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Deep Neural Networks for the Calibration of Timing Detectors

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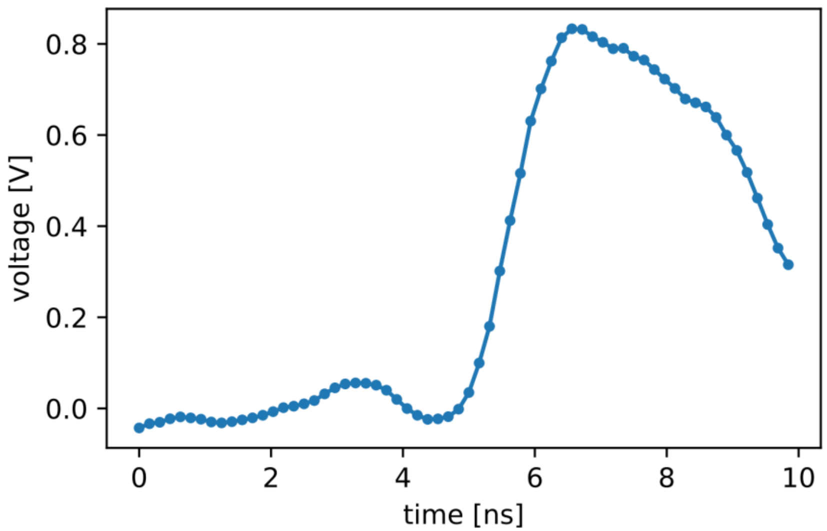
Time of arrival prediction

- Diamond detectors (*double diamond*)
  - Devised and used in the CMS-PPS system, at the LHC (CERN).
- A particle flying through a detector triggers a voltage peak.
- A sampling device produces a sampled time series of voltage.
- **Measurement goal: find the timestamp of a particle.**
- **Project goal: estimate the performance of neural networks with respect to the method used currently.**

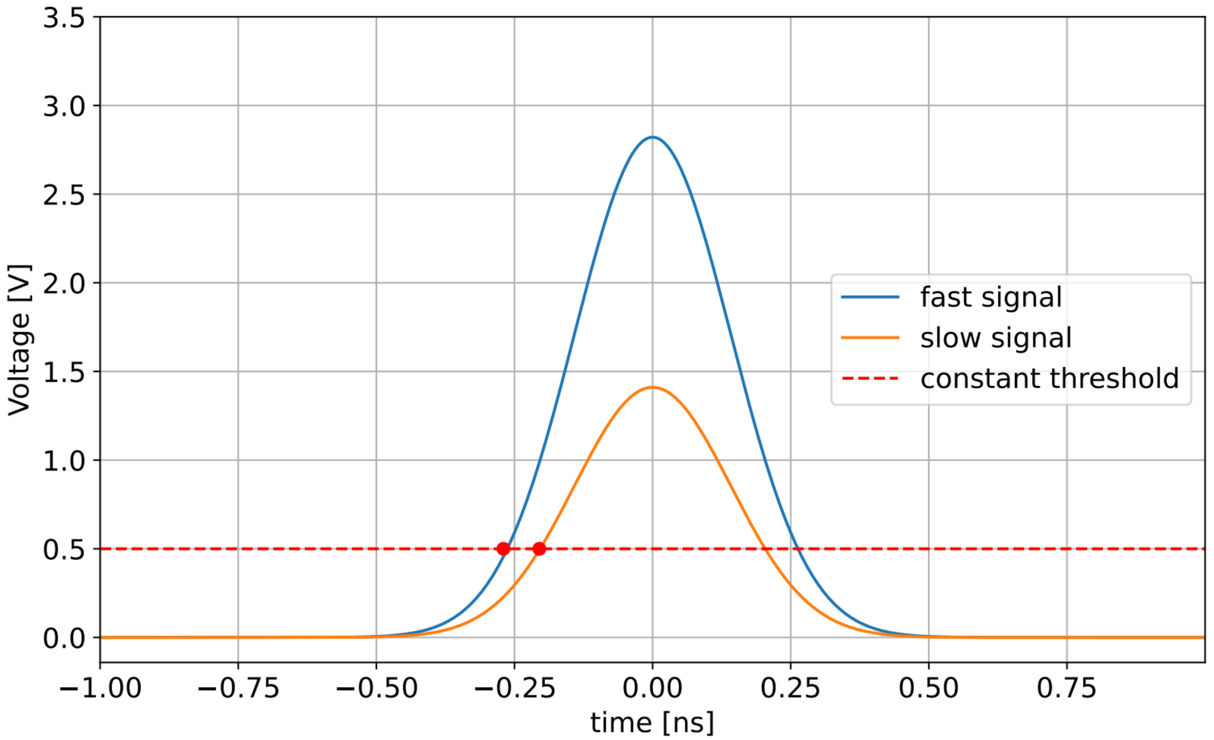


Example time series from a diamond detector

Time walk effect

» Easiest algorithm to compute the time of arrival: **constant threshold**

– Disadvantage: prone to the time walk effect

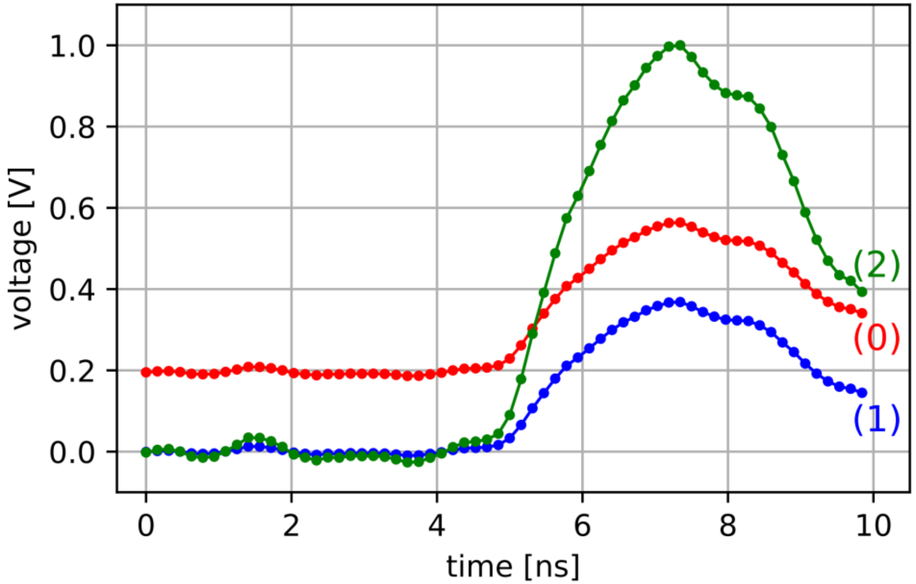


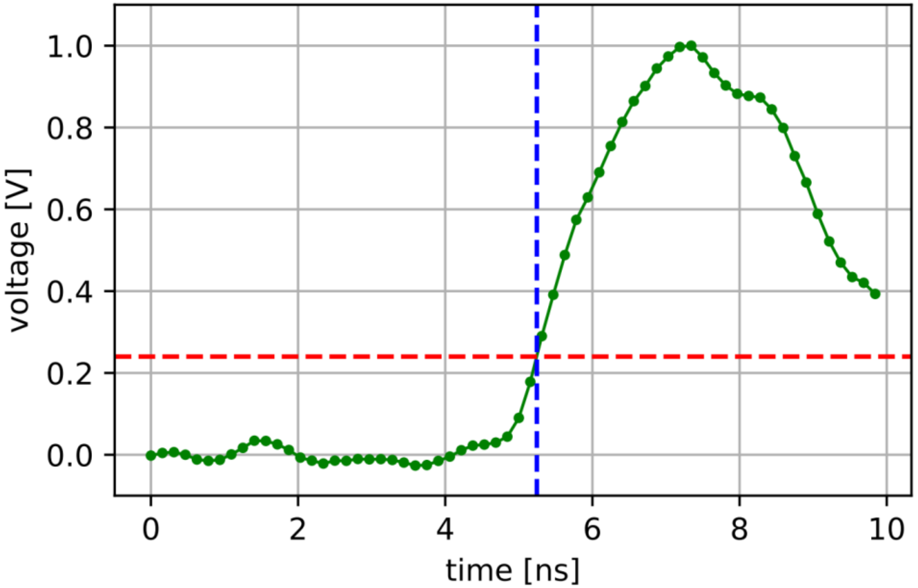
Example of the time walk effect. Although both signals reach their maximum at the same time, the threshold-crossing time is different.

Constant Fraction Discriminator

» The CFD algorithm (Constant Fraction Discriminator)

- Method used currently at the LHC
- Goal: mitigation of the time walk effect
- Implemented as the **normalised threshold algorithm** preceded by the baseline subtraction





The CFD algorithm. Left: (0) before normalisation, (1) baseline subtraction, (2) division by maximum. Right: after the normalisation the timestamp can be found using the fixed threshold algorithm

Dataset

» Data acquired in 2020 in the test beam facility at the DESY-II synchrotron.

» Diamond detectors mounted together with **much more precise MCP detectors**

  – Expected **diamond detector** precision: **50-100 ps**

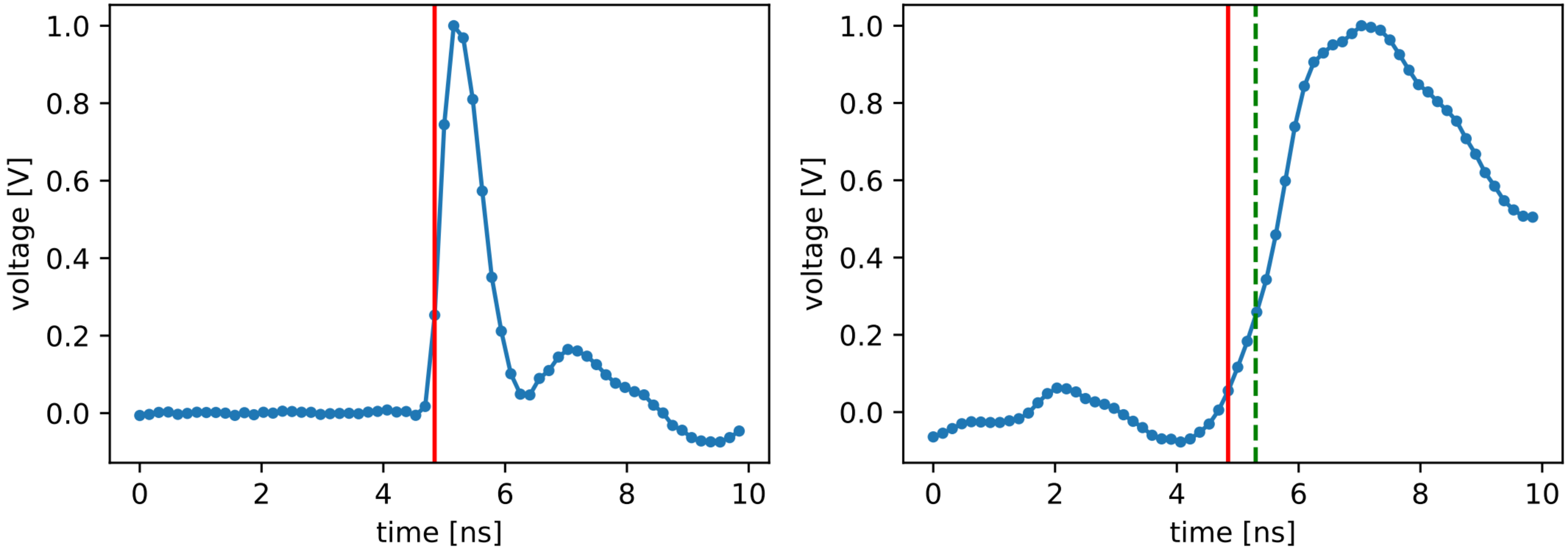
  – Expected **MCP** precision: **~10 ps**

» We used only the events where a particle was detected both by the diamond detector and MCP.

» The true timestamps (**ground-truth**) are based on the **MCP** signals.

» **Training goal: minimise the difference between the predicted and ground-truth timestamps given a time series from the diamond detector.**

Dataset example



Dataset example. Left: an MCP signal with marked ground-truth timestamp. Right: a signal from a diamond detector; red: the ground-truth timestamp (includes the t_0 shift of both signals), green: the CFD timestamps computed on the diamond detector time series (used to compare the neural networks with CFD).

Neural networks

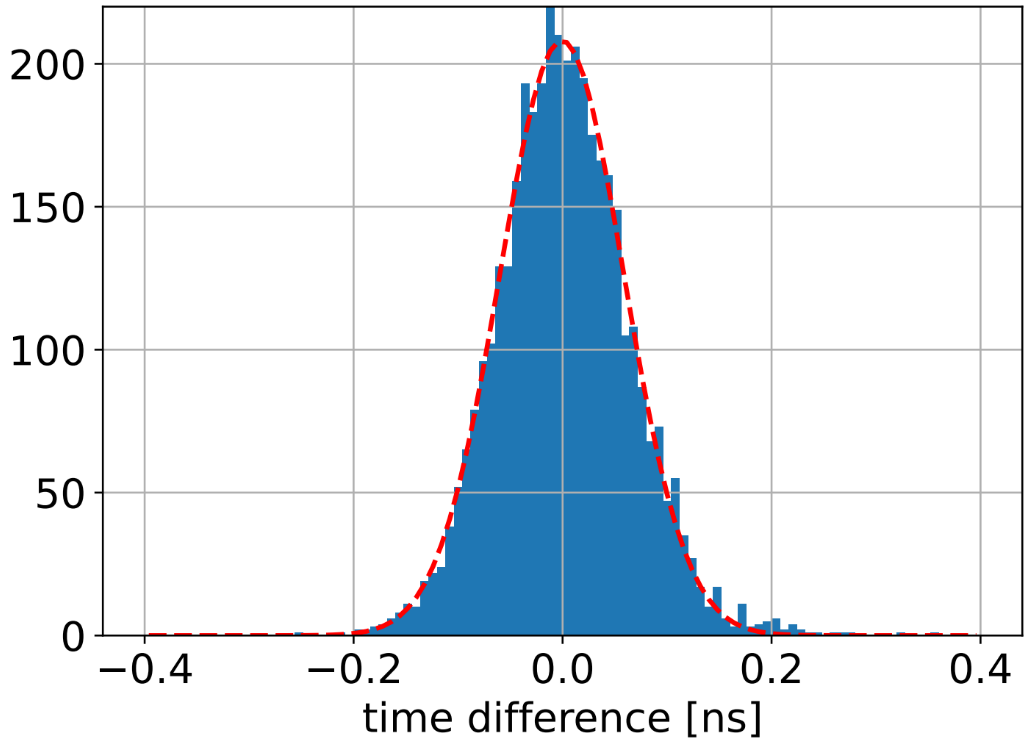
» Tested architectures
  - Multilayer Perceptron (**MLP**)
  - Regular Convolutional Neural Network (**CNN**)
  - **UNet**-based network

» Model selection done using **a two-step hyperparameter tuning procedure**.
  1. Find top five models using **keras-tuner** (a Python framework for TensorFlow)
  2. Use the cross-validation to find the optimal model.

» Following hyperparameters were optimised:
  - network depth,
  - number of neurons (dense layers), number of filters (convolutional layers),
  - batch normalisation application,
  - dropout (dense layers) or spatial dropout (convolutional layers) usage.

Precision assessment method

» Comparison with the “reference” detector – MCP
  – For each measurement: calculate the difference between the diamond det. and MCP.
  – Precision metric: std of differences
» A Gaussian can be fitted to the data to reduce the impact of outliers.
  – **Precision metric: std of a Gaussian fitted to the difference histogram**



Example difference histogram with a fitted Gaussian

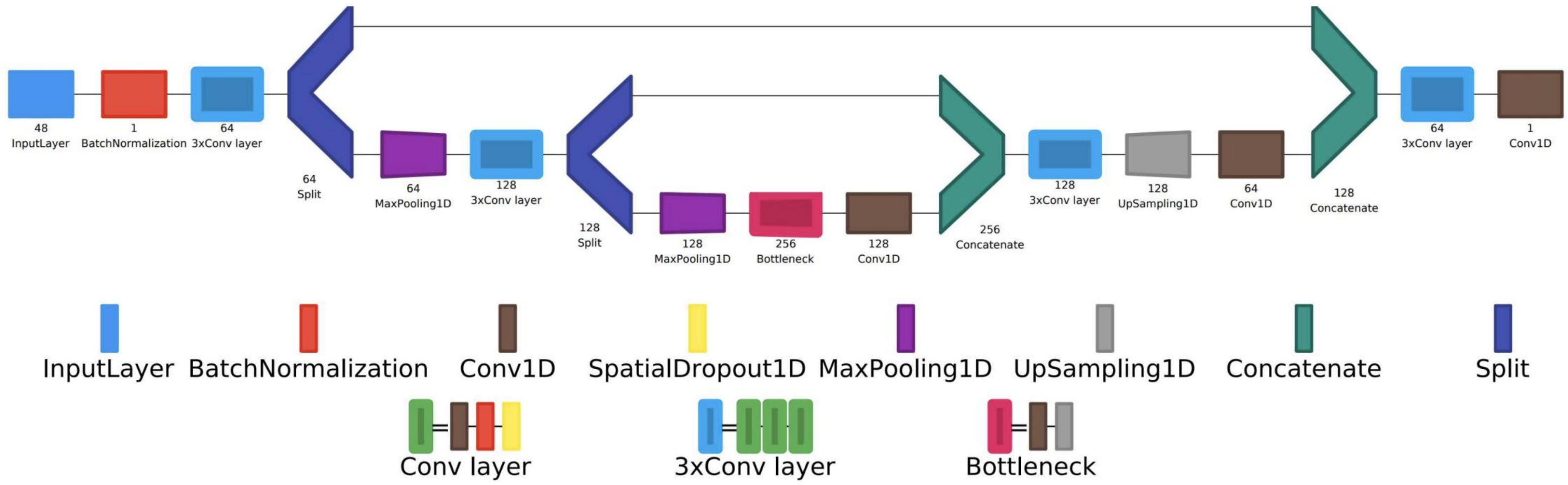
Optimal model selection

» Precision statistics computed through a **cross-validation** of the optimal models

architecture	mean [ps]	std [ps]
MLP	63.9	0.9
CNN	62.8	1.3
UNet	60.7	1.2

» **The best (smallest) precision: UNet**

UNet – optimal architecture



- Symmetric parts: encoder and decoder
- Both the encoder and the decoder contain two blocks.
  - Each block: three convolutional layers before a MaxPooling layer.
- Number of filters increases with consecutive blocks.
- Applied batch normalisation and spatial dropout (rate: 0.1)

Results

- Final results obtained with the **test dataset** not used in the previous tests
- Precision comparison with CFD:

CFD	NN	Improvement
71.6 ps	59.4 ps	17.0%

- Results for the signals trimmed to 24 samples:
  - The same length as at the LHC

CFD	NN	Improvement
73.3 ps	62.1 ps	15.3%

- The tests above were run on a single detector channel (diamond sensor).
  - The improvements for other channels **range from 8% to 23%**.

The end

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