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Signal Processing Techniques for Picosecond-Order Timing with Novel Gaseous Detectors

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ABSTRACT: *The experimental requirements in existing and envisaged accelerators and experiments have stimulated a great interest in R&D for detectors with high precision timing capabilities; thus, novel instrumentation has emerged. During the R&D phase the timing information is usually extracted from the signal using the full waveform, which is collected with fast oscilloscopes. This is fine for the R&D devices which have a small number of channels, but this method becomes impractical when the detector has many channels because it would produce a large amount of data. In practical applications, the detectors much have a data acquisition implemented in dedicated front-end-electronics which should retain enough information about the signal timing characteristics to allow the arrival time of a particle to be measured with a resolution comparable to the R&D devices. In this work we use novel gaseous detectors and we investigate how we can achieve a timing precision in the of order of 10-ths of picosecond with the use of the leading-edge discrimination timing technique. Even though this method introduces a "time-walk", which normally affects greatly the timing resolution, we demonstrate how to mitigate the effect of time-walk using two different approaches. The first approach is based on several Time-over-Threshold measurements; the second is based on multiple Charge-over-Threshold information. In this work we prove that these methods are not only feasibility, but they are actually giving a timing resolution which is comparable to that obtained using the full waveforms. In addition, we investigate a one-step estimation of the corrected signal arrival time using artificial Neural Networks with promising results.*

KEYWORDS - *Precise timing, Leading edge, multi Time-over-Threshold, multi Charge-over-Threshold, Artificial Neural Networks*

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I. INTRODUCTION

In the effort to resolve extremely large event multiplicities ("pile-up" events) on particle detection systems, timing capabilities can be an important feature. The typical timing resolution required for Time-of-Flight measurements in extended systems, is in the order of 10-ths of picoseconds. The PICOSEC Micromegas [1] is a gaseous detector which has been developed for this purpose and during the R&D phase it has proved the ability to time Minimum Ionising Particles (MIP) with a precision of 24 ps. Usually, the timing information is extracted with the Constant Fraction Discrimination (CFD) method that requires the full digitised waveform. Nevertheless, acquisition of the full waveform in each detection device would be impractical for systems with many channels. In order to keep the overall data transfer rate and power consumption to a minimum, it is desirable that the Front-end electronics of such a detector provide the least possible experimental information required for precise timing.

In this work we investigate how we can achieve a timing precision in the order of 10-ths of picosecond with the use of the Leading-edge discrimination timing technique and signal processing techniques applied on data collected by the PICOSEC Micromegas detector on 150 MeV muon beam [2]. In the Leading-edge discrimination technique, the Signal Arrival Time (SAT) is determined when the leading edge of the signal crosses a threshold at a fixed amplitude. Despite the fact that this timing measurement suffers from time-walk, we show that this systematic error can be corrected, and we demonstrate a very precise timing measurement.

It is well known that such a timing correction relies on the knowledge of the pulse size (e.g., the peak amplitude or the pulse integral). Usually, the pulse size is determined by employing Time-over-Threshold (ToT) measurements. Nevertheless, a single ToT measurement is not enough to derive the proper timing corrections because, the ToT value does not provide a precise estimation of the pulse amplitude and actually the precision of the estimate depends on the pulse height. To overcome this problem in the correction of the time-walk, we time the arrival of the signal at three different pulse amplitude thresholds and we also use the respective ToT information; hereafter, we refer to this technique as "multi Time-over-Threshold", multi-ToT method. An alternative way to correct for time-walk has also been investigated, where, instead of ToT, we use the integral of the pulse (i.e., the charge) above a fixed threshold; hereafter, called “Charge-over-Threshold”, CoT, method. Among the two methods, the Charge-over-Threshold method provides a better estimation of the pulse size than the ToT method, because it is almost insensitive on the pulse fluctuations near the threshold. We demonstrate here that with the Charge-over-Threshold method we can achieve timing results with the same precision as those obtained by applying the CFD method on the whole waveform. Both of these timing techniques can be easily realised in Front-end electronics; by using existing very precise constant threshold timing electronics (e.g. NINO chip [3]) or by integrating the pulse over threshold by a single ADC. Last, since a limited amount of experimental information (3 threshold crossings and the respective ADC measurements) is used, we can envisage online precise estimation of the SAT using artificial Neural Networks.

This article is organised as follows: Section 2 describes the application and performance of the multi-ToT method. In Section 3, the application and results of the multi-CoT technique are discussed. The implementation of the above techniques using artificial Neural Networks is presented in Section 4. Finally, a comparison between the methods and concluding remarks are presented in Section 5.

II. TIMING WITH MULTI-TOT METHOD AND COMPARISON WITH CFD

For the work presented here, we use experimental data collected by the CERN-RD51 PICOSEC Micromegas collaboration; a multipad PICOSEC Micromegas detector was used, exposed to 150 GeV muons provided by the CERN SPS H4 secondary beam-line. The analysis of these waveforms based on the CFD technique (timing the arrival of the pulse when it reaches 20% of its amplitude) has been published in [2].

The multipad PICOSEC Micromegas detector used for the present work has hexagonal pads with a diameter of 1 cm. Using the CFD technique, we have measured here a 50.5 ps timing resolution for all tracks passing through a single pad. When we use tracks passing within 2 mm from the center of the pad, the timing resolution has been measured to be 26.5 ps, in agreement with the aforementioned publication [2].

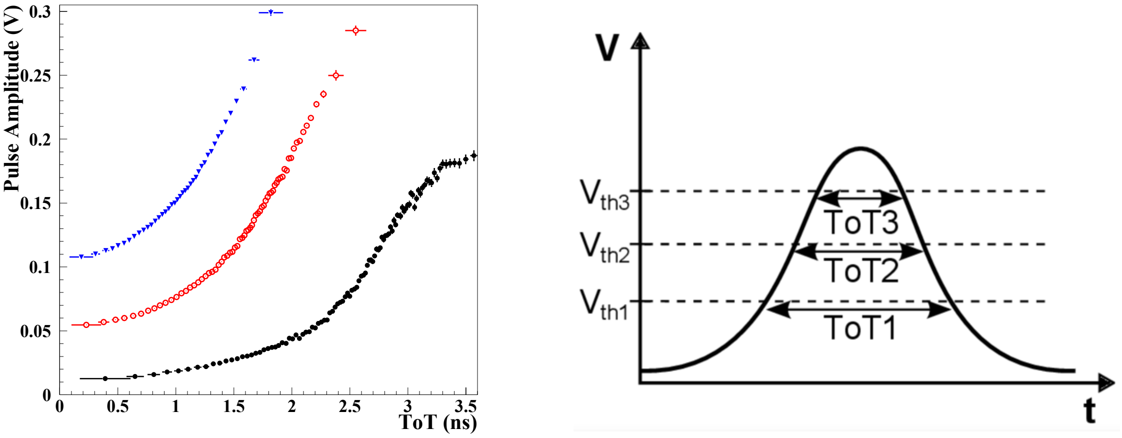

Figure 1: (Left) The pulse amplitude as a function of the ToT using 10 mV (black solid circles), 50 mV (red open circles) and 100 mV (blue triangles) threshold. (Right) A schematic description of the multi Time-over-Threshold concept.

The performance of the multi-ToT technique applied on the same waveforms is reported in this Section. The ToT method takes advantage of the fact that the shape of the pulses is, to some extent, predictable. This is due to the fact that the pulses can be approximated as standard-shape curves or a superposition of many such curves, according to the number of electrons on the anode (sensor) of a gaseous detector. Thus, all the important characteristics of the shape can subsequently be inferred from the Time-over-Threshold information. Therefore, a small amount of digitised information about the input signal can be used to realise the multi-ToT timing technique where the focus is shifted, from the full waveform, to just how long a given pulse remains above a (user-predetermined) voltage threshold. Nevertheless, this method has a defect which originates from a poor linearity between the ToT value and the pulse amplitude. For a 10 mV threshold, this relation is shown in Fig. 1 (left, black circles), where, for pulses with amplitudes up to 50 mV, the ToT value has a low sensitivity in estimating the pulse amplitude (a change in the ToT value describes a relatively small change on the pulse amplitude). Beyond this point the relation is different; a small change in the ToT value yields a large change in the pulse amplitude, resulting in a poorly known pulse amplitude prediction. Unavoidably, the accuracy of this prediction affects the precision of the time-walk correction and thus the timing resolution. Similar problems are observed in the ToT vs. pulse amplitude relation when other thresholds are used; in Fig 1 (left), the red points refer to a threshold of 50 mV, while the blue points refer to a threshold of 100 mV. In order to mitigate the problem of the changing slope and the trouble this change brings, the use of multiple constant thresholds is proposed. Various algorithms were examined, and we concluded on the use of 3 constant thresholds, as illustrated in Fig. 1 (right); for the dataset we use, these thresholds are defined at 10, 50 and 100 mV.

In Fig. 2 (left), the selection of these specific constant thresholds for the dataset at hand, is justified. In this Figure, the black solid circles present the timing resolution as a function of the pulse amplitude obtained by the CFD timing method, while in red open circles, green squares and blue triangles present the timing resolution as a function of the pulse amplitude obtained by the Leading-edge timing method and a time-walk correction with the single ToT method using 10, 50 and 100 mV constant threshold respectively. As it is evident in this Figure, the time resolution improves with the pulse amplitude. Since there are pulses with amplitudes lower than some of the thresholds, we cannot have information from all individual thresholds for all the pulses. Despite this, by using the highest among the 3 thresholds available on an event per event basis, we can achieve a resolution which is comparable to the one obtained by the CFD method. For each of these thresholds, a parameterisation of the SAT as a function of the ToT value has been implemented with the use of a 4th order polynomial. These parameterisations are then used to correct for the time-walk effect. An example of this parameterisation is presented in Fig. 2 (right) for the 10 mV threshold. Fig. 3 shows the corresponding parameterisations for a 50 mV threshold (left) and a 100 mV threshold (right).

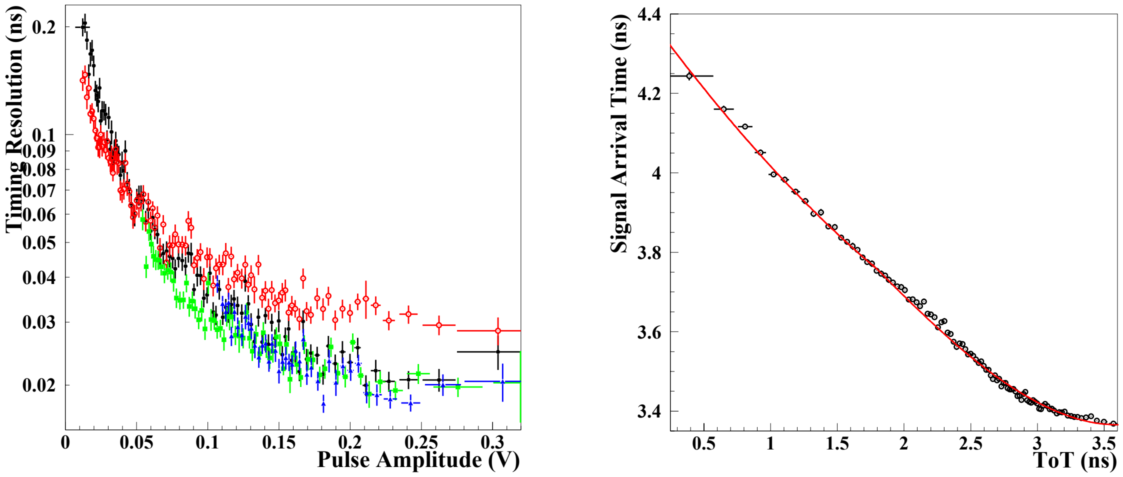

Figure 2: (Left) Compilation of timing resolution as a function of the pulse amplitude using the CFD timing technique (black solid circles), and the Leading-edge timing method corrected for time-walk using the ToT method at a constant threshold of 10 mV (red open circles), 50 mV (green squares) and 100 mV (blue triangles). (Right) The Signal Arrival Time as a function of ToT, parameterised by a 4th order polynomial for the case of the 10 mV threshold.

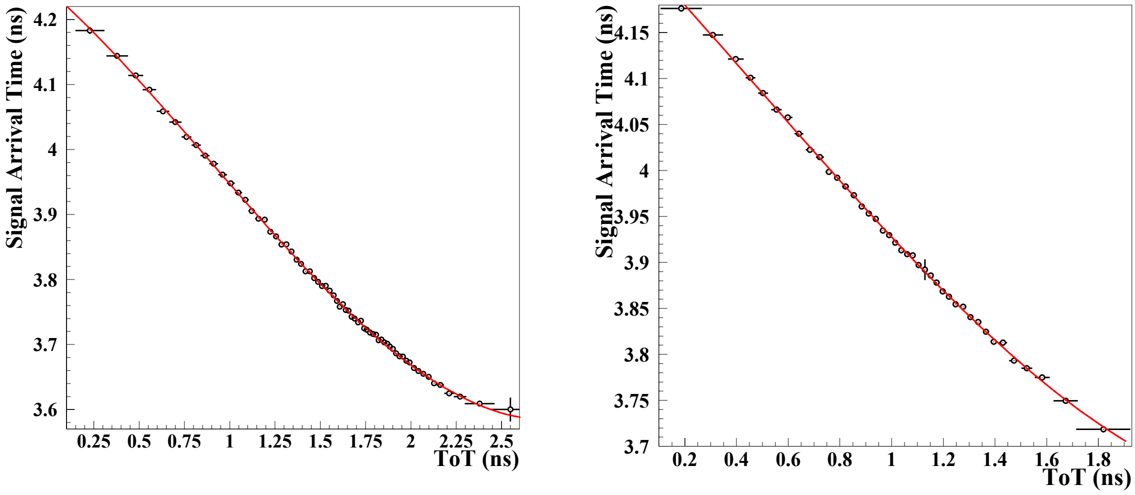

Figure 3: Same as in the right part of Fig. 2, but for a threshold of 50 mV (Left) and a threshold of 100 mV (Right).

Making use of the 3 thresholds and the respective ToT values as explained above, we obtain the SAT from the highest available threshold and we correct this SAT value for the time-walk on an event-by-event basis, using the respective ToT value. The resulting SAT distribution from this method is shown in Fig. 4 (left) for the full dataset, and (right) for events where the tracks pass within 2 mm from the center of the pad (and thus, the signal is fully contained in a single pad); the time resolution, obtained as in Ref. [1], is found to be 48.8 ps and 28.2 ps, respectively.

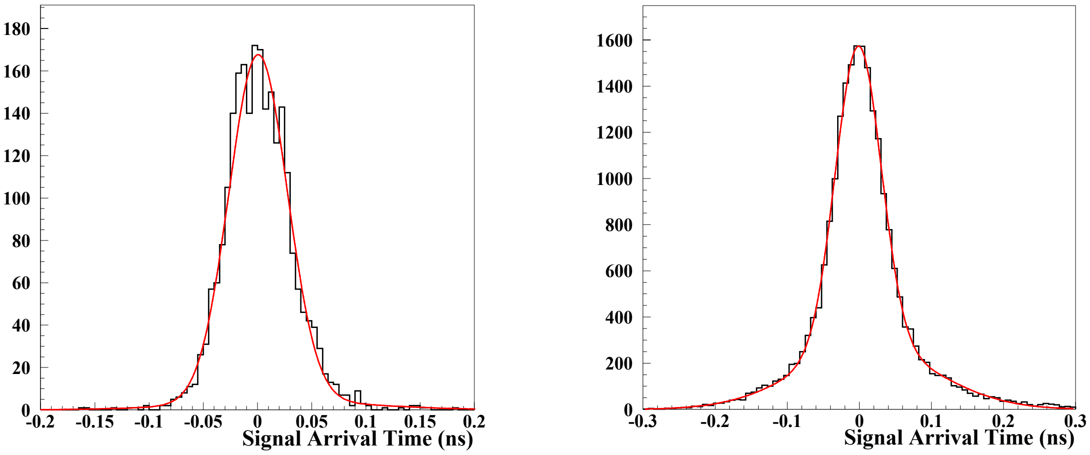

Figure 4: (Left) SAT distribution for events where the signal is fully contained in a single pad in the detector area, after time-walk correction with the multi ToT technique. Making use of the highest available voltage threshold, a 28.2 ps timing resolution is obtained. (Right) Signal arrival time distribution for the full data set. Using the same time-walk correction approach, a 48.8 ps timing resolution is obtained.

III. TIMING WITH THE MULTI CHARGE-OVER-THRESHOLD APPROACH

In this Section we investigate a method which is similar to the ToT method described in the previous section, but, instead of the time that the pulse remains above the threshold, makes use of the charge (i.e., the area of the pulse) above the threshold, as illustrated in Fig. 5 (left).

In analogy with the multi-ToT method described above, the time-walk correction is derived on an event-by-event basis using multiple Charge-over-Threshold measurements. The time-walk is directly related with the pulse size and the charge over the threshold gives an accurate estimate of this size. It is true that, since the pulse amplitude and the charge are closely related, one could have derived a time-walk correction using the amplitude of each pulse instead. However, the use of the charge is more robust compared to the amplitude. First, as mentioned earlier, the use of the pulse charge above a threshold avoids near-baseline fluctuations of the pulse. In addition, the measured pulse can be thought as the result of the superposition of individual pulses from each of the photoelectrons originating in the PICOSEC photocathode when a track passes through; the contribution of all these superimposed pulses to the total pulse charge is linear, while possible delays in the signal formation may distort the maximum amplitude of the measured pulse.

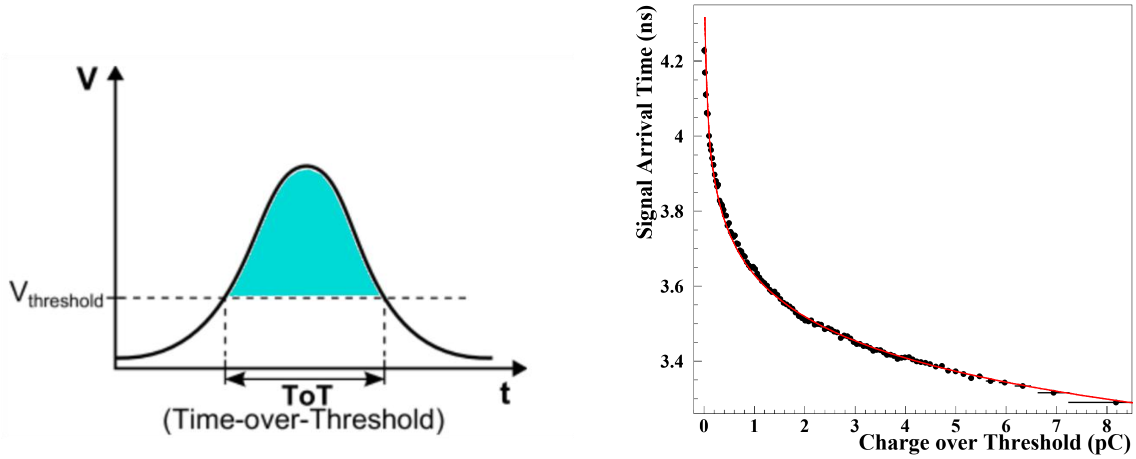

Figure 5: (Left) Demonstration of the Charge over Threshold method. The area of the pulse above the threshold (blue area) is used for the parameterisation of the time-walk correction. (Right) SAT as a function of the Charge above a 10 mV threshold. The dependence is parameterised by a power law and is used for the time-walk correction.

The justification of using the Charge-over-Threshold to correct for the time-walk in an event-by-event basis is demonstrated in Fig. 5 (right), where the SAT is shown as a function of the charge above the threshold for a 10 mV constant threshold. The functional form of this dependence is described by a power law plus a constant factor; the same functional form is valid for all the used thresholds (10, 50, 100 mV), as shown in Fig. 5 (right) and Fig. 6. Like in the multi-ToT method described in the previous Section, the parameterisation from the higher available threshold is used for the correction of the time-walk effect.

The use of the highest available among the three selected thresholds is justified in Fig. 7, where the timing resolution is shown as a function of the total charge of the pulse. The black solid circles correspond to the resolution obtained by the CFD timing technique. The colored circles correspond to the resolution obtained by using the three different constant thresholds (red: 10 mV, green: 50 mV and blue: 100 mV) to estimate the SAT and to correct it for time-walk on an event-by-event basis with the corresponding CoT parameterization shown in Figs. 5 (right) and 6. As seen in Fig. 7, when the CoT from the highest available threshold is used, the time resolution of the CoT method is comparable to the time resolution obtained with the CFD method.

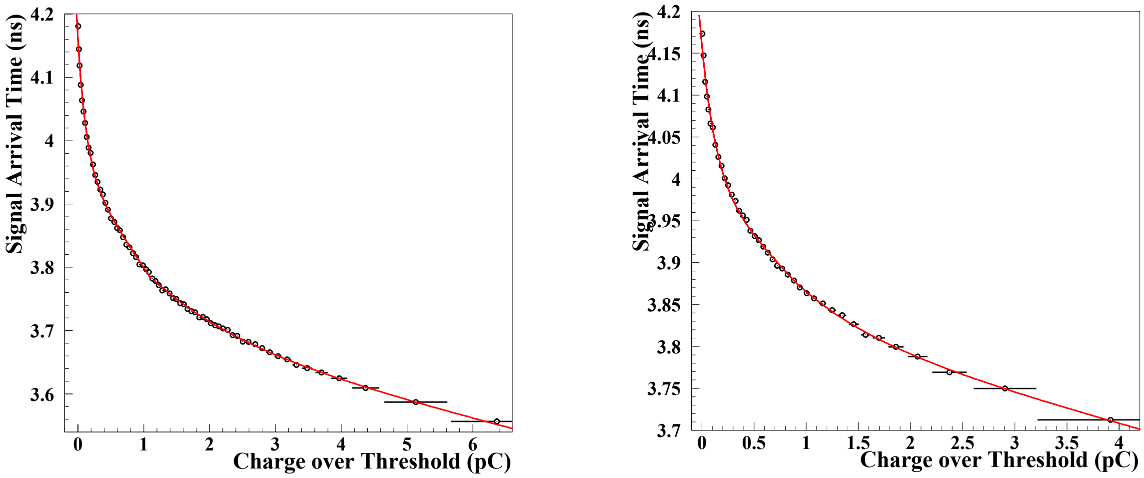

Figure 6: Same as in the right part of Fig. 5, but for a threshold of 50 mV (Left) and a threshold of 100 mV (Right).

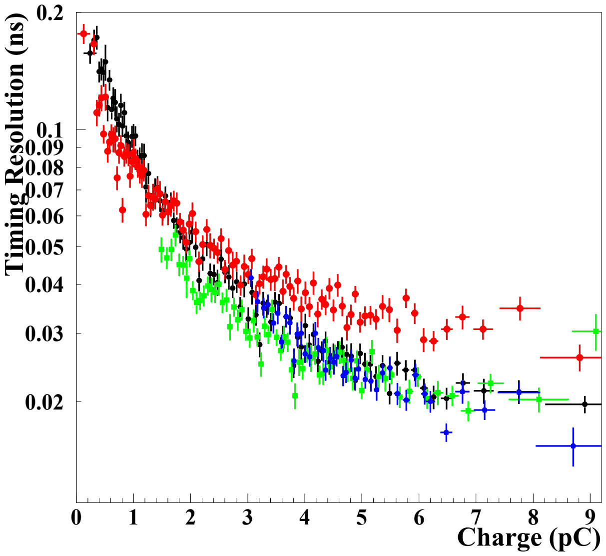

Figure 7: Compilation of the timing resolution as a function of the total pulse charge using the CFD timing technique (black), and Charge over Threshold method at 10 mV (red), 50 mV (green) and 100 mV (blue) constant threshold.

The time-walk corrected SAT distribution is shown n Fig. 8 (left) for events where the signal is fully contained in a single pad; the obtained resolution is 23.2 ps, comparable to the timing resolution obtained by the PICOSEC collaboration [1]. Additionally, a 44.9 ps timing resolution is obtained for the full dataset, shown in Fig. 8 (right); this is somewhat better than the 50.5 ps timing resolution obtained by the CFD method.

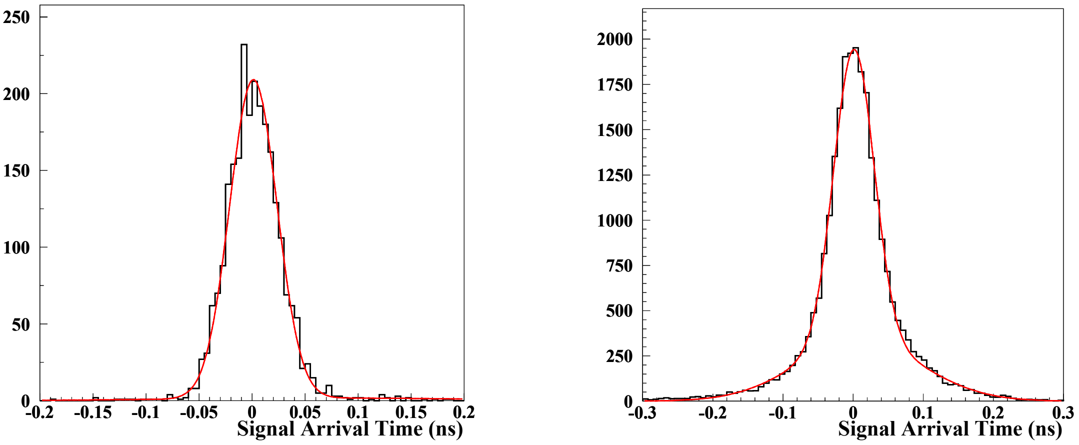

Figure 8: SAT after time-walk correction with the Charge-over-Threshold technique, making use of the highest available voltage threshold. (Left) A 23.2 ps timing resolution is obtained for events where the signal is fully contained in a single pad in the detector area. (Left) SAT distribution for the full dataset obtain a 44.9 ps timing resolution.

IV. TIMING USING ARTIFICIAL NEURAL NETWORK TECHNIQUES

In the previous Sections we described analytical methods to derive the time-walk correction on an event-by-event basis. In this Section we evaluate the use of artificial Neural Network techniques for the same task; the output of the network represents the time-walk correction on an event per event basis. The inputs to the artificial neural network are the SAT values determined by the Leading-edge method along with the corresponding ToT values, for each one of the three predefined thresholds available per event. Since the range of ToT values can be different among different datasets, we provide the network with normalised ToT values; each ToT value is normalised to the maximum ToT value observed in the dataset examined and this keeps the network agnostic of the exact dataset conditions and provides an optimum performance of the network. Since the target value of the SAT in each event is zero, the network would always predict zero whatever the input is. To avoid this, we add a random noise from a uniform distribution (-1,1) to the SAT inputs. For the training of the network, we divide the full dataset into 10 “folds” and we rotate the folds using each time 9 folds for training and one for validation. This way, we obtain 10 different predictions for the whole dataset, one from each training setup. In addition, for each fold, we enhance the dataset, by using the same training data points many times (□10), with different random noise.

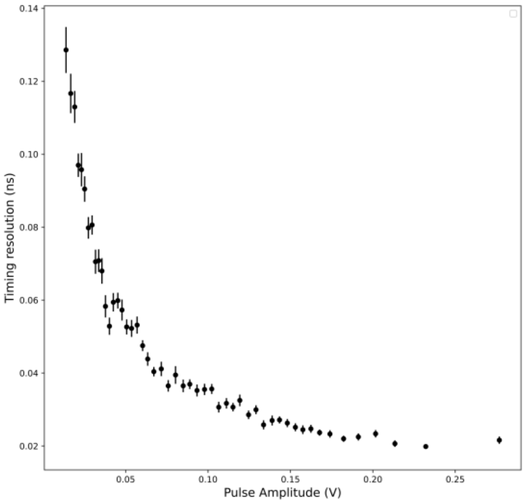

Figure 9: The SAT as a function of the pulse amplitude after time-walk correction.

Using the output of the network the SAT value is corrected on an event-by-event basis and the corrected SAT distribution yields the time resolution. Fig. 9 presents the timing resolution as a function of the pulse amplitude; this figure confirms the power law dependence of the timing resolution as a function of pulse amplitude that has been observed with analytical methods. The distribution of the SAT values (corrected for time-walk) for events where the signal is fully contained in a single pad is presented in Fig. 10 (left) and the timing resolution is found to be 25.2 ps; this value is similar to that obtained by the analytical methods presented above. The equivalent distribution for the whole dataset is shown in Fig. 10 (right); in this case, a time resolution of 46.0 ps is obtained.

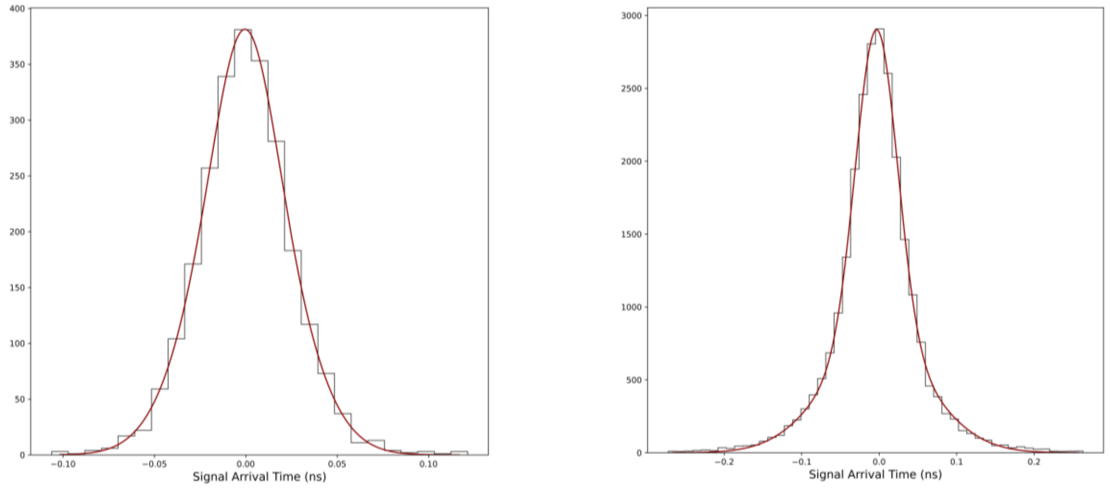

Figure 10: Signal arrival time distribution after time-walk correction using artificial neural networks techniques. (left) Events that the signal is fully contained in a single pad in the detector area obtain 24.4 ps time resolution. (Right) Timing resolution is obtained at 46.0 ps for the full dataset.

V. CONCLUSIONS

In this work we investigated the adequacy of the Leading-edge timing method to provide the timestamp of a pulse, as an alternative to the CFD method, for precise timing with a resolution in the 10-ths of picosecond. The advantage of this method is that it requires minimal information from each pulse, whereas the CFD method is applied on the full waveform of the pulse. Nevertheless, the Leading-edge timing method suffers from an inherent time-walk effect which depends on the size of the pulse. This problem was mitigated by using different approaches which have as a common characteristic the use of multiple thresholds at fixed voltage values. The multi Time-over-Threshold method provided a timing resolution similar to the CFD method, while the multi Charge-over-Threshold method yields even better results. The use of this last method in large-scale detector systems relies on the condition that the Charge-over-Threshold information can be obtained with dedicated front-end electronics. Finally, we investigated a one-step estimation of the corrected signal arrival time using artificial Neural Networks with promising results, something that encourages further investigation of neural network techniques for precise timing.

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