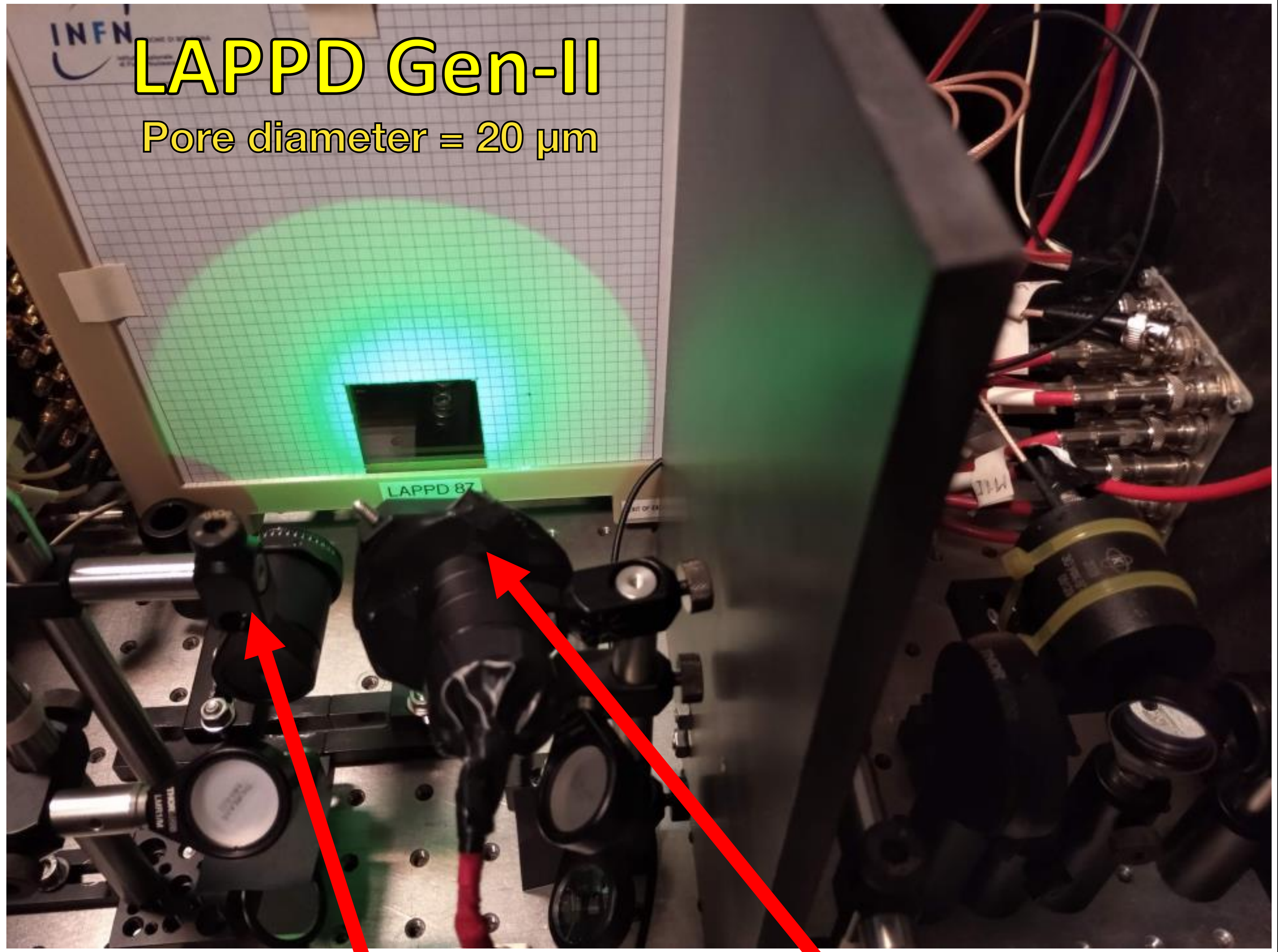
No data collected with 3 active MCPs at 2, 4, 5.8 GeV
Beam position: whole fiducial region, except for:
- 2 MCPs at 5.8 GeV: center of the 4 pixels
- 3 MCPs at 1.0 GeV: center of pixel H5

- 2 MCPs:
  - MCP IN: OFF
  - Gaps: 200 V
  - MCP MID. and OUT: 875 V
  - Remarkable efficiency drop at 1 GeV: $\varepsilon = 76\,\%$
  - Inefficiency almost recovered at 3 GeV: $\varepsilon = 99\,\%$
- 3 MCPs:
  - All MCPs: 750 V
  - Gaps: 200 V
  - Inefficiency mitigated at 1 GeV: $\varepsilon = 89\,\%$

FAST 2021 by S. Perazzini (1)

LAPPD Gen-II: realistic LHCb-U2 environment

- Simulations are used to reproduce realistic LHCb-U2 conditions
  - An LHCb ECAL module is placed in a region close to the beampipe and the number of charged particles per event entering the LAPPD device is estimated
  - **30 MHz/cm^2 of charged particles** are expected to traverse the LAPPD in central region
- Conditions are reproduced using
  - **Green LED** with power tuned to produce a rate of 30 MHz/cm^2 of PEs
  - **Defocused laser** pulse tuned to reproduce EM shower of electrons with different energies
- Same test is also conducted with Katod UFK-5G-2D MCP-PMT



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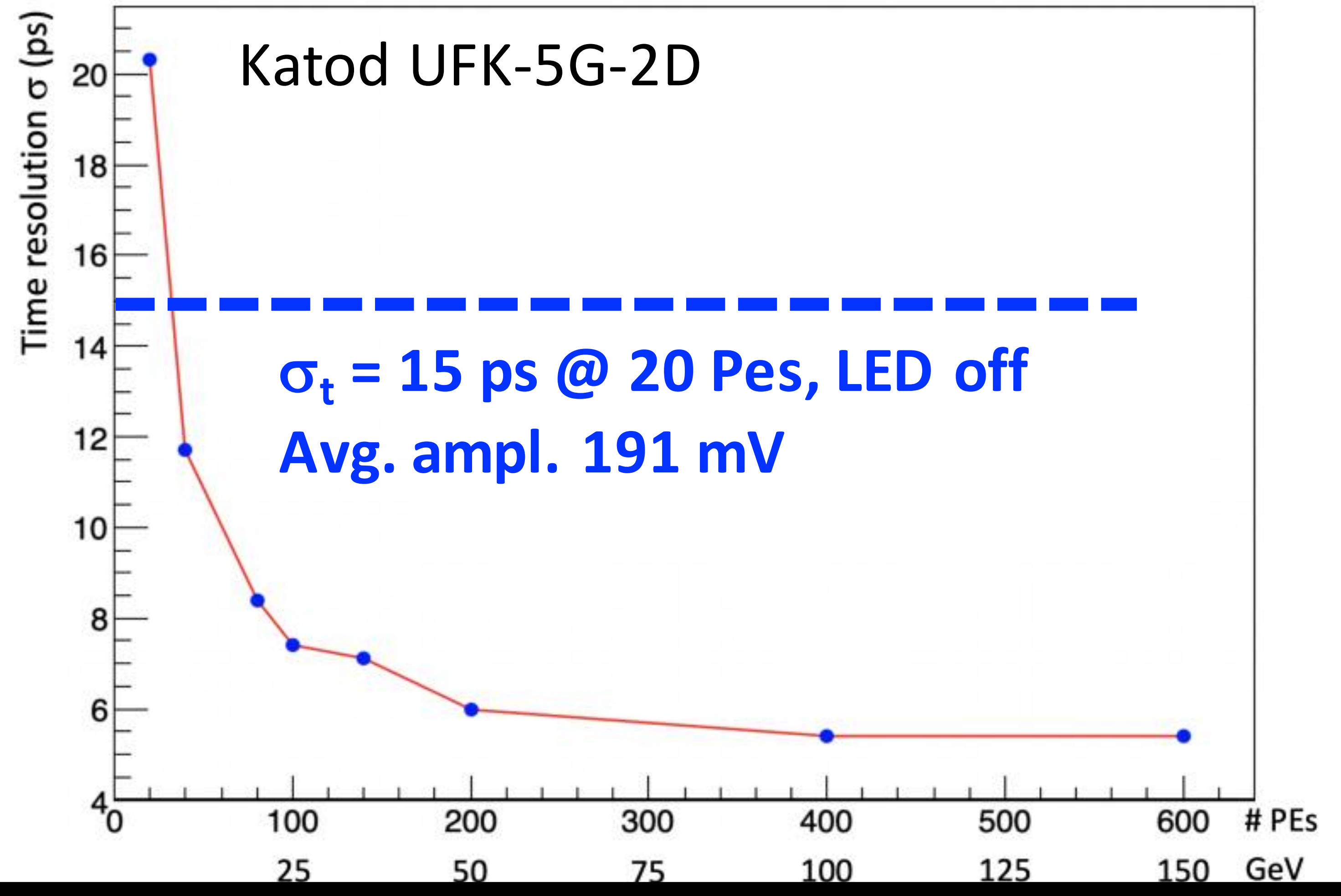
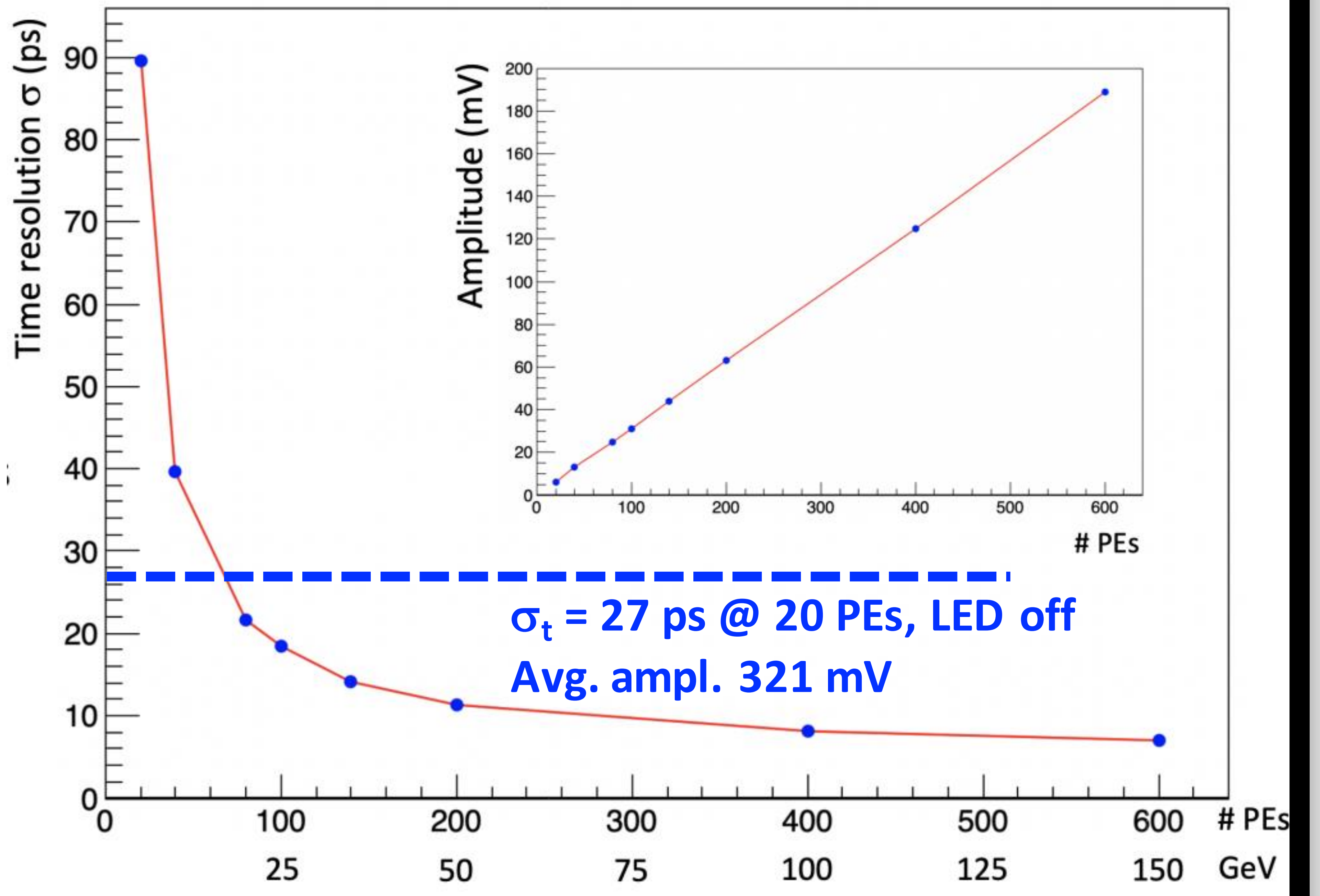
FAST 2021 by S. Perazzini (2)

LAPPD Gen-II: realistic LHCb-U2 environment

- Below 80 PEs (roughly 20 GeV), the **time resolution degrades very rapidly** due to much suppressed signal amplitude
  - E.g., with 20 PEs the **amplitude goes from 321 to 6 mV**
- Katod UFK-5G-2D suffers much less thanks to smaller pore size (6 μm)
  - Average amplitude for 20 PEs goes from 191 to 24 mV



LAPPD Gen-II



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