# Update on LAPPD studies for LHCb ECAL Upgrade II

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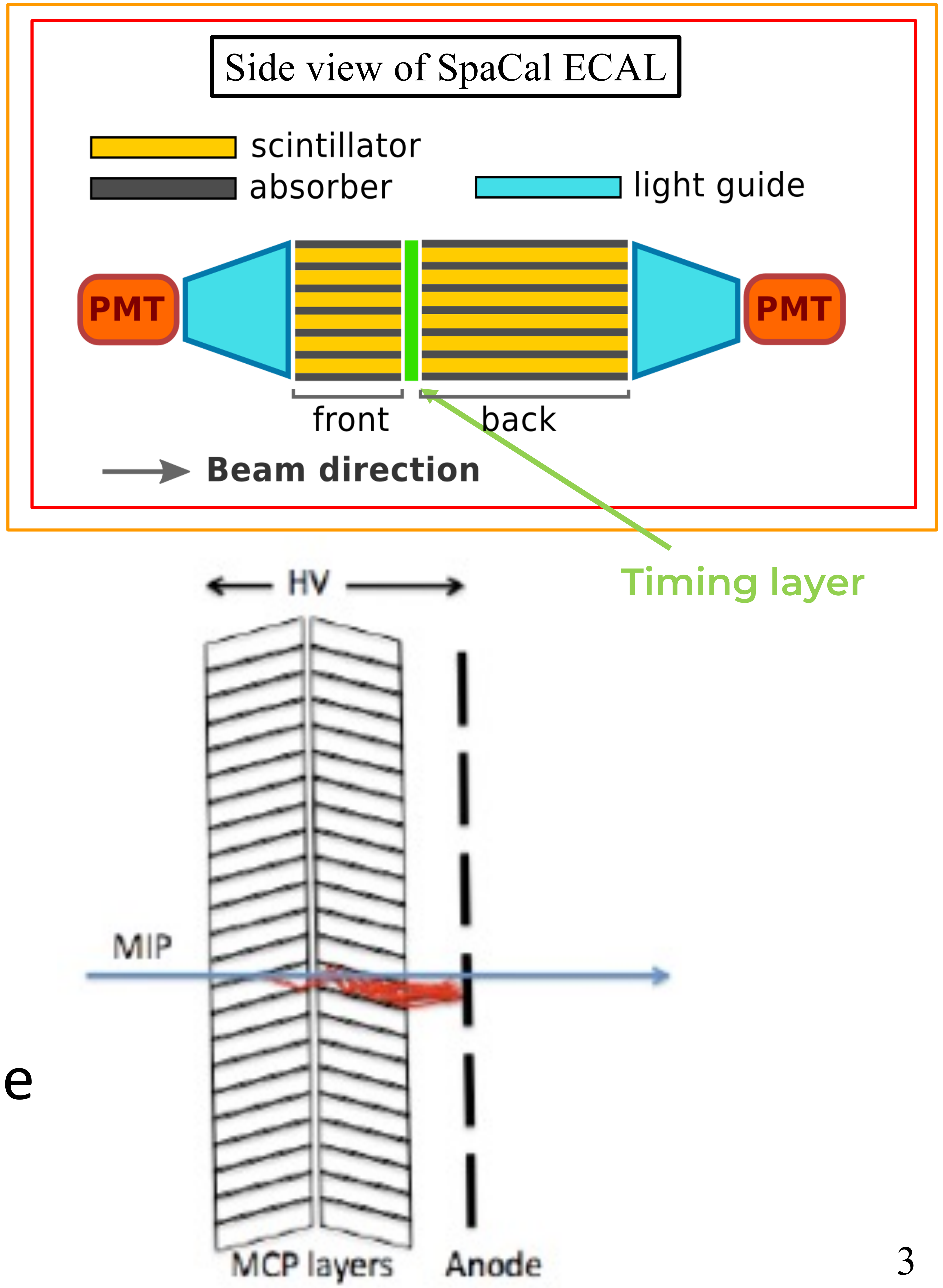
# Outline

- Reminder of project’s aims
  - For further information and previous results, you can have a look at older LAPPD workshops
    - https://indico.bnl.gov/event/17475/
    - https://indico.bnl.gov/event/15059/
- Results from latest beam test at DESY with electrons from 1 to 5.8 GeV (data taken in December 2022)
  - Time resolution
  - Position resolution
  - Detection efficiency

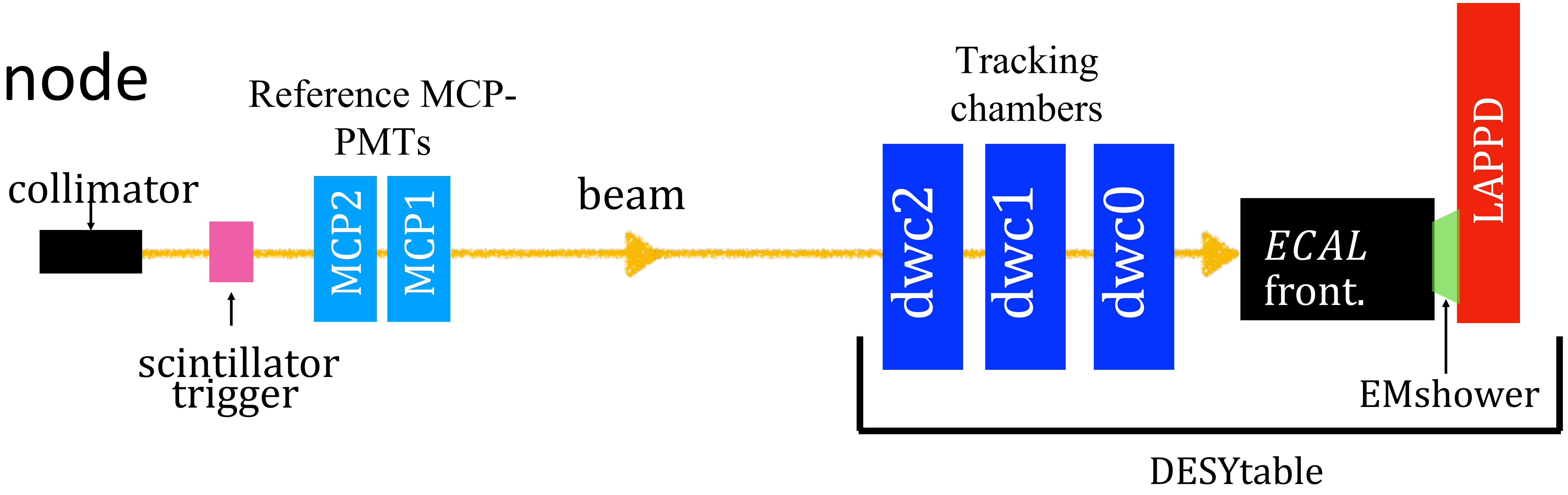
# Reminder: timing layer for the LHCb Upgrade-II ECAL

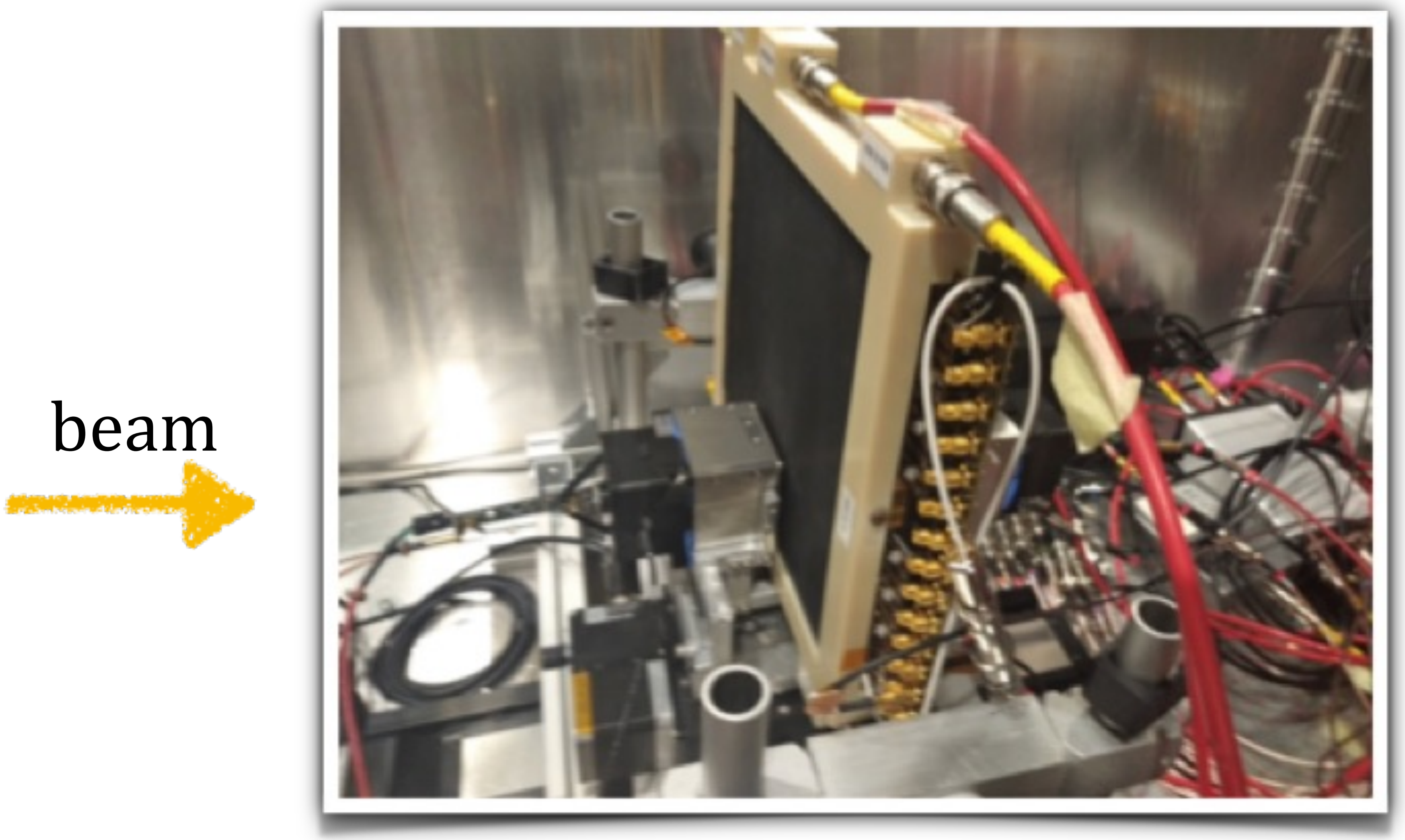
- The LHCb Upgrade-2 will operate in harsh hadronic environment
  - Instantaneous luminosity of proton-proton collisions up to 1.5 x $10^{34}$ $cm^{-2}s^{-1}$
  - High background in most central region
  - Measuring time of hits will be crucial to resolve pileup
    - Simulations indicate a time resolution of O(20) ps as necessary
- Insert a LAPPD-based detector between two sections of a sampling calorimeter
  - Detect charged component of EM showers by direct ionization within MCP wafers (no photocathode)
  - Exploit excellent time resolution of MCPs to determine the time of EM shower with O(10-20) ps precision



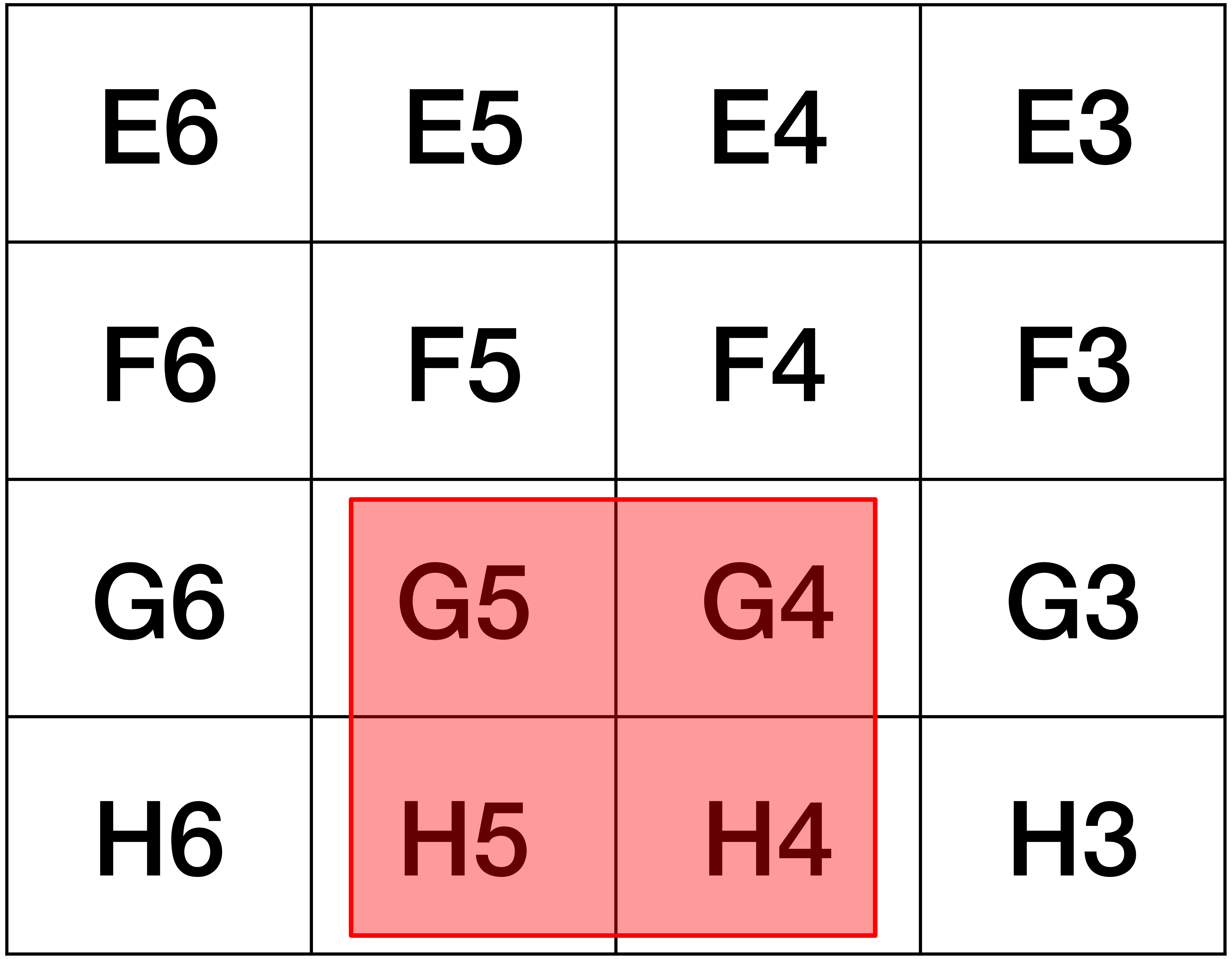
# Experimental setup at DESY

- Z-stack LAPPD with Gen-II anode
  - Stack of 3 MCPs
  - Photocathode-less operation
  - Calorimeter module covering 4 pixels
    - LAPPD pixels: G4, G5, H4, H5
- Data sample
  - Voltage scan with electrons at 5 GeV
  - Fixed voltage, position scan with electrons from 1 to 5.8 GeV



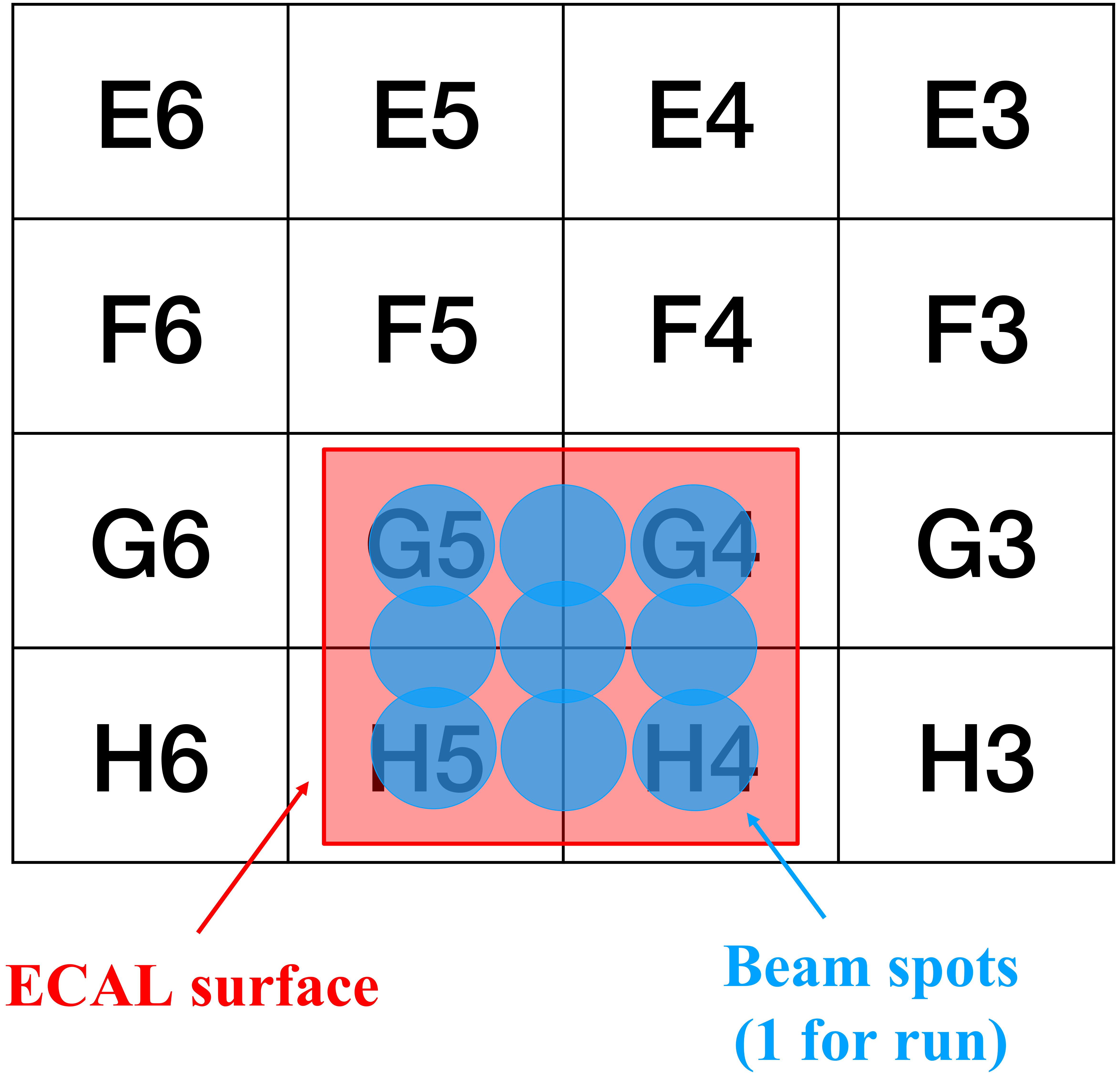



# LAPPD front view: detail around calorimeter area, in red




- Front calorimeter module is positioned to cover approximately 4 pixels of the LAPPD
  - Side of SPACAL module is about 4.5 cm while LAPPD pixel pitch is 2.5 cm

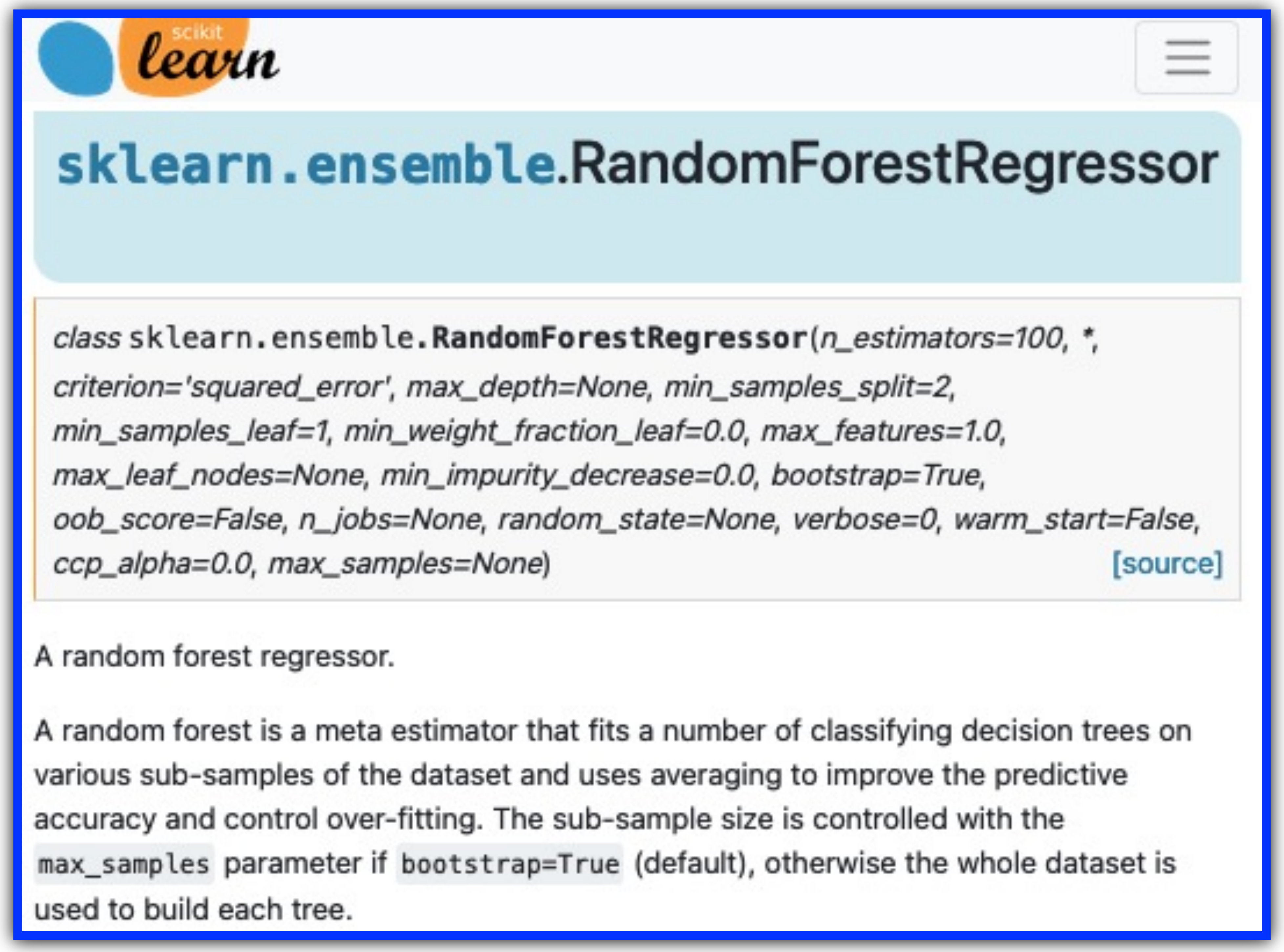
# LAPPD front view: detail around calorimeter area, in red




- Different runs are taken to scan the surface of the 4 pixels behind the front calorimeter module

# Time measurement

- Analog signals from LAPPD and reference MCP-PMTs sampled by DRS4 at 5 GS/s
- Information from the four pixels combined with a machine learning approach
  - Random Forest Regressor (RF)
    - Input variables
      - Signal amplitudes
      - $t_{\mathrm{CFD}}$ at 10%, 50%, 90%
      - Position from tracking chambers
  - Trained on a subsample and then performance measured on the rest of the sample



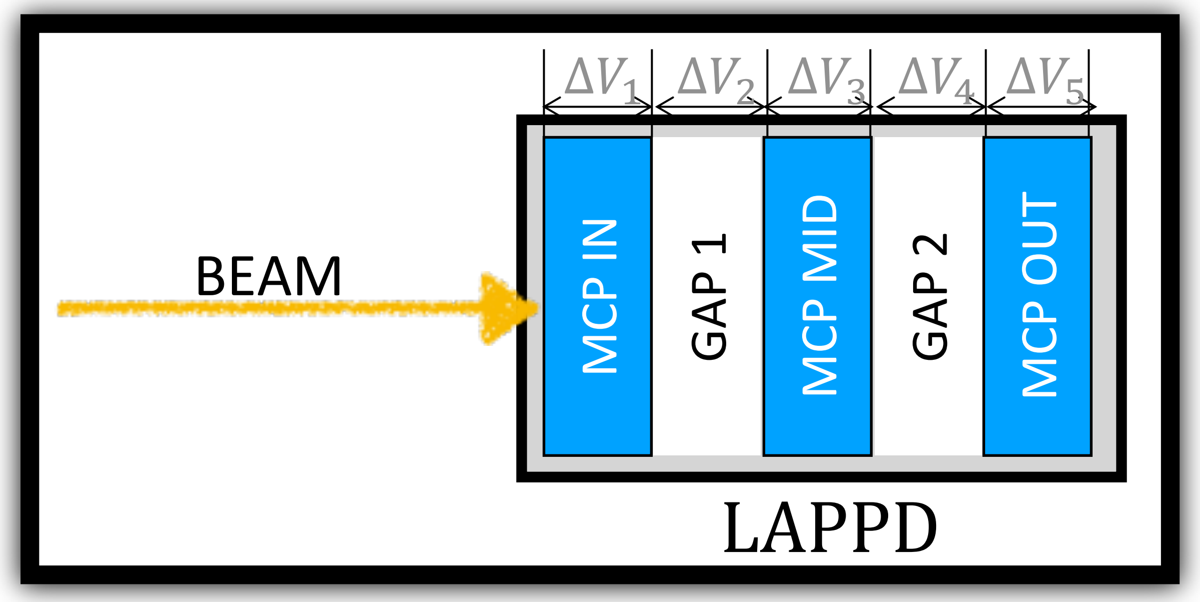
**sklearn.ensemble.RandomForestRegressor**

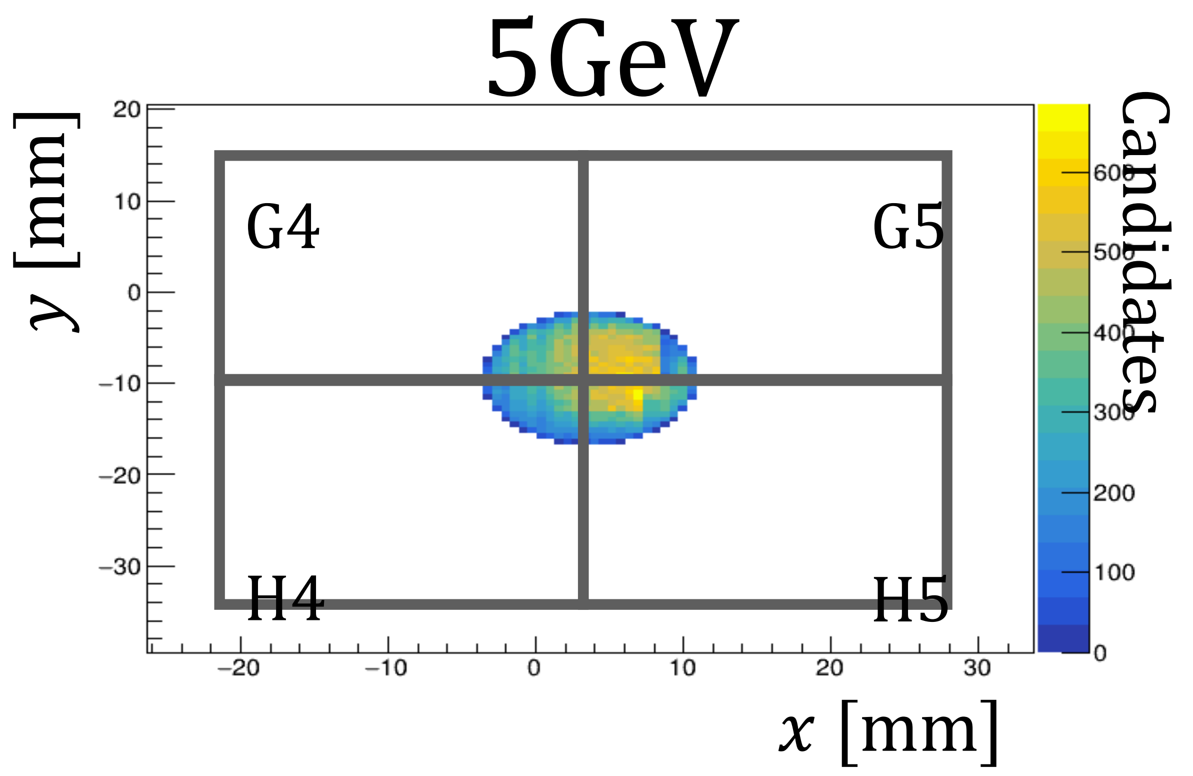
*class* `sklearn.ensemble.RandomForestRegressor`(*n_estimators=100*, ***, *criterion='squared_error'*, *max_depth=None*, *min_samples_split=2*, *min_samples_leaf=1*, *min_weight_fraction_leaf=0.0*, *max_features=1.0*, *max_leaf_nodes=None*, *min_impurity_decrease=0.0*, *bootstrap=True*, *oob_score=False*, *n_jobs=None*, *random_state=None*, *verbose=0*, *warm_start=False*, *ccp_alpha=0.0*, *max_samples=None*) [source]

A random forest regressor.

A random forest is a meta estimator that fits a number of classifying decision trees on various sub-samples of the dataset and uses averaging to improve the predictive accuracy and control over-fitting. The sub-sample size is controlled with the `max_samples` parameter if `bootstrap=True` (default), otherwise the whole dataset is used to build each tree.

# Voltage scan



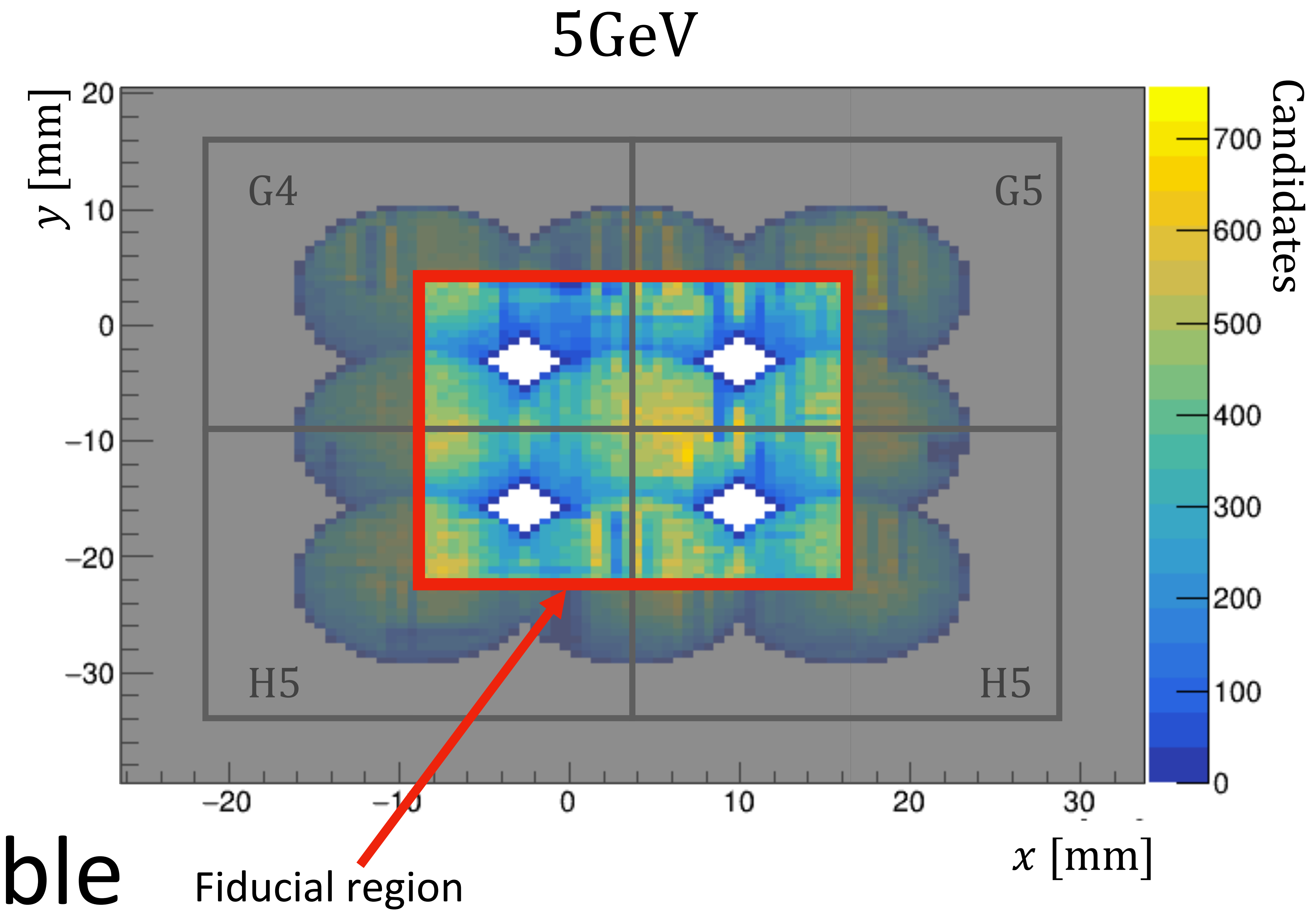

| | MCP IN $\Delta V_1$ [V] | GAP 1 $\Delta V_2$ [V] | MCP MID. $\Delta V_3$ [V] | GAP 2 $\Delta V_4$ [V] | MCP OUT $\Delta V_5$ [V] | TIME RES [ps] |
|---|---|---|---|---|---|---|
| 3 ACTIVE MCPs | 685 | 200 | 685 | 200 | 685 | **32** |
| | 700 | 200 | 700 | 200 | 700 | **26** |
| | 725 | 200 | 725 | 200 | 725 | **26** |
| | 750 | 200 | 750 | 200 | 750 | **30** |
| | 685 | 200 | 725 | 200 | 750 | **27** |
| 2 ACTIVE MCPs | 0 | 200 | 825 | 200 | 825 | **24** |
| | 0 | 200 | 850 | 200 | 850 | **20** |
| | 0 | 200 | 875 | 200 | 875 | **20** |
| | 0 | 200 | 900 | 200 | 900 | **22** |
| | 0 | 200 | 950 | 200 | 950 | **28** |
| | 0 | 200 | 750 | 200 | 950 | **22** |
| | 0 | 200 | 800 | 200 | 950 | **21** |
| | 0 | 200 | 825 | 200 | 950 | **22** |
| | 0 | 100 | 875 | 200 | 875 | **20** |
| | 0 | 200 | 875 | 500 | 875 | **21** |
| | 0 | 400 | 875 | 200 | 875 | **21** |

**This voltage setup is assumed as baseline in the following slides**

- Better performances achieved with just 2 active MCPs
  - Lower transit time and hence spread
- No advantage from configurations with different voltages for each MCP or GAP in the stack

# Spatial distribution of events

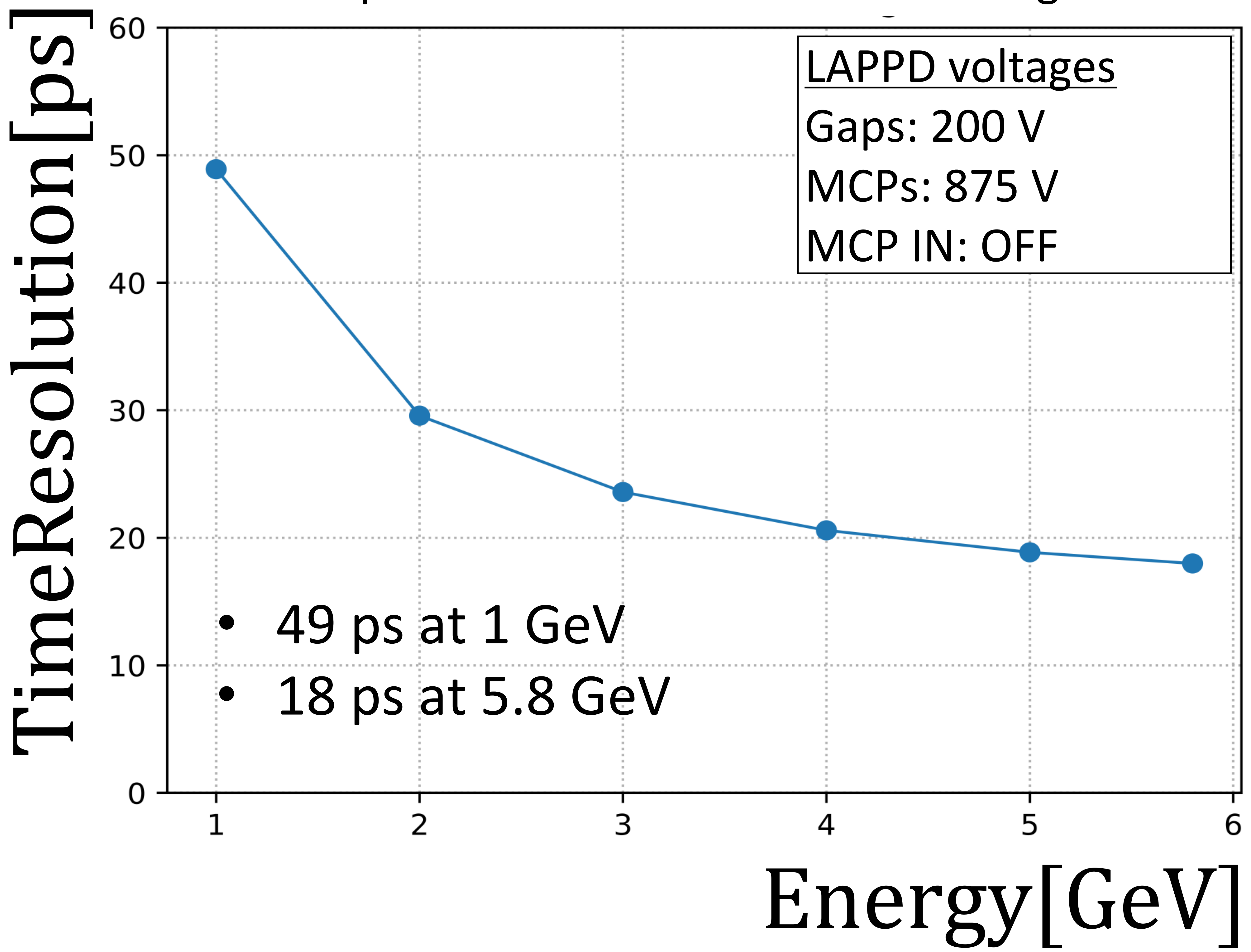
- Fiducial region defined as a rectangle with vertices at pixel centres
- Beam position scanned to cover the entire region
- Due to beam conditions, impossible to have events uniformly distributed, but decent coverage was achieved

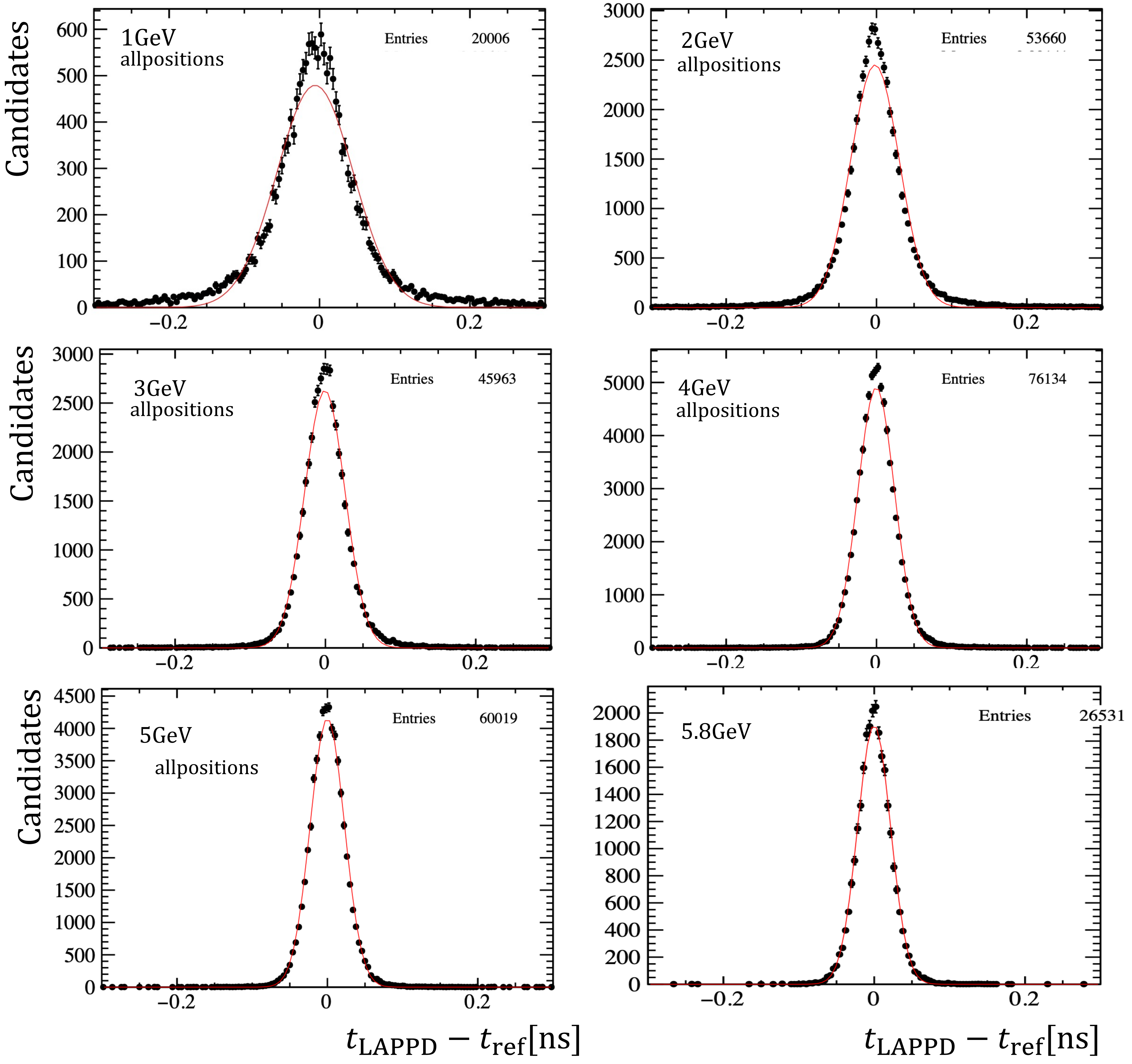


# Time measurement from LAPPD

- Gaussian-like distributions, improving from 1 to 5.8 GeV

Time Resolution combining information from the four pixels with the Random Forest Regressor

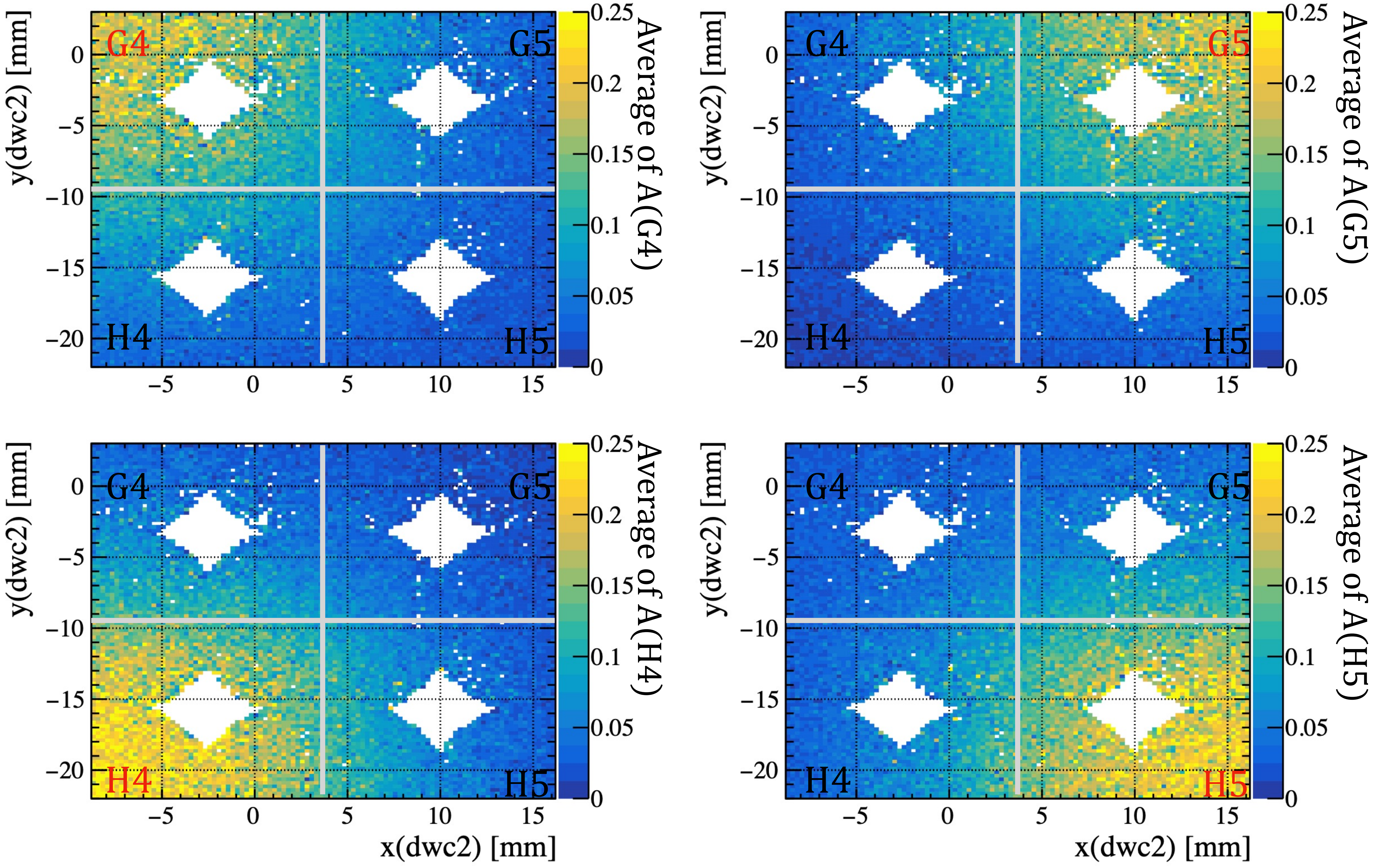



Time resolution of reference MCPs already subtracted in this plot

# Position from LAPPD

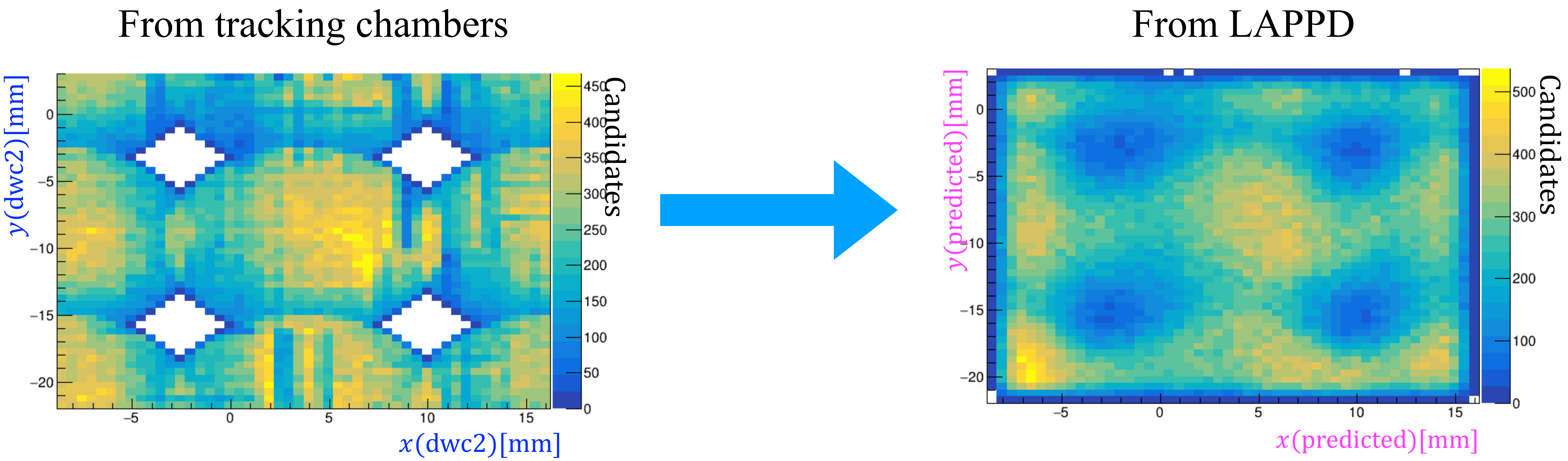
Average amplitudes of the LAPPD signal channels @ 5 GeV
depending on the position measured by tracking chambers




**The signal amplitude encodes information about the position of the impinging electron**

- Also hit position estimated combining the information from the four pixels
- A dedicated RF regressor was trained
  - Targets: x and y from tracking chambers
  - Inputs: signal amplitudes from the 4 pixels
  - Outputs: x and y predictions

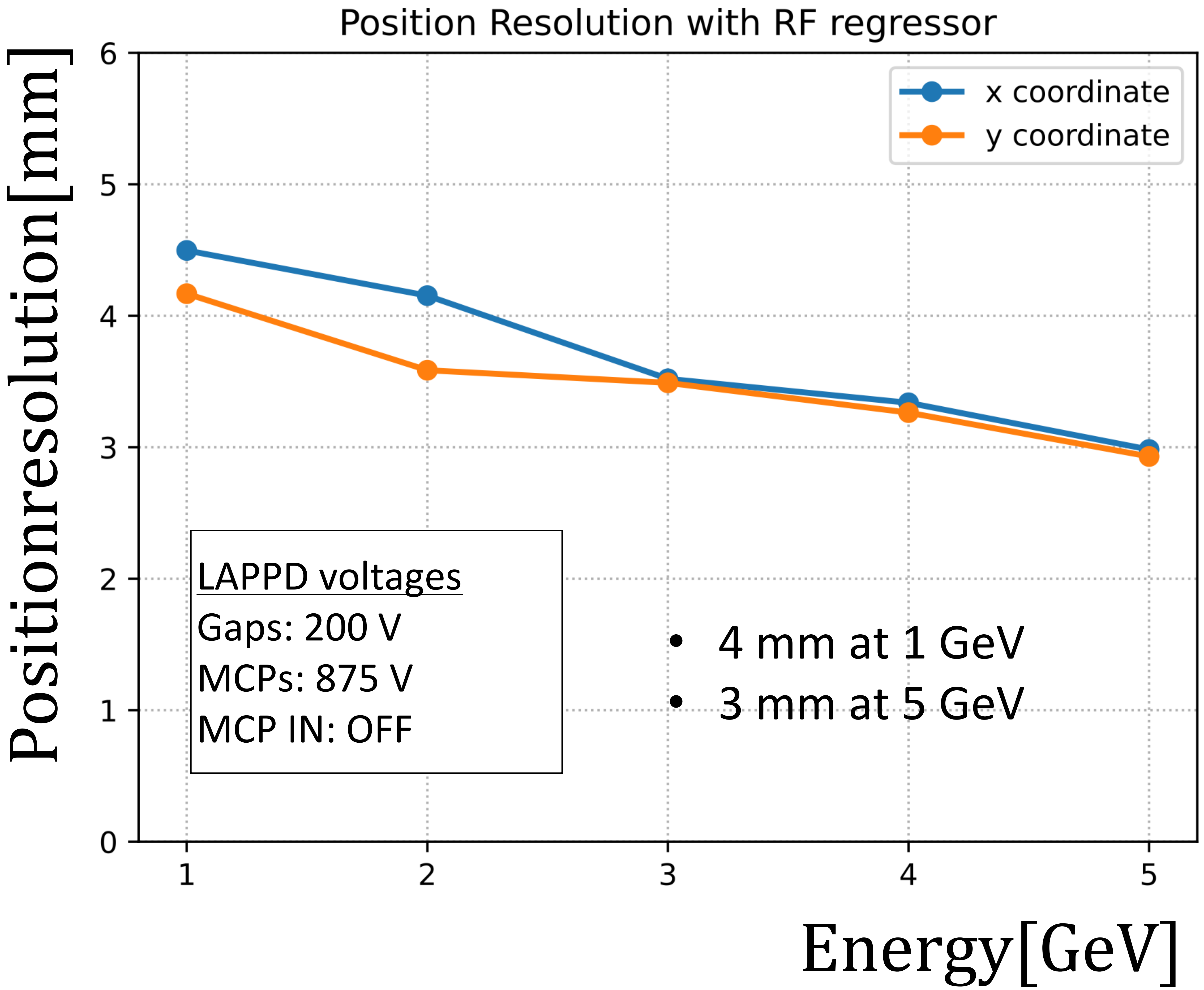
# Position from LAPPD

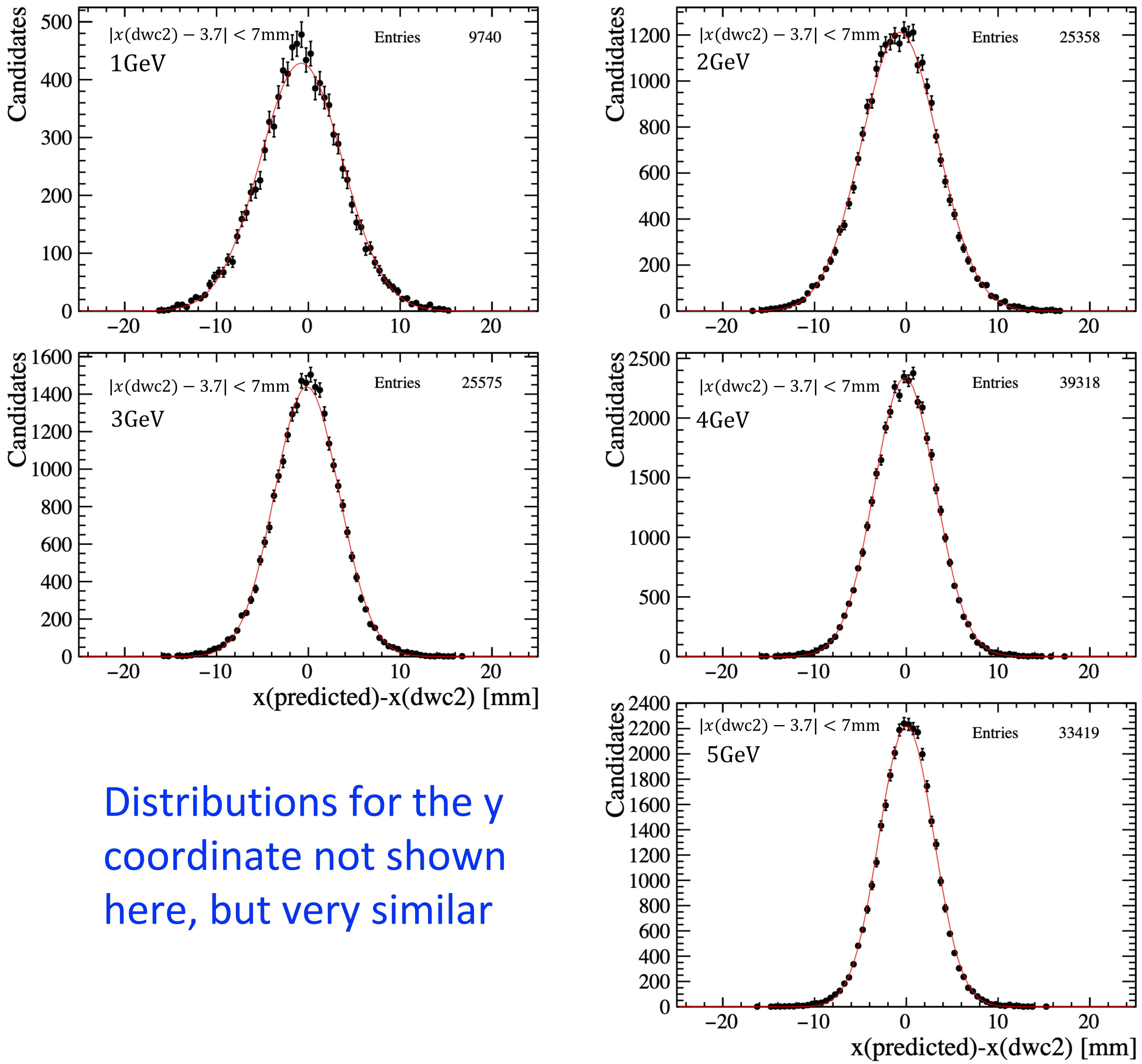



- Much blurred, but remember that LAPPD pixels are 2.5 cm wide

# Position from LAPPD

- Good Gaussianity is observed for each electron energy



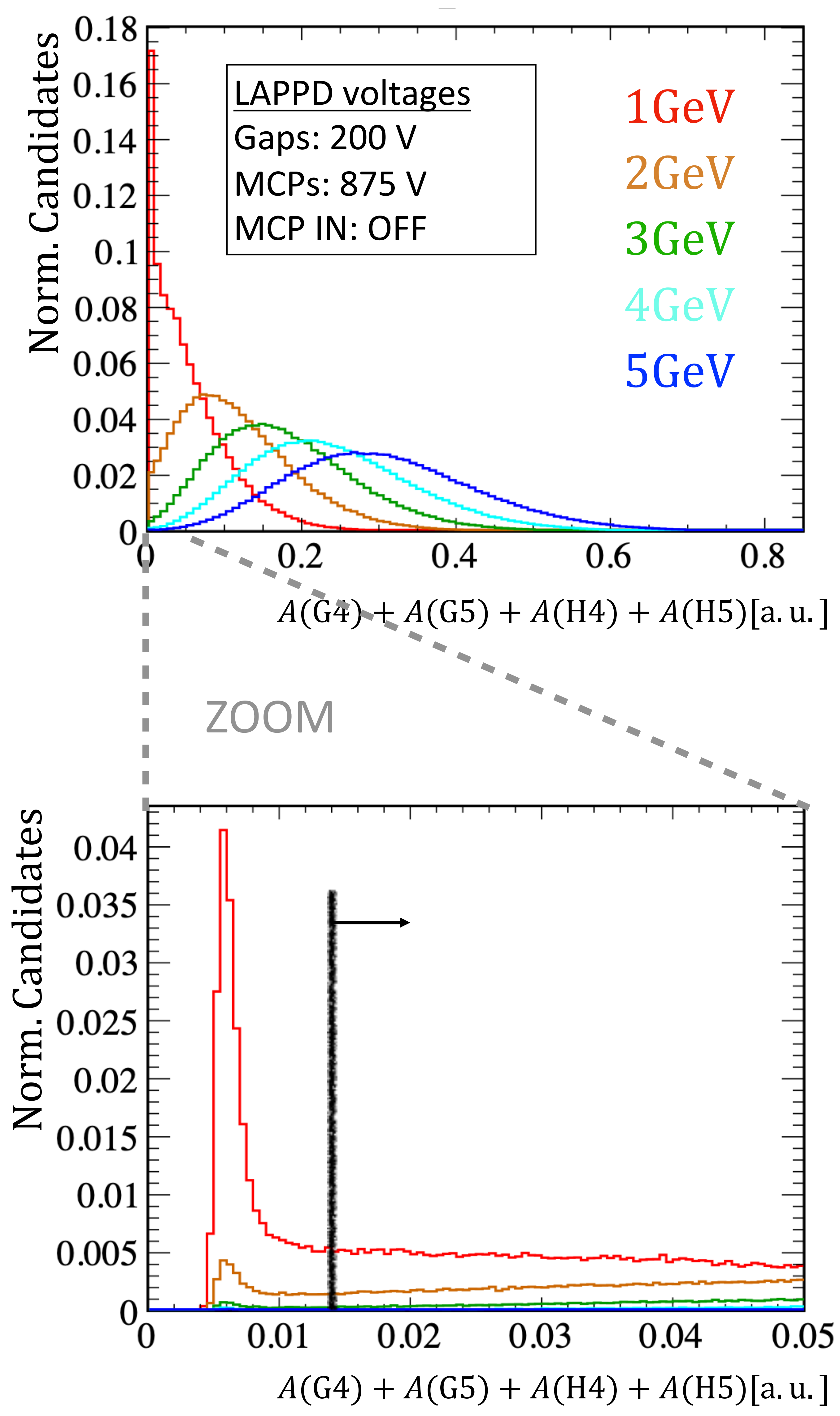

Distributions for the y coordinate not shown here, but very similar

# Detection efficiency

- Study the cases where no actual LAPPD signal is produced
  - Due to EM shower fluctuations and/or LAPPD intrinsic inefficiency

- Consider as empty events those gathering at minimum values in the distribution of the sum of the 4 pixel amplitudes

- Selection cut for non-empty events
  $A(\mathrm{G4}) + A(\mathrm{G5}) + A(\mathrm{H4}) + A(\mathrm{H5}) > 14$ mV



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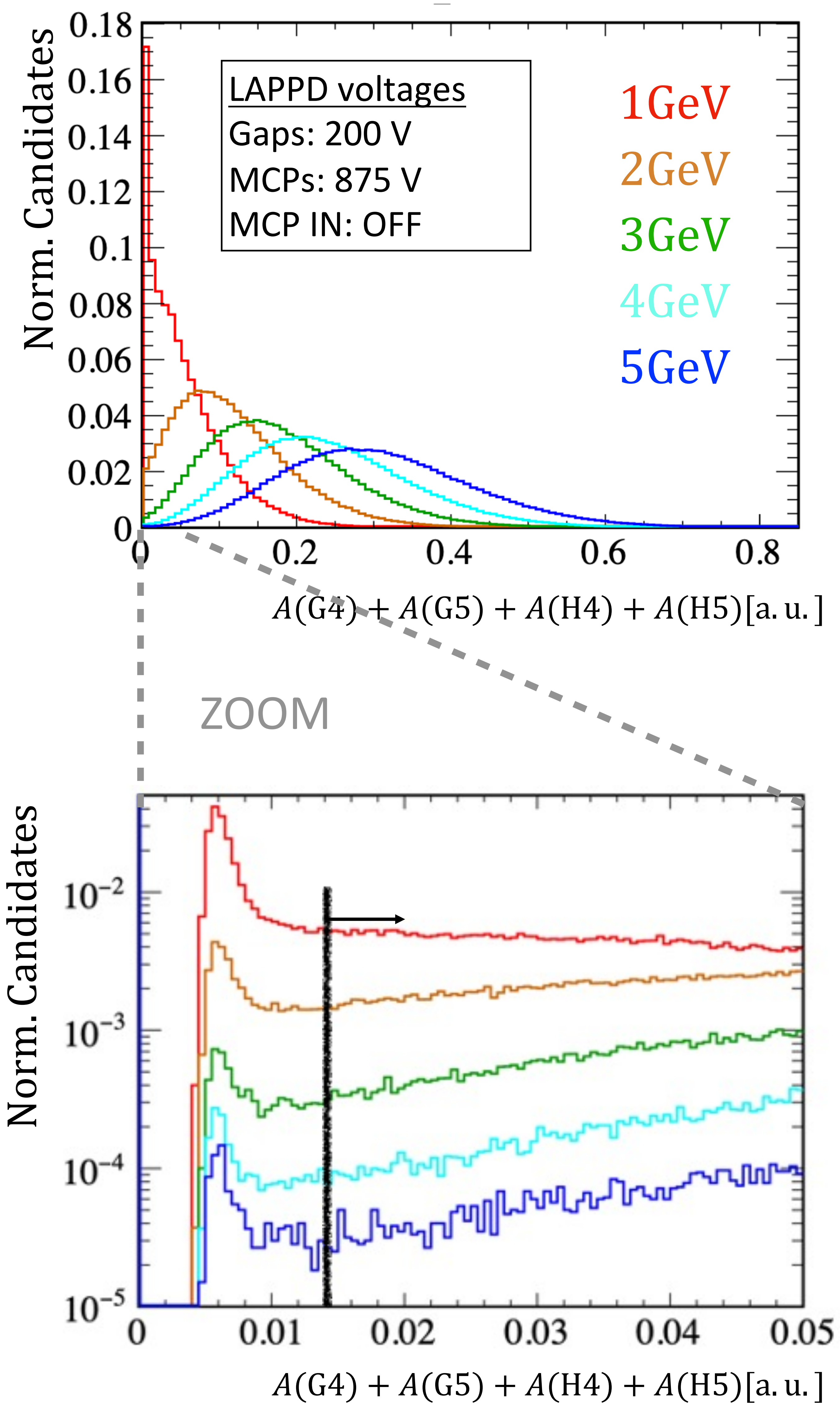
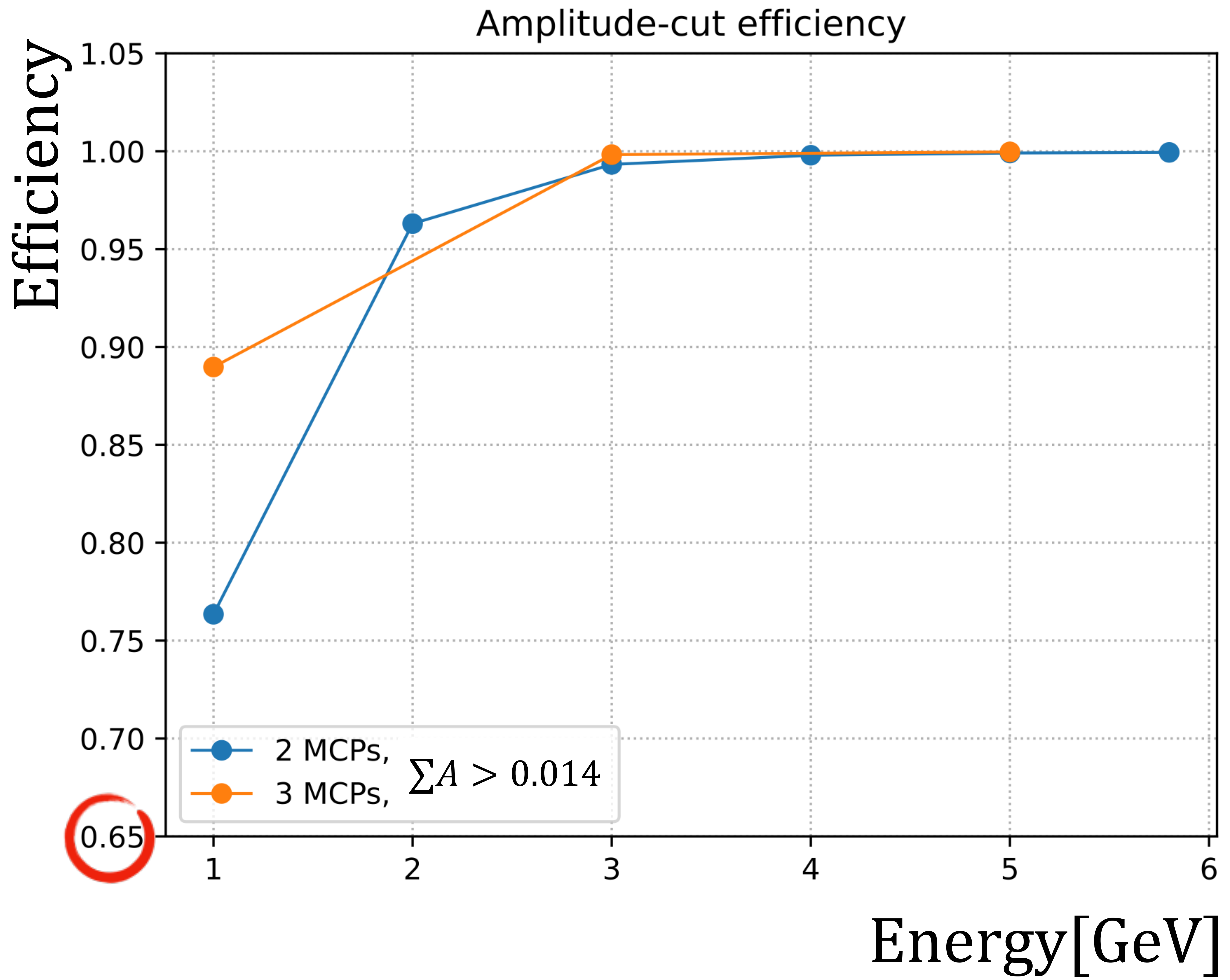


# Detection efficiency




## 2 MCPs:

- MCP IN: OFF
- Gaps: 200 V
- MCP MID. and OUT: 875 V

- Remarkable efficiency drop at 1 GeV: $\varepsilon = 76\%$
- Inefficiency almost entirely recovered at 3 GeV: $\varepsilon = 99\%$

## 3 MCPs:

- All MCPs: 750 V
- Gaps: 200 V

- Inefficiency mitigated at 1 GeV: $\varepsilon = 89\%$

- 3 MCPs are more efficient at lower energies, as expected (more material for initial electron ionization inside the MCPs)
- 3 MCPs may also be beneficial for high-rate operation, but still to be understood

# Conclusions

- LAPPD (z-stack, operated photocathode-less, custom made) data collected at DESY beam test (December 2022) with electrons from 1 to 5.8 GeV
- LAPPD placed at about the shower maximum within a calorimeter module
- Machine learning approach to combine information of multiple LAPPD pixels
- Slightly better time resolution achieved with 2 active MCPs instead of 3 MCPs, in the range 18 ps (5.8 GeV electrons) and 50 ps (1 GeV electrons)
- Although the pixel size was considerably large (2.5 cm pitch), a good position resolution within 3.0 and 4.5 mm was achieved by combining the information of four pixels
- Drop in detection efficiency at 1-2 GeV with 2 MCPs, better with 3 MCPs
- Improvements for both time and position resolutions can be expected with slightly reduced pixel size (e.g., ~1 cm pitch)
- Upcoming beam test: CERN SPS in June 2023 with electrons from 20 to 100+ GeV, where with higher energies we expect even better performances than DESY
- Many thanks to the Incom R&D team for their support!!!