CERN Summer Student Programme 2022

# SPACAL
# Test Beam Data Analysis

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Meyrin, Switzerland, October, 2022

**Abstract**

This report paper will focus on the timing performance of Spaghetti calorimeter (SPACAL) prototypes developed by the LHCb ECAL upgrade 2 group. The analysis will be based on the data collected during a test beam in June 2022 carried out at the SPS in CERN. In the first chapter, I will explain the motivation for the ongoing R&D and present the current working prototypes. Afterward, I will show the key results of the multiple studies I did, starting with the time resolution versus beam energy plots. Later I will highlight the results of the signal shape study where I studied the differences in average signal shape between prototypes, readout configurations, and PMT models. Lastly, in the two cell study, I will show that the SPACAL prototypes can have a good timing performance even in the non-ideal beam positioning.

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# 1 Introduction

This summer I got the chance to join the research and development group working on the future upgrade of the electromagnetic calorimeter at the Large Hadron Collider beauty (LHCb) detector. The experiment is dedicated to heavy flavor physics. The primary goal is to look for indirect evidence of new physics in CP violation and rare decays of beauty and charm hadrons.

## 1.1 Electromagnetic calorimeter at LHCb

The electromagnetic calorimeter (ECAL) at LHCb is a subdetector used mainly to stop and measure the energy of gamma photons and charged leptons such as electrons. In addition, it can identify uncharged particles such as gamma photons and neutral pions, which are invisible to other subdetectors. Regions of the ECAL with good spatial resolution can also provide additional tracking information. Therefore, the electromagnetic calorimeter is an essential subsystem of the LHCb detector system.

## 1.2 Spaghetti calorimeter prototype

During the High-Luminosity phase of the LHC, the LHCb ECAL will face a considerable increase in particle density, especially at lower angles close to the beam-pipe [1]. There, the current Shaslik modules will have to be replaced with a completely new design, implementing radiation hard materials to sustain doses up to 1 MGy, a granularity as low as 15 mm, and precise timing information of a few tens of ps, while keeping the energy resolution at the current level of 10% sampling term and 1% constant term [2].

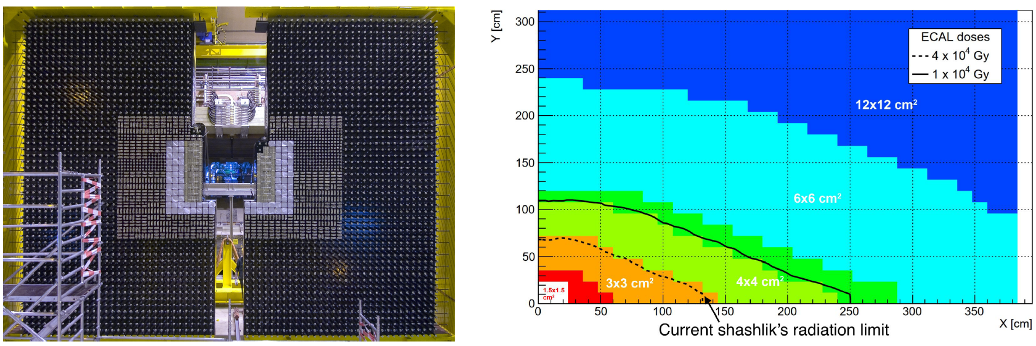


Figure 1: The front view of the LHCb ECAL (left) and the projected dose in one quadrant of the ECAL with the current radiation limit marked (right).

A proposed solution is the spaghetti calorimeter (SPACAL). It is a sampling calorimeter type wherein scintillating fibres are inserted into a dense absorber such as tungsten (W) or lead (Pb). The scintillating fibres convert a portion of the deposited energy into light and transport it to the photodetectors, avoiding wavelength shifters that entail a reduction in light collection efficiency, which worsens even further with accumulated radiation dose.

### 1.2.1 Prototype lineup

The LHCb ECAL upgrade 2 group is currently testing different configurations of SPACAL prototypes, changing the absorber material, the type of scintillator fibres and their providers, the readout configurations, and using different models of photomultiplier tubes (PMTs) as the photodetectors. During my stay, I analyzed the data collected with the following prototypes:

- WPoly: tungsten absorber and continuous polystyrene fibres

- PbPoly: lead absorber and two sections of polystyrene fibres

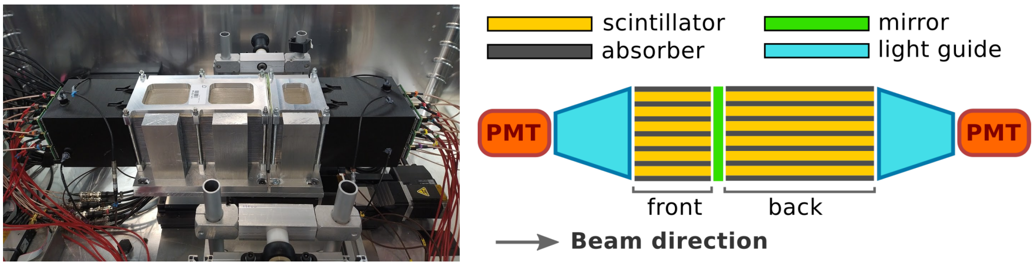


Figure 2: The side view of the PbPoly prototype (left) and the schematics of the SPACAL with a front and back section seperated by a mirror (right).

Aditionally, the WPoly prototype is tested in two readout configurations:

- single sided readout (single, SSR)

- double sided readout (double, DSR)

The single sided readout has one PMT positioned in the back and a mirror placed in the front from which the scintillation light will bounce back to the PMT. A light guide is typically used to collect the photons from a larger incident area and guide them to the smaller active area of the photodetector. The double sided readout has a PMT in the back and a PMT in the front, so the signal can be read from both sides. It has been shown with Monte Carlo simulations that the DSR brings improvements over the SSR when the information from the back is combined with the information from the front.

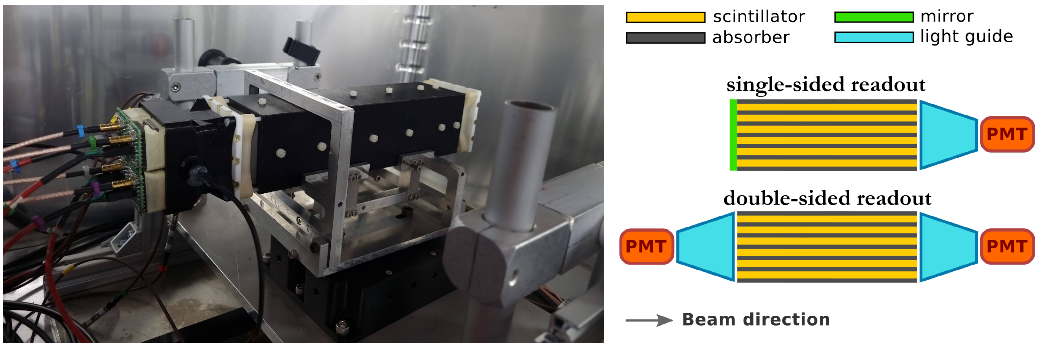


Figure 3: The side view of the WPoly prototype (left) and the schematics of the SPACAL with either a single sided or a double sided readout (right).

Lastly, two different PMT models are being evaluated as the photodetector:

- Hamamatsu R11187 (square PMT)
- Hamamatsu R14755U-100 (round PMT)

For the sake of simplicity I will refer to them based on their shape, so when presenting results, Hamamatsu R11187 will take the name "square PMT" and Hamamatsu R14755U-100 will be known as the "round PMT".

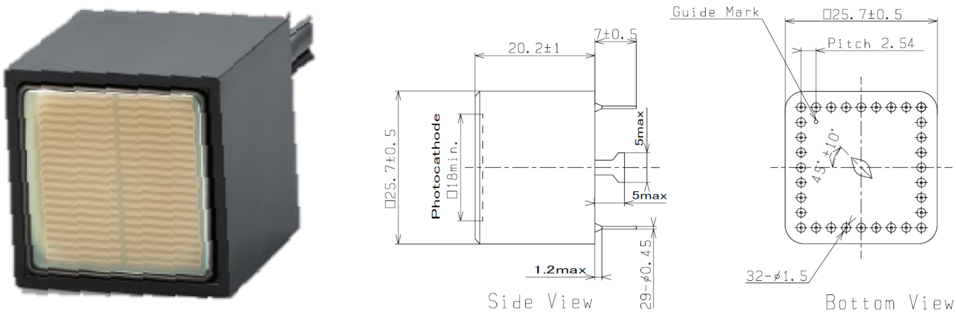


Figure 4: An image of R11187 (left) and the mechanical details (right).

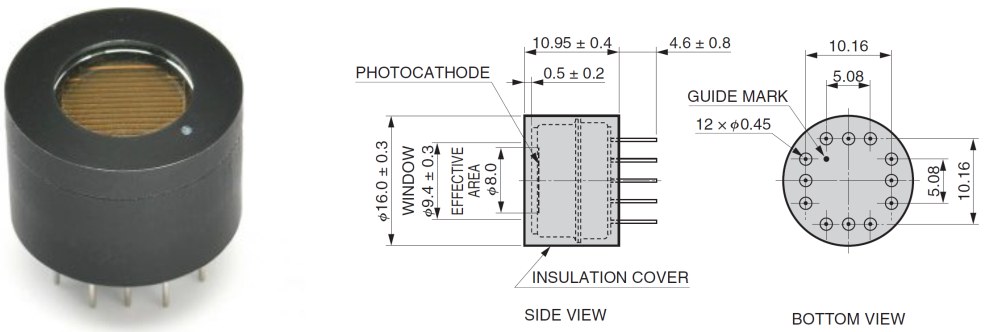


Figure 5: An image of R14755U-100 (left) and the mechanical details (right).

### 1.2.2 Test beam setup

To test and evaluate the physics performance of the prototypes, the LHCb ECAL upgrade 2 group, which I joined over the summer, collects physics data through test beam campaigns both at SPS in CERN and DESY in Hamburg.

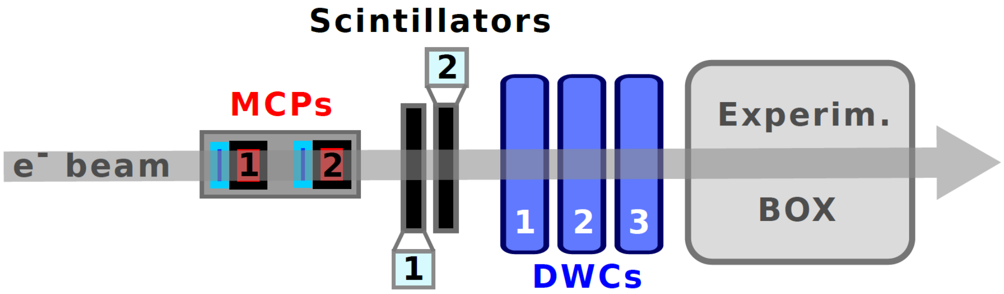


Figure 6: The layout of the current test beam setup. The electron beam moves from left to right, two MCPs provide the time reference, two scintillating pads the trigger signal, and three DWCs the tracking information. The experimental box contains the prototype and the rotating steppers.

# 2 Results

In my analysis, I focused on the timing performance of mentioned SPACAL prototypes but also concerning the impact of different parameters, physical quantities, and readout configurations on the prototype's performance. The standard and widely accepted way of measuring the time resolution of a given device is to calculate the time difference between two timestamps, where one is provided by a reference device and the other by the device under test. A histogram is obtained, on which we can fit a Gaussian function and then present the time resolution as the sigma value of the fit.

## 2.1 Time resolution versus beam energy

The ECAL has to perform well over a broader energy interval. The purpose of this study was to explore parameters such as constant fraction discrimination (CFD) threshold, how the optimal values change with the beam energy, and the impact on the time resolution. The final results are presented with the reference contribution subtracted as the following equation describes:

$$\sigma_T = \sqrt{\left(\sigma_T'\right)^2 - \left(\frac{\sigma_{ref}}{2}\right)^2} \tag{1}$$

In equation (1), $\sigma_T$ is the time resolution after and $\sigma_T^{'}$ the time resolution before the reference contribution $\sigma_{ref}/2$ is subtracted. In the current test beam setup two microchanell plate photomultipliers (MCP-PMTs) are used to provide the time reference and therefore the uncertainty of the reference timestamp is just one half of the timing uncertainty $\sigma_{ref}$ of a single MCP.

### 2.1.1 WPoly - optimal CFD threshold

When using a fixed threshold to generate the timestamp of the signal, a time-walk effect is observed, meaning that the timestamp will move to lower values as the peak amplitude increases. This can be corrected, but there is a more elegant solution which is the constant fraction discriminator method, where the threshold is not fixed but instead defined as a fraction of the peak amplitude. For example, setting CFD = 0.5 means the timestamp is generated when the signal reaches half of its peak amplitude. The digitizer used in the data acquisition (DAQ) system has a limited sampling rate of 5GS/s, meaning a signal is represented with points no less than 200 ps apart. To get a more precise timestamp a line is interpolated around the time point that crosses the CFD threshold, and a new timestamp is generated at the time point at which the interpolated line intersects the CFD threshold.

**WPoly with single sided readout and square PMT**

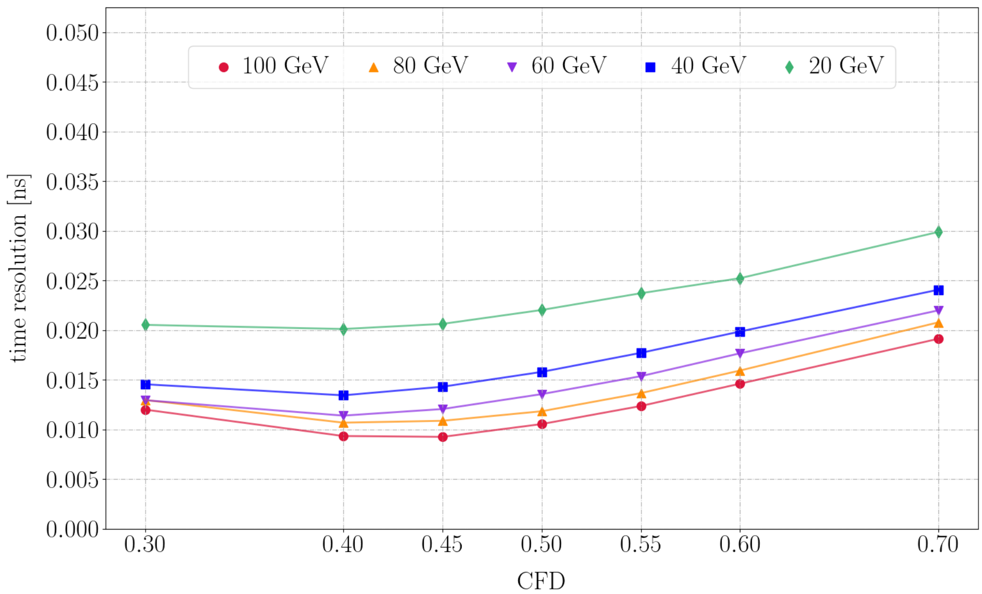


Figure 7: Time resolution vs CFD threshold in the single sided readout. Signal for the timing analysis is read from the back with the square PMT.

**WPoly with single sided readout and round PMT**

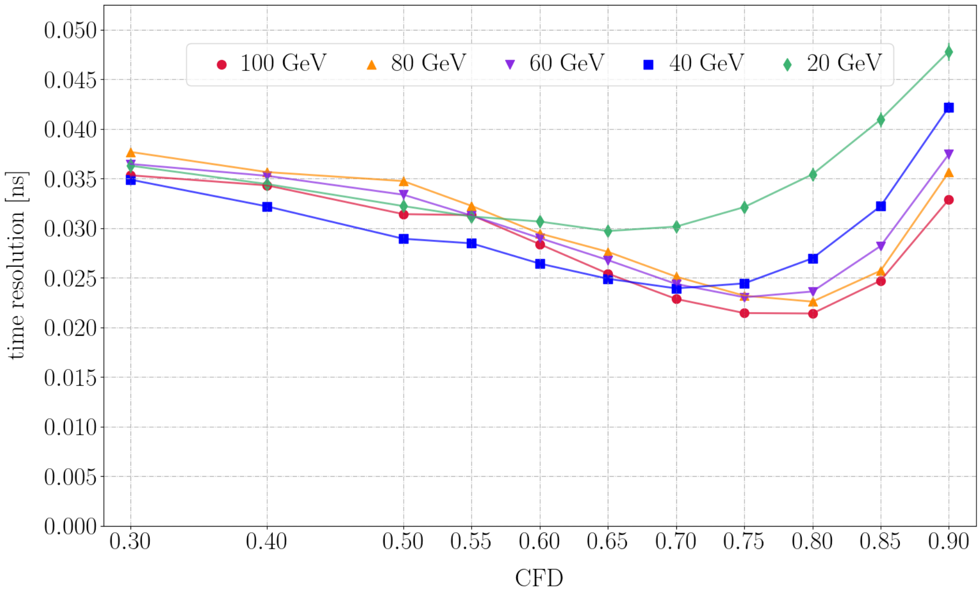


Figure 8: Time resolution vs CFD threshold in the single sided readout. Signal for the timing analysis is read from the back with the round PMT.

**WPoly with double sided readout and round PMT**

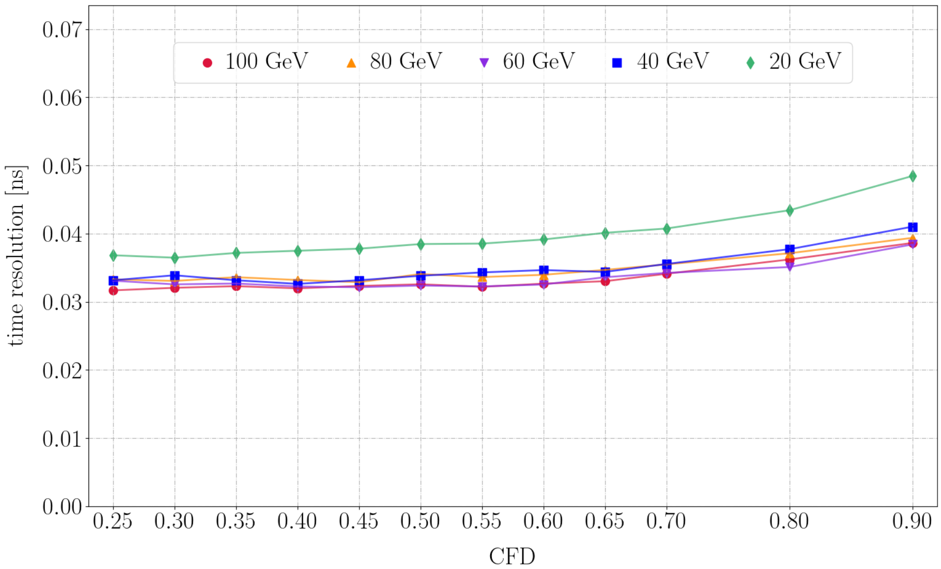


Figure 9: Time resolution vs CFD threshold in the double sided readout. Signal for the timing analysis is read from the back with the round PMT.

**Discussion - square PMT vs round PMT**
The optimal CFD threshold is different for the two PMT models, and it has a lesser impact on the timing performance in the case of the square PMT. Additionally, with the round PMT in the single sided readout, we observe an energy dependence of the optimal CFD threshold. The round PMT has a narrower and faster single photon response and therefore a higher threshold is needed to wait for the light reflected by the mirror. The following is just a possible explanation which has to be yet confirmed with simulation studies.

**Discussion - single sided vs double sided readout**
In single sided readout we only have the information provided by the PMT at the back. The reason why we are treating it separately from the double sided readout is because of the mirror placed at the front. It has an impact on the light transports inside the prototype, and therefore the optimal CFD threshold is not necessarily the same for both readout configurations.

### 2.1.2 WPoly - time resolution versus beam energy

With the optimal CFD threshold known for each prototype configuration, we can now have a look at the time resolution versus beam energy plots.

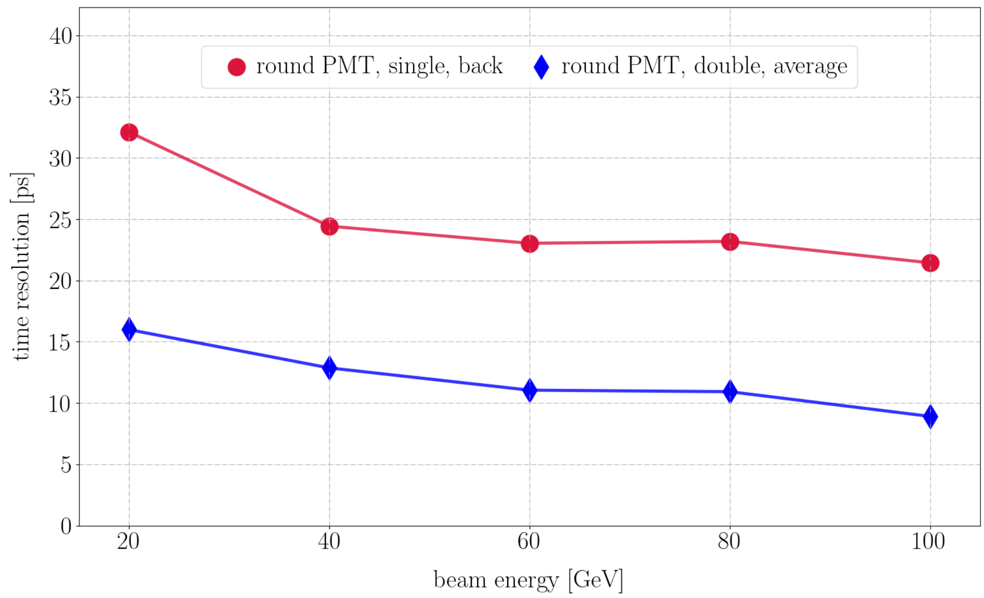


Figure 10: Time resolution vs beam energy compared between the single sided readout (red circles) and the double sided readout (blue diamonds).

As expected, the timing performance improves with increasing beam energy. A more interesting comparison, however, is between the two readout configurations. In the single sided readout we only have one signal produced by the PMT at the back. In double sided readout we have two signals, both from the back and the front, which we can combine, and we can prove that this leads to better timing performance, as shown in figure 10. The averaging of the signals is based on weighting each of the signals with their time resolution. One step further is calculating and using the full covariance matrix to assign appropriate weights to each signal component. If not otherwise specified, this approach is assumed when presenting the "average" signal results.

**Single-side timing performance in the double sided readout**
In my study of the double sided readout, I evaluated the timing performance also separately for the back and the front. In principle, in the double sided readout you always want to combine the timing information from the back and the front because otherwise, you do not use the all information. However, checking the performance of a single side is important in the R&D stage, and it might be useful for reconstruction, e.g. separating overlapping clusters.

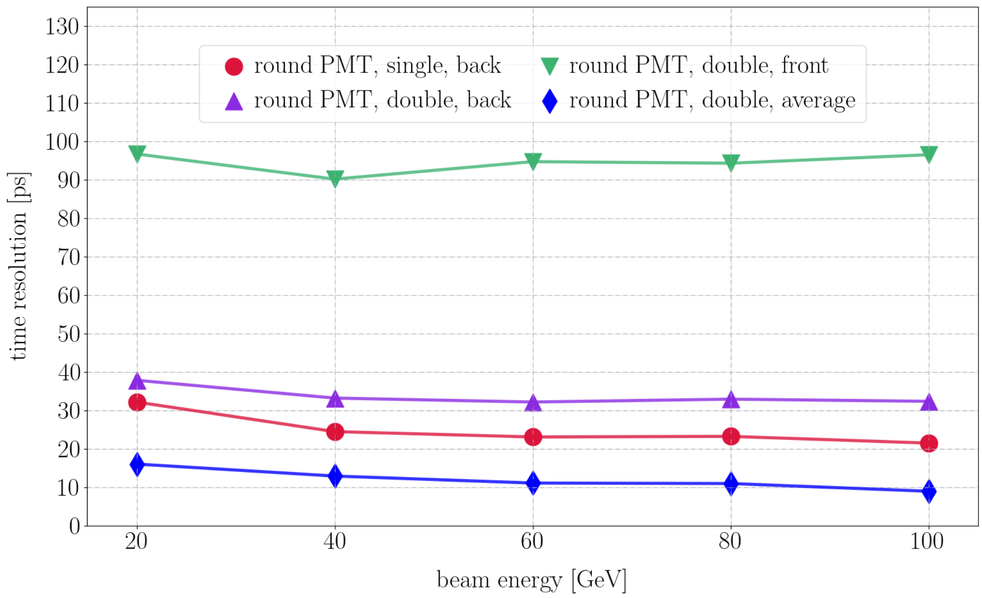


Figure 11: A comparison of the timing performance with respect to the beam energy for different readout configurations of the WPoly prototype.

**WPoly with single sided readout and square PMT**
I will not directly compare the performance between the two PMT models

because, at the time of the test beam, the WPoly prototype was not equipped with the optimal light guides that would match the active area of the round PMT. Therefore, approximately half of the signal was lost.

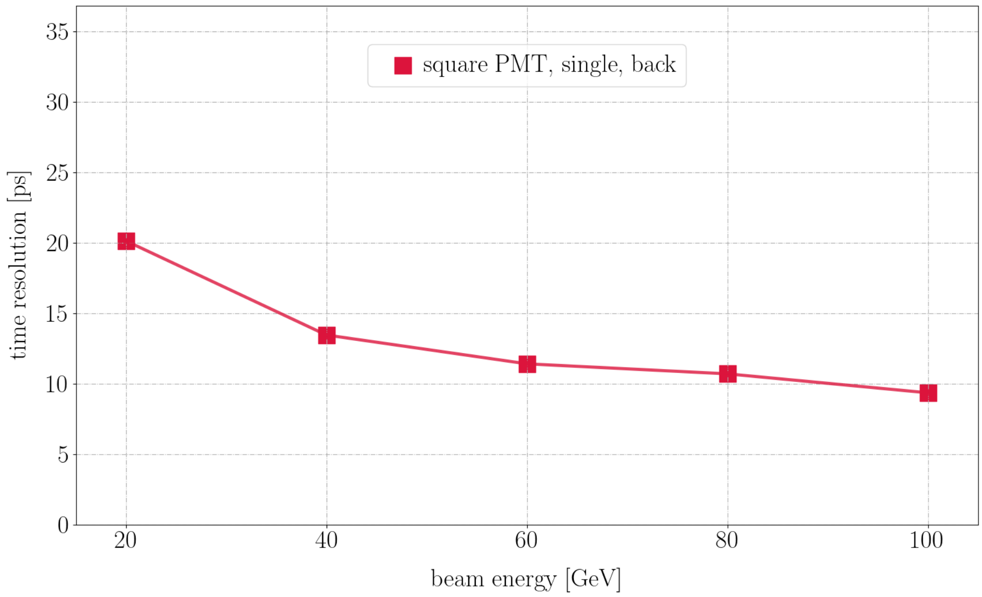


Figure 12: Time resolution vs beam energy with the square PMT.

### 2.1.3 PbPoly - time resoltion versus beam energy

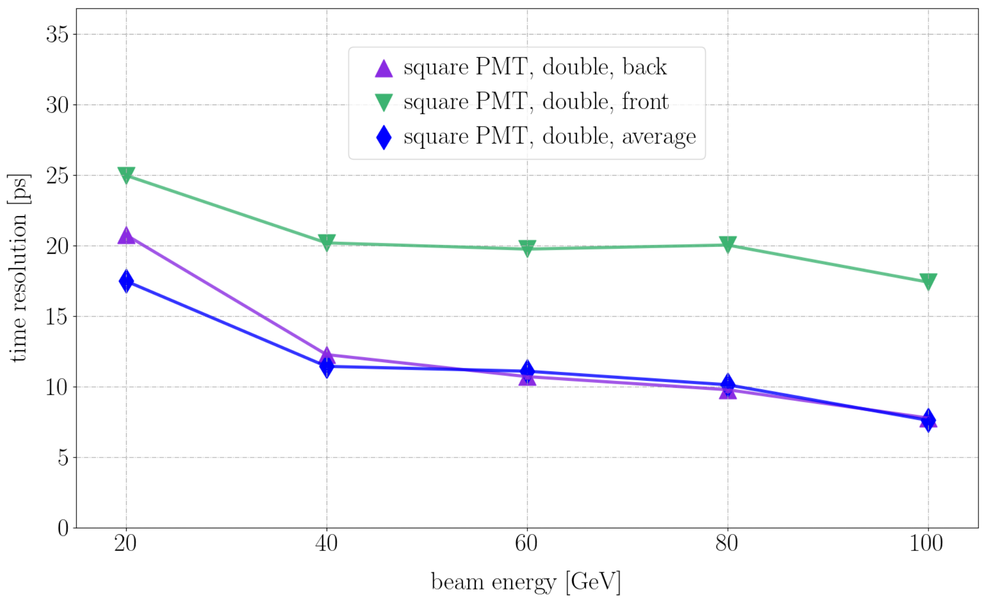

Figure 13: Time resolution vs beam energy for the PbPoly prototype.

This chapter presents the time resolution dependence on the beam energy for the PbPoly prototype. As a reminder, the PbPoly prototype uses split fibres. It has a front section and a back section which are separated by a mirror. The prototype is paired with the square PMTs in a double sided readout. Here for the average, the time resolution weighted average was used.

## 2.2 Signal shape study

To understand better the difference in the timing performance between the square and the round PMT, it is interesting to study their signal shapes. The digitizer used in the test beam setup saves the waveforms whenever the acquisition is triggered. To get the average response of the photodetector, I averaged over many waveforms and obtained an average signal shape. The results of this study are shown for the WPoly prototype at different beam energies, both for the single sided and the double sided readout configuration.

### 2.2.1 Average signal shape

The average signal shape, especially the peak amplitude will depend on the beam energy and the gain of the PMT. Therefore, to compare the average signal of different configurations independently of these two parameters, the average signal is normalized and aligned in time to 1% of peak amplitude. Figure 14 shows the average signals before normalization and alignment.

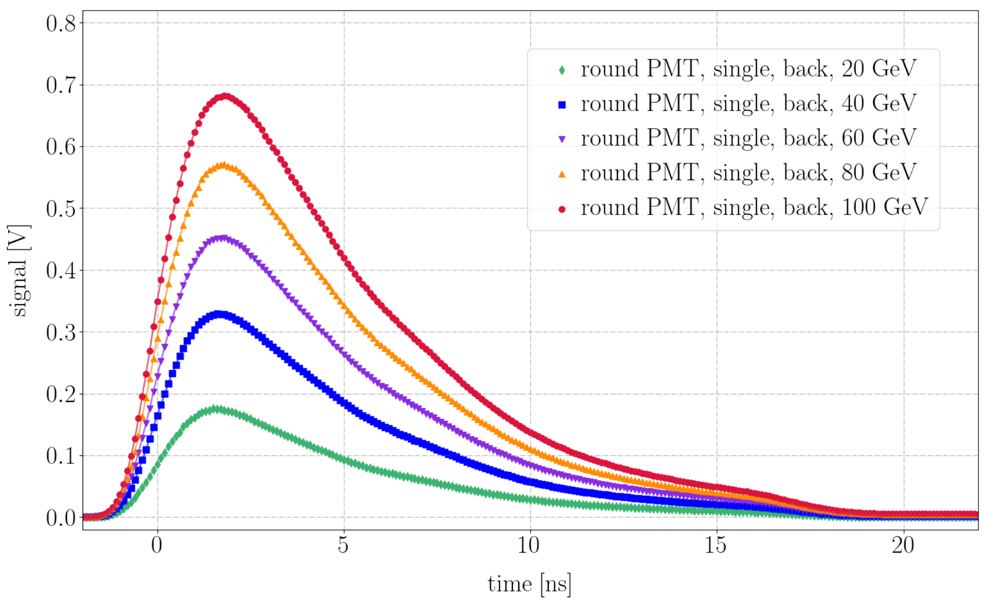

Figure 14: Average signal of the single sided readout with the round PMT.

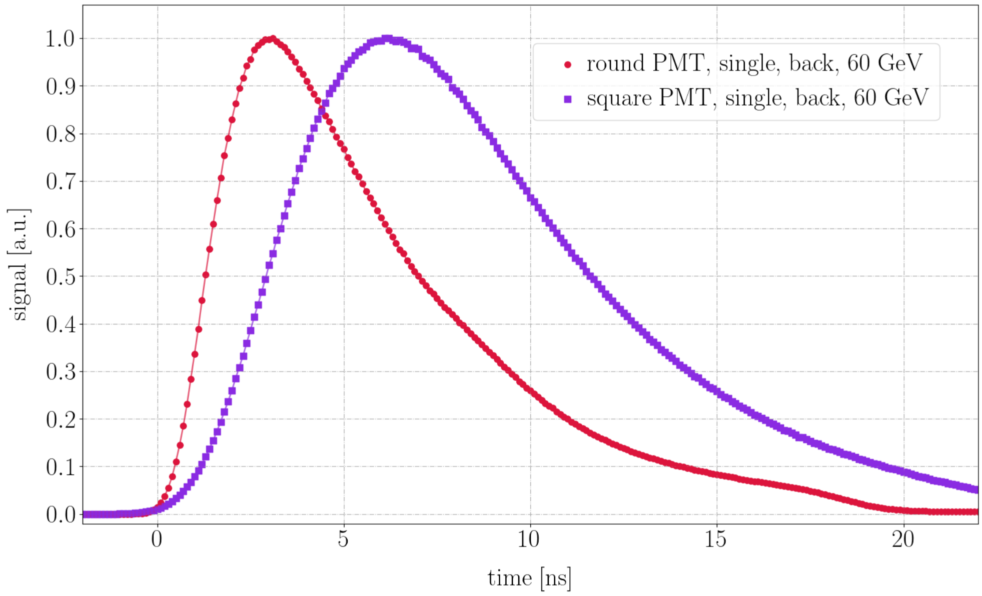


Figure 15: Comparison of the average signal of the round PMT and the square PMT in the single sided readout with the signal read from the back.

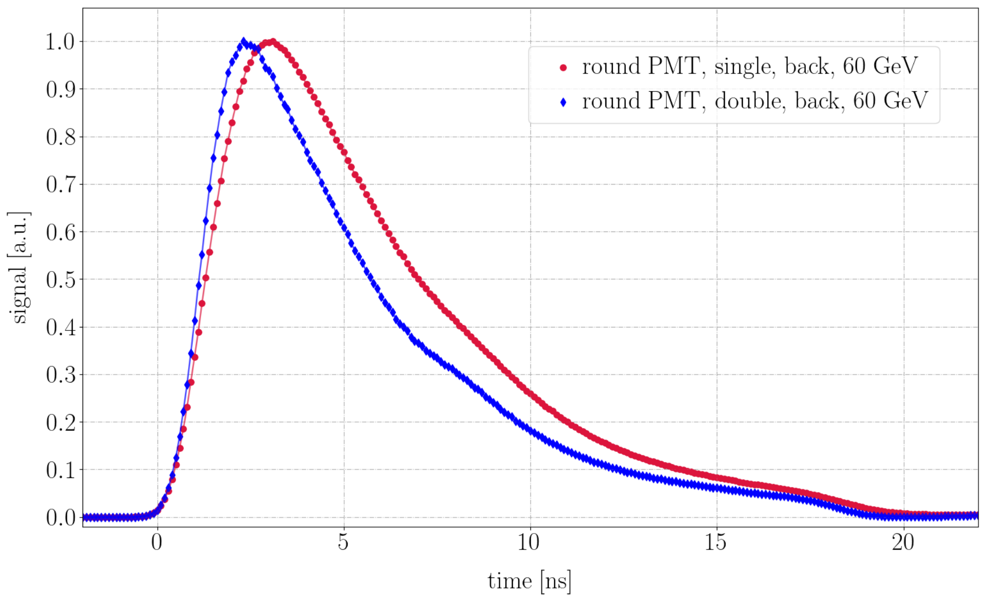


Figure 16: Comparison of the average signal of the single sided and the double sided readout. The signal is read with the round PMT from the back.

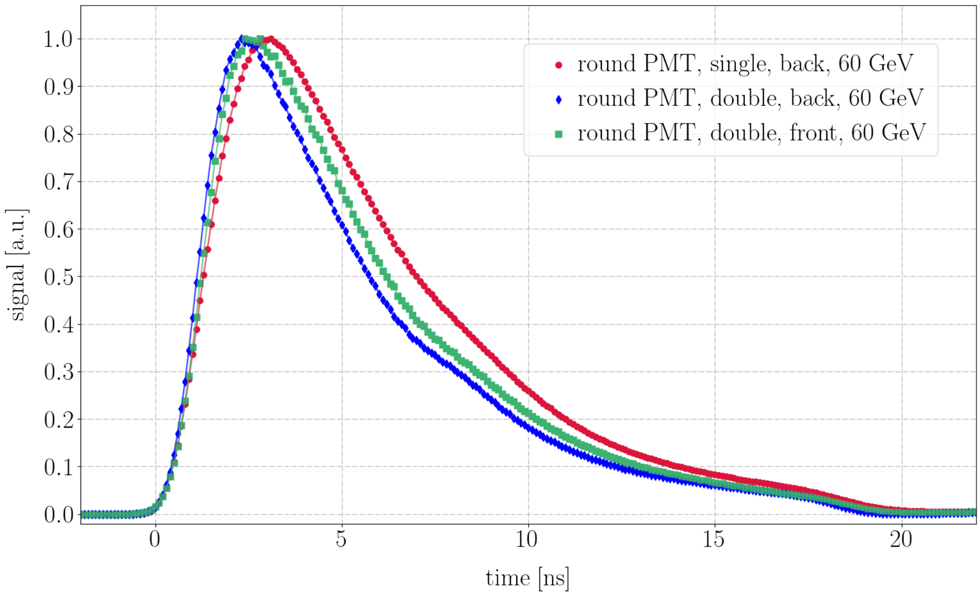


Figure 17: Comparison of the average signal read from the back or the front.

**Discussion**
The average signal from the round PMT has a steeper rising slope and a shorter tail compared to the average signal from the round PMT. The study confirmed what we already expected from the PMT datasheets.
Another observation is the difference in average signal shape between the single sided and the double sided readout, which comes from the light transport inside the crystals. The photons reaching the front in the single sided readout will bounce back from the mirror and will be collected by the PMT at the back. In the double sided readout there is no reflected wave reaching the back because it will be read out by the PMT at the front which has a negligible light reflection and absorbs the majority of the incident photons.
Lastly, the signal from the front is slower in comparison to the one from the back because, at the beam energy of 60 GeV, the shower maximum will be more towards the back. A bigger fraction of photons will be produced closer to the PMT at the back, and the light transport will contribute less.

### 2.2.2 Rise time

The steepness of the rising signal slope can be characterized with rise time, which is the time in which the signal goes from 10% to 90% maximum amplitude. It is interesting to check how rise time changes with beam energy and compare it between the single sided and the double sided readout, the two PMT models, and where the signal is read from the back or the front.

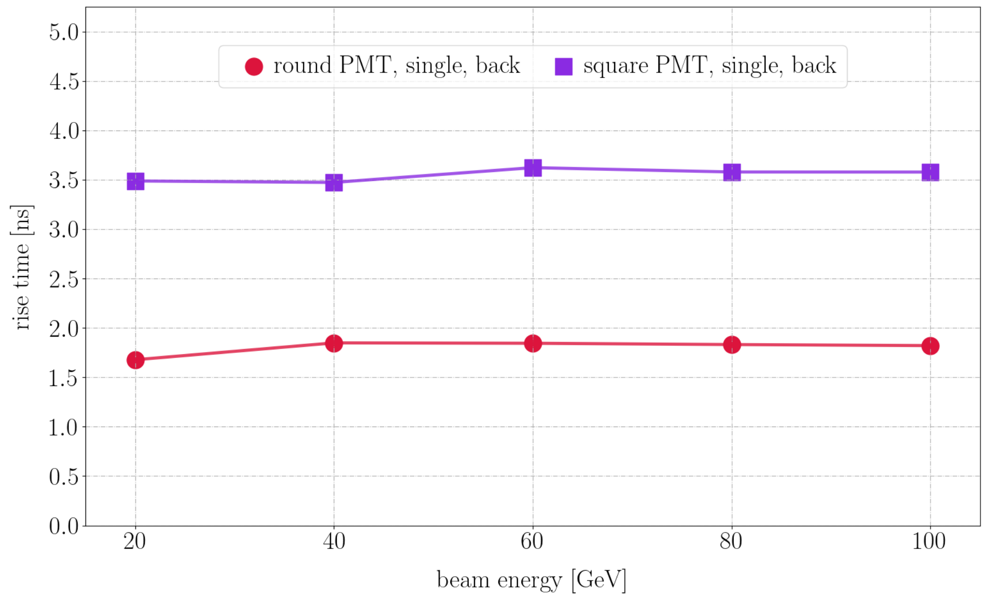


Figure 18: Comparison of the rise time of the single sided and the double sided readout. The signal is read with the round PMT from the back.

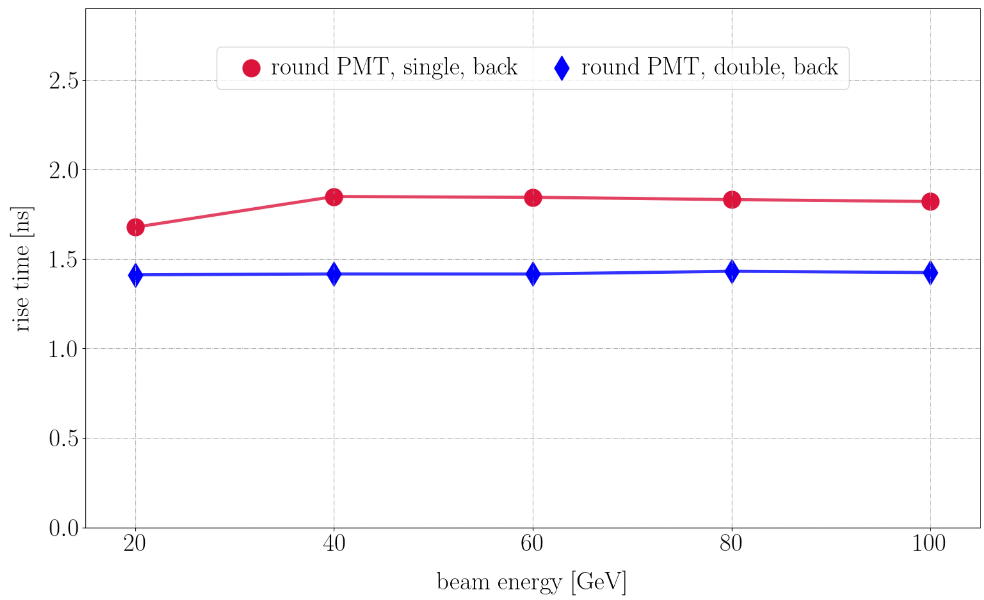


Figure 19: Comparison of the rise time of the single sided and the double sided readout. The signal is read with the round PMT from the back.

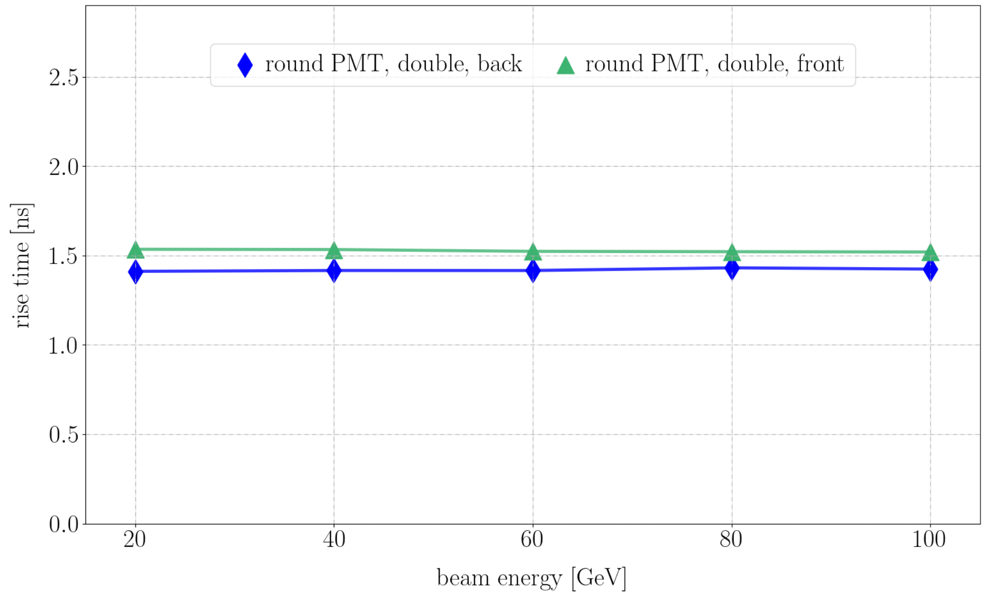


Figure 20: Comparison of the rise time read from the back or the front.

**Discussion**
Rise time is the shortest in the double sided readout using round PMT and with signal read from the back. It is constant with the beam energy. As already seen in chapter 2.2.1, the round PMT has a steeper rising slope than the square PMT, which results in a shorter rise time. Additionally, the signal read from the back is slightly faster than the one read from the front.

## 2.3 Two cell study

It is expected from the prototypes to perform best if the beam is centered on the central cell which is at the center of the module because the energy containment within the cells is better. If we move away from the center, we expect a degradation in timing performance. However, we can recover good timing performance by combining the information from neighboring cells that also see a part of the signal. To study this, the group did a set of measurements during one of the test beam campaigns. The beam was positioned in three ways: in the center of the middle cell, between the middle and the top cell, and in the center of the top cell. For the study, we used the PbPoly prototype, beam energy of 60 GeV, and the signal was read from the back. In the analysis, the appropriate events were grouped based on their position into one of the 9 groups (see figure 21). Each group has a timing histogram from which we could obtain the time resolution.

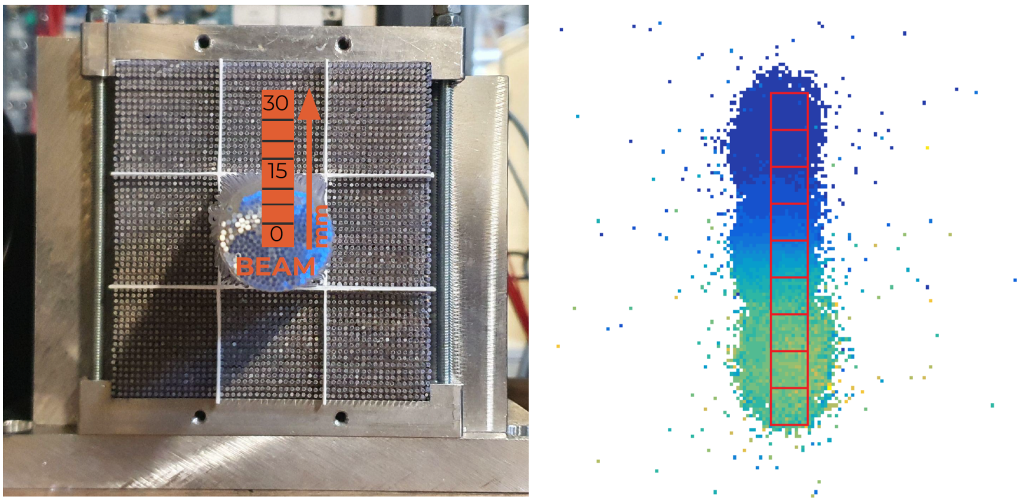


Figure 21: Face view of the PbPoly with beam positions marked (left). The distance between the centers of the middle and the top cell is 30 mm. Position profile of the signal amplitude for the central cell (right).

#### 2.3.1 Time resolution versus beam position

The main interest of the study is how time resolution degrades with beam position and how we can compensate for the loss in performance.

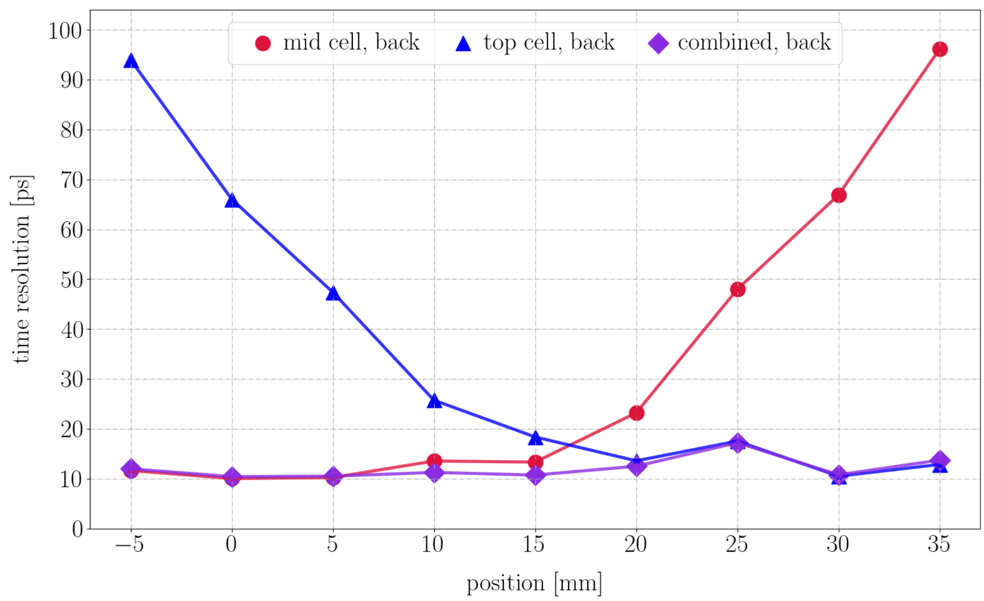


Figure 22: Time resolution vs beam position for signal read from the back.

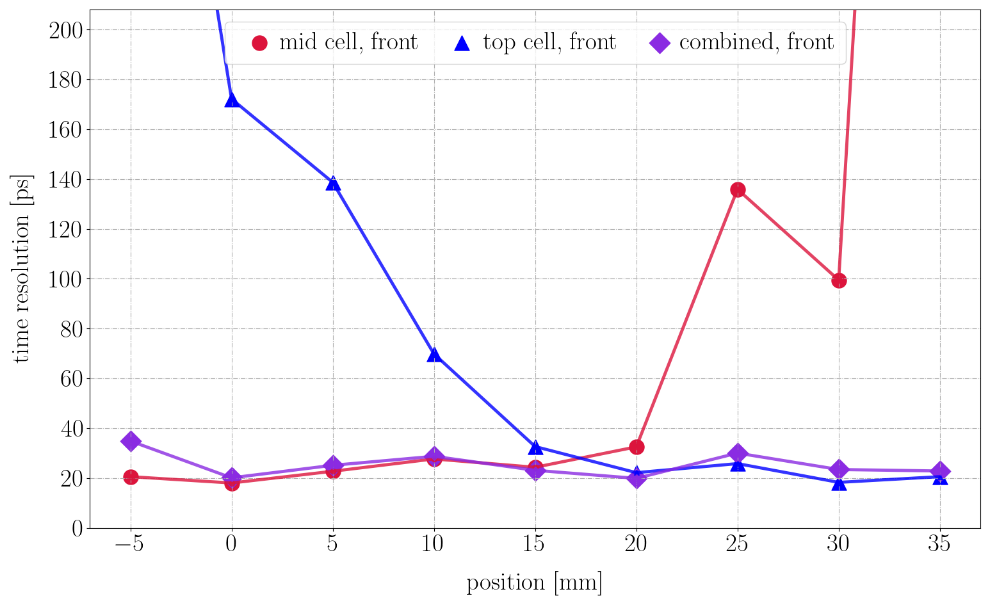


Figure 23: Time resolution vs beam position for signal read from the front.

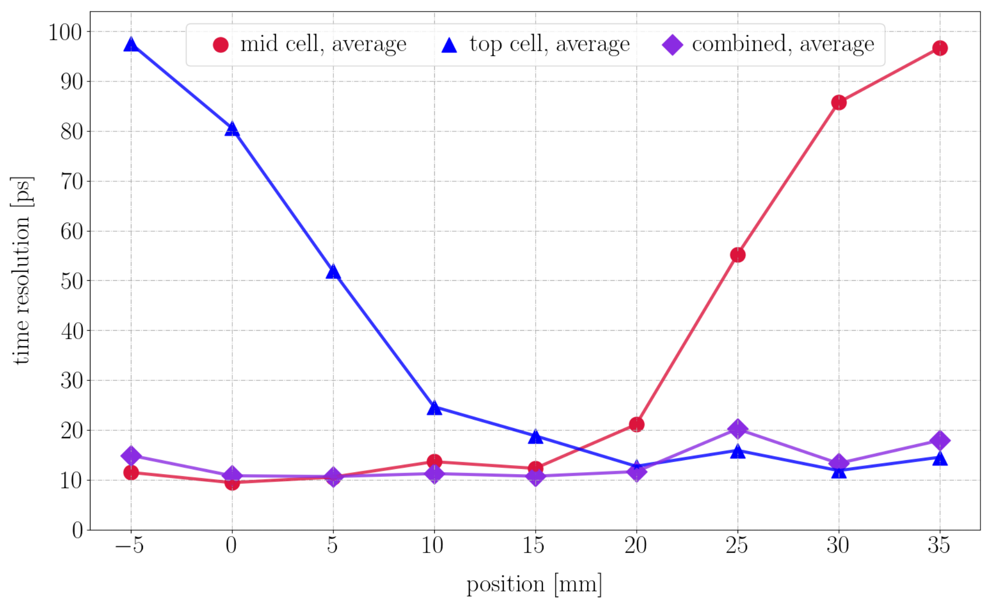


Figure 24: Time resolution vs beam position for the time resolution weighted average of the back and the front signal.

**Conclusions**

The timing performance obtained by combining the timing information from the middle and top cells is relatively constant over the presented beam position interval. This demonstrates that the time resolution weighted average of the middle cell's and the top cell's timestamp is already good enough to get a sub 20 ps time resolution even outside individual cell centers.

# 3 Conclusions

Spaghetti calorimeter prototypes developed by the LHCb ECAL upgrade 2 group outperform the current Shaslik technology in many aspects. The main advantage which makes them a promising solution for the upcoming high luminosity LHC upgrade is their radiation hardness which holds up to 1 MGy. Furthermore, prototypes with the double sided readout can reach around 10 ps time resolution at beam energies above 60 GeV. Having a good timing performance helps to mitigate pileup and leads to better hit position reconstruction. Precise timing information can also be used for background suppression in some of the physics channels, for example $B^0 \rightarrow K^* \gamma$ [1]. The signal shape study proved that the round PMT (Hamamatsu R14755U-100) has a signal with a shorter rise time and tail. If the width of the signal pulse is too large, it can deteriorate performance by spilling over into the following bunch crossing. In this aspect, the round PMT is more suitable. In the two cell study, I showed that a good timing performance can be recovered if the timing information is combined from the middle and the top cell.

# References

[1] LHCB Collaboration, *Framework TDR for the LHCb Upgrade II*, tech. rep., CERN, Geneva, 2021.

[2] Loris Martinazzoli *et al.*, *Performance of a spaghetti calorimeter prototype with tungsten absorber and garnet crystal fibres*, 2022. DOI: 10.48550/ARXIV.2205.02500.